Guoxian Pei
Editor

Microsurgical Orthopedics

Springer

Microsurgical Orthopedics

Guoxian Pei
Editor

Microsurgical Orthopedics

Springer

Editor
Guoxian Pei
Orthopedic Hospital
Xijing Hospital Fourth Military Medical University
Xi'an
China

ISBN 978-94-024-1623-7 ISBN 978-94-024-1625-1 (eBook)
https://doi.org/10.1007/978-94-024-1625-1

This Springer imprint is published by the registered company Springer Nature B.V.
The registered company address is: Van Godewijckstraat 30, 3311 GX Dordrecht, The Netherlands

Preface

Microsurgery, an emerging subdiscipline in the field of contemporary surgery, has reached a new technical height after over half a century of development and effectively improved the technology of surgical interventions. China has been in the leading tier in microsurgery worldwide. Chinese microsurgery has been admired by international peers because of its large number of clinical patients; complex, unique, and innovative operations; excellent surgical outcomes; and ingenious and exquisite microscopic skills displayed by Chinese surgeons. In fact, microsurgery is one of the proud disciplines of China which can catch the eye of the world.

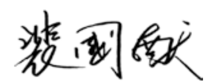
In 2013, upon the invitation of the Springer Press, l took the responsibility to compose a globally distributed English version monograph on the application of microsurgical techniques in orthopedics along with Chinese orthopedists. Considering that Chinese clinicians, many of whom may have limitation in English language, will account for a substantial proportion of the readers and that a Chinese version of this monograph will benefit much more Chinese readers as well, we made a request to Springer Press to publish a Chinese version along with this English one. Springer Press kindly agreed on publishing the Chinese version, which will be issued by People's Medical Publishing House under the authorization of Springer. The Chinese version is basically consistent with the English one in arrangement of contents except for necessary supplements in wording.

The first time for Chinese microsurgery to be noticed by the world is the successful replantation of a severed limb which was conducted by an expert orthopedist, Zhong-wei Chen, in China in 1963. Among all the areas of surgery, microsurgical techniques are applied the most widely in orthopedics, resulting in the largest number of approaches and types and the best professional talents as well. However, there have been few monographs on applications of microsurgical techniques in the field of orthopedics. Unfortunately, *Microsurgical Technique in Orthopaedics*, with Robert W. H. Pho as the leading author, published by Butterworth-Heinemann Press in 1988, is the only relative monograph in English.

This book, entitled *Microsurgical Orthopedics*, focuses on the clinical application of microsurgical techniques in orthopedic practices from the perspective of microsurgery, highlighting the repair, reconstruction, healing, and regeneration of severe traumatic injuries and complex cases in microsurgical orthopedics. From the point of view of orthopedics, this book outlines the history of microscopic orthopedics, the basic techniques, perioperative management, operation principles, indications, surgical techniques, and postoperative treatment in replantation of severed limbs (fingers), reconstruction of hands (thumbs), and transplantation of various types of tissue flap (skin flap, myocutaneous flap, muscle, fascia, composite tissue flap, small joint, bone flap, periosteal flap, and peripheral nerve). In the above chapters, new theories, new ideas, consensus views, new techniques, new diagnostic methods, new testing equipment, and new research achievements are elaborated in particular. Special chapters are dedicated to newly developed techniques in orthopedics such as limb allograft transplantation, regenerative medicine, and tissue engineering technology.

This book is the first monograph which systemically introduces application of microsurgical techniques in the field of orthopedics. It reflects the latest progress and development trends in this field in recent years, representing the latest clinical techniques. This systematic, innovative, and practical book is a clinical reference of high value. At this time when the manuscripts have been completed and submitted for printing, special thanks are conveyed to all the authors for their hard work and precious time devoted beyond their busy clinical work. I am very grateful to my editor assistants, Dr. Xing Lei and Dr. Hui-jie Jiang, for their effective work in arranging contents, coordinating, and text processing for this book. Meanwhile, I would also like to thank Dr. Chuan-lei Ji for his beautiful drawings in part of this book and Bin Hu, editor of Springer Publishing Group, for his guidance, support, and hard work in the planning, editing, and revision of the book.

As the authors are clinical surgeons from different medical institutions who are very busy in their daily practices, it is highly demanding to present all the chapters in uniform writing style and skills. Since errors and shortcomings are inevitable, feedbacks and opinions are sincerely expected from our peers for the improvement of this book.



Xi'an, China Guoxian Pei
August 2018

Contents

1 Overview of Microscopic Orthopaedics

Guoxian Pei and Huijie Jiang

1.1 A Brief History of Microscopic Orthopedics

Microsurgery refers to the surgical techniques for operations with fine surgical instruments and materials under optical amplification equipment (surgical magnifying glass or surgical microscope). Exposure to the amplified surgical field has made a breakthrough which surmounts the natural limit of human's vision, transforming a macroscopic view into a microcosmic world. This makes surgeries more accurate and exquisite, reduces tissue injuries, and facilitates tissue healing, greatly improving the quality and outcomes of surgeries. The scope of surgical treatment has also been expanded because the surgeries which would be impossible in the past under naked eyes can be conducted when tiny structures can be easily identified and manipulations can be precisely fulfilled with the aid of amplifier equipment.

Microsurgery is a new modern surgical technology which brings revolutionary changes to surgery. It can be employed in any of the surgical specialties, but not uniquely associated with a specific clinical department. Nevertheless, it has been applied the most extensively and in the largest quantity in orthopaedics due to the particularity of orthopaedics and the fact that the first successful application of microsurgical techniques occurred in orthopedics. In 1921, Nylen initiatively performed inner ear surgery for patients with ear sclerosis using a microscope. Perritt employed a surgical microscope for corneal suture in 1940, which was a breakthrough from microscopic manipulation to microscopic suture. In 1960, vascular anastomosis was successfully performed by Jscobson for small blood vessels of 1.6–3.2 mm in diameter under a surgical microscope, resulting in a relatively high patency rate. Zhong-wei Chen reported the first successful replantation of a severed limb in the world in 1963 and another successful case in 1965, marking a breakthrough in surgical replantation. In 1966, Dong-yue Yang successfully conducted the world's first case of thumb reconstruction with the second toe graft using microsurgical techniques. The successful replantation of free inguinal flap was respectively reported by Daniel and Dong-yue Yang in 1973, leading to successive success in tissue replantation (free flap, muscle, bone, periosteum and nerve) with anastomosed blood vessels. These laid a cornerstone for microsurgery which was progressing into an age of reconstruction surgery. With the progress in the microsurgical anatomy, more donor areas for various tissue transplantations have been found, resulting in more extensive clinical application of microsurgical techniques. Over the past decade in China, new innovations and progress have been made to combine microsurgical techniques with new technology and new materials, making China constantly hold a leading position in the world's microsurgical circles.

The development of microsurgery has experienced four periods over the past half century. (1) The starting period (1960s): During this period, only a few types of microsurgery were developed in limited regions, such as replantation of finger or limb, inguinal flap and thumb or finger reconstruction by toegrafting in medical centers with very good conditions. (2) Developing period (1970s): This period witnessed increasing types and expanding scopes of microsurgical application, involving multiple disciplines. Replantation of severed limbs (fingers), flap transplantation, muscle or myocutaneous flap transplantation, thumb or finger reconstruction by toegrafting, neural transplantation, bone or periosteum transplantation, and small joint transplantation as well, were all applied in clinical practices to a more or less extent. (3) Maturity period (1980s): This stage witnessed a climax in the development of microsurgery. Microsurgical techniques were widely applied in hospitals not only in large cities but also in small townships where various microsurgical operations were carried out. Almost all the surgical disciplines were involved. Microsurgery was highly recommended by the surgeons for its advanced surgical approaches and excellent curative effects. Many immature theories,

G. Pei (✉) · H. Jiang
Department of Orthopaedics, Xijing Hospital, Air Force Military Medical University, Xi'an, Shaanxi, China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_1

techniques and methods in the early days grew into mature ones. Consensus was reached in many methods, approaches and techniques which had been previously misused or ill-formed. In this period, Chinese surgeons made multiple innovative achievements, leading the world's microsurgical practice and exerting a great influence in the world. For example, the forearm flap, arterialized small saphenous vein and sural nerve transplantation, hand reconstruction, and replantation of ten severed fingers. (4) Improvement period (1990s): Further stable and sustainable developments were achieved in microsurgery in this period. Hand reconstruction, composite tissue transplantation, combined tissue transplantation, contralateral c-7 nerve root translocation in the treatment of brachial plexus root avulsion injury, and allotransplantation of hand all exerted a huge impact in the world. At the same time, interweaving microsurgery with multi-disciplines and multi-fields expanded the definition of microsurgery, such as microscopic surgery under endoscope, biological materials, tissue engineering and genetic technology, pushing microsurgery to leap forward onto a new stage.

1.2 Application Range of Microscopic Orthopedic

As a new surgical technology, microsurgery is applied in all surgical fields. In orthopaedics, microsurgical techniques are mainly used in the following aspects.

1.2.1 Replantation Surgery

Limb (finger) replantation is a classic and iconic microsurgery and an important part of its clinical applications.

Limb (finger) replantation techniques have been highly mature in China. As they are already popularized, hospitals at all levels are able to perform this surgery skillfully, giving a success rate up to 98%. In addition to regular replantation of severed limbs (fingers) in good conditions, successful replantation can be achieved for severed limbs (fingers) in poor or complex conditions, like those with rotational avulsion, multi-segments, longitudinal crack, skin defect, and soaking wounds. Limb (finger) replantation has succeeded in children and the elderly, from the proximal to the distal, from one single digit to ten digits, and from one limb to four limbs. These innovative achievements indicate replantation surgery technology has reached a very high level.

1.2.2 Reconstructive Surgery

The representative operation for reconstructive surgery is reconstruction of hand, thumb or finger using the second toe grafting with vascular anastomosis. In this surgery, an autologous toe is transplanted at one stage to the defect at the hand, thumb or finger and the blood vessels and nerves are anastomosed using microsurgical techniques, to recover the basic appearance and function of the original hand, thumb or finger. This surgery has been widely performed in clinic, benefiting numerous patients with their hand, thumb or finger missed.

Toegrafting techniques can be used to reconstruct the thumb and fingers with various degrees of defect, and to reconstruct part of a finger, one entire finger, or even multiple fingers. For patients with multiple finger defects, the unilateral great, second and third toes can be harvested to rebuild a thumb and two fingers. For patient with five finger defects, one-stage combination transplantation can be done using the great, second and third toes on one side and the second and third toes on the contralateral side as well to reconstruct all the five fingers. At present, thumb and finger reconstruction with toegrafting in China is much advanced worldwide in terms of operative variety, quantity and popularity.

1.2.3 Nerve Repair

Repair of peripheral nerve injury used to be performed by simple epineurium suture under naked eyes for a long time, without accurate anastomosis of nerve bundles, resulting in axon escaping, glioma or nerve tumor which remarkably compromised the outcomes of nerve regeneration. Accurate anastomosis of perineurium and epineurium under a microscope can significantly improve the outcomes of nerve repair. Today, microsurgical repair techniques have become conventional in the treatment of peripheral nerve injury.

1.2.4 Tissue Transplants

Tissue transplantation includes pedicled tissue grafting and revascularized free tissue grafting. In microsurgery, it is the most widely applied, involving brain and maxillofacial surgery, oral surgery, urology, gynecology and obstetrics, general surgery, plastic surgery and orthopaedics where tissue transplantation is the most extensively applied. According to the types of tissue transplants, it can be categorized into skin flap transplantation, muscle flap graft, myocutaneous flap transplantation, nerve transplantation, bone graft, periosteum graft, and small joint transplantation.

In recent years, with constant improvement of microsurgical techniques, a large number of composite tissue transplantations and combined tissue transplantations have been carried out in clinic. The former refers to the transplantation of a vascular pedicle combined with at least two kinds of tissue such as bone flap and musculoskeletal flap; in the latter procedure, after tissue flaps with two different vascular pedicles are harvested, the two vascular pedicles are bridged followed by vascular anastomosis with the vessels in the recipient area for combined transplantation, such as combined transplantation of skin flap-skin flap, combined transplantation of toe-skin flaps and combined transplantation of bilaterally sourced multiple toes, etc.

1.2.5 Applications in Other Surgical Field

The ever-developing microsurgical techniques expand their indications more and more, involving all the surgical fields. For example, operations for intracranial-extracranial artery bypass, intracranial tumors, and cerebrovascular malformation in neurosurgery; removal of cornea or intraocular foreign bodies, and intraocular tumor operations in ophthalmology; deafness treatment and electronic cochlear implant operations in otolaryngology; repair of tissue defects or deformities in oral and maxillofacial surgery; coronary artery bypass transplantation, esophageal defect repair by bowel segment grafting in cardiothoracic surgery; replantation of renal blood vessels, ureter, bladder and testis and severed penis in urology; tubal repatency, ovaries restoration and transplantation in obstetrics and gynecology. Application of noval microsurgical techniques in these disciplines has tremendously expanded their operative indications, upgraded operative outcomes, and boosted their development.

1.3 Indications for Microscopic Orthopaedic Surgery

As a cutting-edge surgical technology, microsurgery applies to all surgical disciplines. With the development of microsurgery, its applications are broadened dynamically and so are its indications. It is very difficult, or even infeasible, to define its overall "surgical indications" to cover all the cases possible. However, despite of its broad applications in various sub-disciplines and enormous types of surgical procedures, microsurgical surgery follows some basic common principles and rules or presents some common characteristics. The following principles should be abided by in determination of microsurgery indications: (1) When a similar outcome could be achieved by simple conventional surgery, microsurgery is not indicated which is relatively complex. (2) When a similar outcome could be obtained by repair using adjacent tissues without vascular anastomosis, free tissue transplantation with anastomosis is not indicated. (3) Only tissues from less important part can be used as the transplant donors to repair the more important recipient sites. (4) The function and appearance of a recipient site should be taken into consideration while the damage to function and appearance of a donor area should be minimized. (5) If an optimal surgical outcome can be probably achieved only by elaborate microsurgery, it is not proper to choose conventional simple surgery under naked eyes for fear of the complexity and challenge of microsurgery.

1.4 The Developing Trends of Microscopic Orthopaedics

In an age of knowledge explosion, rapid changes in science and technology make all the disciplines and fields progress in a closely interwoven manner. New knowledge and new technologies in related disciplines and subjects have already penetrated into every link of microsurgery. The theories and techniques in microsurgery have been closely connected to the development of the relevant fields. Multidisciplinary integration and communication is the inevitable way and also an irresistible trend for microsurgery to make progress. Only in this way can microsurgery maintain a constantly reinvigorated status.

Microsurgical studies should be carried out in a longitudinal manner. That is to say, exploration in each subfield should be deepened and clinical application of lab research results strengthened. A gradual transition should be promoted from morphological, methodological and surgical studies to a combination of microsurgery with high and new technology, new biological materials, endoscopic technology, information technology, artificial intelligence technology, digital technology and regenerative medicine technology. An interdisciplinary development and integration of multiple disciplines and multi-fields can constantly inject new vitality into the development of microsurgery.

Learning from the history and the status quo of microsurgery, we know that the idea of advancing with the times and innovative thinking are of great importance for microsurgery to seize the opportunities for further development. It is our responsibility to make another leap in microsurgery and promote its progress in a sustainable manner by exploring a new mode of development, endowing new connotations to this discipline, and seeking for interdisciplinary development.

Bibliography

1. Zhu J-K. Microsurgery. 1st ed. Beijing: People's Medical Publishing House; 2008. p. 3–7.
2. Wang C-q. Cheng-qi Wang microsurgery. 1st ed. Jinan: Shandong Science and Technology Press; 2009. p. 1–11.
3. Bunck HJ, et al. The fate of autogenous whole joints transplanted by micruvascular anastomoses. Plast Reconstr Surg. 1967;39:333.
4. Cobbett JR. Free digital transfer. J Bone Joint Surg. 1969;51:677.
5. Finley JM, et al. Revascularlzed periosteal grafts. A new method of produce functional new bine without bine graftiug. Plast Recostr Surg. 1978;61:1.

2 Basic Techniques of Micro-Orthopedics

Chunguang Duan and Dawei Zhang

2.1 Basic Microsurgical Techniques

2.1.1 Microsurgical Instruments

2.1.1.1 Magnifier and Magnifying Spectacles

1. Head-mounted surgical magnifier: This magnifier is composed of a negative lens and a positive lens, which are generally connected with the optical frame (Fig. 2.1). Its pupil distance (PD) can be adjusted through the cross bar near the glasses and its focal distance can be adjusted through screwing in or out the objective lens to adapt the surgeons with different diopters. Its amplification factor is also adjustable, generally 1.5–4 times. Light source can be installed between the two magnifiers for the lighting of operation field. The head-mounted operation magnifier has two limitations. (1) As it offers a poor three-dimensional vision and a limited amplification factor to the surgeon, it is very difficult to conduct refined operations with head-mounted operation magnifier. (2) When the surgeon's head moves, the operation distance and visual field will also change correspondingly, leading to a blurry vision. So, a head-mounted operation magnifier is not suitable for long-time operation, and mostly used for anastomosis of large blood vessels, e.g., the ulnar artery and the radial artery.
2. Operation microscopes: They include single binocular microscope, double binocular microscope and triple binocular microscope, of which double binocular microscope is often employed for surgeries. An operation microscope is composed of optical system, lighting system, control system, stand and accessory equipment (Fig. 2.2).
   (a) Optical system: It consists of objective lens, lens cone, ocular lens and zoom expender. The objective lens, as a lenticular lens, is mainly used to collect

Fig. 2.1 Head-mounted surgical magnifier

reflected light in the operation field. The lens cone can image an object within the operation field through the convergence lens at the distal end of lens cone. The ocular lens, with common amplification factors of ×6, ×10, ×12.5, ×16, ×20, is responsible for re-amplification of the intermediate image in the binocular lens cone. Rubber blinders always come along with the ocular lens of an operation microscope to prevent a surgeon from being distracted by the side light when observing through the microscope. The ocular lenses have a function to correct ametropia within a range from −8D to +8D for myopic or hyperopic surgeons, but those with astigmatism still need an extra pair of glasses for vision correction. The zoom expender on the microscope can work in two different manners: stepping variable power and zooming continuous variable

C. Duan · D. Zhang (✉)
Department of Orthopaedics, Xijing Hospital, Air Force Medical University, Xi'an, Shaanxi, China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_2

Fig. 2.2 Double binocular microscope

power. Stepping zoom expender, featuring compact structure and low cost, allows amplification in several specific zooming ratios; while continuous zoom expender, also called non-stepping zoom expender, is more precise than stepping zoom expender and allows a clear image within the whole amplified vision field.

(b) Lighting system: The lighting system, as an essential component for an operation microscope, can be installed inside or outside the lenses and is composed of light source and light path. A traditional light source is an incandescent bulb or a halogen bulb, while a xenon lamp which is usually employed in new types of operation microscope as the major light source is a newly-developed light source featured by offering brighter vision field and producing lower heat. The light path includes two different patterns—co-axial lighting and off-axial lighting. The former means that the light reaches the operation field through an optical collector and the main objective lens and the light path shares the same axis with the microscope; the latter means the light passes the objective lens and reaches the operation field from the lateral side. Today, operation microscopes are mostly in co-axial lighting pattern.

(c) Control system: Movement of visual field, adjustment of focal distance and amplification factor can all be controlled through an electronic foot-switch or a hand-switch.

(d) Support system: According to the way of installation and placement, it is categorized into desktop, floor, ceiling or wall, and balanced models, among which the floor model is the most commonly used.

(e) Accessory equipment: It includes assistant lenses (for co-operator use), demonstration lenses (for surgery-visitor use), an operation seat, recording apparatus (for photo taking and video shooting), etc.

2.1.1.2 Common Microsurgical Instruments

1. General requirements for microsurgical instruments
   As microsurgical surgery usually requires refined operation, it is very demanding on quality, precision and convenience of the instruments. Furthermore, since most of the operations are carried out through the rotating movement of the operator' fingers, the microsurgical instruments shall be installed with a spring handle to alleviate fatigue of the operator's hands, and the handle is carved with grains so that surgeons can hold it in a stable manner.
2. Common microsurgical instruments
   (a) Microscopic tweezers (Fig. 2.3): They are smooth tweezers the occlusal surfaces on the tip of which are grainless so that they will not break suture threads and are easy to clean after surgery. Their tip must be fine and the edges on the tip shall be free of corner angles or rough surfaces. Besides, their occlusal surfaces shall be gapless when they are closed. Their handle is designed as cylindrical in shape to make the rotating movements and other operations easier and more stable. The locating pin inside the handle can prevent the tips from misposition and allow more accurate occlusion. The lateral edges of handle are coarsely grained aiming to increase friction and allow a more stable holding by surgeons. Microscopic tweezers can be used in operations for the following purposes. (1) To assist needle-holding: They are employed to locate a suture needle to a desired position and direction so that the needle-holder can easily hold the needle. (2) To assist suture: They are used to hold a blood vessel, epineurium or other tissues to facilitate inserting, holding and withdrawal of needles; they can also be inserted into a lumen to facilitate suture. (3) To assist knot-tying: They can hold the needle-holder or suture threads to tie knots.

Fig. 2.3 Microscopic tweezers

Fig. 2.4 Microscopic needle holder

(b) Microscopic needle holder (Fig. 2.4): Since regular small needle holders are incapable of holding microscopic needles or suture threads, specifically-made microscopic needle holders are highly required. Compared with ordinary needle holders, a microscopic one has no tooth lock catch at the rear, which will avoid damage to tissues and slip-off of needles and suture threads caused by bounce and vibration of the holder in clamping and loosening operations.

Fig. 2.5 Microscopic surgical scissors

Besides, the occlusal surfaces of a microscopic needle-holder are grainless to avoid breaking suture threads. Microscopic needle holders are mainly used for needle holding, stitching and making knots in surgery.

(c) Microscopic surgical scissors (Fig. 2.5): They are usually 12–16 cm long. Unlike the roundness design of ordinary surgical scissors, the tops of microscopic surgical ones are sharp or bluntly sharp. Their handle is cylindrical in shape and can be easily rotated towards all directions by surgeons. Their tail is provided with a leaf spring to allow easy opening and closing of the scissors. Their cutting leaves are straight or curve. Microscopic scissors are mainly used to peel off tissues and prune blood vessels and lacerated nerve ends as well as to cut suture threads.

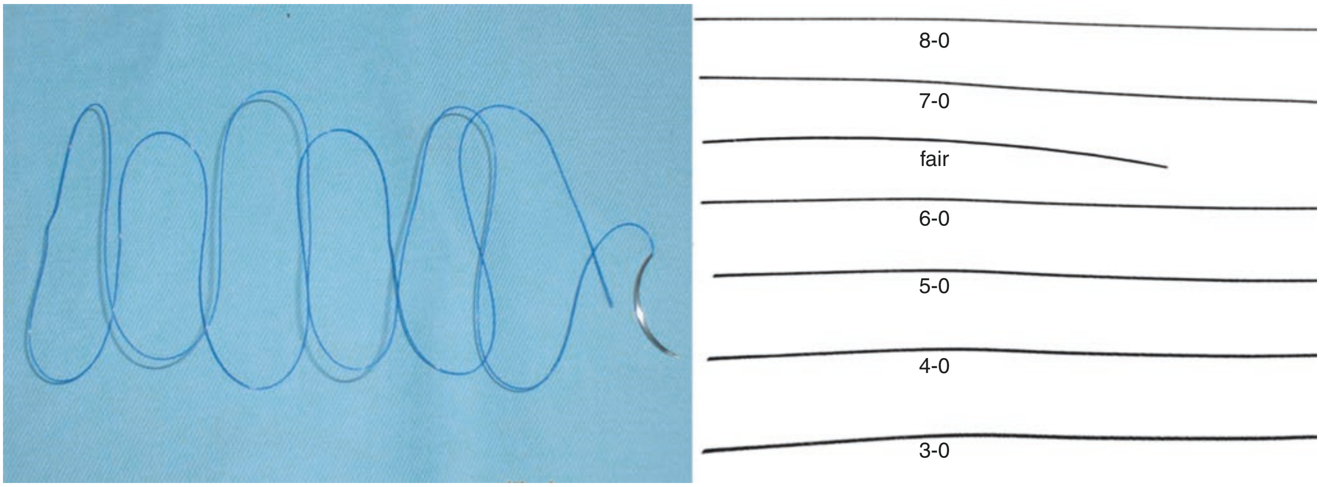


Fig. 2.6 Microscopic needle and suture threads

(d) Microscopic needle and suture threads (Fig. 2.6): As microscopic suture threads are required to be thin, highly strong and smooth, threads made of natural fibers can hardly meet the requirements. Currently, the suture threads are usually made of composite materials, e.g., chinlon (nylon thread) and polypropylene (e.g., Prolene thread). Featuring high tensile strength, uniform quality and slight tissue reaction, suture threads made of composite fibers are suitable for microscopic operation, though these kinds of thread are mostly non-absorbable. Needles and suture threads used for microsurgery are thin and do not leave marked needle eyes as in a general surgery. Besides, as threading a microscopic needle in the middle of microsurgery is not allowed, which is different from the requirement of general surgery, and microscopic suture threads are smoothly and tightly fixed to suture needles, the microscopic suture threads are also called "damage-free suture threads".

The suture needles for microsurgery are generally curved ones. The degree of curvature, also used to describe the specifications of needles, is expressed with the aid of a circumference—cut a circumference into eight equal parts, and measure how many of 1/8 circumference a needle equals to. There are three commonly used needles—3/8, 1/2 and 1/4 of circumference respectively. Domestic microscopic needles are mostly 3/8 circumference ones as they are easy to handle. The length of a suture needle is related to its diameter—the smaller the diameter, the shorter the length. The body of a domestic suture needle is round to prevent unnecessary damage to tissues. Microsurgery suture needles are also categorized into single-needle (a suture with a needle at one end) and double-needle (a suture with a needle at both ends). The specifications of domestic suture needles and suture threads are mainly identified according to the thickness of suture threads. Namely, suture threads of the same specification have the same length and are always equipped with needles with the same thickness and length. However, domestic needles are all 3/8 circumference round ones.

3. Maintenance of microscopic instruments

As microsurgery requires fine instruments, which is different from general surgery, maintenance of the instruments is also demanding. Pre-operative inspection is required to check if the instruments are damaged and if they are suitable for the operation. A variety of conditions should be checked, such as surface perfection, polish quality, scratch, hard spots and rusty spots, degree of tightness, cutting performance of the scissors, and cracks on the cutting edge of scalpels. Make sure the holding surfaces of needle holders can be tightly closed and can hold needles and sutures in a stable manner. The instruments should be repaired or replaced if they are not suitable for the surgery. In the surgical process, the instruments should be handled gently—do not hold tissues like bones, muscle tendons, ligaments with microscopic tweezers or other fine instruments. Properly hold the objects just to prevent them from slipping down. Do not hold the handle of instruments too tightly; always avoid placing the instruments with their tip downward. The instruments should also be appropriately treated after use—clean the instruments and wipe them dry with soft cloth; avoid collision with common instruments or hard articles (e.g. metals or stones); avoid slipping off; store them in a dedicated package with foamed plastics inside to avoid collision.

Fig. 2.7 Sitting position of the surgeon

2.1.2 Basic Technique Training

2.1.2.1 Application of an Operation Microscope

1. Sitting position of the surgeon (Fig. 2.7): Microsurgery usually takes a long time and the surgeon will feel fatigue if sitting in an improper position. Therefore, the surgeon should sit in a most comfortable manner—straighten up the backbone, do not shrug shoulders or tilt the head, slightly bend the upper body forward, stretch the lower limbs naturally under the operation table and keep feet flat on the floor or foot-switch, underlay the wrists with cushion and do not leave them hanging in the air to prevent tremble of fingers.
2. Fixation and exposure of operation tissues: As microsurgery requires high precision and slight tremble under naked eyes will be amplified to significant shaking under a microscope, the operation tissue shall be stably fixed and fully exposed.
3. Microscope adjustment: A microscope generally works at a distance about 20 cm. If the distance is too long observation and operation by surgeons may be difficult while if it is too short the operation instruments will touch the lens. Once a working distance is identified, the surgeon and assistant will obtain optimal operation fields through adjusting pupil and focal distances. The surgeon and assistant generally sit opposite to each other (separated by 180°) or next to each other. Some microscopes are provided with observation lenses for nurses or surgery visitors, but they should avoid touching the observation lenses.

2.1.2.2 Application of Microsurgery Instruments

1. Holding method: To ensure accurate and stable operation movements and minimize the tremble during operation, the operator is required to hold the instruments in a pen-holding manner with three or four fingers (Fig. 2.8)—stably hold the microscopic needle holder in a tilted way on the first web with the thumb, index finger and middle finger.

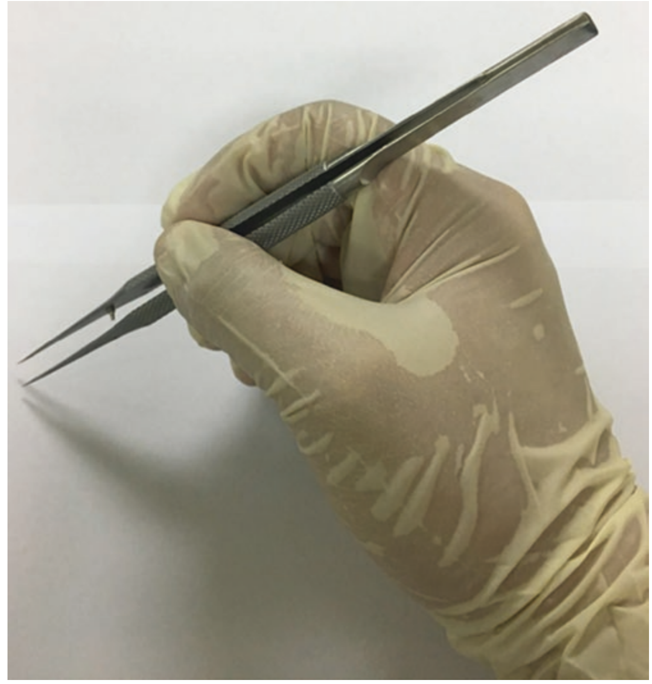


Fig. 2.8 Method for holding microscopical instruments

2. Application method: The body of a microsurgery instrument is generally round, enabling operators to run the instrument controller with fingers more easily. The thumb, index finger and middle finger are usually used to run the instruments, and the wrist is also hired to assist bigger movements, e.g., leading sutures or tying knots. Try to avoid elbow joint movement during operation.

2.1.2.3 Training of Basic Operation Techniques

1. Non-invasive techniques: The goal is to minimize the damage caused by surgical instruments and operations. As microsurgery always involves cutting, isolation, ligation, hemostasis and suture of tissues, the most common damage in these operations is tissue damage caused by tweezers. Therefore, operators are required to avoid holding tissues, especially vascular smooth muscles and tunica intima vasorum, with tweezers unless necessary. Try to hold the tunica adventitia vasorum when tweezers are needed for assisting operations.
2. Hand-eyes coordination training: Unlike in surgery under naked eyes, beginners of microscopic surgery have difficulty in determining the accurate positions of instruments. So, long-time training is necessary to get accustomed to the condition. The practice procedure is as

follows: learn to use tweezers and scissors, clamp and cut gauze and suture threads in the first place; next learn to suture gauze or rubber gloves as well as to suture, lead threads, tie knots and cut stitches with tweezers and needle holders. Surgical operation training can be carried out when an operator is proficient in these basic operations. Beginners can start with blood vessels and nerves of chicken thighs and then tail arteries of rats. Training items include isolation, cutting, suturing and general inspection of blood vessels.

2.2 Microscopic Vascular Anastomosis Techniques

2.2.1 Basic Principles for Microscopic Vascular Anastomosis

2.2.1.1 Non-invasive Principle

As the tissue of a small blood vessel is delicate, operators must always remain vigilant in the suture process to avoid man-made injury to the vessel tissues. Do not clamp the endangium tissue in particular. Appropriate non-invasive suture threads shall be selected when suturing the blood vessels. See Table 2.1 for detailed options.

2.2.1.2 Proper Tension Principle

Hypertonia of an anastomotic stoma will tear apart the blood vessel while hypotonia will cause tortuosity of the blood vessel after blood circulation is recovered. Both tearing and tortuosity of a blood vessel may trigger thrombosis of the anastomotic stoma, resulting in failure of the surgery. The lacerated ends of a blood vessel shall be adjusted to an appropriate position before anastomosis, and the blood vessel should be sutured with a proper tension but without distorting stress.

Table 2.1 Non-invasive suture threads for blood vessels with different diameters

Diameter of blood vessel (mm)	Model of suture threads	Blood vessels
>5.0	3-0 ~ 5-0	Thoracic aorta and abdominal aorta
3.0 ~ 5.0	6-0 ~ 8-0	Femoral artery, brachial artery and popliteal artery
2.0 ~ 3.0	8-0 ~ 9-0	Ulnar/ radial artery and dorsal pedal artery
1.0	10-0	Digital proper arteries of fingers (toes) and common digital artery
0.5	11-0	Digital proper arteries from proximal interphalangeal joint to distal interphalangeal joint
0.2	12-0	Branches beyond finger (toe) arterial arch

2.2.1.3 Approximate Diameter Principle

Anastomosis of blood vessels requires similar diameters of the lacerated ends, otherwise the anastomosis will be difficult to conduct, and blood leaking, vortex and subsequent thrombosis may happen after surgery. When diameters of two lacerated ends are quite different, operators can take measures to narrow the end of the thicker blood vessel or to expand the thinner end by making a diagonal cut to match the two ends. End-to-side anastomosis can also be adopted if the two ends are too different in size to match.

2.2.1.4 Principle of Even and Extrophy Anastomotic Stoma

Uneven or introverted anastomotic stomas will cause focal mural thrombosis. Operators should adopt extrophy suture for blood vessels with a diameter >1 mm, and apposition suture for blood vessels with a diameter <1 mm.

2.2.1.5 Principle of Evenness and Symmetry of Edge Distance and Needle Pitch

Operators should try to perform anastomosis with minimal sutures to minimize injury to blood vessels. Evenness and symmetry of edge distance and needle pitch are prerequisite for a high-quality blood vessel anastomosis. An excessive edge distance will cause introverted vessel walls and anastomotic stenosis while a too short edge distance may result in vessel wall laceration. The needle pitch should be about 2 times of an edge distance.

2.2.2 Methods of Microscopic Vascular Anastomosis

2.2.2.1 Basic Skill Training for Microscopic Vascular Anastomosis

Basic trainings should enable operators to be proficient in using a microscope, a microinstrument, non-invasive techniques and hand-eye coordination. In addition, microsurgical suture practice with silicone tubes can also be adopted in the training.

2.2.2.2 Methods of Anastomosis

1. Management prior to anastomosis
   (a) Separate the lacerated ends of a blood vessel: The two ends of the blood vessel shall be properly denudated with the adjacent joints kept in a semi-flexion posture to reduce tension on the blood vessel. Some inessential collateral branches can be cut off to increase the freeness of a main artery.
   (b) Examine the blood flow: Active blood ejection at the proximal end of the artery can be observed when operators are cleaning the injured tissues in the pre-

determined vessel resection field in the debridement procedure. If not, operators should consider that thrombus may exist at the proximal end of the blood vessel and insert a plastic needle into the artery for aspiration and irrigation. If it still does not work, operators should cut off another length of blood vessel. If the bleeding is active, a vascular clamp should be used to block the bleeding. Then loosen the vascular clamp at the distal end of the blood vessel to examine countercurrent of the blood in the same manner. Thrombus at the distal end, if there is any, must also be removed. A blood vessel must be fully open before anastomosis.

(c) Strip the tunica adventitia vasorum: Clamp and pull the adventitia at the lacerated end of the blood vessel with microscopic tweezers and shear it off to avoid thrombosis in case the adventitia is sutured into the lumen of blood vessel. Or, meticulously strip and shear the adventitia at the lacerated end of the blood vessel with small scissors. Be careful not to injure the vessel wall.

(d) Irrigation of lumen at the lacerated end: After the two lacerated ends are well trimmed, irrigate the lumen at the two lacerated ends with 0.1% heparin normal saline (or 0.5% procaine or 3.8% sodium citrate solution) until clots are flushed out to prevent thrombosis at the anastomotic stoma.

2. End-to-end Anastomosis

Selection of interrupted suture or continuous suture for anastomosis depends on the size of blood vessels. Generally, interrupted suture is better for blood vessels with a diameter below 2 mm while continuous suture can be used for vessels with a diameter above 2 mm. Continuous suture is better in hemostasis but may narrow anastomotic stomas if suture threads are over-tightened. Usually, 4-0 ~ 8-0 non-invasive suture threads (8-0 ~ 11-0 noninvasive suture threads for small blood vessels) with non-invasive suture needles at both ends are employed. Simple and operation-friendly biangular suture is commonly used while triangular suture can avoid suturing a vessel wall to the opposite side.

(a) Biangular interrupted anastomosis: Pull both ends of the blood vessel together with clamps at the ends of blood vessel. Conduct fixed-point suture at both ends at 180-degree corresponding positions. Maintain extrophy of vessel walls to avoid thrombosis in case the residual adventitia is sutured into the blood vessel. Be gentle and stable when blood vessel ligation is performed so as not to tear up the vessel walls. Then, stitch another suture between the fixed points and add sutures appropriately according to the bore size of the blood vessel. Generally, the needle pitch and the edge distance are 0.5–1 mm respectively, and 0.3–0.5 mm respectively for small blood vessels. The assistant may gently lift the suture thread after each ligation to help the operator moving to the next suture. After the anterior wall is well sutured, the operator should turn the blood vessel clamps at both ends upward and suture the posterior wall according to the above method. During the suturing process, the operator should insert a flat head needle into the lumen and irrigate the blood vessel with heparin all the time. When the final suturing is conducted, examine the lumen once again and gently irrigate the vessel to ensure all clots are cleared out of the lumen. After the posterior wall is well sutured, turn the blood vessel clamps back to reposition the blood vessel. If the blood vessel is thick enough, biangular extrophy mattress suture can be adopted to ensure the extrophy of endangium.

(b) Continuous triangular anastomosis: The technique is basically the same with that of biangular anastomosis except for the selection of suture points. Suture three fixed-point threads on the circumference of the blood vessel at an equal interval, and pull the threads to form an equilateral triangle. Firstly ligate the posterior wall, and then the fixed-point suture thread of the anterior wall. Lift both fixed-point suture threads and suture the one third of the blood vessel between the fixed-point suture threads with non-invasive suture needle and threads. Suture the one-third of the other side in the same manner. Finally, turn the two blood vessel clamps upward to expose the one-third of the posterior wall of blood vessel and conduct anastomosis.

3. End-to-side anastomosis

Indication for end-to-side anastomosis is that the transplanted blood vessel and the recipient blood vessel differ greatly in diameter (2 times difference or more), or there is no branch vessel at the recipient site except the main vessel. Close both ends of the blood vessel with clamps before anastomosis, lift the vessel wall with microscopic tweezers and shear off a small part of vessel wall with microscopic scissors. The bore size depends on the diameter of blood vessel for anastomosis. Suture one thread at each side of the vessel in a 180° direction and do not cut off the threads. Then conduct continuous suture or interrupted suture to the anterior wall and the posterior wall respectively.

2.3 Microsurgical Nerve Suture

Nerve suture is to conduct an end-to-end suture for a ruptured peripheral nerve to recover continuity of the nerve and promote neural regeneration.

2.3.1 Types of Nerve Suture

Peripheral nerve sutures include epineurium, perineurium and epineurium-perineurium ones. As the epineurium suture only involves the epineurium, a good curative effect can be expected if the anastomosis can be done precisely. The perineurium suture is conducted for corresponding nerve tracts after separation of the nerve tracts at both lacerated ends under a surgical microscope. This method can increase preciseness of nerve tract anastomosis at the lacerated ends, but there is still no rapid and reliable method to precisely identify the nature (to distinguish the motor fiber from the sensory fiber) of the nerve tracts at two ends. Therefore, there is possibility of misconnection in perineurium suture. In addition, extensive interfascicular separation can possibly injure the interfascicular nerve branches and cause extensive scar formation at the anastomotic sites after surgery. A great number of clinical and experimental researches believe that there is no significant difference in the therapeutic effects between the two suturing methods. So, the epineurium suture is generally adopted in clinical practice because it has been proved to be simple and effective by long term clinical validation. The perineurium suture can be used in circumstances where the motor fibers and sensory fibers at the distal end of a nerve have separated naturally, or the cross section contains limited or thick nerve tracts which are easily identified. For some conditions of nerve injury, the perineurium suture is suitable to restore injured nerve tracts after the injured and normal ones are identified.

2.3.2 Methods of Nerve Suture

2.3.2.1 Preparation

1. General preparation: Procedures such as denudating nerves, bending joints, gently pulling nerves or nerve translocation can be carried out to overcome the difficulties caused by nerve deficits and to relieve tension for end-to-end nerve suture.
2. Preparation of lacerated nerve ends: Exposure and properly separation of both lacerated nerve ends are usually appropriate emergency procedures for nerve restoration. Typically, the operator should vertically cut off the neuroma at the proximal lacerated end and the neuroglioma at the distal lacerated end with a sharp blade. Then observe under a microscope whether there are normal nerve tracts in the cross section. A normal nerve tract is light gray and has glossy tissue, with granular protrusions on the section and loose interfascicular tissue. If no normal nerve tract is observed, cut off 1 mm of the nerve each time continuously until a normal nerve tract appears.
3. Anastomosis of the lacerated ends: Carefully observe the distribution of nerve tracts at the lacerated ends of the nerve trunk, and mark the positions of nutrient vessels at the surface of the nerve before precise anastomosis of the lacerated ends.

2.3.2.2 Procedures of Nerve Suture

1. Method of epineurium suture: Suture the epineurium only with 7-0 or 8-0 nylon threads. Do not suture the neuronal cytoplasm. Make a traction stitch on each side of the lacerated ends, and then suture the anterior side of the nerve. Pass one traction suture thread to the posterior side of the nerve to overturn the nerve and suture the posterior side. Precisely align the lacerated ends and do not twist them. A proper needle pitch can be determined by anastomosis effectiveness.
2. Method of perineurium suture: The perineurium suture is conducted under a surgical microscope. Firstly, circlewise cut off 1–2 cm of the epineurium at both lacerated ends, and separate nerve tracts according to their size and distribution. Cut off the scar tissue at the lacerated ends until the normal tissue appears. The nerve tracts are allowed not to be on the same level at the cross section. Stitch the perineurium only with 10-0 nylon suture thread, and do not stitch the neuronal cytoplasm. The number of stitches can be determined by anastomosis effectiveness, generally 2–3 for each nerve tract.
3. Method of epineurium-perineurium suture: Longitudinally cut open the nerve epineurium at both the proximal and the distal ends to expose the nerve tracts, and suture the posterior side of the nerve. Suture the epineurium at one end and a certain perineurium to its corresponding perineurium and epineurium at the other end with 9-0 or 10-0 non-invasive nylon threads. Conduct interrupted perineurium suture for the central part of the nerve.
4. Suture for partial nerve rupture: It is conducted under a microscope or magnifying glasses. Carefully identify the injured and normal parts of the nerve, and cut open the epineurium along the longitudinal neural axon between the two parts. Separate the nerve tracts in the normal part for protection, and cut off the injured parts at both ends of the ruptured nerve and then suture precisely using the perineurium suture method.
5. Suture of small nerves: It is difficult to suture small nerves using common suturing techniques. The reverse nerve suture technique can be adopted and knots can be tied outside the epineurium.

2.4 Microsurgical Tendon Suture

Traditional tendon suture techniques are usually used in a tight tendon suture with tendon suture threads, but not used to treat tendon sheaths or paratenons. As a result, nutrition supply is compromised and healthy tendon beds may also be damaged, causing tendon adhesion after surgery and poor restoration of tendon function. Microscopic tendon suture should address delicate anatomical structures of the injured tendon. Small blood vessels around the tendon can be identified clearly enough to conduct a non-invasive operation. The problems in traditional tendon suture operation, such as aimlessly and roughly clamping the lacerated tendon ends, should be avoided to minimize tissue injury. Microsurgical tendon suture is mainly used for the zone II flexor tendon of fingers.

2.4.1 Methods of Microsurgical Tendon Suture

2.4.1.1 Suture of Tendon

Improved Kessler technique is commonly used for tendon suture. The procedure of traditional Kessler technique is as follows. Insert a needle at the lacerated tendon end with 3-0 non-invasive Prolene thread, and withdraw the needle at 5 mm to the lacerated tendon end. Then horizontally pass across the tendon and finally vertically withdraw the needle from the lacerated tendon end. Treat the other lacerated tendon end with the same method. Anastomose the lacerated ends and tie knots inside the lacerated tendon ends. The improved Kessler method uses a continuous suture thread which is directly inserted into the other side of the tendon after suturing one side of the tendon as per the above method. After the needle is inserted into the other side of the tendon, the operator should tighten the threads and suture the other side of the tendon using the same method, and tie the only knot inside the lacerated tendon end. 8-0 or 9-0 non-invasive suture threads are employed to conduct introverted suture for the tendon adventitia. This method can avoid exposure of lacerated tendon ends, ensure a smoother anastomotic stoma of the tendon, increase the capability to resist tendon tension, and relieve post-surgery tissue adhesion.

2.4.1.2 Restoration of Tendon Sheaths and Peri-Tendon Tissues

7-0 non-invasive suture thread is used to conduct the extrophy suture. Keep a smooth inner layer of the tendon sheath in the cases where the wound of the tendon sheath is smooth and the tendon sheath has no defect or its deficit after restoration is not more than 2 mm. In the cases where the defect of the tendon sheath is too large to suture directly, autologous venous walls can be used for tendon sheath repair. A proper length of autologous saphenous vein can be collected to repair a tendon sheath with segmental defects. Sheathe the saphenous vein segment into the proximal end of the tendon before tendon anastomosis, and conduct an extrophy suture for the vein transplanted to both lacerated sheath ends with 7-0 non-invasive suture thread after tendon anastomosis to reconstruct the completeness of tendon sheath.

3 Perioperative Management in Microsurgical Orthopaedics

Yong-Qing Xu and Yue-Liang Zhu

Microsurgery techniques are being applied to an expanding range of orthopaedic problems. The success of microsurgical surgery depends not only on the operation, but also on the proper management of the perioperative period. If we only pay attention to intra-operative operation and neglect the preparation of perioperative period, these practices may cause surgical failures. Such lessons are common occurrences in the operating room. Therefore, as a microsurgeon, you must correctly grasp the surgical indications as well as the skillful surgical ability. More importantly, you should deal with the related issues during the perioperative period. This chapter deals with perioperative management in microsurgery for replantation, repair of vessels and nerves, and flap transfer.

3.1 Preoperative Planning and Preparation

3.1.1 Team Approach

Team members include surgeons, anesthesiologists, nurses, and other members of the surgical team. Many replantations begin at night when surgeons and nurses may easily become fatigued. Reviewing the operation site and assessing the need for any special supplies and equipment, such as external fixators, electric drills and fracture tables, will surely contribute to efficiency and optimal results.

Due to the demanding technique and lengthy operation time of a fine microsurgery, the operator should take adequate rest before the operation to ensure sufficient energy to cope with the long-term operation. In the meantime, the surgeon must have superb microsurgical techniques to ensure the quality of the microvascular anastomosis, which is a key of the operation success. If conditions permit, the surgery should be performed by multiple groups of people. For example, in the surgery of dissociating a toe transplant to rebuild thumb. When one group is cutting the toe, the other group is responsible for dissecting the corresponding tissue of the hand receiving area, which can shorten the operation time accordingly.

3.1.2 Replantation

3.1.2.1 Management and Transportation of Patients and Amputated Limbs (Finger)

The traumatic conditions of the patients at the scene are of the utmost importance. In addition to paying attention to the amputated limbs, priority should be given to major injuries that affect life, ensuring that vital signs are stable. The bleeding point should be stopped by pressurized dressing, instead of clipping or ligaturing the vessels. If bleeding persists, a tourniquet or a blood pressure cuff should be used to stop bleeding.

For the severed injured limb (finger), the correct preservation method is dry and refrigerated method, the amputated limb (finger) is wrapped with a clean dressing, towel, cotton fabric, etc., Then we use waterproof plastic bag or rubber gloves to contain the limb and place it in a container containing ice cubes in order to keep the amputated limbs (finger) in a dry, low temperature environment. For large limbs containing more muscle tissue (such as forearms, calves, etc.), the ischemic time should be less than 6–8 h. For fingers without many muscle tissues, the ischemic time can be extended accordingly. It has been reported a case of successful replantation of finger disconnection after 72 h in dry and refrigerated storage. But the ischemic time of the limb (finger) should be shortened as much as possible. The broken limb (finger) should avoid to contact any liquid and be separated from ice to avoid frostbite.

Surgical microscopes should be normal and prepared for any emergency operation. If possible, two microscopes should be prepared by scrubbing nurses for the convenience of two teams' work (Fig. 3.1).

Y.-Q. Xu (✉) · Y.-L. Zhu
Department of Orthopaedic Surgery, Kunming General Hospital of Chengdu Military Region, Kunming, China
e-mail: xuyongqingkm@163.net

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_3

Fig. 3.1 High quality microscopes, like ZEISS and LEICA, are helpful for good surgical results

3.1.2.2 After Arrival at a Hospital

The first thing we should do is carefully evaluating the function of the re-implanted limb (finger) if it has a better prognosis than the prosthesis or amputation before the patient undergoes surgery and lengthy rehabilitation. Assessment factors: patient age, severity of injury, plane of division, injury site, time interval between disconnection and replantation (especially ischemia time), multiple disconnection, and the general conditions of patients, including other associated emergencies (Such as fractures, hemorrhagic shock, etc.) and underlying diseases (such as diabetes, high blood pressure, etc.), the patient's recovery potential (such as mentally handicapped people generally do not comply with the rehabilitation process) and economic factors.

Check for blood type and cross-matching and blood transfusions are administered if needed. Preoperative medical staff must help the injured and their families do a series of necessary preparations. Inform patients and their families of the damage situation, the uncertainty about survival of the disconnected part, the uncertainty about the degree functional recovery, and the possibility of multiple surgeries.

3.1.3 Free Flap Transfer

Principal surgeons of an operating team must be proficient in microvascular techniques before a program of reconstructive surgery can be established involving microvascular free flaps. In addition, familiarity with vascular anatomy of various flaps should be acquired through cadaveric dissection or lots of microsurgical operations. Microsurgical instruments must be used for careful microsurgery under a surgical microscope. The main requirements for microsurgical instruments are sharp, thin, stable, lightweight, easy to manipulate, non-glare and demagnetizing (Fig. 3.2).

Fig. 3.2 Fine microsurgical instruments can improve the success rate of microsurgery

The free flap of the donor site should be carefully evaluated before performing a microsurgery. We use a special list for evaluation of a candidate for a free flap.

Pre-operative Flap Surgery Checklist (Experience from failures).

General Situations

- ☐ Lower HB? Lower HB leads to spasm of vessels. If no, blood transfusion and wait.
- ☐ Good blood circulation? Check the lip and hand and fingers. If pale, be very cautious.
- ☐ Nutrition? If a patient is transferred from another hospital and has received a long time treatment, improve it.
- ☐ Diabetes? Treat it first.
- ☐ Smoke? Abandon it.
- ☐ Old? >50 years? Highly risky for complications, especially in a situation of hypercoagulability.
- ☐ Young? <12 years? Highly risky for complications, especially vascular spasm.
- ☐ Operators must be healthy and in good mood. If not, change the schedule.
- ☐ Wounds preparation: Is more debridement, VSD, or skin graft needed?
- ☐ Donor site: Is it intact?
- ☐ Recipient site: healthy enough? If there is any large area with bone exposure or there is minimal healthy soft tissue for flap anchoring or nutrition, make improvements. Create more soft tissues or change protocols. Is the recipient artery good or not? The veins? If not, which are options? Are pedicles of the vessels long enough?
- ☐ Fracture? External fixation, plate with one stage flap coverage, or splint?
- ☐ Joint? Is arthrodesis needed? Or two-stage treatment.

3.1.4 Peripheral Nerve Repair

Just like other microsurgical procedures, preoperative preparation for peripheral nerve injury begins with a detailed preoperative assessment. If necessary, recovery and maintenance of important cardio-pulmonary function should be carried out. Rational use of antibiotics and tetanus antitoxin should be used and prepare necessary resuscitation measures. Accurate assessment of peripheral nerve injury or defect is required. Open peripheral nerve injury wounds need to be carefully debrided. If the wound is clean and sharp instrument injury, and at the same time the patient's general condition is stable, neuroanastomosis should be performed immediately in a quiet and calm environment. If the general condition is poor, we choose the sub-emergency repair after 3–7 days. At this time, the wound was closed and aseptically wrapped after emergency debridement. Postoperative wound exudation should be carefully observed. If the wound is an blast injury (firearm injury) or with serious foreign body contamination, Thorough and careful debridement and sterile wrapping are necessary. If the nerve can be detected during surgery, it should be marked with suture or stainless steel wire for secondary surgery. If there is a nerve defect, the suture should be loosely attached to the surrounding soft tissue to prevent retraction. Local soft tissue coverage is required if necessary. If the wound cannot be sutured, it should be covered with a flap so that nerve repair can be performed 3–6 weeks after surgery.

3.2 Anesthesia

Each surgical patient should be properly identified in a holding area (by name, date of birth, or medical record number). The correct operative site should be marked and confirmed prior to transporting a patient to an operating room. This procedure is more important when there are at least two patients with multiple fingers amputated. Amputated fingers without any marks kept in the same refrigerator may lead to wrong reattachments later. Once in an operating room, the patient should be identified once again by operating room staff. It must be done prior to any surgical procedure. Anesthesia begins only after repeated identification.

The surgical risk of microsurgery is related to anesthesia. Although anesthesia-related complications are relatively uncommon, once an anesthesia accident occurs, the consequences are serious. The incidence of death in patients receiving anesthesia is approximately 1/200,000.

Since anesthesia for microsurgeries may last several hours or more, its complication rate becomes higher. As some replantation patients may have already endured a long journey transfer and a great loss of blood before surgery, the risk of anesthesia also increases. Surgeons should discuss these problems with a patient and his family in general terms, allowing anesthesiologists to provide the most detailed explanations.

Generally we prefer axillary brachial plexus block for simple microsurgery in an upper extremity, spinal anesthesia for surgery limited in a lower extremity. General anesthesia is preferable when surgery is complicated, to be performed for several hours or at multi-sites, or when a patient's condition is not steady. We rarely use local anesthesia like finger block or ankle block, because its effects are not reliable. A patient may feel pain or move their limbs automatically on a table, and it is not good for intraoperative monitoring of the patient's whole situation.

3.3 Intra-Operative Care

Once anesthesia is given to a patient in an operating room, every effort should be made to make him or her comfortable. The placement of arterial catheter, central venous canal, and

Foley catheters should be performed after successful anesthesia as far as possible. The operating table should be adjusted to the best position that the shadowless lamp can reach, and the surgical teams are reasonably arranged to take turns. At least two shadowless lights are needed to allow both teams to perform surgery at the same time. Placing the patient's posture during operation requires the efforts of all personnel. Poor placement of the position pad can lead to postoperative neurological paralysis, resulting in a surgical imperfection. In the lateral position, special care should be taken to protect the nerve's peroneus communism from compression at the capitula fibula, and to reduce the pressure on the brachial plexus near the bed.

A tourniquet is frequently used for microsurgery on limbs. Typically a tourniquet is set to 250 mmHg and 350 mmHg for the upper and lower extremities, respectively. A tourniquet is placed as high up on an extremity as possible to avoid interference with a sterile operative field. Usually the continuous upper tourniquet should not exceed 2 h; shorter time of operation will reduce postoperative adverse reactions. Ninety minutes of tourniquet time with a 5 min between reinflations minimize ischemic damage. Before release of a tourniquet, meticulous hemostasis of an open wound by electric knife or ligature of small vessels is very important to decrease following blood loss. We routinely do pressure dressing with bandages in the intervals between tourniquet inflations. This procedure also lessens blood loss.

An elastic Esmarch bandage could be used before tourniquet inflation, but it may make veins more invisible and hamper later anastomosis. We prefer elevation of an extremity for 5 min for limb exsanguination prior to tourniquet inflation.

Whether it is limb replantation or free flap transplantation, two groups of surgeons should carry out the operation to save time. During replantation, one group treated the severed limb with debridement and labeling, and the other group treated the breaking end of body. Then suture the severed limb and body for bone fixation and microscopic replantation. When it comes to transfer the free flap, one group deal with the skin flaps in the donor site, and the other group is cleaning the recipient area and exposing the arteries and veins. Then the flap is microscopically anastomosed, and the other group sutures the donor zone in order to save time (Fig. 3.3).

Although the manner a patient awakens from anesthetic is difficult to predict, every effort should be made to avoid violent straining, shivering, and flailing about, which sometimes accompany this stage of the procedure.

The following list of key points is summarized from our failure experience. We use it for preoperative checking and reminding.

Fig. 3.3 Two teams simultaneously performed anterolateral thigh perforator flap repairing the contralateral traumatic leg soft tissue

List of Intra-Operative Key Points

- ☐ Simultaneously begin surgery on donor and recipient sites, but do not ligate flap pedicles until vessels at the recipient site are confirmed to be suitable for anastomosis.
- ☐ Mark arteries during flap harvest, especially those with a minor caliber. A pedicle artery sometimes has a single concomitant vein with thin tube wall.
- ☐ Observe under a microscope while release a clamp to make sure which is an artery. Sometimes a vein looks very similar to an artery. Concomitant veins of an anterior or posterior tibial artery have a thick wall and a large caliber, while an ulnar artery or radial artery have a thin wall and a small caliber. If there is any doubt, try subcutaneous veins like the great saphenous vein or the cephalic vein. They are larger and healthier.
- ☐ Use carefully an electric knife because it may damage small vessels. Use more knife-dissection than electro-dissection; use more pins than direct electrocoagulations; use more ligature than pins.
- ☐ After anastomosis, wait at least 3 min to make sure there is no need for more repairs.

☐ Check capillary pulsation. It must be very normal. If there is any doubt, reexploration should begin immediately. This procedure saves much more time than later reexploration.

3.4 Postoperative Monitoring and Nursing

3.4.1 General Considerations

Successful microsurgical repair only means a good start of restoring limb function. There is more work to be done after surgery which is as important as surgery. Therefore, postoperative observation, treatment require highest attention. The hospitalization environment of patients undergoing microsurgical treatment should meet certain requirements. The ward should be quiet, clean, temperature-controlled, and the air is freshly circulated. To prevent postoperative vascular crisis, we should keep the ward absolutely smoke-free. Patients who have a smoking hobby should be advised to quit smoking. Minimize the number of visitors. In order to facilitate the observation of blood circulation of the transplanted tissue, medical lamp should be provided. Temperature has a great effect on the anastomosis of the blood vessels. If the room temperature is too low or suddenly drops, it will cause vasospasm and vascular crisis. Generally, the room temperature is required to be controlled at 25–30 °C.

3.4.2 Observation Indicators

After replantation of the severed finger, the finger should be lightly bandaged to show the replantation finger. The root and suture should be free of pressure so as not to affect arterial perfusion and venous return (Fig. 3.4).

The skin of replanted tissue which has normal blood supply is ruddy. Skin temperature is normal or slightly lower 1–2 °C. Capillary filling test should be normal and tissue tension is moderate. There is bright red blood flowing out after incision; Arterial dyslipidemia will show that the skin is pale, skin temperature drops significantly, capillary filling disorder, the tissue tension drops significantly, and the blood does not flow out of the incision. When the venous reflux disorder occurs, the skin is dark purple and blisters appear, skin temperature drops, the capillary filling accelerates, purple blood flows out before red blood from the incision. Vascular crisis is most likely to occur 3 days after operation, and we should observe the change of blood circulation every hour and record timely. It was adjusted to every 2 h from the fourth day and every 4 h from the seventh day. Once unusual situations happen, it should be handled correctly and immediately. The blood circulation will be relatively stable after 10 days.

Fig. 3.4 Correct dressing after replantation of severed fingers

3.4.3 Treatment of Vascular Crisis

Including arterial crisis and venous crisis, which are often caused by angiemphraxis. Early-onset vascular compromise is usually caused by thrombus. Venous outflow obstruction can be easily recognized when a flap presents with a violaceous color, brisk capillary refill, and production of dark blood after pinprick. Artery thrombus, however, may not produce a dramatic color change or swelling of a flap. Theoretically arterial insufficiency can be recognized by decreased capillary refill, pallor, reduced temperature, and absence of bleeding after pinprick. The truth is at an early stage most of these criteria are not so reliable. A surgeon may be “cheated” by an abnormal flap with normal temperature, color, and bleeding after pinprick. Additionally, pinprick cannot be repeatedly used to monitor flap circulation. According to our experience, capillary refill is the most sensitive and reliable sign for early detection of flap failure. When capillary refill of a flap seems a little too quick, a violaceous color always appears several hours later. Sometimes the change is so insidious that it can be neglected by less experienced surgeons. The time the first signs of vascular compromise appear dictates salvage outcomes of a free flap transfer. Upon recognition of anastomotic failure or venous congestion, continuous massage is needed to improve circulation of a flap. Intravenous Urokinas (40 mg) is given. If there are no signs of getting better within an hour, patients should be returned to an operating room for reexploration.

3.5 Routine Postoperative Medication

According to clinical and experimental observations, even the excellent vascular anastomosis may turn into vascular blockage as a result of vasospasm, infection, thrombosis and other factors after surgery. Therefore, postoperative anti-spasmodic, anti-thrombotic and anti-infective drug treatment is important measures for preventing postoperative complications of microvascular surgery and enhancing patency rate of vascular anastomosis. Commonly used drugs include antispasmodic drugs (such as sympathetic antagonists papaverine, tolazoline and salvia miltiorrhiza injections), anticoagulant drugs (such as heparin, low molecular weight heparin, low molecular weight dextran, aspirin and fibrinolytic protein drugs, etc.), anti-infective drugs and neurotrophic drugs (such as methylcobalamin, vitamin B1, etc.).

Our routine postoperative management for an adult patient uses intravenous sensitive antibiotics, Low-Molecular-Weight Heparin Sodium (0.3 mg, b.i.d.), Low Molecular Dextran (500 mL, q.d.), intramuscular injection of Papaverin (60 mg/6 h) and pain killers. Administration of these drugs maintains a week after surgery. For pedicled perforator flaps, we use sensitive antibiotics and aspirin, 300 mg twice daily for 5–7 days as the only anticoagulation.

Bibliography

1. Canale ST, Beaty JH. Campbell's operative orthopaedics. 11th ed. Philadelphia, PA: Mosby Elsevier; 2008.
2. Green DP, Hotchkiss RN, Pederson WC, Wolfe SW. Green's operative hand surgery. 5th ed. Philadelphia, PA: Elsevier Churchill Livingstone; 2005.
3. Cioppa-Mosca JM, Cahill JB, Cavanaugh JT, et al. Handbook of postsurgical rehabilitation guidelines for the orthopaedic clinician. St. Louis, MO: Hospitalfor Special Surgery; 2008.
4. Skinner HB. Current diagnosis and treatments in orthopaedics. 2nd ed. New York: McGraw-Hill; 2000.
5. Sheth NP, Lonner JH. Gowned and gloved orthopaedics. Philadelphia, PA: Saunders/Elsevier; 2009.
6. Wei FC, Mardini S. Flaps and reconstructive surgery. Philadelphia, PA: Saunders/Elsevier; 2009.

Major Limb Replantation

4

Jianli Wang and Zhaohui Pan

4.1 Introduction

Amputations of the extremities are being increasingly encountered as fallout of industrialization and road traffic. The loss of the extremity is a devastating event, both physically and psychologically, leading to a lifelong disability of an individual.

Experimental success of replantation was first achieved in 1903 by Hopfner, who replanted the leg of a dog, which remained viable at 10 days, at which point the animal died of anesthetic complications. In 1953, Lapchinsky first reported the long term functional results of successful replantation on dog hindlimbs. They also investigated the influence of cold preservation on amputated extremity in 1960. Mehl et al. investigated the systemic influence of replanted extremity and established effective approach to manage it. In one study performed by Williams et al. on amputated dog hindlimb replanted at room temperature after various periods of warm ischemia, the patency rate was found to be 90% after duration of less than 6 h, and 20% after 6 h.

It was not until the operating microscope allowed the repair of small vessels in the 1960s that replantation surgery achieved successfully in clinical research. The first successful replantation of an upper arm amputation was reported by Malt and MacKann in 1962. That first revolutionary report was followed by the first case of a distal forearm replantation by Chen et al. in 1963. Since that time, thousands of successful replant procedures have been performed. In 1973, Wang et al. reported successful replantation of bilateral arm in a 3-year-old boy in the Chinese literature. From 1966 to 2003, there are 712 major replantations performed in our institution, and the survival rate is 95.6%, which is consistent with previous reported rates of 60–100%. The evolution of microsurgical techniques and an accumulation of experience worldwide, along with the organization of specialized centers, has made replantation of completely or partially amputated extremity a generally accepted treatment of choice. Despite that the exact number of replantations performed annually is uncertain, the replantation procedures can be successfully performed not only in urban teaching hospitals but also in rural hospitals in China.

During the past 50 years, the techniques involved in replantation surgery have substantially influenced traumatic and reconstructive surgery. Therefore, successful extremity replantation should be considered as a milestone in the field of surgery.

J. Wang (✉) · Z. Pan
Department of Orthopaedics, PLA 89th Hospital, Weifang, China
e-mail: 13905367003@163.com; Ihfwk876@163.com

4.2 Anatomic Considerations

Replantation surgery involves several tissues repairing including bone, muscle, nerve, vessel, and so on. Therefore, thorough knowledge of the anatomic structures is mandatory (Fig. 4.1).

4.2.1 Proximal 1/3 Section of the Arm

Humerus is almost round structure in the proximal 1/3 section of the arm. The pectoralis major attaches to the lateral lip of bicipital groove of humerus, while the teres major and latissimus dorsi muscles attach to the medial lip. The biceps brachii and coracobrachialis run between them. The deltoid attaches laterally to deltoid tubercle of humerus. The triceps attaches posteriorly. The critical neurovascular structures lie medial to the humerus. Three major nerves run along the brachial artery which is accompanied by two veins: the median nerve lies anteriorly, while the radial nerve behind and the ulnar nerve medially. The musculocutaneous nerve is close to the biceps. The cephalic vein lies in the deltopectoral groove.

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_4

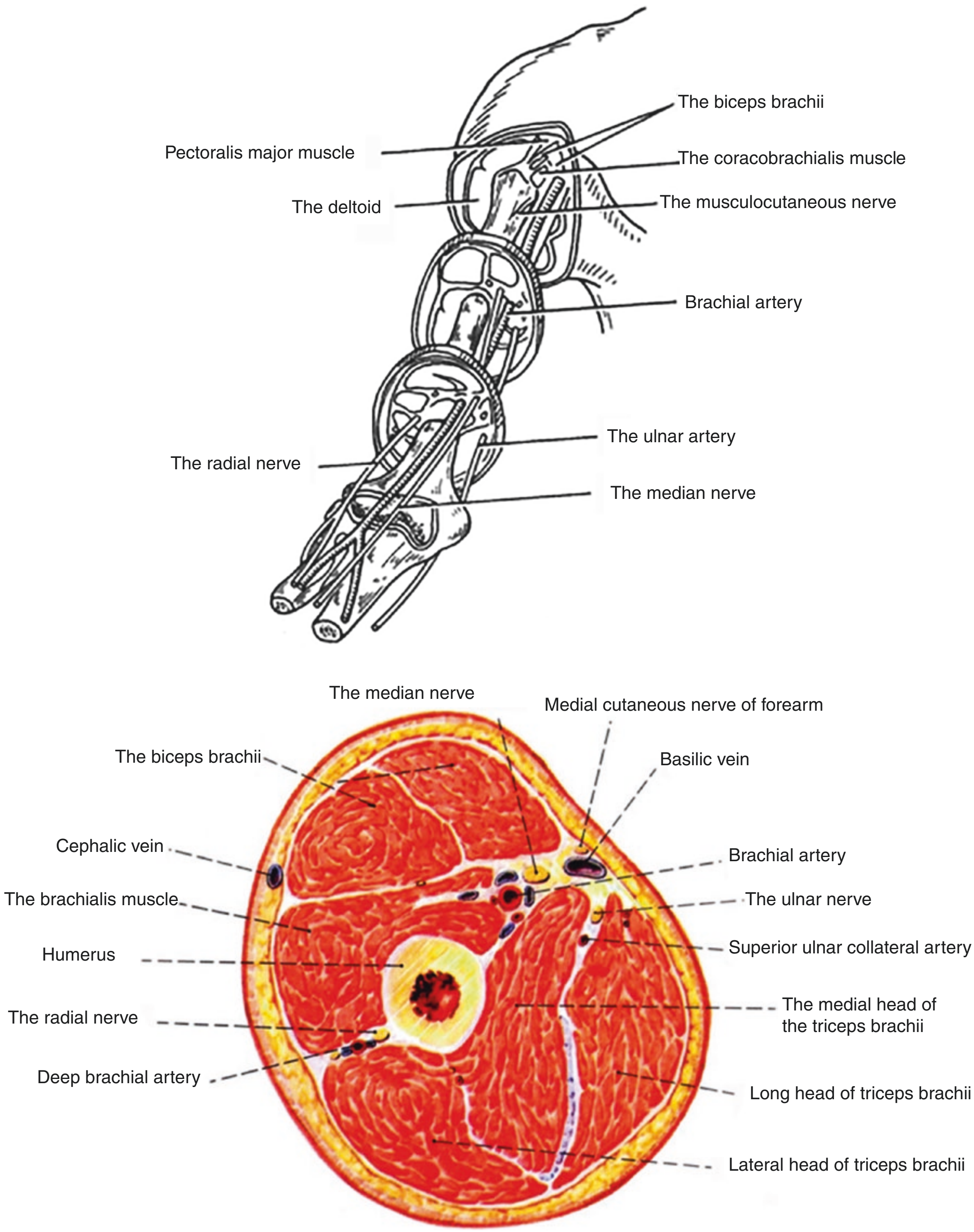


Fig. 4.1 Cross-section of the arm

4.2.2 Middle 1/3 Section of the Arm

Humerus is round structure with thick cortical bone. The anterior compartment contains two muscles: the brachialis and biceps (which is the outer layer of the musculature). Extensor compartment consists of the triceps. Basilic vein courses medially through the superficial layer. The median nerve runs anterior to the brachial artery. The ulnar nerve lies medially to the artery. The musculocutaneous nerve gives off branches to the brachialis supplying it and continues distally as lateral antebrachial cutaneous nerve. The profunda brachii artery runs laterally with the radial nerve between the brachialis and triceps. The cephalic vein passes through superficial layer of the lateral arm between the biceps and brachialis.

4.2.3 Distal 1/3 Section of the Arm

Humerus is a triangular structure in the lower 1/3 section of the arm with the triceps attaching to the posterior part and the biceps attaching to the anterior part. The critical neurovascular structure lies on the medial side. The median nerve runs anterior to the brachial artery. The ulnar nerve travels on the back of the medial epicondyle of the humerus. The basilic vein courses medially through subcutaneous layer accompanied by the medial antebrachial cutaneous nerve. The biceps lies anterior to the brachialis with the lateral antebrachial cutaneous nerve between them. The brachioradialis lies lateral to the brachialis with the radial nerve between them. The leach vessel between the profunda brachii artery and recurrent radial artery accompanies the radial nerve. The cephalic vein passes through the subcutaneous layer.

4.2.4 Proximal 1/3 Section of the Forearm

The forearm is divided to anterior and posterior compartments by the interosseous membrane and intermuscular septum. The radial neurovascular structure runs down on the lateral side. The radial artery accompanied by two veins lies between the brachioradialis and pronator teres. The superficial radial nerve runs down laterally with the radial artery in a somewhat distance. The ulnar neurovascular structure runs down the ulnar side of the anterior compartment. The ulnar artery accompanied with two veins passes deep to the deep head of the pronator teres. The ulnar nerve lies between the flexor carpi ulnaris muscle and the flexor digitorum profundus in a certain distance. The cephalic vein accompanied with the lateral antebrachial cutaneous nerve courses through the radial subcutaneous layer. The basilic vein accompanied with the medial antebrachial cutaneous nerve courses through the ulnar side. The anterior interosseous artery lies on the anterior side of the interosseous membrane.

All the muscular structures have not been totally divided. The common flexor origining from the medial epicondyle and the pronator teres lies in the anterior side of the anterior compartment. The flexor carpi ulnaris and the flexor digitorum profundus origining from the ulnar lie in the medial side. The supinator muscle covering the proximal 1/3 section of the radius and the extensor digitorum lie in the posterior compartment.

The neurovascular structures in the posterior compartment are usually small. The posterior interosseous nerve, which winds spirally around the radius, runs down between the supinator and common extensors. The posterior interosseous artery courses down close to interosseous membrane. The posterior antebrachial cutaneous nerve, which origins from the radial nerve, passes through the subcutaneous layer.

4.2.5 Middle 1/3 Section of the Forearm

The anatomic structure on this level is typical and visible. The flexor-pronator group is arranged in three layers. There are five flexors in the superficial layer from lateral to medial side: the brachioradialis, pronator teres, flexor carpi radialis, palmaris longus and flexor carpi ulnaris. The middle layer consists of the flexor digitorum superficialis. The deep layer is comprised of the flexor pollicis longus and flexor digitorum profundus. There are three main neurovascular structures. The radial structure consisting of the radial artery, two accompany veins and the superficial branch of the radial nerve lies under the brachioradialis. The two structures are together. The ulnar artery and nerve travel in the medial side lying on the flexor digitorum profundus. The median nerve is in the middle side lying between the flexor digitorum superficialis and profundus. The anterior interosseous nerve and artery also run down the middle of the forearm, but are deeper than the median nerve.

The muscular structure in the posterior compartment can be divided into superficial and deep layer. There are extensor carpi radialis longus and brevis, extensor digitorum communis, entensor digiti minimi and extensor carpi ulnaris from lateral side to medial side in the superficial layer. The deep layer consists of the abductor pollicis longus and extensor indicis. The neurovascular structure is small. The posterior interosseous nerve and artery lie between the superficial and deep extensors. The cephalic vein accompanied by the lateral antebrachial cutaneous nerve courses through the radial subcutaneous layer. The basilic vein accompanied by the medial antebrachial cutaneous nerve passes through the ulnar subcutaneous layer. The posterior antebrachial cutaneous nerve courses through the posterior subcutaneous layer.

4.2.6 Distal 1/3 Section of the Forearm

In the distal third of the forearm, the main structure surrounding the ulna and radius is tendons except pronator quadratus, which lies anterior to the interosseous membrane. There are flexor carpi radialis, flexor pollicis longus, palmaris longus, flexor carpi ulnaris, flexor digitorum superficialis and profundus in the anterior compartment. Both flexors are separated into several tendons. Portion of the ring finger flexor usually is separated initially. Tendons to the index and small fingers lie in the anterior side, while tendons to the middle and ring fingers lie in the posterior side. There are nine tendons including abductor pollicis longus, extensor pollicis brevis, extensor carpi radialis longus, extensor carpi radialis brevis, extensor pollicis longus, extensor indicis, extensor digitorum communis, extensor digit minimi and extensor carpi ulnaris lying in the posterior compartment.

The neurovascular structure in the distal 1/3 section of the forearm is relatively superficial. The cephalic vein and the superficial branch of the radial nerve lie in the radial subcutaneous layer. The radial artery and two vena comitantes lie under the deep fascia in the radial side. The median nerve runs down the middle of the forearm immediately below the palmaris longus. The ulnar nerve courses through the ulnar side of the forearm with the ulnar artery and two veins lying on the lateral side (Fig. 4.2).

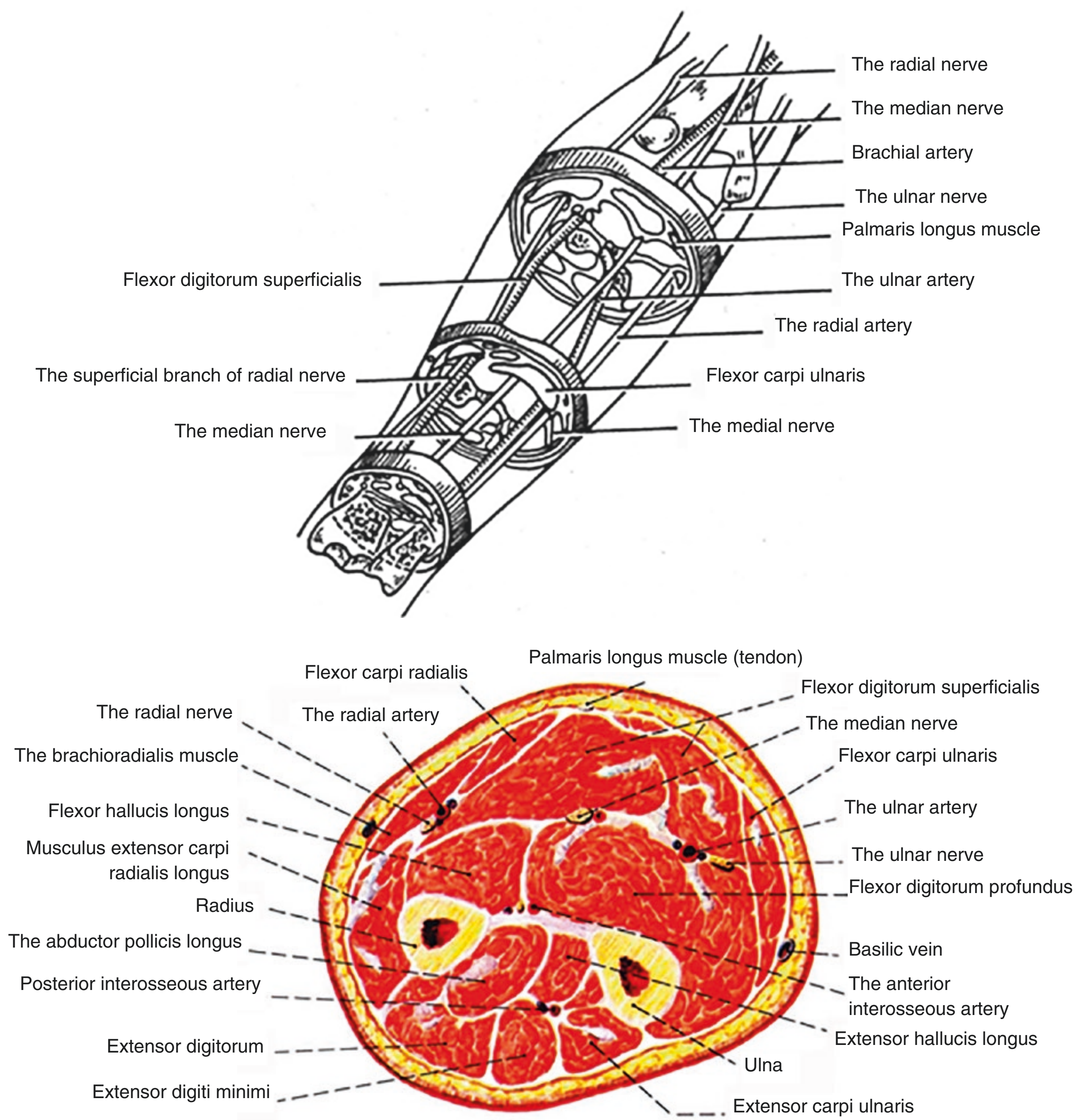


Fig. 4.2 Cross-section of the forearm

4.2.7 Proximal 1/3 Section of the Thigh

If amputation is through femoral triangle level, the femur, corresponding to the greater trochanter and the smaller trochanter, is broad and irregular. If amputation is through canal of Hunter, the femur is almost cylindrical in form. There are three muscle groups in the thigh: the posterior muscle groups including the gluteus maximus, long head of biceps femoris, semitendinosus and semimembranosus; the adductor muscles including adductor magus, adductor longus and gracilis. At its lower end, the anterior muscle group is quadriceps femoris and sartorium muscle. At its upper end, it includes iliopsoas muscle.

There are two main neurovascular structures. The femoral nerve and the femoral vessels lie between iliopsoas and the adductor muscles at the amputation through femoral triangle level. At the level of canal of Hunter amputation, femoral artery, vein and saphenous nerve course down between the anterior muscles and the adductors, and the profunda femoris artery, vein and their branches lie deep to the adductor longus muscle. The sciatic nerve lies in the posterior segment of the thigh, deep to the gluteus maximus and the posterior muscles. The greater saphenous vein courses in the medial subcutaneous layer. The posterior femoral cutaneous nerve passes through the posterior thigh.

4.2.8 Middle 1/3 Section of the Thigh

The middle femur is almost cylindrical form. There are three obvious intermuscular septums attaching to the linea aspera, which include the anterior muscle group, the posterior muscle group and the adductor muscle groups. The anterior muscle group is the largest among them. The adductor muscles consist of the adductor longus, adductor magus and gracilis. The posterior muscles consist of the long and short heads of biceps femoris, semitendinosus and semimembranosus. There are three main neurovascular structures. The femoral artery and vein, saphenous nerve lie between the anterior muscle group and the adductors, just deep to sartorium muscle. The profundus femoris artery and vein run posterior to the adductor longus muscle. The sciatic nerve lies between the posterior muscles and the adductors, deep to the long head of biceps femoris, semitendinosus and semimembranosus. The greater saphenous vein passes at the medial side of the thigh.

4.2.9 Distal 1/3 Section of the Thigh

The femur is almost triangle in form. The belly of the anterior muscle group increases. The adductor muscles only consist of gracilis and the tendon of the adductor magus. There are two main neurovascular structures. The femoral vessels and saphenous nerve lie in the canal of Hunter. The sciatic nerve lies among the posterior muscles. The saphenous vein changes its position to the medial subcutaneous layer (Fig. 4.3).

4.2.10 Cross Section of the Leg

The tibia transmits most stress of the leg. Its form changes from triangle to the cuboid. The tibia has a broad accessible subcutaneous surface with poor blood supply, while the fibula is surrounded by muscles. There is tough interosseous membrane connecting them. Three separate muscular compartments consist of the anterior muscle group, the lateral muscle group and the posterior muscle group.

The middle cross section is a typical section. The anterior compartment contains tibialis anterior, extensor digitorum longus and extensor hallucis longus. One main neurovascular structure consists of the anterior tibial artery, two venae commitantes and a deep peroneal nerve lying anterior to the interosseous membrane. The posterior compartment consists of two groups of muscles, superficial (gastrocnemius, soleus, plantaris) and deep (tibia posterior, flexor digitorum longus, flexor hallucis longus) muscle layers. There are two main neurovascular structures lying between the two layers. The posterior tibial artery and two veins and tibial nerve pass in the medial side, while the peroneal artery and two veins pass in the fibular side. The lateral compartment contains peroneus longus and brevis, with superficial peroneal nerve passing through. The greater saphenous vein and saphenous nerve course in the medial subcutaneous layer. The small saphenous vein and sural cutaneous course in the posterior side. At its upper end, the medial sural cutaneous accompanies with the small saphenous vein with the lateral sural cutaneous lying in the lateral side (Figs. 4.4 and 4.5).

4.3 Classification of Amputated Limb

Trauma is the most common cause of limb amputation. Gunshots, landmines, fireworks and other forms of explosives used in war or terrorist attacks can also cause amputation. The operative treatment for each injury must be individualized based on the complexity of the trauma and contribution of injury characteristics.

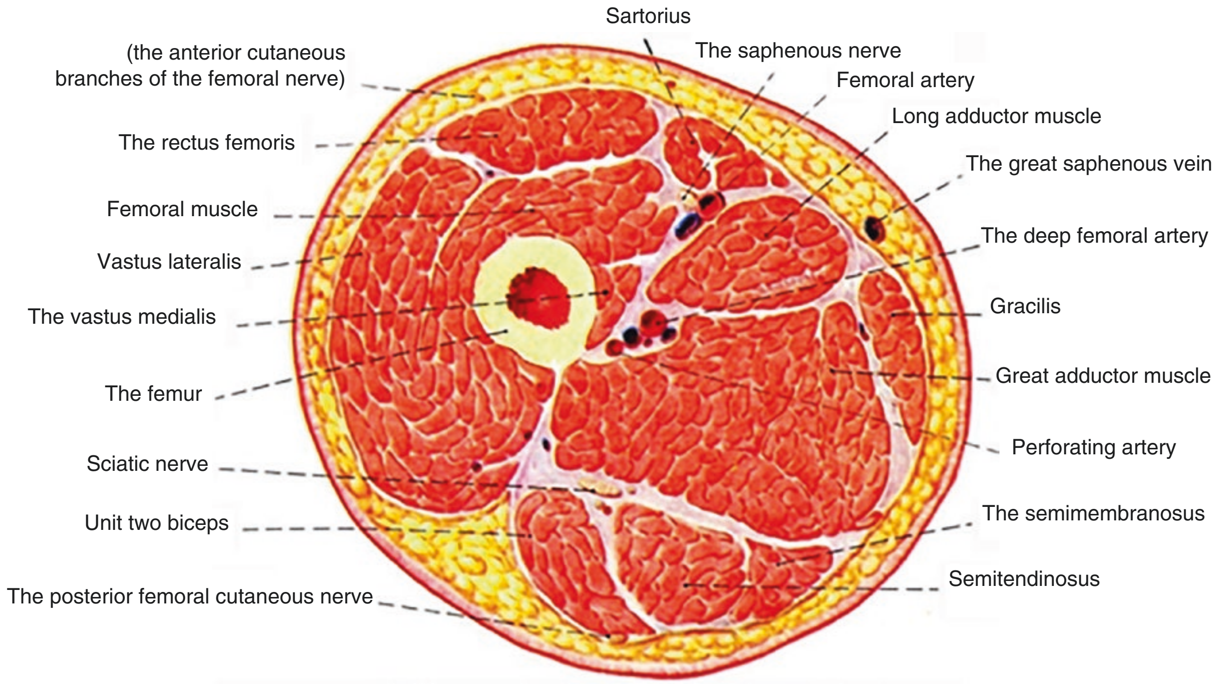


Fig. 4.3 Cross-section of the middle 1/3 section of the thigh

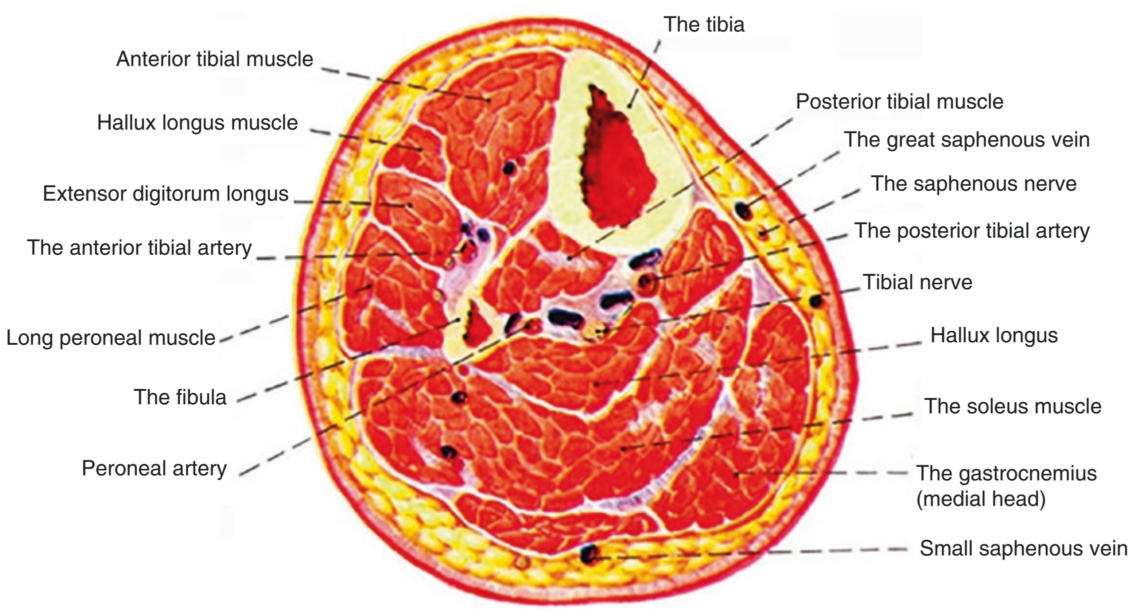


Fig. 4.4 Cross section of the middle of the leg

4.3.1 Classification According to the Nature of the Injury

4.3.1.1 Amputation Resulting from Guillotine Injury

The cause of the penetrating injury includes knife, power saw, blade injuries, and so on. This type of injury is more likely to sustain an upper extremity amputation. A sharp amputation results in less trauma to adjacent tissues, and the sharply divided structure characteristic of this injury mechanism is more suitable for the repair.

4.3.1.2 Amputation Resulting from Narrow Crush Injury

The cause of the injury includes wheel of railway or vehicle, gear wheel of a machine, which frequently leads to all tissues

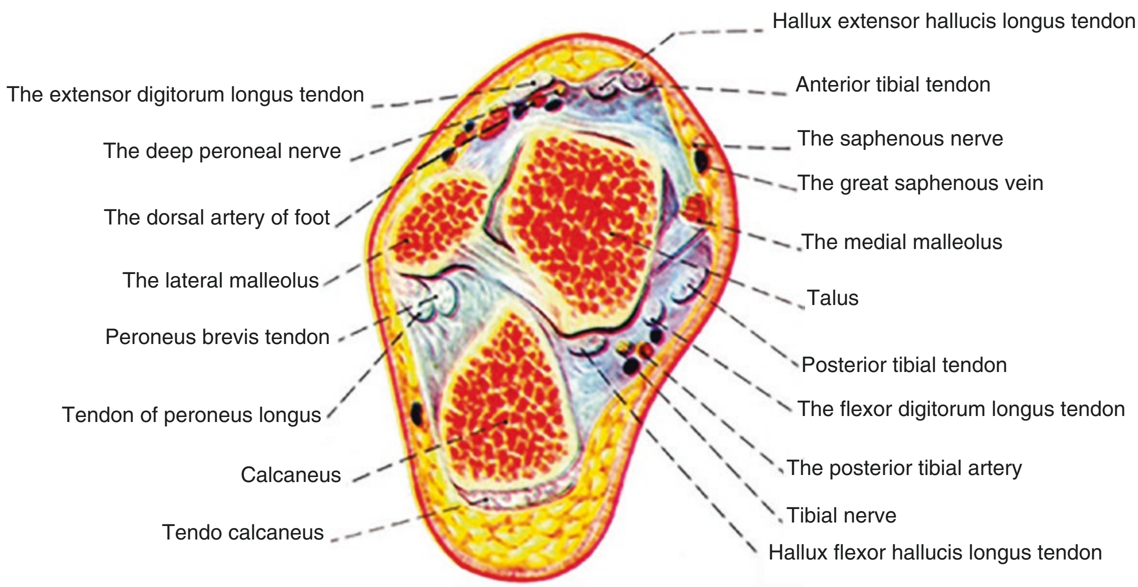


Fig. 4.5 Cross section of the ankle joint

amputated at the same injury level with comminuted fracture. Although a severely contaminated extremity undoubtedly increases the chance of infection and replant failure, this can be lessened through debridement of necrotic tissue and vigorous irrigation of the injury along with appropriate use of antimicrobial therapy.

4.3.1.3 Amputation Resulting from Extensive Crushes Injury

The usual mechanism of a major amputation of a limb involving crush includes heavy machine, stone, and other compressing machine, causing mutilating injuries with disruption of bones, soft tissues, vessels and nerves at different levels.

4.3.1.4 Amputation Resulting from Avulsion Injury

The injury usually causes by roller, circular, fan, and so on with a high rolling speed. Avulsion injury usually results in the upper extremity amputation with irreparable shearing of soft tissues including arteries, veins, nerves, muscles, and tendons. Severe avulsion at the level of the amputation can be converted to sharp wounds by means of systematic tissue debridement and bone shortening, and severely damaged vessels and nerves can be resected and repaired by interpositional grafting. Avulsion injury accompanied with high temperature completely precludes replantation.

4.3.1.5 Amputation Resulting from Gunshots

This injury characteristic has severely injured tissues.

4.3.2 Classification According to the Type of Amputation

The amputation was defined as complete when absolutely no connection remained between the patient and the severed limb, including some nonviable tissue which has to be disconnected during debridement, and as partial when a negligible soft-tissue connection remained (e.g., skin or muscle bridge less than one fourth of the amputated area) in an otherwise complete amputation with total major vessel transaction, no possibility of adequate collateral flow and discontinuous nervous structures. The survival rate of the partial amputated limb is not higher than that of the complete amputated limb, because the former is usually associated with extensive soft-tissue crushing injury.

The incidence of upper limb amputation is superior to that of lower limb amputation. The forearm and palm are the most commonly injured body parts, following by arm, while the leg and ankle are the most common amputated parts than the thigh. The level of injury has a considerable influence on the functional outcome of replantation. In general, the more distal the amputation of the extremity part, the better the functional result of replantation. Proximally amputations have a poorer functional recovery for a number of reasons. First, there is more muscle mass in the proximal limb with increased effects of ischemia/reperfusion injury. Second, more extensive rehabilitation is required because of the increased time required for axonal elongation and end-organ reinnervation.

4.4 Indications

Careful patient selection and meticulous surgical technique allow return of an acceptable level of function which is now the goal of treatment. The decision to attempt the replantation or not should be made according to the following basic factors. This highlights the need for a case-by-case evaluation of the patient and clinical situation before deciding to attempt the replantation.

4.4.1 Patient's General Condition

Patients with traumatic limb amputation and associated significant injury to other organs, such as the head, chest or abdomen, usually meet a challenge. These combined injuries are usually life-threatening and often preclude replantation. Previous reports have recommended that candidates for extremity replantation should be free of any serious concomitant injuries or significant medical comorbidities. Initial diagnosis should be performed via a multidisciplinary approach according to the established advanced trauma life support protocol and Injury Severity Score (ISS). A patient with a life-threatening injury or major medical comorbidity would be at high risk for the prolonged anesthesia and, as a result, this would generally be considered an absolute contraindication. Replantation efforts should not jeopardize the chances of survival of the patient. The replantation may have to be delayed until the patient is stable enough to undergo the lengthy procedure.

4.4.2 Status of the Amputated Part

Assessment of injured limb must consider trauma mechanisms, wound dimensions and all functional components (soft tissue, vessels, nerves and bones). Cross-extremity replantation should be considered when the patient has suffered from bilateral complete or partial amputation at different levels and there is no possibility of orthotopic replantation. As savage procedure, cross-extremity replantation can be performed to save at least one functional extremity so that the patient can accomplish daily living activities. Crush margins sometimes may be changed into neat lesions by accurate radical debridement. Extensive crush and avulsion amputation not only causes obvious compromise to the overlying soft tissue, but also disrupts the intimal lining of blood vessels which is illustrated by observing multiple cutaneous hemorrhages which is considered a prognostic indicator for poor replantation success. If the amputated part is submerged in hypoisotonic or hyperisotonic solution, the successful rate may be decreased, because this can cause severe injury to soft tissue, especially to the intimal lining of blood vessel.

4.4.3 Ischemia Time

In major limb amputation, the amputated part contains rich muscle tissues that are ischemic until revascularization is completed. Prolonged ischemia causes irrevocable change to tissue, so this is limb threatening. Furthermore, revascularization after prolonged ischemia may cause ischemia related toxin backflow into the systemic circulation presented as reperfusion syndrome, which is life threatening. At normothermia the critical ischemia time of muscles is 4 h, nerves up to 8 h, fat up to 13 h, skin up to 24 h, and bone up to 4 days. Cooling may extend the time frame for replantation. Dilemma still remains regarding the safe limit for cold ischemia time in relation to the level of amputation and possible reperfusion injury, morbidity, limb survival, functional outcome, and potential mortality following such procedures. In general, warm ischemia times greater than 6 h and cold ischemia times greater than 12 h portend a poor prognosis for replantation of major limbs.

4.4.4 Goals of Replantation

Goals of replantation are to obtain a nearly normal functioning limb with an acceptable cosmetic result. For the lower extremity, limb shortening greater than 7 cm will result in significant limping, with shorter inequalities compensated for by platform shoes. However, in children, more shortening may be acceptable because compensational growth may occur. In the upper extremity, the premise that salvage of a sensate hand with prehensile and grasp function is preferable as prosthesis guides for many surgeons' decides to perform the replantation. However, the decision to replant arm amputation involving brachial plexus avulsion injury should demand very careful consideration, because it is more likely to be a functional hindrance.

4.5 Emergency Treatment

Replantation of an amputated limb is a rigorous race against time. Thus, patient should be transferred to the replantation centers and to complete the revascularization as soon as possible.

4.5.1 Initial Management on the Spot

All replantation surgeries depend on a good organization of the assistance afforded to the patient. The first aid must be given by informed or trained personnel. Patient should be given pressure to the severed end to control bleeding before transportion to the replantation service in an expedient manner. Correct information and protocols should be informed in work place. For example, disassembly of machine should be undergone to take the amputated part instead of reverse. It is better not to apply a tourniquet on the stump. Application of a tourniquet should be performed by an experienced person and not delegated to someone who does not understand its use. There is no rule as to how long a tourniquet may be safely inflated. We prefer to leave the tourniquet inflated for no more than 1 h. Active bleeding should be controlled by applying pressure on the artery of the amputation stump by fingers. The involved limb should also be immobilized to avoiding secondary injury.

The amputated part should be wrapped in moist saline gauze and placed in a sealed plastic bag, then the bag is dressed with gauze and placed inside a second container (either sterile bag or specimen cup), and then placed in ice. The ice should never come in direct contact with the amputated extremity to avoid frostbite damage. Only when the patient is haemodynamically stable with no other significant life threatening injures should transfer for definitive treatment be considered.

4.5.2 Treatment in Emergency Unit

Once the patient arrives, preparation for surgery should proceed rapidly. In the emergency room, patient should be stabilized hemodynamically and administered broad-spectrum antibiotics and analgesics. The acute decision in favor or against replantation primarily depends on whether the patient's general conditions at the time of the primary diagnostic phase or during operation allow extensive reconstruction. "Life for Limb" must be an ultimate guideline. X-rays of the amputated part and the limb suffering of the amputation are taken.

Once the patient has been worked up in the emergency room, the amputated part is taken to operating room, washed and cleansed with scrub and saline for examination and preparation. The dominant artery is then identified, cannulated with a size of 18 infusion cannula and anchored with silk suture. A continuous perfusion with cold heparinised normal saline solution and complete vascular washout is done, and then it is cooled externally with ice cold saline pads, and kept in a cold environment prior to and during the procedure. Blood is cross matched as needed at admission. The patient is prepared for surgery in the usual manner. The operating theater is also prepared, and the anaesthetic and surgical teams are organized.

4.6 Surgical Technique

Nowadays, although the evolution of sophisticated microsurgical techniques has made successful limb salvage possible, replantation of a limb is a major surgical endeavor. Because an amputation is the sum of a vascular injury, an open fracture, a soft tissue injury and a nerve injury, reattachment of the individual parts can result in severe morbidity during and after surgery. We simply recall some basic rules about operation sequence and techniques. The choice of procedure should be based on the experience of the surgeon and the injury status of the patient.

4.6.1 Preparation in the Operating Room

The emergency department evaluation permits the surgeon to alert the operating room staff of the specific instruments that are required to best treat the injury. For efficiency in the operation room, three operating tables are required. One for the amputated part, another for the debridement equipment, the third for replantation equipment, including skeletal shortening and fixation equipment, polypropylene suture for muscle and tendon repairing, 7/0 to 9/0 nylon suture, clamp, micro-instrument for vascular anastomosis and nerve repair, 12–18 gauge needle, a 20 mL syringe and heparinised normal saline solution (25 μl/ml) to keep moist by frequent irrigation.

4.6.2 Anesthesia

Surgeon's desires and expectation for the anesthesia team must be communicated effectively. There are pros and cons to any anesthesia method. Generally, many procedures can safely be accomplished under epidural anesthesia. During the operation, sedative and/or analgesic drugs are administrated systemically for patient comfort as needed. The morbidity on the circulation and respiration is minimized, and the block can be maintained as needed. However, general anesthesia assisted with intubation and mechanical ventilation is required for the patient associated with cervical, thoracic or abdominal injury.

4.6.3 Debridement

Debridement is a key step in surgical management and evaluation of traumatized tissue. It is also useful in the decision-making process. Whether or not the replantation should be attempted is clearly dependent on the circumstance of the trauma.

4.6.4 Generally Management

Scrub: Both the severed extremity and the amputated part are scrubbed with sterile soap, then copious lavage is carried out with physiologic solution. This procedure is repeated three times, each with 2–3 min.

Immersion: After scrub, the amputated stump and part are immersed into physiologic solution with addition of chlorhexidine at 1 g/2000 mL to cleanse bacteria in wound.

Wound debridement: Debridement is performed on the severed extremity and the amputated part by two separate surgical team to decrease operating time. However, both teams should communicate effectively about the status of the tissue injury to adjust surgical planning.

Debridement of the severed extremity: According to bleeding, color, and other characteristics, the debridement comments in an orderly fashion, starting with the skin and moving to the tissue in the deeper aspects of the wound. Debridement of nonviable tissue is paramount. Effective debridement converts a dirty, crushed wound to a clean and guillotine-like wound. Longitudinal midlateral incisions are made of sufficient length to provide wide expose. The tendons, vessels and nerves can be exposed through the incision. The critical structures (main vessels and nerves) are tagged to avoid difficulty in identification during replantation. The contaminated bone end should be removed and small loose fragments are also removed. Larger fragment with soft tissue connection should be saved for use if necessary. Soft tissue bridges to the subtotal amputation, provided vital, should be retained since they may contain capillary and lymph vessel which may be beneficial for survival.

4.6.5 Debridement of the Amputated Part

It is impossible to evaluate tissue vitality according to blooding. The devitalized skin which appears blue with hematoma in severely crush injury should be removed. However, avulsing skin from the proximal extremity can be retained initially, especially to protect superficial veins. If it is well perfused after revascularization, the resulting flap will ultimately be used to cover the wound. Otherwise, it can be used as split-thickness skin graft. Muscles distal to the amputation level that have lost their circulation must be debrided. Tendons may need to be trimmed to give a clean end, but excessive trimming should be avoided. Both the severed stump and the amputated part should be immersed into physiologic solution with addition of chlorhexidine at 1 g/2000 mL to remove nonviable tissue and debris. Copious lavage is carried out. Then the instruments used are removed and then the surgical team changes gloves.

4.6.6 Vessel Perfusion

The purposes of perfusion amputated part with cold heparinized physiology solution are following mentioned.

First, evaluating the integrity of vessel bed is necessary. No venous outflow or subsequent extravasation and edema demonstrate possibility of damage to vessel bed.

Secondly, it is to flush out stagnant blood. The effects of perfusion may be advantageous, in that it provides immediate cooling to the deeper tissues and flushes out clots and stagnant blood. It decreases the resorption of toxin after revascularization.

Thirdly, it is to dilate the vessels. Capillaries and small vessels in the amputated part are always narrowed. Perfusion may facilitate vasodilatation.

Perfusion protocol: Clots are removed to allow for insertion of a 12–18 gauge blunt needle into a less important artery. Then heparinised normal saline solution (25 u/mL) is maintained through 20 mL syringe with stead pressure to avoid damage to intima. The outflow solution can normally be seen at the connection of artery, medullary and veins. Perfusion is continued until the outflow solution is clear. An increase in perfusion pressure or edema in the distal part demonstrates that vessel occlusion or rupture must exist, which needs exploration (Fig. 4.6).

4.6.7 Replantation Sequence

4.6.7.1 Bony Fixation

Stable bony fixation is very important to maximize healing and avoid motion that may disrupt vascular repairs. Because of the soft tissue shrinkage on both ends and debridement of unviable tissue, bone shortening should be performed to facilitate tension-free primary repair of other structures. Whereas there has been no documentation of the maximum length of acceptable shortening, in our experience, muscle and nerve should be given priority over vessel and skin. Periosteum of the bone end can be maintained to facilitate bone union. Anatomic and functional differences make the upper extremity more amenable to bone shortening than the lower extremity. A “bad hand” may be more functional than a “good” amputation and prosthesis fitting in the upper extremity. However, limb shortening of 10 cm or more will resulting in significant limping, with shorter inequalities compensated for by platform shoes. Because of the high potential of regeneration and adaptation to a new situation in

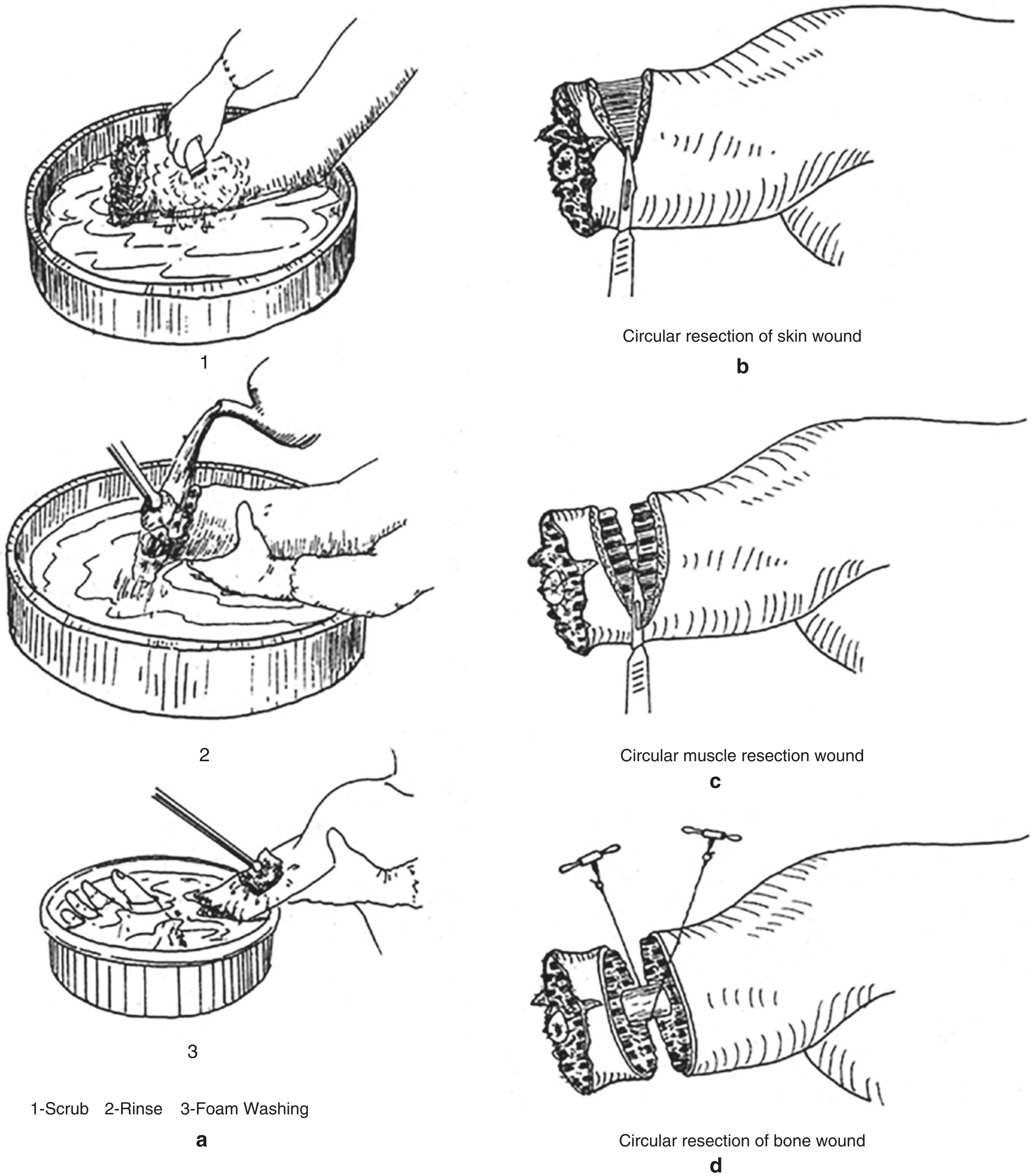


Fig. 4.6 Illustrates debridement

children, discrepancy length can be secondarily corrected by epiphysis growth control or lengthening using the Illizarov technique.

In certain instances, the surgeon may elect to defer shortening of the bone to preserve an articular surface. Thus, some joint function can be restored. If the joint is irreparable, immediate arthrodesis should be considered. In major replantation, time is at a premium, and hence bone fixation has to be quick and simple. Two bone ends can be fixed with plate and screws, or maintained with intramedullary wires. The cross K-wires is the other commonly performed fixation in epiphysis replantation (Fig. 4.7).

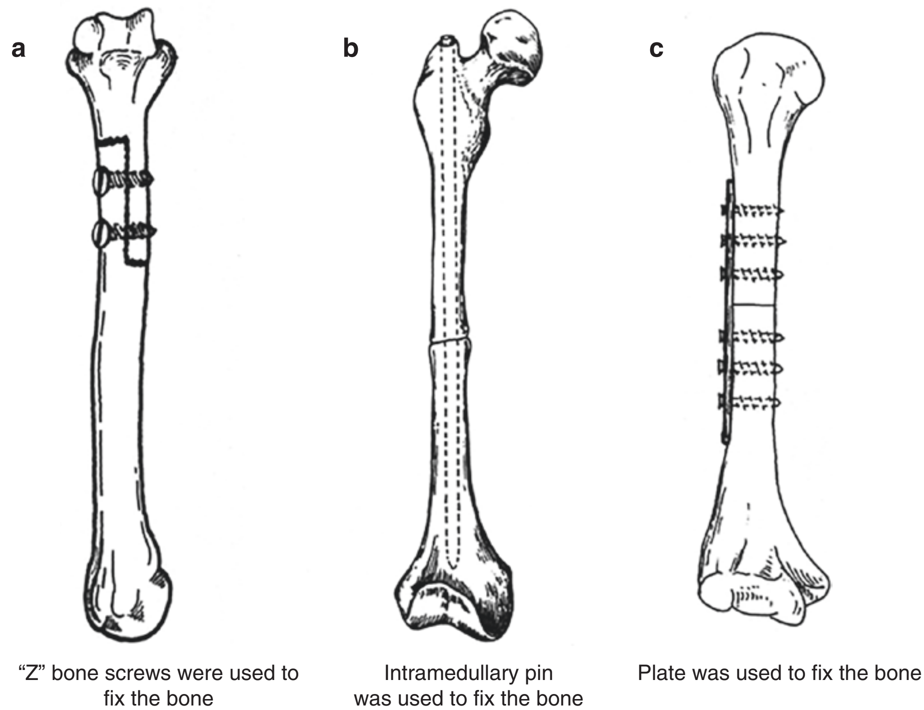


Fig. 4.7 Illustrates skeletal fixation

4.6.7.2 Vessel Anastomosis

The survival of the replanted extremity depends on vessel anastomosis and patency. In order to improve the quality of anastomosis, the procedures must be carried out under an operating microscope or loupe magnification.

4.6.7.3 General Management Before Vascular Anastomosis

Blood volume supplement: Replantation surgery is usually long and associated with extensive blood and fluid losses. Frequent blood and fluid must be infused to maintain a systolic blood pressure greater than 100 mmHg before anastomosis. Meanwhile, inadequate blood volume cam also leads to vasoconstriction and shock.

Vascular debridement: The vessels must be dissected and examined carefully under strong loupe magnification or the microscope. The status of an injury vessel is demonstrated as "red line sign", "ribbon sign", bleeding throughout the region of injury, thrombus or intimal separation, and so on. This segment of vessel should be excised until a normal appearing intima is visualized. If there is inadequate vessel length for direct anastomosis, interpositional vein graft can be used. The adventitial within 5 mm should be trimmed to avoid it to be caught in the intravascular lumen and leads to thrombi formation. Furthermore, pulsatile blood flow must be confirmed from the proximal artery after clamp release.

Control of vasospasm: The occurrence of vasospasm can be induced by trauma stimuli and natural defense mechanism to control bleeding. Vasospasm may result in marked reduction of blood flow, especially in children. Anastomosis without vasospasm relief is likely to fail. Topical agents (papaverine, lidocaine) are used to diminish vasospasm.

Deep soft tissue repair: In order to decrease anastomosis tension, diminish dead space around vessel, protect against contacting with bone and internal fixation, and deep soft tissue should be repaired before vessel anastomosis.

4.6.7.4 General Planning Before Vessel Anastomosis

Artery to vein ratio: The minimal artery to vein ratio is 2:3 to ensure hemodynamic equilibrium. It is advantageous to repair as many vessels as possible.

Commitant vein to superficial vein ratio: For amputation at the level of wrist or ankle, superficial vein should be anastomosed primarily because the blood flow direction is from superficial vein to commitant vein. For the amputation proximal to the wrist or ankle, at least one commitant vein should be repaired because it transports a substantial amount of blood.

Repair sequence: It is usual to reestablish venous continuity first. If ischemic time has been prolonged, to establish circulation as soon as possible, initially repair a single artery and a single vein should be performed. Then, the other vein anastomosis is performed under the circumstance of revascularization.

Anastomosis method: Analysis of the fitness of the artery and vein or commitant vein should be made by the surgeon. Suturing or substantial anastomosis techniques can be selected.

Simple intermittent suture technique has been used very often. It is suitable for vessels repair with different diameter. Vessel wall can be relatively precise contact with each other to prevent narrowing. However, it requires more time and surgical skills.

Continuous suture technique: It is suitable for vessel anastomosis with diameter greater than 2 mm in the amputation above elbow or knee. The first two or three knots are applied. Before the sutures are cut, simple continuous suture is applied, avoiding repetition of the stages of recurrent. Therefore, anastomosis time is shortened. However, this suture technique may carry inversion and eversion irregularity risk.

Sleeve suture technique: It needs only two or three-stitch sleeve sutures; therefore, the anastomosis duration is fast and there is minimal intraluminal suture material exposure. However, adequate length and diameter compatibility are required. Additionally, it may cause narrowing on small vessels (Table 4.1).

Substantial anastomosis techniques include laser aiding suturing, vessel connecting device, vessel adhesive, and so on. These techniques prove to be time-saving. However, requiring special equipment makes them impracticable for universal implementation.

Table 4.1 Different stitch distance, edge distance and stitch numbers for vessels with different diameters (Chenqi Wang 1982)

Diameter (mm)	Microsuture	Stitches	Stitch and edge distance (mm)
2	8-0, 9-0	13–16	0.35–0.4
1	9-0	8–10	0.3–0.35
1	11-0	10–12	0.2–0.3
0.5	10-0, 11-0	6–8	0.15–0.2
0.3	11-0	4–6	0.13–0.19
0.2	12-0	3–4	0.10–0.15

4.6.8 Management of Vascular Defect

Joint flexion will provide a gain in less than 2 cm in length to allow primary anastomosis for vascular defect whose diameter is greater than 2 mm. Vascular grafting should be used whenever deemed necessary. Graft materials may be veins or arteries from individual vascular system. Autologous vein remains an ideal material. It has many advantages, such as their loss causes little inconvenience to the patient's circulation and has less tendency to thrombose. Care must be taken to ensure that anastomosis site should be covered by soft tissue or skin with blood supply. Otherwise, most thromboses occur within 4–5 days.

4.6.9 Signs of Circulation Recovery

After completion of the vascular anastomoses and releasing clamp, the circulation recovery is verified if it fulfills one of the following criteria. The vessel patency is checked and pulse of the distal artery can be touched. The replanted limb should "pink-up". Its capillary refill may take a period less than 2 s. The skin temperature of the replanted limb increases gradually till normal level. There should be brisk bleeding from the veins and small incision. A persistent cadaveric appearance may cause by vasospasm or thromboses. If no signals of good perfusion is appeared after topical use of 2% Lidocaine or intravenous use of 3% Papaverine, revision of the anastomosis or vessel graft is required (Fig. 4.8).

4.6.10 Repair of Skeletal Muscle and Tendon

Optional suturing of muscle and tendons may permit early rehabilitation with a low risk of adhesion and result in better recovery of function. Primary repair of muscles may also help to protect the fracture site and facilitate bone union. In favor of correctly repairing muscle rupture, we prefer simple stitch to repair intermuscular septum or interosseous membrane initially.

Muscles which should be primary repaired depend on the amputated level. In wrist to distal 1/3 section forearm level amputation, the anterior muscle groups including the flexor pollicis longus, the flexor digitorum profundus and the flexor

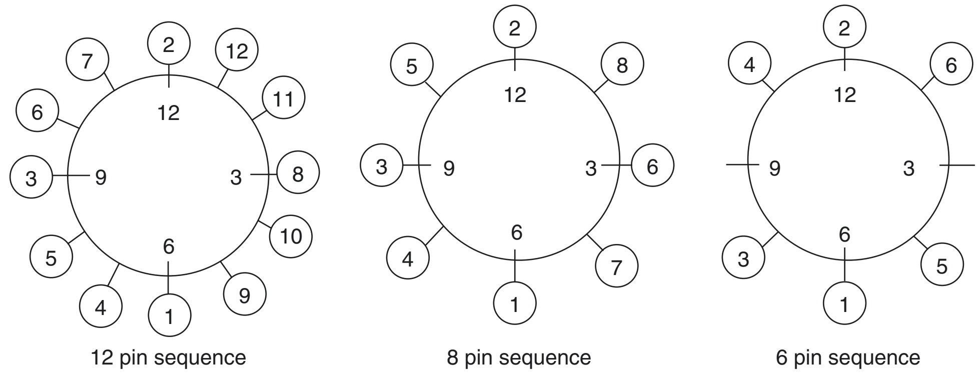


Fig. 4.8 Illustrates vascular anastomosis

digitorum superficials tendons, should be repaired. The posterior muscle groups include the extensor pollicis longus, extensor carpi radialis longus and brevis, extensor digitorum communis tendons. In mid-forearm to proximal third forearm level amputation, the anterior flexor muscle groups, the posterior extensor carpi and digitorum muscle groups should be repaired respectively. In elbow or distal to middle 1/3 section arm level amputation, the biceps and the triceps should be repaired respectively. In thigh level amputation, the quadriceps muscle groups, the biceps femoris, the semimembranosus, semitendinosus muscles and adductors muscle groups should be repaired. In the leg level, the soleus and gastrocnemius muscles, tibialis anterior, Peronei longus and brevis muscles, the flexor hallucis longus, flexor digitorum longus should be repaired. In ankle amputation, the Achilles tendon, tibialis anterior, peroneous longus and brievs muscles, the flexor hallucis longus, flexor digitorum longus should be repaired.

4.6.11 Repair Techniques

The type of the used suture methods should depend on the amputation level. Horizontal mattress sutures are usually used to repair muscle belly rupture according to the direction from deep to superficial muscles. Each stitch should incorporate the epimysium to improve the mechanical property. For those mass belly ruptures, peripheral suture should be enhanced by several central stitches, to diminish dead space. If the injury involves the tendons, it can be repaired with several suture techniques. According to the experience described by Chenqi Wang, a double core suture technique is usually chosen for the flexor tendon rupture. Figure of eight stitches is used to repair extensor tendons. Fish mouth suture technique can be used to repair tendons with discrepant diameters. It is difficult to repair the rupture at the musculotendinous junction. The tendon ends can be woven into the proximal muscles to provide adequate strength. Due to fibrotic tissue forming at the injury site may cause adhesion, you'd better avoid repairing all tendon ends at the same level (Fig. 4.9).

4.6.12 Nerve Repair

Nerve repair is essential to guarantee a good functional result and must be done carefully not delaying it to a secondary repair if possible. Technically, a primary repair is easier to dissect and allow anastomosis without tension by the methods of bone shortening, joint flexion or nerve transfer. Nerve may avulse from the proximal level; however, the nerve end shows normal appearance after debridement. In this circumstance, an additional incision at the severed nerve level may be made to pull back the nerve through a subcutaneous tunnel. If the extents of resection is very difficult to judge and primary nerve repair is not possible after an avulsion injuries, the nerve ends can be tagged and placed in accessible location. This step facilitates later identification for nerve grafting.

Major nerves in the upper and lower extremity include the brachial plexus, median nerve, ulnar nerve, radial nerve, musculocutaneous nerve, sciatic nerve, femoral nerve, and tibial nerve, while common peroneal nerve should be repaired primarily. Such nerves as the superficial branch of radial nerve and saphenous nerve which has no influence on the hand or foot sensory recovery can be abandoned.

4.6.13 Repair Techniques

The nerve ends are handled with care using microsurgical instruments. A surgical blade or a pair of sharp micro scis-

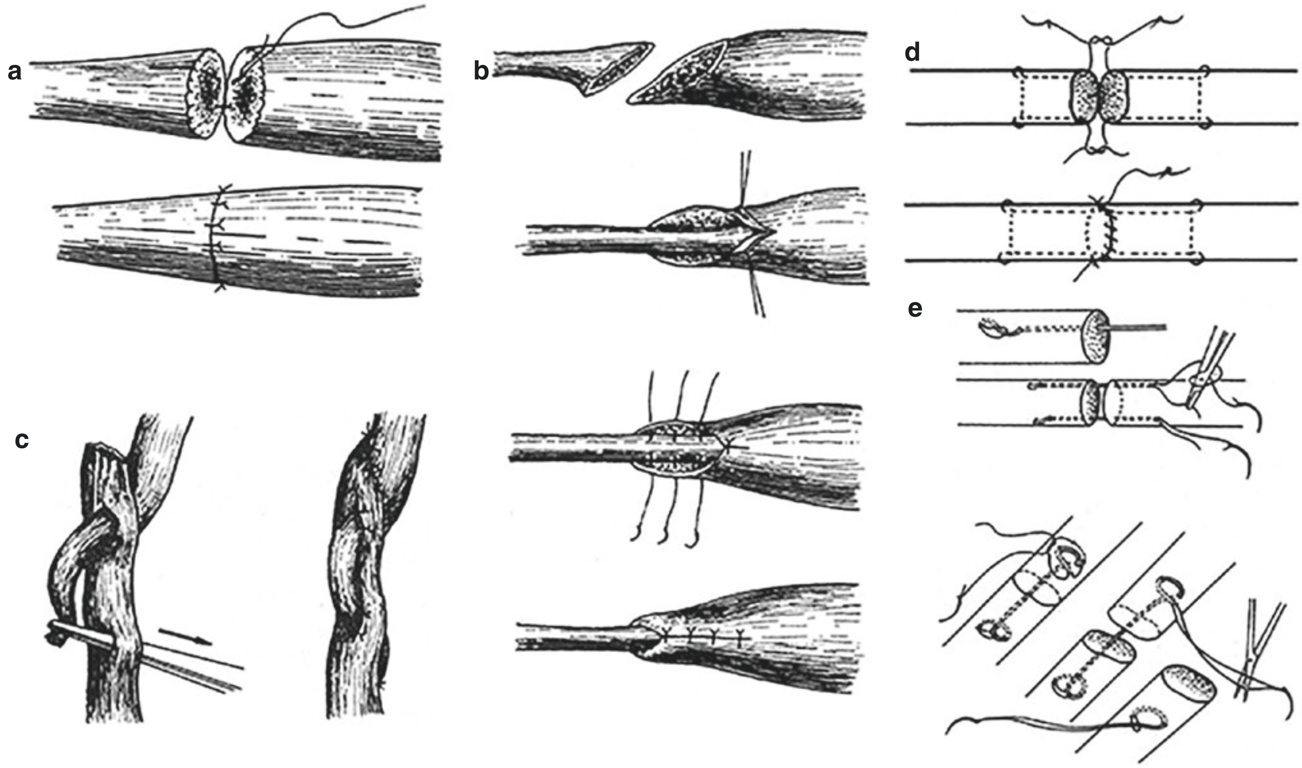


Fig. 4.9 Illustrates repair techniques of muscle and tendon

sors can be used to remove the necrotic parts of the ends until a normal fascicular pattern can be visualized under the microscope. Active bleeding should be ligated at the same time. The rotation of nerve segment can be easily judged by its structure and characteristic such as sensory and motor components, the location of longitudinal intraneural blood vessel, and so on. In specific cases it is possible to identify individual fascicular groups for attachment, predominantly at a distal level where fascicles with specific targets are well defined. It is important to perform nerve repair without tension and to leave a minimal gap between the nerve ends. Nerve repair should be reinforced with fascia suturing around nerve to provide additional strength to release tension. Though joint can be flexed to allow direct nerve anastomosis, the flexion degrees should be less than 30° for the wrist and 90° for the elbow and knee. Nerve transposition can also facilitate tension release. For example, the radial nerve can be transported to the anterior aspect of the humerus in the arm amputation with a compensation of 3–4 cm length. The ulnar nerve can be transported to the distal humerus for the level of elbow amputation. The median nerve can be transported by dissecting superficial head of pronator teres. Nerve gap should be grafted when required. Sources of nerve graft include the medial antebrachial nerve from the forearm, saphenous nerve, sural nerve and lateral femoral cutaneous nerve. Group fascicular suture or tubular repair techniques can be used. However, only less than 50% of the normal function can be restored. The authors prefer the epineural repair with 9-0 or 10-0 nylon under microscope magnification, ensuring accurate fascicular apposition (Figs. 4.10, 4.11, and 4.12).

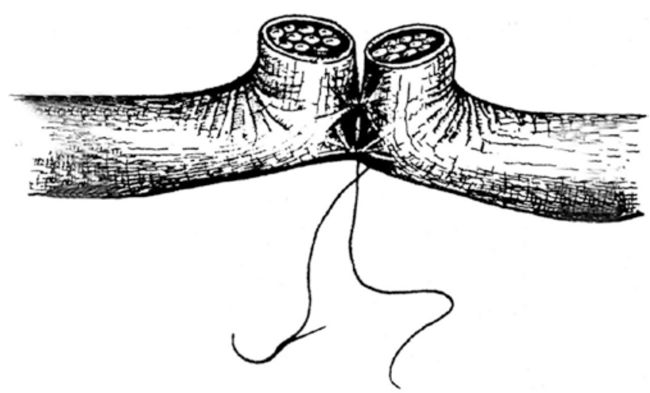


Fig. 4.10 The relieving tension suture

4.6.14 Skin Coverage

Good soft tissue coverage will help limb survive and prevent infection. The skin is closed without tension. A tight closure may cause pressure on vein. After debridement, wound closure depends on the type of trauma. A zigzag incision will be helpful in sharp injury. In the presence of a good muscle bed, a simple meshed split thickness skin graft can be performed. Free flaps may be required to repair the wound of crushing amputation. The wound is closed over a deep-seated tube and superficial drains to prevent fluid collection.

4.6.15 Dressing and Immobilization

Postoperatively, the replanted limb is covered in a bulky dressing and plaster splint, and is elevated and kept warm to promote perfusion. For the upper extremity replantation, a splint is applied with the elbow at 130° of flexion, the wrist at 15° dorsal flexion, and the hand at functional position. For the lower extremity replantation, a splint is applied with the knee at 10° of flexion, and the ankle at 0° flexion.

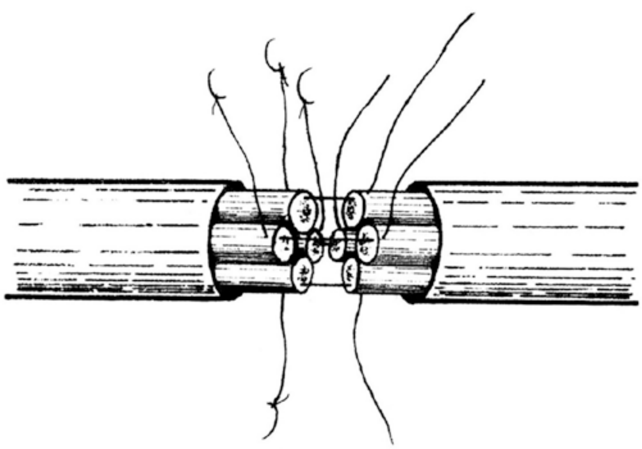


Fig. 4.11 Interfascicular suture

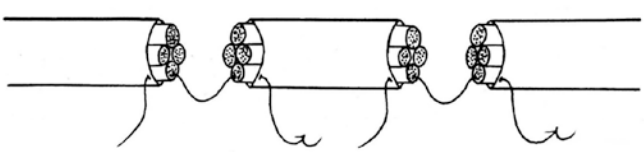


Fig. 4.12 Nerve-grafting interfascicular suture

4.6.16 Postoperative Management

The most important tasks of the early postoperative phase are stabilization of the patient and detection as well as treatment of local and/or systemic complications. Continuous monitoring of the vital functions and the replant should be carried out.

4.6.17 General Complications Monitoring and Management

Patients who undergo replantation demonstrate an increased rate of postoperative complications compared with patients who receive revision amputation. Thus, some vital signs should be monitored besides associated organ injury.

4.6.18 Hypovolemia

Replantation surgery is usually long and associated with extensive blood and fluid loss. Inadequate blood volume may lead to haemorrhagic shock. Low blood pressure can potentially induce circulation stagnation and thrombosis formation, which may cause replantation failure. Hence maintaining a systolic blood pressure greater than 100 mmHg through blood and colloids transfusion is absolutely essential in the perioperative period. The use of vasopressors or inotropes should be avoided if possible, because it may cause peripheral vasoconstriction or spasm. Blood loss volume can be grossly estimated by the level of amputation and injury characteristics. That is 7500 mL for thigh amputation, 4500 mL for leg amputation, 4000 mL for arm amputation, 3300 mL for forearm amputation, and 2000 mL for ankle or wrist amputation. Adequate blood volume can be demonstrated by good peripheral perfusion with a warm limb. The use of central venous pressure to monitor the adequacy of intravascular volume may be helpful. The decrease of central venous pressure may demonstrate the inadequate of blood volume. Meanwhile, red cell counts, hemoglobin value and haematocrit value can also be used as references for blood transfusion.

4.6.19 Prevention and Treatment of Acute Renal Failure

One of the most dreaded complications of limb replantation is acute renal failure, which may cause surgery failure and threaten patient's life. The renal damage may be brought about by persistent hypotension, crushing injury, prolonged ischemia, inadequate debridement, secondary infection, or vasopressors. Renal ischemia and toxic product are two main damage mechanisms. Oliguria, anuria, azotemia, hyperkalaemia and metabolic acidosis may be observed in an early stage. The management of acute renal failure includes: limiting total fluid intake, controlling hypertension, decreasing acidaemia and blood urea nitrogen. Preventing the onset of renal failure is very important. The following prevention factors must be taken into account.

In the case of extensive tissue damage, especially when warm ischemia time is longer than 6 h, it must be abandoned for replantation. Additional debridement is always repeated after revascularization and during the early replantation follow-up. Otherwise, muscle necrosis and toxic metabolites can lead to renal failure.

At the end of repair, extensive fasciotomy must be performed to prevent compartment syndrome. Moreover, fasciotomy can lead to some renal functions in the cases of oliguria or anuris.

Given a good cardiac and pulmonary function, maintenance of a high fluid intake can reduce the concentration of toxic products in renal tubules damage. For example, if an accounted fluid intake is 4000 mL per day, 5500–6000 mL fluid can be administered to maintain adequate urine output.

A number of symptoms, such as fatigue, vomitting, distension, a subsequent dysphoria, stupor may be observed in early stage of renal failure. Monitoring urine output, color, regular analysis and biochemical analysis seem to play an important role. If treated early and aggressively, an excellent prognosis can be achieved.

If acute renal failure occurs and cannot be managed through effective treatment, replanted limb has to be re-amputated in an effort to overcome this problem. The surgery should be performed by applying a tourniquet. Removing sutures of vein to release blood from the vein allows dissipation of toxic lactic acid and also lessens the potassium burden.

Fat embolism syndrome occurs in most cases of severe trauma. Widespread obstruction may cause sudden death. Fat embolism may get lodged in capillaries of organs like lung, brain, and kidney. Pulmonary signs include cough, tachypnea and hypoxemia. The chest x-ray may show snow storm appearance. Fat drops may be observed in sputum. Central nervous system signs consist of a change in level of consciousness, stupor, and coma. Renal signs include oliguria and fat drops in uria. Additionally, a rash that appears on the upper anterior portion of the body including chest, neck, oral mucosa and conjunctivae can be observed. Early diagnosis and aggressive management can get an excellent prognosis.

4.6.20 Reperfusion Injury

Revascularization of amputated extremities after ischemic is complicated by reperfusion injury. The cellular damage that results from ischemia has been studied intensively in humans, experimental animals, and cell culture systems. In the early phase of ischemia, adenosine triphosphate is provided by glycolysis. However, glycogen stores are soon depleted, with the accumulation of lactate and other toxic metabolic products. This triggers the activation of chemical mediators and enzymes, including phospholipase A_2 and lysozymes. The main putative mechanisms involve leukocyte-endothelium interactions, reactive oxygen species, and the complement system. Reperfusion injury adversely affects both the replanted limb and distant organs like lungs and kidneys. In many clinical situations, the duration of ischemia is beyond the surgeon's control, and other measures are required to reduce the extent of reperfusion injury. Appropriate multidisciplinary management of reperfusion injury should be undertaken with the anesthesia and critical care team. Several scavengers of free radicals have been examined in animal models. Recombinant human superoxide dismutase has been shown to improve the outcome of musculocutaneous and skeletal muscle flaps when given parenterally to animals. (Prada FS, Arrunategui G, Alves M, et al. Effect of allopurinol, superoxide-dismutase, and hyperbaric oxygen is on flap survival. Microsurgery. 2002, 22:352.) Vitamins A, C, and E are micronutrients with antioxidant properties. These vitamins are not effective as radical scavengers when given alone, but in combination with other vitamins or pharmacologic agents; moreover, they are able to work synergistically to reduce reperfusion injury. Despite many small clinical studies showing variable success in the treatment of reperfusion injury, at present, there are no well-validated pharmacologic interventions that reduce the adverse effects of ischemia-reperfusion injury (Khalil AA, Aziz FA, Hall JC. 2006, 117:1024–1033).

4.6.21 Local Complications Observation and Management

4.6.21.1 Local Circulation Observation

Post-operative evaluation of vascular patency and tissue perfusion is an essential element in the management of operation. The patient must be kept in a warm, draft-free room with a constant temperature about 23 centigrades. It is essential to recognize the vascular compromise early, because the effectiveness of intervention is inversely related to the time that has elapsed between suspicion of vascular compromise and reexploration. Clinical judgement (colour, turgor, capillary refill of the nail bed) and several methods have been developed to monitor microcirculation or establish the patency of microvascular anastomoses. If the procedure seems to be successful, the intervals between observations are gradually prolonged, at first to 4 h and then to 8 h, after which they are eventually stopped.

Skin color and characteristic of pulp: Signs of red skin, pink nail and plump pulp demonstrate sufficient circulation. Conversely, signs of pale and flaccid mean insufficient circulation.

Skin color while limb position changing: Another simple method to evaluate arterial in-flow is elevating the involved limb for 5–10 min, and then put it down. The skin color normally turns red within 4–6 s.

Capillary refill upon compression: Capillary refill on the replanted limb is normal within 3 s.

Cutaneous temperature measurement: Cutaneous temperature measurement has been demonstrated as a method of monitoring following microvascular surgery. The temperature of the replanted part should be compared with that of the uninjured limb. A difference of 2 °C between the two should indicates circulatory impairment.

Pulse detection: The pulse of radial or dorsal artery can be touched in the replanted limb. Otherwise, it should be investigated further.

Doppler flowmetry: It offers an easy and reliable way to monitor anastomoses. It can also distinguish venous from arterial occlusion.

Bleeding: Leakage of blood from the fingertip or toetip using a needle or small incision indicates adequate blood supply.

In general, arterial and venous occlusion can be differentiated by changes mentioned in the following table (Table 4.2).

Any sudden occurrence of circulation disturbance is usually caused by thrombi. However, frequent inflow or outflow insufficient indicates vasospasm. Vasospasm can be prevented by maintaining a warm environment, administering analgesics, and possibly performing regional blocks. The dressing may be too tight and should be removed or replaced as the first step. Vasospasm usually can be treated by adequate infusion therapy and or application of vasodilatation drugs. If it is not resolved within 1 h, the patient should be returned to the operating room as soon as possible. In the case of local thrombosis in the area of anastomosis, it has to be excised and repaired again.

Table 4.2 Circulatory compromise after limb replantation

Monitoring method	Arterial insufficiency	Venous congestion
Skin color	White or pale	Blue
Temperature	Decrease greater than 2 °C	Decrease greater than 2 °C
Resistance	Flaccid	Feel tense to touch
Doppler detection	No flow signal	No or weak flow signal
Capillary refill	Poor or delayed	Poor or brisk
Bleeding	No bleeding	Quite dark

4.6.21.2 Postoperative Swelling Control

The replanted part often swells slightly due to body's natural reaction to trauma. However, persistent swelling is one of most serious reasons threatening limb survival, which requires immediate management. Because when the interstitial fluid pressure equals to the small arterial pressure, blood circulation will stop. Venous outflow insufficiency, inadequate debridement, hematoma, the severity of injury, and so on are the common reasons.

Loss of normal skin creases and extremity contour, circumferential and two designated land marks measurement are helpful to evaluate the degree of swelling. Treating its cause can alleviate the problem. For example, it appears that the better the deep venous drainage, the less frequent postoperative swelling will appear. As many as veins are anastomosed, and alleviating dead space, fasciotomy, interventions, such as hyperbaric oxygen, can effectively decrease swelling.

Management of Wound Infection

Wound infection is one of the most dreaded complications. If uncontrolled by medical and surgical means, it will inevitably lead to vascular thrombosis and replantation failure, even life-threatening. Wound infection may cause vessel necrosis, vascular thrombosis and corrosion bleeding. To prevent infection, adequate debridement should be emphasized. Not infrequently additional suction must be used to obliterate space. Patency of the suction catheters must be maintained until drainage is diminished. It is also recommended that the patient should be kept warm in the ICU to decrease the risk of cross infection. The patient should receive appropriate antibiotic and tetanus prophylaxis. Once the infection occurs, the wound is surgically cleansed every day and cultures should be obtained from the wound. The appropriate antibiotics are administered according to the variation of the wound bacterial culture and its sensitivities.

4.6.21.3 Anticoagulation Protocols

Based on published data, there is no single accepted protocol for anticoagulation. Microsurgical technique is the most critical factor for survival. No studies have demonstrated conclusively that anticoagulants will improve the patency rates of technically good performance. Nevertheless, because the failure of replantation always is associated with vascular thrombosis, there may be a subset of patients who can benefit from the use of systemic anticoagulants. The main risk of therapeutic anticoagulation is hematoma formation, a complication that can lead to obstruction of the vascular pedicle. Postoperative systemic heparin therapy is not required in high quality anastomoses. In our experience, a pharmacologic protocol including low-molecular-weight Dextran, low-dose Aspirin and Papaverine Hydrochloride is routinely used for 7 days. On the contrary, systemic heparinization is indicated if the vessels appear severely damaged or vascular thrombosis occurs in the operating room. The contraindications such as associated brain, thoracic or abdominal injury, and ulcer and so on must be excluded. About 5000 u heparin in 500 mL saline intravenously per 24 h is administered for 5 days. Meanwhile, coagulation profile (prothrombin time, international normalized ratio, activated partial thromboplastin time) has to be analyzed at regular intervals.

4.6.21.4 Hyperbaric Oxygen Therapy

Hyperbaric oxygen therapy is a treatment modality in which a person breathes 100% O_2 while exposed to increased atmospheric pressure. Pressures applied while in the chamber are usually 2–3 atmospheres absolute. It is well accepted that breathing greater than 1 atmospheric pressure O_2 will increase the production of reactive oxygen species. Reactive oxygen species and also reactive nitrogen specimens serve as signaling molecules in transduction cascades for a variety of growth factors, cytokines and hormones. Hyperbaric oxygen therapy may decrease edema and improve microcirculation. Patient selection remains the key to successful outcome. In cases of prolonged warm ischemia time, postoperative circulation disturbance or re-establishment of circulation after exploration, hyperbaric oxygen therapy may be selected. The rationale for hyperbaric oxygen therapy treatment should be based on the amputation level, ischemia time, circumstance temperature and hyperbaric chambers. Albumin or dextran has been recommended for additional therapy.

4.7 Secondary Procedures and Rehabilitations

The goal of replantation is not only viability of the replanted limb but of obtaining function and appearance. Thus, besides meticulous microsurgical technique, it is important to carry out a well designed postoperative rehabilitation program to optimize clinical outcomes.

4.7.1 Rehabilitation

Rehabilitation program should be adapted to different stages of functional recovery. For the initial 3 weeks, the patient must remain in bed to avoid the risk of compromising the newly repaired vessels. A protective splint is fabricated and any stress to wound or repair sites should be avoided. Four to five weeks after the surgery, vascular status is stabilized. Early rehabilitation therapy begins. Gentle active and passive motion is initiated gradually as tolerated to improve microcirculation and functional recovery. Retrograde massage and functional electrical stimulation can be used. Between 2 and 3 months, fracture is stable and can tolerate stress. Therefore, exercise of joint motion can be enhanced. Heat modalities should be avoided because of the lack of sensation and the fact that the lymphatic system is unable to dissipate heat effectively.

4.7.2 Psychological Therapy

Although the replantation is successful, amputation trauma leads to devastating physical and psychosocial repercussions besides reduction in work ability. All these may have a profound impact on patient's quality of life. A psychiatry consult should routinely be held.

4.7.3 Vocational Retraining

The ability to return to productive employment requires the functional and psychological recovery. According to patient's profession, special work conditioning should be implemented as early as possible.

The goals of treatment are: control of pain and vasospasm, prevention of thrombosis, promotion of vasodilatation, and restoration of blood flow. The hand is protected with a large bandage and the extremity is kept elevated while the patient is in bed.

4.7.4 Secondary Procedures

The functional results of replanted limb should be evaluated including limb contour, reinnervation, range of motion, circulation, strength and use of the injured limb in activities of daily living.

Contour: In order to evaluate muscle atrophy, scar contracture and deformity, limb length and circumferential measurement are required and should be compared with the unaffected limb.

Function of bone and joint: Malunion or non-union of bone should be evaluated. Joint mobility including active and passive range of motions should be recorded.

Recovery of nerve: Recovery of nerve is tested by means of pain, touch, tremor, topesthesia and proprioception. Two-point discrimination is an objective measurement and is particularly useful for evaluation. The two-point discrimination on normal finger pulps is less than 6 mm, on palm and plantar is less than 20 mm, and on dorsal of hand or foot is less than 30 mm. Tinel's sign can be detected to evaluate the regeneration speed. Electromyography can also be performed. Muscle power is a most important sign of motion function recovery. Sweat pattern tests with different staining techniques which are based on chemical reactions (iodine-starch, ninhydrin printing test) offer information about regeneration of sympathetic fibers.

Comprehensive functional analysis: Today, functional recovery after replantation has become the ultimate goal. The patient can perform daily living activities such as dressing, washing, eating, weight bearing, writing, weaving, using tools, and so on. In addition, entertainment and sports activities should be tested.

4.7.5 Secondary Reconstruction Procedures

Bone repair: The need for secondary surgery after replantation is common. Malunion, non-union, or bone defect up to 4 and 5 months should be managed by bone graft. If the shortening of the lower extremity exceeds 6–7 cm, orthopedic footwear does not provide an adequate compensation of the function. In these instances, lengthening of the leg by means of distraction on osteogenesis or artificial shortening of the uninvolved leg has to be performed.

Muscle and tendon repair: To restore impaired physiologic function, the following techniques may be selected accordingly.

Tenolysis: Tenolysis is frequently necessary as early motion is not possible in most patients undergoing replantation. Tendons often become adherent at the site of injury. If the function has no improvement after rehabilitation 3 months postoperatively, tenolysis should be performed.

Tendon grafting: Tendon grafting can be performed 3 months postoperatively in the case of tendon defect without primary reconstruction. Tendon grafts can be harvested from the palmaris longus, plantaris or toe extensor tendon.

Tendon transfer: Tendon transfer can be performed to replace those muscles or tendons are unable to repair. Muscle power should be examined before operation.

Pedicled muscle transfer: For the arm level replantation, the pectoralis major muscle can be used for restoration of elbow flexion and the latissimus dorsi muscle for elbow extension.

Free functioning muscle transfer: If the above mentioned techniques are not practicable because of local severed injury, different muscles are available for free functioning muscle transfer. Commonly used muscles include the gracilis, pectoralis major, latissimus dorsi and tensor fascia lata muscles. Besides vascular anastomosis, individual nerve branches must be coaptated to specific branches at the recipient site. In case of associated soft tissue defect, musculocutaneous flap can be performed simultaneously.

4.7.6 Secondary Nerve Repair

The outcome of nerve repair is influenced by many factors such as amputation level, timing of repair and so on. If nerve function does not improve as prediction, the following techniques can be performed accordingly.

Neurolysis: The time of surgical neurolysis is important for optimal recovery. If the Tinel's sign does not progress within 3–4 weeks and a neuroma may be palpated at the anastomosed site, the surgery is indicated. Scar tissues trapping the nerve have to be dissected longitudinally till the normal nerve fiber is seen.

Secondary coaptation: When the degree of injury has not yet been ascertained, two nerve ends should be tagged and sutured with surrounding soft tissues under approximate tension. Then, secondary coaptation can be performed 2–3 months postoperative.

Repair of nerve defect: If the nerve cannot be repaired primarily because of long segment defect involved, the following techniques can be performed.

Nerve transfer: During recent years, nerve transfers have been more frequently used whereby less important nerve fascicles from a donor nerve are transected, intraneurally dissected and redirected to be attached to a functionally more important injured distal nerve segment. Alternatively, a whole distal branch of a nerve (e.g. distal anterior interosseous nerve) can be transected and transferred to an injured thenar motor branch. Thus, by the technique of nerve transfer a proximal nerve injury is transformed into the distal one with short regeneration distance to target. The procedure to transfer nerve trunks is frequently used in reconstruction of the brachial plexus, like transfer of intercostal nerves to the musculocutaneous nerve.

Nerve graft: Nerve grafts are usually indicated as the nerve ends have usually contracted and/or scars needed to be resected. Either nonvascularized or revascularized nerve graft may be selected. The grafts are usually from the medial antebrachial cutaneous nerve, sural nerve and so on. In some instances, cable nerve graft has to be performed. Nerve tubes or other alternatives may also be selected.

4.7.7 Management of Late Circulation Disturbance

The reasons for late circulation disturbance are as follows. First, arterial inflow disturbance may induce late arterial thrombosis. If there is evidence of ischema within 2 weeks, it means sufficient collateral circulation has not been established. Ultrasonic examination may be used to evaluate the blood flow. Once the arterial thrombosis is verified, vascular exploration should be performed. On the contrary, positional or passive congestion training may be undergone to facilitate establishment of collateral circulation. Secondly, venous outflow insufficiency may be often caused by circular scars trapping. Several zigzag incisions or pedicle flaps may release this kind of contracture. Thirdly, lymphedema associated with lymphatic circulatory failure may prolong the period required for improvement of swelling. It usually remits when normal lymphoma circulation restores 3–4 weeks after replantation. Conservation treatment such as compression and manual drainage is commonly used for lymphedema. Lymph vessel transplantation, lymph node transfer, and stem cell transplantation have been studied as free tissue transfer methods to treat lymphedema. In our experience, lymphatic-venous anastomosis and free flap transfer may also offer improved treatment for persisted lymphedema. Treatment with flap transfer resolves scar contracture and fills the tissue with abundant blood flow, forming favorable scaffolds for lymphangiogenesis, and normal lymph vessel regeneration may occur between subcutaneous tissues, successfully in producing remission of edema (Mihara M, Hara H, Araki J, et al. 2013, 66:e338–340).

4.7.8 Functional Evaluation

With the success of replantation, great focus is now placed on functional and esthetic recovery of the replanted limb. Restoration of tissue viability is no longer the sole measure of success. A poor functional outcome must be weighed against an amputation or prosthesis. However, the arguments about functional evaluation of major limb amputation results are still on debate. Chen's classification is the most widely used evaluation system. However, according to the authors, ability to work, protective sensibility and acceptable aesthetic result are the most important criteria for a successful replantation (Tables 4.3 and 4.4).

The end result of replanted extremity that is viable yet functionally deficient usually is better than prosthesis. Request for amputation of a replanted extremity is seldom even the function is poor. However, in some circumstances, such as severe pain at the replanted part, chronic osteomyelitis, septic arthritis, severe discrepancy of length in the lower extremity also interferes with prosthesis, and ultimately amputation should be considered.

Table 4.3 Shows criteria for the evaluation of the upper extremity functional after replantation in our experience

Grade	Function
I	Able to resume previously held employment; range of motion exceeds 60% of normal; complete or nearly complete recovery of sensibility; muscle power of grade 4 and 5; no longer have cold intolerance; nearly normal appearance
II	Able to resume professional activities; ROM exceeds 40% of normal; nearly complete sensibility; muscle power of grades 3 and 4; mild cold intolerance
III	Able to lead normal daily life; ROM exceeds 30% of normal; partial recovery of sensibility; muscle power of graded 3
IV	Almost no useable function in survived limb

Table 4.4 Shows criteria for the evaluation of the lower extremity functional after replantation in our experience

Grade	Function
I	Able to resume previously held employment; walks with normal gait; good sensibility; almost normal knee and ankle joint mobility
II	Able to do some light work; walks with slight limping; good sensibility; range of motion of the joints is more than 40% of the normal
III	Useful in daily life; request for wearing an elevated shoe; poor plantar sensibility without pressure ulcer
IV	Walk with the aid of crutches; no sensation in the sole; likelihood of pressure ulcer

Bibliography

1. Hopfner E. Ueber gefassnacht, Gefasstransplantationer und replantation von amputirten extremitaten. Arch Klin Chir. 1903;70:417.
2. Malt RA, McKhann CF. Replantation of severed arms. JAMA. 1964;189:716.
3. Chen ZW, Yu HL. Current procedures in China on replantation of severed limbs and digits. Clin Orthop. 1987;215:15–23.
4. Chen ZW, Zeng BF. Replantation of the lower extremity. Clin Plast Surg. 1983;10(1):103–13.
5. Yaffe B, Hutt D, Yaniv Y, et al. Major upper extremity replantations. J Hand Microsurg. 2009;1(2):63–7.
6. Hierner R, Berger AK, Frederix PR. Lower leg replantation—decision making, treatment, and long-term results. Microsurgery. 2007;27:398–410.
7. Battiston B, Tos P, Clemente A, et al. Actualities in big segments replantation surgery. J Plast Reconstr Aesthet Surg. 2007;60:849–55.
8. Larson JV, Kung TA, Cederna PS, et al. Clinical factors associated with replantation after traumatic major upper extremity amputation. Plast Reconstr Surg. 2013;132:911–9.
9. Salgado CJ, Jamali AA, Ortiz JA, et al. Effects of hyperbaric oxygen on the replanted extremity subjected to prolonged warm ischaemia. J Plast Reconstr Aesthet Surg. 2010;63:532–7.
10. Ricketts S, Steiger RD, Breidahl A. Eleven-year follow-up of cross-leg replantation for traumatic bilateral amputation. J Reconstr Microsurg. 2009;25:111–6.
11. Friedrich JB, Poppler LH, Mack CD, et al. Epidemiology of upper extremity replantation surgery in the United States. J Hand Surg Am. 2011;36A:1835–40.
12. Laing TA, Cassell O, O'Donovan D, et al. Long term functional results from major limb replantations. J Plast Reconstr Aesthet Surg. 2012;65:931–4.
13. Lloyd MS, Teo TC, Pickford MA, et al. Preoperative management of the amputated limb. Emerg Med J. 2005;22:478–80.
14. Tantry TP, Kadam D, Shenoy SP, et al. Perioperative evaluation and outcomes of major limb replantations with ischemia periods of more than 6 hours. J Reconstr Microsurg. 2013;29:165–72.
15. Constantinescu MA, Knall E, Xu XF, et al. Preservation of amputated extremities by extracorporeal blood perfusion; a feasibility study in a porcine model. J Surg Res. 2011;171:291–9.
16. Sabapathy SR, Venkatramani H, Bharathi R, et al. Replantation surgery. J Hand Surg Am. 2011;36A:1104–10.

5 Replantation of Amputated Palm

Yong Liu

5.1 Applied Anatomy of the Palm

Anatomically, the vessels, nerves, muscles and tendons on the carpus and metacarpus are arranged at multiple levels. The tiny branches and communicating of vessels and nerves spread in an especially complex manner. Therefore, difficult replantation of amputated palm does not yield a satisfactory rate of survival and functional recovery as does replantation of a severed limb or digit. The key to ensuring survival and functional recovery of a replantated palm as maximally as possible is familiarity with the anatomical structures of different sections at the carpus and metacarpus.

5.1.1 Division of Amputation Planes on the Carpus and Metacarpus

The scope of amputation on the carpus and metacarpus ranges from the carporadial articulation plane proximally to the plane of proper palmar digital arteries spread from the common palmar digital artery distally. Chinese and international scholars have conducted numerous clinical and microsurgical researches on the replantation of the amputation within the above scope, but no consensus has been achieved on the typing of the amputation. Generally, there are two ways of typing. One divides the amputation into carpometacarpal type, mid-metacarpal type and metacarpophanlangeal type, bases on the the distribution of carpometacarpal vessels. The other divides the amputation into five types, adding a mixed type and a smashing type to the above three types according to the characteristics of the injury. Taking the general anatomy of the palm and the common practice in the literature into account, we will deal with the carpometacarpal amputation in three sections: proximal metacarpal section (carpometacarpal section), mid-metacarpal section, and distant metacarpal section (metacarpophalangeal section). The following will introduce the anatomical structures of the three sections.

Y. Liu (✉)
Department of Orthopaedics, PLA 89th Hospital, Weifang, China
e-mail: 13793694402@163.com

5.1.2 Anatomical Characteristics of Sections of the Carpus and Metacarpus

5.1.2.1 Proximal Metacarpal Section (Carpometacarpal Section)

This section approximates the carpale or proximal arcus palmaris profundus. Origination of the thenar and hypothenar eminence muscles is remote to this section. The flexor digitorum superficialis tendon, flexor digitorum profundus tendon, flexor pollicis longus tendon and median nerves are concentrated on the carpal tunnel. The ulnar nerve and ulnar artery are located in the ulnar carpal tunnel. The digital extensor longus tendons are concentrated on the dorsal wrist. The flexor carpi tendon and extensor carpi tendon of the radialis and ulnaris are on display in the dorsal and metacarpal sides. The median nerves and ulnar nerves are nerve trunks. The radial artery and ulnar artery and their main branches are arranged in dorsal and metacarpal levels. The dorsal superficial veins have been gathered into vein trunks which can be divided into a radial and an ulnar group. On average, the radial group has 2.0 (1–4) branches and the ulnar group has 3.0 (2–5) branches. They are respectively located at the dorsoradial side of the second metacarpal bone and the dorsoulnar side of the third metacarpal bone. The total cross sectional area of the ulnar group is 15.6% larger than that of the radial group (Fig. 5.1).

5.1.2.2 Mid-Metacarpal Section

This section approximates the part of the metacarpal bones between the arcus palmaris profundus and the arcus palmaris superficialis. On the radial and ulnar sides of this part are the thenar eminence and the hypothenar eminence. The metacarpeae palmares concludes the intrinsic muscles of the hand (interosseous and lumbrical) and flexor digitorum superficialis and profundus tendon. The digital extensor

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_5

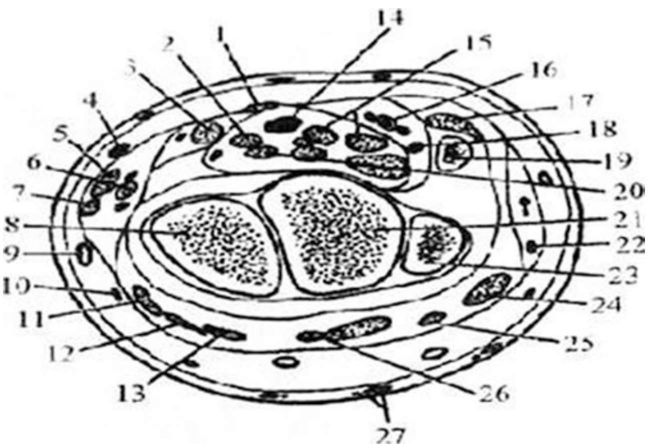


Fig. 5.1 The main structure of the proximal metacarpal section. (1) Almaris longus. (2) Flexor pollicis longus muscle tendon. (3) Flexor carpi radialis muscle tendon. (4) Radial nerve, superficial; ramus superficialis nervi radialis. (5) Abductor pollicis longus. (6) Radial artery and vein. (7) Extensor pollicis brevis. (8) Scaphoid bone. (9) Cephalic vein. (10) Dorsal branch of radial nerve. (11) Extensor carpi radialis longus. (12) Extensor pollicis longus muscle tendon. (13) Extensor carpi radialis brevis. (14) Median nerve. (15) Flexor digitorum superficialis. (16) Ulnar artery and vein. (17) Flexor carpi ulnaris. (18) Ulnar nerve. (19) Pisiform bone. (20) Flexor digitorum profundus. (21) Lunatum. (22) Dorsal branch of ulnar nerve. (23) Triquetral bone. (24) Extensor carpi ulnaris muscle tendon. (25) Extensor digiti minimi muscle tendon. (26) Extensor tendon. (27) Superficial vein cutaneous nerve

tendon is in its dorsal part. The median nerve, ulnar nerve and radial nerve divide into muscular branch, palmar digital total nerve and recurrent nerve. The artery has a number of branches which are arranged into the superficial palmar, deep palmar and dorsal palmar levels. The superficial palmar level mainly contains the arcus palmaris superficialis whose eminence is at the middle 1/3 of this part. Three branches of palmar digital total arteries and palmar little digital ground arteries arise from the arcus. The deep palmar level contains the arcus palmaris profundus and arteries of the metacarpeae palmares derived from the arcus. The arcus palmaris profundus is located in the proximal 1/3 of this section where the main vessels of the thumb are also located. The dorsal palmar level has the first dorsal metacarpal artery. The superficial vein on the back of the hand has 8.9 branches (4–13) on average. 83.3% of the human beings have a venous arch on the back of the hand.

5.1.2.3 Distal Metacarpal Section

This section is located beyond the distal palmar crease. The flexor digitorum superficialis tendon and flexor digitorum profundus tendon are situated in the digital epitenon. Digital extensor tendons begin to expand to form dorsal aponeurosis. Arteries change from three levels to two levels. Palmar digital total arteries and palmar digital total nerve are proximal to this area and located in the space from the second to forth thenar (Fig. 5.2). They divide into palmar digital ground vessels and nerves at the distal end. The palmar digital ground vessel and nerve of the radial index finger and ulnar little finger are located in the corresponding radial and ulnar aspects of metacarpal bones. Opisthenar superficialis veins concentrate relatively on the corresponding thenar space. There are 10.3 branches of superficialis veins on average (8–15 branches), and their inner diameter is 1.2 mm on average (0.4–2.0 mm).

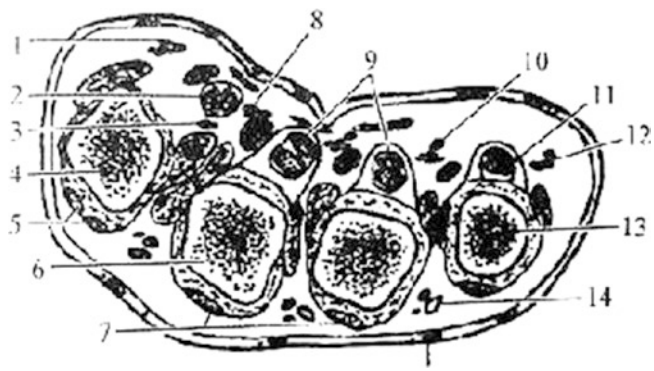


Fig. 5.2 The main structure of distant metacarpal section. (1) Palmar digital vessel and nerve. (2) Unguiflexor. (3) Centre of the palm blood vessel. (4) The second metacarpal bone. (5) Extensor tendon. (6) The third metacarpal bone. (7) Extensor tendon. (8) Palmaris blood vessel and nerve. (9) Flexor digitorum superficialis. (10) Palmaris blood vessel. (11) Flexor digitorum profundus. (12) Palmar digital vessel and never of little finger. (13) The fifth metacarpal bone. (14) Dorsal blood vessel and nerve of finger

5.2 Types of Amputated Palm and Characteristics of Replantation

5.2.1 Classification According to the Anatomic Location of Palm Arteries

Type I: proximal palm amputation: amputation proximal to the arcus palmaris profundus, or upper-arcus amputation.

Type II: mid-metacarpal amputation: amputation between the arcus palmaris superficialis and the arcus palmaris profundus, or arcus amputation.

Type III: distal metacarpal amputation: amputation distal to the arcus palmaris superficialis.

Type IV: mixed amputation, in which the injury plane is oblique or complex, involving two or three types.

5.2.2 Classification According to the Anatomy of Palm

Type I: fore-palm amputation: amputation distal to the metacarpophalangeal joints.

Type II: mid-palm amputation, in which the injury plane is at metacarpal bones, and proximal to the metacarpophalangeal joints in most cases. Since the metacarpeae palmares and arcus palmaris superficialis are often damaged in this part where there are several branches of digital total nerves and muscular branches derived from the median nerve and ulnar nerve, it is very challenging to repair the injury.

Type III: metacarpal base amputation, in which the amputation plane is near the carpometacarpal joint where the carpal tunnel structures gather. Because the ulnar and radial arteries are thick in diameter and nerves are relatively concentrated, the repair is not difficult, but adhesion often occurs postoperatively.

Type IV: mixed amputation, in which the injury plane is oblique. As this type is more complicated than the above-mentioned types, the replantation should be performed flexibly depending on the different injury planes.

Type V: smashed amputation, in which the injury to the palm is destructive and massive. The severed palm is accompanied with massive tissue defects, comminuted fracture or dislocation of the carpometacarpal bones, and damaged vessels which are difficult to repair. Since orthotropic replantation in situ is impossible, migratory replantation, which replants the distal severed segments onto the metacarpus, carpus or forearm, can restore part of the function of hand.

5.2.3 Classification According to the Shape of Amputation

Type I: Transverse amputation, in which the injury plane goes transversely or slightly obliquely.

Type II: Oblique amputation, in which the injury plane is oblique seriously (more than 20°) and crosses more than two regions.

Type III: Longitudinal splitting amputation, in which the injury splits up the palm between two metacarpal bones. The transection not only involves the distant, middle and approximate parts of palm, but also often injures the forearm where the nerves and vessels are mainly located.

Type IV: Circular amputation, in which of the injury plane is circular, usually involving every part of the palm. Since the severed bones, vessels, nerves and tendons present two cross-sections which require simultaneous repair in the inlaid replantation, the surgery is very difficult.

Type V: smashed metacarpal amputation, in which the palm is partially or completely destructed because of serious punch or extrusion. It is impossible to replant the severed palm, but heterotopic replantation can be performed for integrated fingers.

A simple and practical classification can be used in clinic which integrates the above-mentioned types into one. For example, completely transverse amputation of the fore-metacarpus (metacarpophalangeal amputation), oblique partial amputation of the carpometacarpus, smashed amputation of the mid-metacarpus.

5.2.4 Characteristics of Replantation of Amputated Palm

The key to a successful replantation of amputated palm is repair and reconstruction of damaged vessels. Clinical observation indicates that adequate blood supply promotes functional recovery of nerves, muscles and tendons and improves nutritional status of the replanted palm. Meticulous repair of nerves, tendons, muscles, bones and joints determines the functional recovery of the replanted hand. Since repair of nerves is of the first priority to the rehabilitation of hand function, no effort should be spared to repair both sensational and motor nerves as best as possible.

5.2.4.1 Vascular Repair in Each Section

Proximal Metacarpal Section

Radial and ulnar arteries are often injured in this section and should be repaired immediately. Vascular defects can be bridged using free vein grafts. There is no consensus regarding which of the radial and ulnar arteries chiefly supports the blood supply to hands. Zhang SX believes that repair of radial artery is more significant because of its location and course, cross sectional area and preferential blood-supply area. However, XU ED believes that repair of the ulnar artery is of more priority because it is the dominating vessel for hand blood supply. They argue that the arcus palmaris superficialis which delivers each palmar digital total artery and each palmar digital ground artery to supply blood to three and a half fingers at the ulnar side, or even five fingers eventually. The ulnar artery undertakes 87.4% of the total blood supply to the hand. Besides the radial and ulnar arteries, the palmaris superficialis of radial artery, median artery, anterior interosseous artery and posterior interosseous artery can be a dominant vessel for hand blood supply in some individuals if any of the four is thick enough. Therefore, care should be taken to repair them besides the radial and ulnar arteries. The superficial vein at the dorsal carpus which divides into the cephalic vein and basilic vein is thick in this area. There are also two or three thick superficial veins between the cephalic and basilic veins. All these veins should be repaired.

Mid-Metacarpal Section

The arcus palmaris superficialis, arcus palmaris profundus and their branches are often injured in this section. The arcus palmaris superficialis is often ruined and defective. Because each main artery has its own blood supply scope, distal and proximal vascular injury should be carefully evaluated before an effective blood supply can be reconstructed. According to Zhuang YQ and Wang Y, grafts of the arcus venosus dorsalis pedis can be used to repair a defective arcus palmaris superficialis. Generally speaking, the blood supply to the thumb and index finger can be reconstructed by repairing the radial artery and arcus palmaris profundus, and the blood supply to the long, ring and little fingers can be reconstructed by repairing the ulnar artery, arcus palmaris superficialis and palmar digital total artery. There are 4–13 dorsal superficial veins in this section, 83.3% of which have an arcus venosus. Choose four to six thick superficial veins to repair them.

Distal Metacarpal Section

Amputation in this section may injure the original part of the palmar digital total artery and palmar digital ground artery. If the palmar digital total artery is damaged, the radial digital ground artery of the index finger and the ulnar digital ground artery of the little finger should be repaired in addition to repair of three branches of the palmar digital total artery. Free transplantation of a Y-type vein and bridging reconstruction are used to repair defects of the palmar digital total artery and the digital ground artery. If the palmar digital ground artery is damaged, the prior vessels should be repaired. Interosseous veins in the inter-metacarpal space should be repaired immediately.

5.2.4.2 Nerve Repair in Each Section

Distal Metacarpal Section

As the nerve segments injured in this section are mostly of the trunk, it is easy to repair them.

1. The median nerve is superficial in position in the anterior carpal region and located between the flexor carpi radialis tendon and the palmaris longus tendon. It inserts into the palm through the profound aspect of the flexor retinaculum. It divides into the medial and lateral branches under the lower edge of the flexor retinaculum. The lateral branch contributes to the recurrent branch of median nerve (the branch of hypothenar muscle). It should be noted that the lateral branch, besides the median nerve trunk, is prone to damage which needs repair.
2. The ulnar nerve is in the radial aspect of pisiform bone, inserting into the palm through the ulnar carpal tunnel which is formed by the flexor retinaculum and carpometacarpal lateral ligaments. It divides into superficial and profound branches at hamular process of unciform bone. The ulnar nerve trunk, the origins of superficial and profound branches of the ulnar nerve can be injured in this section.
3. The superficial radial nerve divides into medial and lateral branches at 3.5–6.5 cm away from the distal styloid process of radius. Averagely, the medial branch is 2.1 mm in diameter and the lateral branch 1.3 mm. They can be found in the space between the first and second metacarpal bones.
4. The dorsal branch of ulnar nerve turns to the opisthenar at the styloid process of ulna, dividing into medial and lateral branches. On average, they are respectively 1.1 mm and 2.0 mm in diameter. They can be found at the lower aspect of the styloid process of ulna.

Mid-Metacarpal Section

There are numerous nervous branches in this section. Each of them innervates a corresponding muscle and a sensory domain. It is difficult to repair motor nerves because they have many tiny branches. The recurrent branch of median nerve, motor branch of ulnar nerve, palmar digital total nerve and digital ground nerves of radial index finger and ulnar little finger should be repaired preferentially. The superficial branch of radial nerve and the dorsal branch of ulnar nerve may be distributed but can be found in the interosseous space between dorsal metacarpals.

Distal Metacarpal Section

Nerve repair in this section is similar to replantation of severed fingers. The palmar digital total nerve and the palmar digital ground nerve of each finger should be repaired first. In addition, the dorsal digital nerves should be repaired for the thumb and little finger.

5.3 Indications for Replantation of Amputated Palm

Progress in microscopy, micro-instruments and microsurgical techniques is constantly increasing the survival rate following replantation of amputated palm. Great accomplishments have been achieved in very difficult replantations of seriously amputated palm which result in successful functional rehabilitation of the hand and fingers. Along with enhanced understanding and improved techniques of replantation, indications of replantation of amputated palm are expanding. In order to rejoin an amputated palm to make it useful as much as possible for a victim, we must judge whether the amputated palm can be replanted or not according to a holistic evaluation of traumatic, systemic, environmental, technical and equipment conditions.

5.3.1 Systemic Condition

Since traumatic amputation of palm is often caused by explosion, extrusion, traffic accident and contusion except in the cases of pure cutting injury, it is usually combined with traumatic shock and injuries to major organs in the chest and abdomen, even to the brain. Therefore, it is vital to perform an immediate evaluation of the systemic condition of the patient to know whether there is any accompanied injury and how serious it is. Lethal injuries should be handled preferentially while the amputated palm can be kept temporarily in cryopreservation until the systemic condition of the patient improves well enough for replantation. Alternatively, while the systemic lesions of the patient are managed aggressively, preparations are being made for replantation of the amputated palm. Once the improved systemic condition permits an operation, replantation of amputated palm can be conducted at once. Remember a replantation performed with no correct assessment of the systemic condition of the patient will likely aggravate the concomitant lesions of the patient or even endanger his or her life.

5.3.2 Age

1. Since most of the victims of amputated palm are young adults, they usually have a strong desire for fine appearance and function of the replanted hand which will allow them to resume normal social activities and work. For senior patients, it is essential to evaluate whether they have degenerative disease or hypofunction of organs, whether they can tolerate long time operation, lying in bed and immobilization after operation, and whether they can sustain postoperative medication for anticoagulation and anti-spasm. If his or her systemic situation permits and the patient strongly desires, replantation of amputated palm be performed.
2. Since the pediatric patients have strong self-repairing capabilities of tendon, nerve and bone, as well as high physiological adjustment and plasticity, their replantation likely results in fine outcomes. Therefore, any tissue that is possible to be replanted should be replanted so as to ensure maximum survival and functional recovery of the replanted hand. Remember any physical impairment or disability will have a life-long negative impact on them and cause them psychological agony.

5.3.3 Time Limit for Replantation

The time limit for replantation refers to the maximum duration between palm amputation from the body and restoration of blood circulation during which a severed palm can be successfully replanted. A severed palm tolerates anoxia and ischemia better than a severed limb, but longer time of ischemia will lead to more serious secondary injury (e.g. anoxic and ischemic lesions of tissue and ischemic reperfusion injury). When the secondary injury reaches a certain level, irreversible pathological changes will take place in the tissues which will harm survival of the replanted palm.

The time limit for replantation of amputated palm varies with season and temperature, because tolerance of tissues to anoxia and ischemia is influenced by temperature. The time limit is shortened in a hot season when a high temperature accelerates degeneration and necrosis of the tissue of a severed palm. In a cold season or in cryopreservation, the in vitro tissue of a severed palm has a much prolonged time limit because its degeneration and necrosis becomes much slower. Clinical practice has proved that the time limit should be less than 24 h in a normal temperature. Technical advances in cryopreservation may further prolong the time limit for replantation of amputated palm.

5.3.4 Status of Severed Palm

5.3.4.1 Integrity

An amputated palm should possess a certain degree of integrity more or less to ensure survival and functional recovery after a successful replantation. Amputation at any level with a tidy cutting plane is indicated for replantation. Comminuted palm or digits caused by explosion, completely disshaped or destructed palm or digits caused by extrusion do not satisfy the indications for replantation. In some cases the traumatic palm or digits keep body integrity, but replantation is not feasible because the serious extrusion has damaged the subcutaneous venous network, capillary bed and digital arteries. It is difficult to succeed in this situation. For fingers with slight extrusion and a few sporadic hypodermic ecchymosis but still with fluent arteries and veins, replantation can be tried. Skin defects in an amputated palm can be covered by graft of local flaps.

However, some integral amputated palms are still difficult to replant because they have been immersed in normal saline, 75% alcohol, benzalkonium bromide, glucose liquid or melting ice water on the way to hospital for so a long time that edema or dehydration occurs in the tissue and soak solution invades the lumen of blood vessels and tissue space. In this situation, since vascular endothelial cells are injured in different degrees, a replanted palm can hardly survive. Replantation may succeed when the immersion time is not too long and the tissue is damaged only slightly.

5.3.4.2 Functional Recovery

For a replanted palm, promising survival is important, but functional recovery is more significant. If a replanted palm will not function or will even harm the normal function of the hand after the surgery to be performed, replantation is not indicated.

5.4 Key Points in Replantation of Amputated Palm

5.4.1 Thorough Debridement

Thorough debridement is a prerequisite for successful replantation. Sometimes debridement is not conducted thoroughly enough because it is difficult to correctly assess in clinic the scope of necrotic tissue caused by contusion and there is always a worry that excessive removal of tissues will harm functional recovery of the hand. It is critical to make a holistic evaluation of the injury based on color and thickness of soft tissue, skin, and subcutaneous tissue. For cutting injury, it is appropriate to resect skin margins by 1–2 mm and to shorten bones by 0.5–1 cm. For circular saw injury, removal of soft tissue should exceed 3–4 mm, and removal of bone tissue should be slightly more. For contusion or a torn off palm, resection of dead tissues should be complete and resection of bone is determined by how serious and massive the contusion is. In cases of proximal avulsion of nerves or tendons, the forearm should be probed routinely. During debridement of soft tissue, tissue structures should be identified and marked for the following repair. Debridement of blood vessels and nerves should be performed using microscopy, because in some seemingly normal vessels under gross observation, rough endomembrane or separation of endomembrane from vessel wall may be found under microscopy. Vessels should appear normal after debridement under microscopy.

5.4.2 Bone and Joint Treatment

Palm carpal allows for a bit more shortening to accommodate repair of vessels and soft tissue. However, metacarpophalangeal joints should be preserved as much as possible to help functional recovery of grip and to facilitate secondary arthroplasty or transplantation if necessary. As the carpometacarpal joint of the thumb is a key joint, it should be saved as much as possible for the sake of motion recovery. Carpometacarpal fractures should be treated by fixation at dorsiflexion of 25–30° and thumb abduction using Kirschner wire passing through the first metacarpal, the carpal and the wrist joint, as well as fixation of the second and fifth metacarpals. Fractures of mid-palm should be treated with fixation of each metacarpal using Kirschner wire which passes through the carpometacarpal joint proximally and pierces the dorsal metacarpal distally as far as possible.

5.4.3 Vascular Anastomosis Is the Key to Successful Replantation

It is not difficult to anastomose distal and proximal arteries of palm (Fig. 5.3). In mid-palm replantation, the vascular distribution in the palm can present multiple types, like complete deep and superficial arches formed by radial and ulnar arteries, or incomplete arches or dendritic distribution. If the superficial palmar arch is damaged, and there are only two proximal ends but several distal ends of the arteria digitalis communis and finger arteries, vascular anastomosis should be performed flexibly. Generally speaking, anastomosis of branches of the radial artery can save the thumb and index finger; anastomosis of the ulnar artery can guarantee blood supply to the middle, ring and little fingers; anastomosis of the arteria digitalis communis can supply blood to two adjacent fingers; anastomosis of a digital artery can also save neighboring fingers through rich collateral circulation in the finger web. Replantation of a palm amputated at different planes usually lead to a problem of disparity in vascular caliber, like anastomosis of the trunk of radial or ulnar artery with the arteria digitalis communis, or anastomosis of the arteria digitalis communis with a digital artery. The problem can be resolved by making the caliber roughly equal at both ends. a smaller caliber can be expanded by tunica externa injection of 3% papaverine or by cutting into a slope or M-shape. Note that during vascular anastomosis the tunica intima should be reversed and stitches narrowed appropriately and arranged evenly. An artery anastomosed should be slightly tensile, not twisted and free of spurting blood leakage. If failure of arterial blood supply occurs recurrently during operation, that means inexhaustive debridement, defective anastomosis, mixture of bits of gauze fiber or tunica externa, or angiospasm. If this situation does not responds to antispasmodic treatment, the anastomosed artery should be cut off and re-anastomosed. Number of stitches should be determined by vascular caliber. The ulnar or radial artery in the carpometacarpal part should be sutured with 12 stitches using a 10-0 or 11-0 noninvasive nylon line, the arteria digitalis communis with 8–10 stitches, and a digital artery with 6–8 stitches. Venous anastomosis needs fewer stitches and slightly larger margins. In replantation of a whole hand severed at carpometacarpal plane or mid-palm plane, blood supply of the thumb should be checked after blood flow. If blood supply to the thumb is insufficient, the thumb artery should be probed and anastomosed. In replantation of amputated palm, anastomosis of only dorsal hand veins is enough to guarantee venous returning so that anastomosis of deep veins is not necessary.

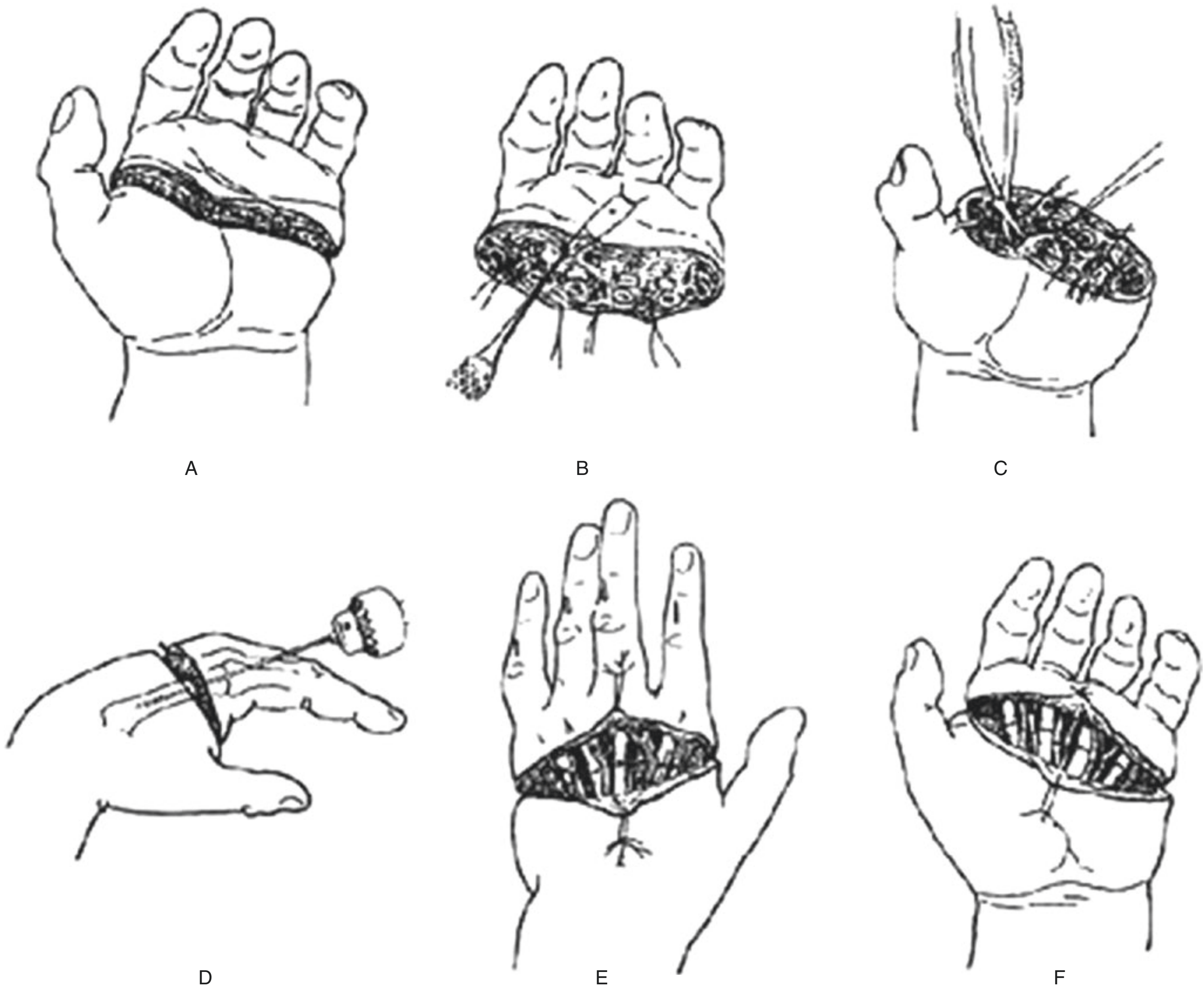


Fig. 5.3 Proper order of vascular anastomosis in replantation of amputated palm

5.4.4 Nerve Treatment

Try to repair all the sensory and motor nerve branches in the hand. In the mid-palm, it is important to repair the thenar recurrent branch of the median nerve and each digital intrinsic nerve. When branches of the ulnar nerve are injured, separate proximal nerve cords, and suture their perineurium to the distal ends corresponding to the sensory and motor cords. The nerve defects can be repaired using grafts from within the cord.

5.4.5 Tendon Repair

Long flexor and extensor tendons of the thumb should be repaired primarily. Digital extensor tendons are sutured before anastomosis of dorsal hand veins. After the distal end of digital superficial flexor tendon is resected, the proximal end of superficial flexor tendon or digital deep flexor tendon can be sutured to the distal end of digital deep flexor tendon. Remove the transverse carpal ligament at the wrist, and remove part of the fibrous sheath at the metacarpophalangeal part. As long as the tendons are tightly sutured, primary repair of the broken tendon within the metacarpophalangeal sheathing canal or near the sheath lead to good results. Scarring and tissue adhesion after palm replantation make it very difficult to dissect and discriminate tissues in the secondary surgery so that blood vessels and nerves are likely to be injured accidentally, endangering survival of the replanted fingers. Consequently, digital flexor tendons should be repaired primarily.

5.4.6 Skin Covering

In primary wound closure, bone should be reasonably shortened to allow for tensionless skin suture to protect deep tissues. If the skin defect is too large after debridement, a free skin flap or a skin graft can be used to close the wound, avoiding necrosis and infection, and creating conditions for later repair as well.

5.4.7 Observation and Management After Replantation

Accomplishment of replantation is only half of the task. To achieve successful outcomes, observation and management after surgery is also essential. Although replantation of severed fingers or palm does not exert great impact on the systemic condition of the patient, careful observation and proper management postoperatively is indispensable. It is worth noticing that condition of a replanted finger often changes after replantation of amputated palm.

5.4.7.1 Antibiotics

After replantation of a severed finger or palm, antibiotics are routinely used to prevent infection. For prophylaxis, penicillin and streptomycin are preferred due to their safety and efficacy. Only when infection occurs, effective broad-spectrum antibiotics are chosen specifically based on the results of susceptibility testing. The conventional usage is as follows: penicillin 800,000 U, intravenous infusion, once/8 h; streptomycin 0.5 g, intramuscular injection, twice/day.

5.4.7.2 Anticoagulants and antispasmodics

After replantation of a severed finger or palm, anticoagulants and antispasmodics are routinely used, mainly as follows: papaverine 30 mg, intramuscular injection, once/6 h; Tolazoline 25 mg, intramuscular injection, once/8 h; low molecular dextran 500 mL, intravenous infusion, twice/day. The above medication can also be combined with other drugs like 645–2 and aspirin (0.25G, thrice/day). Generally, the medication should be withdrawn after administration for one week.

5.4.7.3 Observation of Blood Circulation

Observation of the blood circulation is very important after replantation of a severed finger or palm, because crisis of blood circulation happens. Constant observation and timely management ensures successful salvage of a digit replanted. In the first 3 days after replantation, the blood circulation to a replanted finger should be observed hourly to evaluate the color, temperature, capillary pressure and bleeding at a side incision. If a replanted finger appears red, its skin temperature approximates that of a healthy one or lower less than 2 °C, capillary pressure is normal, bleeding at the side incision appears adequate and red, all these indicate good blood circulation. If a replanted finger appears pale or bluish, its skin temperature is more than 3 °C lower than that of a healthy one, bleeding at the side incision is absent or appears dark red, it is necessary to determine whether they result from arterial insufficiency or from venous return disorder. Whatever the cause, they should be treated timely. As it is difficult to identify vasospasm from embolism in clinic, blood circulation crisis should be treated first as vasospasm by intramuscular injection of 30 mg papaverine and 25 mg tolazoline, or intravenous infusion of 30 mg papaverine. If no response is observed after one hour, surgical exploration should be performed without any delay.

5.4.7.4 Dressing Change

Within 1 week after replantation of a severed finger or palm, it is preferable that dressing is changed daily to timely observe whether swelling, hematoma, infection, or compression from blood scab or dried sterile gauze is present at the replanted finger. A gauze whose inner layer sticks onto blood crab cannot be removed forcefully. Soak the replanted finger with warm 1:2000 chlorhexidine liquid for 2–3 min until the gauze becomes soft and easy to be removed. When no abnormality is observed, the replanted finger can be wrapped with sterile dressing after it is rinsed with warm 1:2000 chlorhexidine liquid. The injured finger should not be rinsed with cold ethanol, iodine or saline in case coldness may result in vasospasm. The following is one case of replantation of severed palm in an infant (Fig. 5.4).

5.5 Functional Recovery

An amputated palm, though it has been successfully replanted, will surely lead to limited range of motion of the fingers which often makes the daily life and work of the patient difficult. However, timely and appropriate rehabilitation will benefit the injured hand the uttermost. Otherwise, inadequate exercise of the replanted hand after operation for fear of pain only results in a stiff and useless hand.

5.5.1 Active and Passive Functional Exercise

Doing active and passive functional exercise positively is the easiest and most effective way to recover hand function. It can improve blood-supply and nutrition, regain more range of joint motion, increase muscular strength and harmonize motion of the injured hand. Active exercise plays a major role while passive exercise an auxiliary role. The patient should be encouraged to do exercise initiatively after he or she is informed of the significance of the hand exercise. In addition, outcome of rehabilitation should be followed up regularly in case the active and passive functional exercise is stopped due to fear of pain or negligence or is not carried out timely, persistently or appropriately.

Fig. 5.4 Replantation of severed palm in an infant. (**a**) view en face of distal end of palm mutilation; (**b**) dorsal view of distal end of palm mutilation; (**c**) proximal of palm mutilation; (**d**) the first day after replantation; (**e**) 3 weeks after replantation

5.5.2 Minimizing Immobilization Time

The external fixation is removed 3 weeks postoperative. The joints fixated at the distal and proximal ends can be subjected to passive exercise at a small range of motion. Because the fracture ends has been linked by enough rigid fibrous bony callus before the digital bone achieves bony union, early removal of the external fixation may not lead to malposition of the fracture ends. Steel needles internal fixation are usually removed 4 weeks postoperation to facilitate exercise of the free hand. Passive exercise of the flexion and extension of digital joints is the first step. When the joints achieve a target range of motion, chief active exercise follows. When the range of motion expands gradually and the exercise is more frequent, positive effects will appear.

5.5.3 Exercise Rehabilitation

Active and passive exercise should not be done in an empty-handed manner. Simple objects and instruments can help increase the rehabilitative effect except. For example, grasping a board about 6 cm in width can assist controlling the palmar joints of thumb and fingers. The extension, flexion, abduction, adduction and coordination of fingers can be practiced by rotating a metal ball or a walnut. Kneading plasticine, holding or grasping a rubber ball, a cone, a fingerboard or a gear are effective ways to exercise the replanted fingers. In addition to active exercise, it is important to use a replanted finer as much as possible in normal daily life to promote the finger rehabilitation. For example, striking a match, buttoning up and unbuttoning, lacing up shoes, wearing a belt, writing, washing clothes, and so on.

5.5.4 Physiotherapy

During the early, middle and late periods in the treatment, adjuvant physiotherapy can be applied according to the condition of recovery. For example, infrared ray, TDP, microwave, audio frequency, wax therapy and massage. When conditions permit, an individualized brace can be designed and manufactured to facilitate the rehabilitation, like a monodactyly or polydactyly inflexional brace, a monodactyly or polydactyly extentional brace, a proximal interphalangeal joint extending brace, a thumb opposing functional brace and so on. They can be used to do active exercise to remove scars, avoid and rectify deformity. Effective exercise helps an injured hand to become flexible and useful.

Bibliography

1. Quan-Rong Z, Kui-Shui S, Zheng-Feng L, et al. Replantation and functional reconstruction of severed palm caused by crush injury. China J Orthop Trauma. 2004;6(11):1307–8.
2. Wang CQ, Wang JL, Wang ZJ, et al. Digit transpositive replantation in severed hand trauma. Chin J Microsurg. 1995;18(6):244–5.
3. Cai JF. Repairation and reconstruction of destructive palm. Chin J Microsurg. 2001;24(2):172–4.
4. Ning-Fu L, Shao-An Y, Jing Z, et al. The pathogenic mechanism and prevention and treatment of muscle contracture after replantation of severed palm or wrist. Chin J Rep Reconstr Surg. 2000;14(1):27–9.
5. Shao-Cheng Z, Fu-Ling G, Xin-De Y. Intrinsic muscle contracture of the hand following replantation of arm wrist and palm: a report of 51 cases. Chin J Hand Surg. 1997;13(2):204–5.
6. Reid RL, Travis RT. Acute necrosis of the second interosseous compartment of the hand. J Bone Joint Surg Am. 1973;26(6):1123–7.
7. Qiu-Sheng C, Song-Jian L, Xiao C, et al. Preservation of hand function and enhancement of muscle strength in replantation of severed mid-forearm. Chin J Hand Surg. 2001;17(1):168–70.

6 Replantation of Amputated Finger

Xiaoheng Ding

6.1 Anatomy

6.1.1 Skin and Fascia

The finger skin of the volar part is different from that of the dorsal part because of different uses. The latter is thick and tough, which has keratin layer. The corium layer of the volar side is thicker, which is made of dense connective tissue. The papillary cristae of the skin covering the volar surface of the tips of the fingers has furrows and crdases, which are unique to each individual and are used for identification. The skin of the palm is rich of sweat glands but contains no hairs and sebaceous glands. There are a lot of opening tip of sweat glands on the papillary cristae and it can excrete or evaporate sweat to increase adhesion of grip without oiliness. A moderate amount of fat underlies the skin of the fingers, enhancing its pliability. The skin of the palm is bound to the underlying deep fascia by numerous fibrous bands so that the skin cannot slip to increase the rigidity of the holding. Palmar skin has rich sensory nerve, which contains a lot of nerve ending and neural receptors. So the finger is called the eye of the blind. The superficial fascia is connected with the deep fascia tightly, hard to peel. When there are infections below, the fiber bundles must be cut off for drainage. In some places, the superficial fascia is absent, which will lead to injuries or infections of the tendon sheath when stabbed.

The palmar superficial fascia is full of whippy fat tissues. The skin, superficial fascia and deep fascia is connected tightly by fiber bundles, which is hard to move.

The dorsal skin of the hand is soft and flexible. In order to make the skin easy to slide, the subcutaneous cellular tissue is looser. The superficial fascia of the dorsum is thin, which makes it easy to stretch and it separates the skin from the deep tissues, giving the skin good sliding ability, which also make it easy to cause avulsion.

X. Ding (✉)
Department of Orthopaedics, PLA 401st Hospital, Qingdao, China
e-mail: dxhqd@126.com

6.1.2 The Blood Vessels of the Finger

The blood vessels of the fingers go along with the tendon of flexor digitorum on both sides. The proper palmar digital artery goes along the dorsolateral of same nerve and gives out two dorsal branches which connect with dorsal digital artery. The artery on the way give out the branches at the base of distal phalanges to skin and joints. One of the branches goes to the central of finger pulp composes the arch with the opposite branch. The diameter of proper palmar digital artery at the root of the finger is from 1.0 to 1.5 mm, while the distal branch is from 0.2 to 0.3 mm. The dorsal digital veins origin from two little veins (0.3 to 0.4 mm) which lies at two lateral sides of the nail bed, with a distance of 1–2 mm to the nail groove. The two veins join each other to one central vein with a diameter of 0.3–0.6 mm at the base of the distal phalanx. At the converge there are other very little veins (0.1 mm), from nail plica and nail bed, running into the central vein. It continues to crossing distal interphalangeal joints. At its two sides, there are two veins with stable location coming from lateral surface of distal phalanx. Their radius is near 0.2 mm, locating from 11 to 1 o'clock. At the central of middle phalanx, dorsal venous combine to each other forming venous network, concentrating from 11 to 1 o'clock. The superficial veins on the dorsum of the proximal phalanx concentrate to each other, which finally form one to three layers venous arch with the diameter of 1.0–1.5 mm. The dorsal superficial vein of the thumb cannot form venous arch. The neighbour venous arch form the dorsal metacarpal vein, going through finger web to intermetacarpalis.

6.1.3 The Tendons and Nerves of the Finger

There is only one flexor tendon in thumb, but two in the other fingers, which go through the tendon sheath. The flexor digitorum superficial tendon lies on the palmar side of the flexor digitorum profundus tendon in the part of proximal phalanx, and divides into two parts in the distal, inserting

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_6

into the middle phalanx. The proximal interphalangeal joint is moved by the flexor digitorum superficial tendon, while the droximal interphalangeal joint and the proximal interphalangeal joint are both moved by the flexor digitorum profundus tendon. The two tendons moves individually, but cooperate with each other.

The tendon sheath encircles the flexor digitorum superficial tendon and the flexor digitorum profundus tendon, made up of fiber sheath and synovium sheath. The fiber sheath is the thicker part of the deep fascia, forming a bone-fiber tunnel, which has the function of restraining and lubricating the tendon. The synovium sheath is divided into two parts, the visceral layer and the parietal layer. The visceral layer is attached to the inside of the tendon fiber sheath and the bone. The tendon synovium sheath is closed from both sides, and there are blood vessels and nerves going through it, which is called mesotendon. Most part of the mesotendon are disappeared because of the movement of the tendon, and the only part kept is called vincula tendinum. The synovium sheath of the thumb communicates with the radialis sac, while that of the little finger communicates with the ulnar sac. The synovium sheath of the second to the forth finger go from the bottom of the distal phalanx to the metacarpophalangeal joint.

The extensor tendon extends to both sides, forming dorsal aponeurosis (extensor tendon hood), which wrapping the head of metacarpal bone and the dorsal part of proximal phalanx. The dorsal aponeurosis divides into three parts, the central bundle and two side bundles. The central bundle ends at the bottom of middle phalanx, and the two side bundles end at the bottom of distal phalanx after merging at the dorsal part of the middle phalanx. The proximal interphalangeal joint cannot straighten if the central bundle brakes, while the distal interphalangeal joint cannot straighten if the side bundles brake.

The proper digital nerve walks in the palmar inside of the proper digital artery, from the root to the tip of the finger. The dorsal branch separate from it at the dorsal side of the proximal phalanx, and distributes to the skin of the middle and distal phalanxes. The dorsal branch do not exist in thumb and little finger, but only a few small branches in the dorsal skin of the distal phalanx. The proper digital nerve separates several branches under the nails and into the finger pulp. The diameter of the proper digital nerve is from 1.0 to 1.5 mm, and that of the dorsal branch is 0.5 mm.

6.1.4 The Phalanx and the Interphalangeal Joint

There are two interphalangeal joints in the thumb, and three in the others. The proximal phalanx is the longest, while the distal is the shortest. The metacarpal bone is longer than the proximal phalanx in the same finger. The length of the total finger and the proximal phalanx of the middle finger is the longest, the second is the ring finger or the index finger. The shortest is the thumb. The longest middle phalanx is in the thumb, which is broad and thick, by the order of the length of the middle phalanx is middle finger, index finger, ring finger and little finger.

The phalanx has three parts, the bottom, the body and the trochlea. The bottom is in the proximal part, which has sunken joint surface. The trochlea is in the distal part. The transverse section of the body has the shape of half-moon.

The interphalangeal joint belongs to the ginglymus. There are nine in one hand, which can only have the flexing and extending movements. The proximal joint can flex to 120°, and the distal joint can flex to 60°. The extending movement is restricted because of the flexor tendons and the dorsal collateral ligament. The part exposed when flexing the interphalangeal joint is the trochlea.

The movement of the interphalangeal joint is associated with the metacarpophalangeal joint so as to facilitate the function of the hand. It is easy to becoming stiffness when the joint gets hurt. So it is better to put it in the functional position.

The blood supply and innervations of the interphalangeal joint is from the branches of the artery and nerve of the finger.

6.2 Classifications of Amputated Fingers

There are two classifications: completely and in completely amputated fingers.

6.2.1 Complete Amputated Fingers

The distal part of such a finger is completely separated from the hand with no tissues or small crushed tissue connecting. It must be cut off or removed for debridement. This kind of amputed fingers almost inactive and pale. If the finger is intact without obvious contusion, replantation can be performed under the request of the patient.

6.2.2 Incompletely Amputated Fingers

This means most tissues are separated from the hand after the trauma except for some skin or other tissues, and the replanted finger can't survive without the anastomosis of blood vessels. And the residual tissues which haven't separated from the stump can influent the survival and function of the finger in and after replantation. The incompletely amputated fingers can be classified as follows:

6.2.2.1 Incomplete Amputated Finger Connected with Skin Pedicle

1. There is connection of no visible blood vessels in the skin pedicle. The finger appears pale, arteries and veins need to be anastomosed during replantation.
2. There is connection of visible veins in the skin pedicle, but no arterial blood supply. The finger appears dove-colored and weak. Capillary refill presents, but slowly. Arteries need to be anastomosed during replantation.
3. There is artery connection in the skin pedicle without venous return, The finger appears dark purple with increased tension of the pulp. So the finger should be cut at one side to drain out dark purple blood first, and then bright red blood flows out. At this time the purple finger turns red, and veins can be anastomosed. This is needed for the survival of the replanted finger.

6.2.2.2 Incomplete Amputated Finger Connected with Nerves

Almost all tissues are separated from the hand except for the nerves when the finger is amputated. Arteries, veins and tendons need to be repaired except for the nerves. But the arteries are likely to spasm after replantation. Once the replantation succeeds the finger can obtain sensory function, and finger pulp will be well-stacked and in good shape.

6.2.2.3 Incomplete Amputated Finger Connected with Tendons

All tissues are separated from the hand except for the flexor and extensor tendons after the injury. Arteries, veins and nerves all need to be repaired except for the tendons. Due to the consistency of tendons, the finger can undertake functional exercise earlier after replantation, so the function recovery is more satisfactory.

There are some cases where most structures of the finger are amputated with only a few strips of skin connected even they are only 1/10 of the finger radius. If there is still blood circulation, these cases are not included in the incomplete amputated fingers category.

6.3 Indications for Replantation of Amputated Fingers

The purpose for the finger replantation is to recover the function and integrity. The principle is that survival, function and appearance, of which, the important is function. If the replanted finger survived, but without function and good appearance, it will take great burden to the patient. The indication is as follows: (1) The status of patient is good enough for replantation. (2) The status of the amputated finger is good, such as the blood vessels, nerves and tendons. (3) The tissues did not degenerate.

It will cause the patient disabled, if the amputated finger can be replanted, but was amputated. It will also take great burden to the patient, if the replanted finger did not survive, not only for the money, but for the great pain of the patient. So, it is very important to think about the indication.

Of all the elements taken into the indication, the most important one is the status of the blood vessels. The second important is the skin, and another one is the accident cause. Without good status of the skin, the replanted finger will also not survive for the cutaneous necrosis. In addition, the age of the patient, the admission time, the status of the tendon, bone and nerve should be thought about, though, they are not the most important.

In the early 1970s, many scholars considered that if the finger is amputated at the distal end of the middle of the mid-plate of the finger, the replantation is not recommended. In 1981, Chengguoliang performed the replantation of amputated fingers based on many researched on the neurovascular anatomic features of the paratelum, and increased the survival rate to 96%. So we first proposed the view that replantation could be applied to finger paratelum. Then, Tianwancheng gave the viewpoint that replantation could be done even at the fingertip. The treatment of the amputated thumb is another evidence of improvement in replantation. In the past, replantation of a thumb with rotated and avulsed amputation was regarded impossible by many scholars because of the severe avulsion of the blood vessels, nerve bundles and tendons from the proximal thumb, so that injuries like this were included in contraindications. However, the improved replantation techniques, such as the transplanting of blood vessels, nerves and tendons from adjacent fingers, can now be chosen to replant the thumb which many have been hopeless before, and the shape and function of the thumb can be preserved on the whole. In the past, surgeons dared not to treat an amputated finger with multiple amputations, but now we can connect every amputated part together to make a successful replantation of the finger and restoration of some functions. All the facts above illustrate that indications for replantation of amputated fingers should be appraised constantly along with the improvement of medical science.

Chengguoliang consider that if the patient who is under 60 years old has the request, and the stump and amputated part have intact structure without visible contusion and multiple fractures, the replantation is strongly suggested regardless of the cause of trauma, even though the complete mutilation is proximate to the base part of distal phalanx, or the incomplete amputation requires revascularization. Concretely, the greatest efforts should be made to replant an amputated thumb. If the amputated finger is not suitable for replantation or the stump won't have functional length after the apical stitch, the second toe can be transplanted for the reconstruction of the thumb under the request of patient as an emergency case. Also, when multiple fingers are amputated, replantation in situ or shifting replantation should be done according to the conditions of the amputated fingers; if the second to the fifth fingers are fully destroyed and they won't have functional length after the apical stitch, the second toe can be transplanted for the reconstruction of the fingers as an emergency case. If other single fingers are amputated with appropriate condition of replantation, the performance of replantation or not depends on several factors such as the type of the finger, the gender, age, occupation and desire of the patient.

6.4 Procedures of Amputated Finger Replantation

There are two different operative orders for replantation of amputated finger, antegrade and retrograde. Brief procedures are as follows: debridement on distal and proximal ends-intraarticular fixation of bone and joint-reparation for extensor and flexor tendon of finger-anastomosis of dorsal digital veins-suturation of dorsum skin-suturation of bilateral digital nerves-anastomosis of digital artery-suturation of palmar skin. Followings are the above procedures in detail:

6.4.1 Debridement

Debridement is the foundation of all open injuries. Careful debridement cannot only get rid of the contaminated and ruined tissues to decrease and prevent infections, to avoid the postoperative adhesion, but also be an important step to repair various tissues, reduce scar tissues, establish collateral circulation earlier and restore the postoperative function, and be an important link to enhance the ratio of survival and success of the replantation of amputated finger. If debridement is incomplete, local infection could be the first complication, then the inflammatory reaction of peripheral tissues that can cause tissue swelling and the disturbance of venous return. The inflammatory stimulus can also cause vascular crisis and then the impaired blood supply of fingers, and finally, failure of replantation, still with the incomplete debridement, even the replanted tissues survived, excessive remaining of the necrotic tissues in cross-section can create a local tissue space of necrosis after operation and later lead to a barrier of massive scar. Overall, those can affect the establishment of collateral circulation, the regeneration of the nerves and cause tendon adhesion, which as a result, impedes the function recovery after the operation. Therefore, members of the replantation team should pay enough attention to debridement before the operation of replantation. On the other hand, the process of debridement is also a perfect chance or operators to investigate the overall conditions of vessel, nerve, tendon and bone damage of each section that can provide reliable evidences for working out the operation scheme of the replantation, thus improves the operative proceeding and sets up a satisfactory platform for the replantation operation.

6.4.1.1 Debridement of the Amputated Finger

First, cut off the amputated finger's nails. For finger with grease stain, we can wash it by detergent or soap is washed, and rinse with tap-water. Continuous wash after three times with running water, then the amputated finger is washed with sterile saline solution, dried with disinfected gauze, disinfected with thimerosal. Section is disinfected with 1‰ presoaked eliminate saline solution or other disinfectant soak, then the debridement is started under the surgical microscope. The first step of debridement is finding arteries, veins and nerves and mark. Methods for searching:

Artery: The artery will be found successfully according to the normal anatomical position generally. Digital artery locate at two sides of the flexor tendon sheath which go through a long narrow neurovascular bundle of osteo-dermal ligament with digital nerve. Because neurovascular bundles of two sections both have retracted, it is impossible to find them in the section directly. The anatomic relationship of digital artery and nerve anatomy is constant. Their relationship is: digital artery lies in dorsolateral side of digital nerve. Its diameter is thinner than nerve. And the digital nerve is located in the inside palmar side of the artery. Therefore, as long as the understanding of this relationship, if one tissue can be found, the other will be able to successfully find according to their anatomical relationship. Then marked the end with 5-0 line.

Vein: Operators generally choose to suture the dorsal vein during the finger replantation. Occasionally they use palmar subcutaneous veins. As the dorsal subcutaneous veins have no fixed anatomical position, in order to avoid missing, the operator can find them from left to right, or from right to left between in the subcutaneous and extensor tendon. The broken veins also contract. Because there is a small amount of blood in the vein, so we can find them according to bloody point of their broken apex. Besides, because of the netted structure of the vein, so when find a vein which can be separated to the distal by retrograde approach, the second and three adjacent veins can be found. In order to facilitate the search for vein, the distal finger could be squeezed for the appearance of bloody red points. Recognizing that point the veins can be found. General finding found in the finger dorsal subcutaneous tissue, with no obvious injury, finger could be still survival, as long as the quality of vascular anastomosis is assurance. If only one small vein is found in the finger dorsa, searching for palmar subcutaneous vein is necessary, Because subcutaneous palm vein close to the dermis tightly, with small diameter and thin wall, so when finding them the operator sometimes in the middle of palmar skin, the large vein with thick diameter and thin wall could be found, then, mark out them.

Debridement of finger section can be implemented after the blood vessels and nerves of finger are marked. Skin edge about 2–3 mm of the revered finger is cut with the naked eyes close to subdermal of section using ophthalmic tissular scissor. Especially when scissors is moved to the dorsal skin, operator should be more careful to prevent injury dorsal finger subcutaneous veins. Section debridement should be in the surgical microscope. According to Chengguoliang's habits, palmar one side of the neurovascular bundle is selected as the center of debridement. First the vessels and nerves of this side are debrided, and the contaminated and contused tissues are removed using the spring shear carefully. After simple stripping arterial adventitia as well as outside organizations, debridement range is gradually expanded from here to around and contralateral tissues, meanwhile, please pay attention to protecting palmar thicker subcutaneous veins. When debridement extended to the contralateral neurovascular bundle, ensures the contralateral the neurovascular bundle to the center for the same debridement, as well as the sheath around the same organization for the debridement, palmar debridement through cutting a thickness of 2–3 mm the contaminated and contused fat and other organizations to enable cross-section as a clean, healthy soft tissue bed base. By the same way, the debridement is expanded to left and right with the dorsal digital vein as the denter. Resects a layer with a thickness of 2–3 mm and polluted subcutaneous adipose tissues. During debridement, the marked arteries, veins, nerves and stretch flexor tendon should be protected. When debridement is being done, one film should be lifted and sheared, not cut it into pieces with the haphazard manner. In the same time operators could make a comprehensive understanding for the artery, vein and nerve injury of the section, and make an implementation of plans for finger replantation. Debridement of bone and tendon can be conducted under the eye. When the section debridement end, the finger is dipped into 1‰ gentamine saline solution or other skin disinfectant about 5 min, then sterile saline wash it twice and then finger debridement have come to an end wrapped with gauze. Put it into refrigerator cold-storage and the second finger is done according to the above procedures debridement.

6.4.1.2 Debridement of the Proximal End

After anesthesia, gas tourniquet is put on the upper 1/3 of the arm. Shear normal finger nails then wash away with the fluid of detergent or soap from inferior 1/3 of the upper arm, forearm to injured hand, then rinse with running water, and wash them three times consecutively with sterile saline rinse. Dry them with sterile dressing. Forearm and hand injuries are implemented conventional skin disinfection, and the section is disinfected with 1% geranium saline solution, and then lays the scarf. Proximal vascular and nerve is more easily found according to the anatomical location and relation of the above mentioned. The proximal field isn't clear due to the existence of proximal finger blood supply. In order to facilitate the search for the tissue, pneumatic tourniquet should be loosen, then on both sides of the flexor tendon sheath which are pulsatile shall be referring to the digital artery. Nerves can be found on both sides according to anatomy relations. The proximal digital dorsal veins can be easily found because of their filling state. After the arteries, veins and nerves has been found and been marked, the pneumatic tourniquet is used continuously, and the debridement is implemented as the debridement method of distant served section. The field of surgical debridement is not very clear because there is a small hemorrhage and bleeding of the proximal tissue, therefore, the proximal debridement operation need special care. Generally, the proximal amputated flexor digital tendons retract severely. Surgeon can pinch the proximal end of the retracted flexor digital tendon along the sheath with a small vascular forceps and tow out it, then make a perforative marking with 3/0 thread. Sometimes the end of the amputated tendon has been excess the fiber sheath and compressed at the proximal end of the sheath, so there is troublesome in searching the amputated tendon. In order to the reduction of the amputated end, the operator can massage the palmar side of the finger, then, drag out it carefully with the aforementioned method. Sometimes we couldn't find the amputated end, so as to avoid hurting sheath, not limpingly pinch. A transverse incision can be made at the transverse metacarpus in order to find the amputated end at III zone. The amputated end can be induced by probe from the section. After the fracture segment being shortened and debrided, the section of the hurting hand is disinfected using 1‰ geranium saline solution or other disinfectant soak, and then is washed with sterile saline solution. At the end change the sterile gauze, glove, and prepare replantation.

In order to shorten warm ischemia time and speed up the surgical process, for the debridement of over three fingers, comprising two surgical group is necessary for the debridement of the proximal and distal end, and another surgical group implement replantation.

6.4.2 Internal Fixation of the Bone and Joint

The fixation of bone and joint is the beginning of the replantation. Reasonable and correct fixation of the bone and joint is not only the treatment principles, but also create the conditions for the follow-up restoration of tendon, nerve, vessels.

1. The two broken tips need to be debrided thoroughly and to be limited shortening. Generally shortening length of the bone at each sided is 3–5 mm to the adult, and 2–3 mm to the children.

2. Retain joints as much as possible. When the finger was amputated at the proximal end 1/3 of the proximal or media phalanx, distal phalanx is shortened mainly. When the finger was amputated at the distal end 1/3 of the proximal or media phalanx, proximal phalanx is shortened mainly. And retain joint as much as possible. When the finger was amputated near the joint, the joint wasn't open, and the articular capsule was integrity, the phalanx with the longer shaft should be shortened in order to preserve the integrity of joint.
3. If the thumb was amputated at the level of the metacarpophalangeal joint, the fusion of the metacarpophalangeal joint can be done. For the patient with finger severed of metacarpophalangeal joint, arthroplasty is appropriate, not the arthrodesis.
4. Arthrodesis is suitable for all the finger which amputated at the level of the interphalangeal joints, and the amputated finger require to be fused at the functional position.
5. The shortened length of the children's amputated phalanx is limited within 5 mm, and tries to retain the joint and the epiphysis. Arthrodesis is not appropriate for all the amputated joints. Merely arthroplasty is suitable.
6. When Kirschner wire is used to fix, the bone ends must be in close contact to prevent rotation. The saturation of periosteum is required, avoiding Kirschner going through joint or several joint. When there is no other capsule and the joint space. Oblique or crossing internal fixation using single Kirschner wire is suggested.
7. All the phalangeal internal fixation and arthrodesis are asked to anatomical reduction. When the finger is flexed, the extension line of the longitudinal axis of the finger aims at the scaphoid nodule of the wrist.

6.4.3 Repair of Tendon

The extensor and flexor tendons are repaired following the skeletal fixation and periosteum suture. The tendon repair of digital replantation is done according to the amputated part and different anatomic structure. The perfect tendon repair affects the appearance and function of finger directly. The surgeon should be strictly non-invasive operation, carefully restored. Repair order: extensor tendon is repaired first, and then flexor tendon is repaired. This order is benefit for the adjustment of tendon tension.

6.4.3.1 Repair of the Extensor Tendon

Generally, the extensor tendon severed levels of digital replantation at the distal end of metacarpophalangeal joints. When the finger was amputated between metacarpophalangeal joint and proximal interphalangeal joint, not only central tendon should be repaired but bilateral tendon bundle should be repaired. When the finger was amputated at the proximal interphalangeal joint, bilateral tendons should be repaired after fusion of joint. The extensor tendon should be repaired when the finger was amputated at the mediate phalanx. The arthrodesis or internal fixation is done, not repair the tendon, when the level of the amputated finger is at the interphalangeal joint and beyond interphalangeal joint. When the children's finger was amputated at the distal interphalangeal joint, arthroplasty is done, not arthrodesis, at the same time, the extensor and flexor tendon should be repaired.

The repairing method of the extensor tendon: Two broken ends mutilation condition of the extensor tendon should be examined carefully before repair the tendon. Generally, once the bone shortens, and extensor tendon can be sutured directly after debride. Generally, sutures of 8-0 or 9-0 nylon can be used for the "8-shape" suture. The tendon is connected closely, no fiber ends disclosed. The principle of the tension adjustment of the extensor tendon is that mediate and terminal segments of the fingers can be straightened. If the extension is small, it will lead to lacking of strength of extensor digitorum. If the extension is too large, it will impact the tendon healing. Special emphasis, before repairing the extensor tendon, periosteum should be sutured or there are some soft tissues over the connection of the bone. Otherwise, postoperative adhesions will be caused, and it will impact finger functional recovery.

6.4.3.2 Repair of the Flexor Tendon

The blood supply of flexor tendon is segmentally from the vincula tendinum.

The method of repair is that cut of the redundant tendon using sharp knife and put a 12# syringe needle at both end of the tendon to make it loose after adjusting the tension. Suture the tendon with the method of Kessler or Tsuge with thread 3/0 and make an annular and continuous suture under the microscope with thread 7/0 to make the anastomosis smooth and trim.

6.4.3.3 Repair of the Tendon Sheath

There are a lot of arguments on whether to reconstruct the tendon sheath. Some thought it should be reconstructed because of the importance of the nutrition of the synovial for the tendon. For example, Barde used the four hydrogen ethylene polymer membrane to reconstruct the tendon sheath. There are other materials such as silicone wafer, fascia, myolemma, peritendineum, retinaculum et al. Some thought there is no need to reconstruct the tendon sheath, because they found that there will be cells covering the naked tendons 1–2 days after the suture through experiments, just as the completion of the trochlea system.

6.4.4 Repair of Blood Vessel

There should be thorough debridement before anastomosis, taking off all the injured vessels. If the blood vessel is not long enough to anastomose, a blood vessel graft can be used. The thrombogenesis is relevant to the bad debridement of the blood vessels. Before anastomosis, you must make sure that the inner membrane is smooth, intact and without blood clot, and find the reason why there is no blood sprayed out of the artery. The adventitia should be cut off properly to make it easy to suture. The diameter of the vessels should be basically the same. The suture margin should be 2–3 times as thick as the vessel wall, and bilateral symmetry. The ratio of the artery to the vein should be considered, and suture as many as possible.

Usually, you should anastomose one artery and one vein in the distal part of the finger, or one artery and take off the nail or make a cut for bleeding. The ratio of the artery to the vein in the middle part of the finger should be 1 to 1, and 1 to 2 in the proximal part. A superficial vein from the forearm can be used as a graft when the vessel is too tight or defective.

The two amputated ends of every vein are debrided carefully before repairing them. The contused and infected outer tissues of the vein ectoblast should be separated and removed. The damaged vascular is removed after understanding of the venous amputated ends. Vascular cannel is irrigated with heparin saline solution, to make sure without gore, cellulose aplomb, so that the endomembrane is bright and integrity. The amputated ends are dissociated 5 mm to the proximal side, for placing the vascular clips and overturning the vessel during suture. When vein is anastomosed, the vascular clips should be open timely. Generally, venous blood can be seen through anastomotic stoma to the distal lumen and making it filling. Sometimes, venous blood can be seen overflow from the distal end of the vein. To protect the sutured veins, the corresponding skin of the vein should be sutured.

The venous opening anastomosis: when meeting the repair of veins for finger replantation of the near distal interphalangeal joint, the distal amputated vein doesn't permit to dissociate too long and because of its small diameter and thin wall, the vascular wall is damaged easily when using vascular clips to stop the blood. So the venous opening anastomosis method is applied. The venous opening anastomosis is done when there is venous blood refluxing. In order to guarantee the clear field of needle acupuncture and out, washing and suture can be done alternately. Sometimes a little blood refluxes into vascular cavity making it filling and showing the contrast of red and white, not only benefit for the vascular anastomosis, but also for the avoiding suturing the opposite vascular wall. Especially for the last several sutures, blood reflux along the repaired vascular but do not overflow. Refluxed blood make the distal vein fill, which is favorable for the vascular suture. So venous opening suture although has the defect of amputated ends blooding, impacting the operation, it can also enhance the contrast of blood and venous wall to avoiding suturing the opposite wall. It is an alternative method.

When the dorsal veins are repaired enough, the distal ends of the amputated veins, which are not repaired, should be ligated with the sutures, before the suture of the dorsal skin, to prevent blooding of section after arterial recanalization and forming local hematoma which affect venous return and causes infection. Suturing skin is the surgical operating routine, the surgeons is accustomed to it. But suture of the amputated finger is different from a general skin suture. To avoid needle and sutures damaging the repaired vascular, the gap of no subcutaneous veins is selected when suture the dorsal skin. When suture of skin with subcutaneous veins repaired, the operation should be done under the microscope. When suturing skin, the skin edge is demand tidy pairing and perfect valgus, to facilitate healing. Otherwise, curly skin flap will compress veins to affect blood circulation.

The diameter of the bilateral digital artery is different in the different finger. The digital anastomosis methods are selected according to the patient's position. The injury degree of the digital artery, the proficiency of assistant and the operator's anastomotic skill for the small vessel. Ulnar digital artery, the proficiency of assistant and the operator's anastomotic skill for the small vessel. Ulnar digital arteries of the thumb and index finger have the larger diameter than radial arteries. Radial part of little finger is thicker than ulnar part, the diameter of bilateral arteries is similar in the middle finger and ring finger. During replantation, the artery with the large diameter anastomosed first generally. Then the artery with the small diameter is repaired based on the different condition. The amputated finger could survive after anastomosis for the unilateral artery. Bilateral arteries should be repaired if the operator has no confidence for the suturing quality. Otherwise when the vascular crisis appears, another operation is need, which will take more time and vigor and bring more pain to the patient than the bilateral repair for the arteries during replantation. To enhance the survival rate, bilateral arteries should be anastomosed. The digital artery has the constant anatomic position, which has been marked during debridement. So before the artery anastomosis, two ends of the artery injury states and the vascular outer diameter should be understood. Then make a repairing program for the digital artery. If both side digital arteries can be sutured, both of them should be repaired simultaneously. If only one side can be anastomosed, and the other has been defected obviously, the anastomosis should depend on the diameter of this artery. If the artery with large diameter can be sutured directly, then repairs it, and let the artery with the small diameter alone. When the artery with large diameter has defected, besides sutures the opposite artery, the large artery should be repaired through vascular graft. When the both arteries have defected simultaneously, the large diameter artery should be repaired through vascular graft.

6.4.5 Repair of Digital Nerve

After suturing the dorsal skin, turn over the hand to make the palm-side up. The edge of the palmar two sections skin, equal to the neurovascular bundle position, is retracted, exposition wound adequately and surgical microscope is shifted to the surgical field. Two labeled neural ends ate debrided under the surgical microscope. The contused and superfluous digital nerve is excised, adjusting nerval tension, so that the nerval is sutured without tension. The 9-0 noninvasive single nylon suture is used to do perineurium suture or epineurium interrupted suture. The appropriate number of suture is 4–6 for each nerve. Make the two sides of nerve couple shapely. The principle of suture is not exposing the nerve bundles. Bilateral digital nerves should be repaired so as to postoperative satisfactory recovery of sensory function. When there is nerve defect, the nerval graft or cross nerve anastomosis is used to repair. If one sided or both sides has more nerve defect, it is difficult for graft or transposition repairing. The repair can be done through anastomosing lateral digital nerve mainly. Its restoration principle is that ulnar side nerve is repaired mainly for the thumb and little finger and radial side nerve is repaired mainly for the index finger, mediate finger and ring finger.

When the digital nerve was repaired perfectly, not only with plump finger pulp, satisfied shape, sweating, but also pain, temperature sensation and tactile sensation all recover. The two point discrimination is slightly weak than the normal finger. All of them could satisfy the based require of digital normal sensation function, to achieve the purpose of replantation. When the digital nerve is not repaired or repaired poorly, the finger is not only with withered pulp and body, but also dry, no sweating, having torpent tactile sensor, algesthesis and thalposis. Its two-point discrimination is poor, easily being empyrosis and chilblain. Hyperalgesia and finger cooling appear in a few patients, which impact the function of other fingers, leading to entire upper extremity shrinking. Bringing the pain for the patient's work, study and life, the replanted finger became a burden, which lost the replantation significance.

6.4.6 Treatment for the Vascular Crisis During Operation

The artery crisis is more than others in the process of operation, which mostly occurred in the patient only unilateral artery anastomosis, The present is after soon the reconstruction of the blood circulation, the body of finger changes from ruddy to pale and becomes cool, the capillary back filling phenomenon disappears, the pulp tension is low and wither, fingertip lateral incision is not bleeding, and occasionally a small amount of dark purple blood spills. Intraoperative vascular crisis categories:

6.4.6.1 Arterial Spasm

This is a frequently met arterial crisis in the replantation operation, caused by arterial spasm, reversibly. It occurs during the skin suture, caused by pain, when the anesthesia function becomes weak or disappears. Because of the same reason, when met the multiple finger replantation, after finished one finger replantation, during replantation, another finished finger occurs spasm caused by pain. So the operator should know the status of anesthesia, when it is necessary, increasing the narcotic medication, which is an effective method of prevention and treatment of arterial spasm. Another reason occurred the arterial spasm is the lower temperature of operating room, and instituted by chilly. It occurs in late fall and winter. Especially, at night operation, heating cannot supply timely to cause the arterial spasm. Therefore, the operating room temperature should be maintained at around 25 °C. When the room temperature is at below 20 °C, warming is necessary timely. And wet dressing is done in the local part using warm saline solution to keep warm. Of course, for the artery in the operating field or suture of skin after replantation, papaverine or lidocaine is still used for external application, or injected through the sutured skin gap. If, after the above treatment, showing no improvement, suture should be removed, and the outside tissue of vascular adventitia is done through countertraction and hydraulic distension methods. Some patients occur intermittent spasm no any reason. So surgery is difficult to make progress, and the treatment is same to the above method. The treatment and observation is simultaneous. The result of spasm is optimistic, and all the spasm can be relieved keeping the good blood supply. If it is no changes after the treatment and observation, passing blood test (strangling blood test) is used at the distal end of anastomosis. If there is a short blood pass, anastomotic embolism should be doubt without blood pass soon.

6.4.6.2 Arterial Thrombosis

Arterial thrombosis mostly occurred in the part of near anastomosis. Its two major reasons: first, not thorough debridement; second, the bad quality of anastomosis. There is no different in clinical presentation between arterial thrombosis and spasm. The key distinction lies in the changes after spasm relieved.

6.4.7 Bandaging

When the operation of amputated finger replantation finished, observing the color of the skin between the normal and the replanted amputated fingers. It is better clearing all the bloodstain of the amputed fingers by using sterilized warm saline. A layer of tweaked dried alcohol gauze is covered on the sutured skin to better to drainage. The multilayer sterilized gauze is used to cross overlapped bandage. The replantation of the amputated fingers end should be exposed to observe the blood circulation. The fingers should be bandaged and brake at the functional position. Bandaging is not too tight so as to avoid affecting the circulation, not is too relax to prevent shedding dressings.

6.4.8 Retrograde Reimplant

The procedure of retrograde is converse to antegrade. Its replantation operation is done as follows: suture the palmar skin—anastomose bilateral digital arteries—suture the nerve—suture the reflux digital tendon—fix the bone—suture the extensor digital tendon—anastomose the digital dorsal vein—suture the digital dorsal skin. During the operation of retrograde, the fixation of bone and joint is done between the repair of reflux and extensor tendon, but the preparation has to be done before suture of skin on the palmar side. If the Kirschner crossing internal fixation is used, the amputated finger is pierced crosswise after finished the debridement. When repaired the reflux digital tendon, the two Kirschners are fixed obliquely at the proximal phalanx. Similarly, if using the crossing steel wire for internal fixation, the two ends should be drilled, even put on wires. When repair the reflux digital tendon, the steel wire is fixed tightly. This method can avoid damaging the repaired artery, nerve and tendon.

Different operators have the different operative habit. Once the habit has formed, it is difficult to change it. Because both of the antegrade and retrograde have their advantages and disadvantages, which method should be taken, should according to the operator habit to finished the operation with good quality and quantity.

6.5 Replantation of Bilateral Hyperdactylia Amputation Injuries

6.5.1 Overview

In 1984, Wei (Taiwan) first reported a 26-year-old man who had all 10 fingers amputated by a paper cutting machine on January 30, 1982. A replantation team of six surgeons replanted all ten fingers in a 26-h operation. Seven of the ten amputated fingers were replanted successfully, with the exception of the left thumb, ring finger and the right little finger. On March 8, 1985, Chengguoliang had a patient who had eight fingers amputated, of which seven fingers were replanted successfully except for the left thumb paratelum without proper replantation condition. This report brought wide attention from around the world. In January 1986, the Affiliated Xingjing Hospital of the Fourth Army's Medical University, Xi'an, successfully replanted 10 completely amputated fingers from the same patient. During the same year in December, the 89th Army's Hospital reported the exact same case as above.

6.5.2 Causes of the Injury and Their Indications

Bilateral hyperdactylia amputation is the absolute indication for replantation of the amputated fingers. Most causes of bilateral hyperdactylia amputation are malfunction (continuous cutting) or faulty manipulation by co-workers on paper cutting machines, punching machines, and shearing machines and so on. There is a close relationship between the condition of severed fingers and the particular devices. Concerning the conditions of amputated fingers, the punching injury is the worst, shearing injury is bad, and the paper cutter injury is somewhat better. The finger amputated by pater cutter is the best replantation candidate because of its intact and neat section in shape. But in our experience, not all severed fingers injured by the paper cutter are suitable for replantation, especially those having phalangette finger mutilation. The Trochanter of phalanx is stripped from the soft tissue of the finger and severe contusions of the soft tissue were often observed under the operation microscope. As a result, no operational conditions for replantation can be found. The same situation exists with the paper cutting injury. The working mechanics of the pater cutting machine is that a steel board for pressing and fixing paper (thickness 10 mm) falls down just ahead of the cutting knife. The amputated fingers are subject to the same mechanics.

6.5.3 Cold Storage

For bilateral multiple digital replantation, after the patient is hospitalized all severed fingers should be promptly labeled and refrigerated. Debridement followed by replantation should be done one by one from the refrigerator. Untreated fingers remain under refrigeration, which create good conditions for replantation.

6.5.4 Replantation Procedure

Bilateral multiple digital replantation is a very delicate and difficult surgery. To ensure all severed fingers survive, it not only has to save time, but also assure good quality. A plan to organize surgeons is necessary, to ensure the best technological lineup, physical and energy state, and eventual successful replantation in the shortest time.

There is no significant difference in order and method between bilateral and unilateral multiple replantations. Generally we take thumb-index-middle-ring-pinkie procedure of replantation. Each finger was replanted using the anterograde replantation method: fixing the bone and joint, repairing extensor and flexor tendons, anastomosing the dorsal vein, suturing dorsal skin, suturing the digital nerve, anastomosing the digital artery, and then suturing palmar skin. For amputated fingers which are joined by web, bone and joint fixation; tendon repairing; vein, artery and nerve suturing are needed simultaneously. Thus, we repair the same tissue of multiple fingers at one time, and reduce repeated injury to the severed fingers on the operating table, and also shorten the operation time. Of course, we could also replant fingers one by one, after fixing phalanx, joints and repairing the rendons of the all fingers.

Technically, there is little distinction between bilateral multiple digital and single digital replantation. But for multiple digital replantation, it is a very difficult to ensure that all fingers survive. Often, surgery cannot be done as smoothly as programmed, due to long operation times and unpredictable situation during the operation. Therefore, it is a test of replantation technique, and also a test of team collaboration. The surgeon's high responsibility, fearless spirit toward difficulties and fatigue, determination, and will for all digits to survive, plus superb technique, all guarantee the achievement of a successful replantation.

6.6 Replantation of Multi-Level Hand Severances

If the divided finger is more than two parts, it will be called the hand multiple level severances, which are rare. It is usually caused by a rapid multiple cut of different kinds of cutting-off machines or punching machines. Because of the different hand positions, a variety of knives and the cutting speed and styles, different forms and positions of multi-segment severances result.

6.6.1 Characteristics and Indications

Multi-level severed hands should be managed according to the patient's age, severity of the injury, and full consideration of the finger length and functional prognosis after replantation. It can be replanted, only if the severed segment contusions are mild, more than 1 cm after debridement and it is expected that it could maintain normal blood circulation and structural integrity, and also could be able to provide bridging for the distal segment. For served segments without these conditions, we should give up replantation. If the distal part has integrity, with adequate replantation condition, we can use the corresponding segment of the toe for bridge-transplantation, according to the severity of the finger's injury, and the patient's age and willingness to undergo replantation.

6.6.2 Replantation Procedure and Method

Usually, the distal divided part of the fingers are replanted together in bloodless status, and then the proximal parts are replanted. In order to save the time, the doctors can be separated into 2–3 groups according to their skills and the number of the severed fingers. Thus under reasonable arrangement and close cooperation, the replantation can be completed as soon as possible.

6.6.3 The Characteristics and Matters Needing Attention

In Chengguoliang's opinion, the characteristics of multi-level severed fingers are that the middle segment is bridge tissue, the replantation needs not only to make sure the middle segment survives, but to act as a bridge and ensure that the distal severed finger also survives, and regains organization continuity, consummate external form and function. To ensure that all segments of the finger will survive, the accurate and high-quality small vascular anastomosis is the key to this kind of replantation. It demonstrated which show the strength of replantation skill. To ensure successful replantation and good function, in the operation we should pay attention to:

1. The severed segments with replantation condition should be chosen correctly and treated with in situ or translocation replantation. The segment which is too short so that no blood supply or bridge function is after replantation, should be abandoned.
2. The integrity of the various tissues and structures must be ensured, so as to bridge the various organizational structures in surgery.
3. All major arteries and veins of the proximal and distal ends should be repaired, in procedure to ensure the blood supply of the middle bridge segment, and to create adequate blood supply and venous drainage. The blood vessels between the distal part and the severed finger should be anastomosed in as many places as possible, so as to ensure the distal finger blood circulation, and also to prevent postoperative vascular articulo.
4. In addition the tissues of the middle segment should be restored except for the index finger and pinkie inherent

extensor tendon, and the superficial flexor tendon, to reconstruct the continuity of these structures.
5. The segments and fingers that have not been debrided or replanted, and the fingers that have been replanted in bloodless but not replanted to the proximal end, should be marked and stored in a refrigerator.
6. Nerve suture must be precise, to ensure the proximal nerve fibers pass through the middle bridge section, and can continue to the distal segments to restore the sensory function to distal part.
7. Bones should be internally fixed based on the different fracture position. In procedure to accelerate the replantation process, generally, fixation with a Kirchner pin running through the segment is the first choice.

6.7 Replantation of the Rotationally Avulsed Fingers

6.7.1 Progress at Home and Abroad

The rotationally avulsed fingers are a special type of severed fingers, which are also the most complicated. The blood vessels, nerves and the tendons are taken out with bad injuries, so they are hard to be replanted because of the defects after the debridement. Since 1978, the author has gradually adopted vessel, nerve and tendon of patients with rotational avulsed thumb primary shift's method to carry out transplantation, and formed a more integrated transplantation method, in 1984, 13 cases survived of 14 cases of this kind of replantation of an amputated finger. A novel replantation method provides for transplantation of rotated avulsive severed thumb, and has changed contraindication to indication.

6.7.1.1 Characteristics and Traumatic Mechanism of the Rotationally Avulsed Fingers

The rotationally avulsed fingers often happen when the patient take out the hand with gloves being entangled to the rotating machine in high speed. The fingers are injured by the power of rotation and avulsion. The separation first happen in the metacarpophalangeal joint, for the metacarpale is fixed to its position. Then the interphalangeal joint will get involved. Fengguangyu had taken the experiments on this and found that the separation usually happened at the metacarpophalangeal joint and interphalangeal joint. Then tendon will separate from the muscle belly which is the weaked part. The skin is elastic and tough, so it will be avulsed and then be broken. The wall of the vein is weak, so the vein will break at the edge of the skin. The nerve is tough, so it will be taken out from the proximal for a long distance, which will be like the mouse tail. The length of the artery taken out will between the vein and the nerve. Inside the artery, the intima will first break, and next will be the adventitia. The injured artery will be like the ribbon or segmental.

6.7.1.2 The History and Progress of the Rotationally Avulsed Thumb

Because the tendon, nerve and blood vessels were taken out from the proximal part, it is hard for the replantation. O'Brien thought: Avulsed wound create some difficult problems, only a little can be achieved, only a little can be achieved. If the avulsed finger with its vessel is avulsed too long at its distal part, it can't be replanted. Cenzhongwei thought: for the avulsed finger, its extensor tendon and flexor tendon often tear apart from the juncture of tendon and muscle. The finger nerve and blood vessel usually don't tear at the mutilation plane of the severed finger. There are longer blood vessel torn into pieces and injured, exceeding 3–4 cm. Because there are too many blood vessel defects, it is not suitable for blood vessel transplantation. The finger shortens too much. A transplant operation usually loses meaning. Pho reported a thumb avulsion mutilation case in 1979, they adopted ulnar vascular nerve tract of the index finger, dorsal digital vein of the index finger and the dorsal cutaneous nerve of the index finger and middle finger shift and suture to repair a vascular nerve. Of five cases replanted, three survived. Chengguoliang reported they use the method of vessel, nerve and tendon of patients with rotational avulse finger primary shift's to carry out transplantation in 1984, 13 cases survived of 14 cases. Ward reported they use the method of phalanx shortening and blood vessels and nerves anastomosing directly in 1991, only 6 survived of 13 cases. Yangxiaohui reported they took the blood vessels and nerves from the adjacent finger and used the vein graft for replantation, all 9 cases survived.

6.7.2 Methods of Transplantation of the Rotationally Avulsed Thumb

6.7.2.1 Anatomy Characteristics of the Thumb

The function of the thumb accounted for 40% of the whole hand, which are feeling, flexition, extension. Both the proximal and the distal part accounted for 50%.The metacarpophalangeal joint has the function of rotation. The artery are the proper artery on both sides of the flexor tendon and the dorsal artery. The diameter of the artery in the distal part is 0.2–0.5 mm, which connected with each other and form the artery net. The veins lay between the superficial and deep fascia, forming the two dorsal vein which usually have three communicating braches. In the proximal part, there are radialis and ulnar vein with the diameter of 0.3–0.6 mm. The nerves are the proper nerves, which are in the skin ligaments on both sides of the flexor tendon with the diameter of 0.2–0.3.

6.7.2.2 Debridement

Meticulous and thorough debridement is the basement of the replantation. (a) Wash the surface of the wound with sterile soap, and dip it in the chlorhexidine (1:1000) and then the hydrogen peroxide (3%) for 5 min. (b) Cut off all the dead skin and tissues. (c) Sew the nail or skin in the sterile drapes when debride the finger tip or the children's finger, so that it will be easy to find the blood vessels under the microscope. (d) The blood clot is usually the end of the vein, which can be the guide. (e) Make cuts of 1 cm on both sides of the flexor tendon to expose the sheath of the artery and nerve. Find the nerve, and then you can find the artery on the dorsal lateral side. Sometimes you can find satisfactory veins in the palmar side. (f) Cut the blood vessel to the normal, we would rather take the blood vessel graft than anastomose the bad ones.

6.7.2.3 Bone Reconstruction

(a) Shorten the backbone so as to keep the integrity of the joint when the dividing is near the joint. (b) Keep the integrity of the joint by tieing it up with thread or syringe needle when the joint is broken. (c) Fuse the joint with Kirschner wires after shortening the bone by 0.5–0.8 cm when the dividing is in the joint. (d) Use the tendon ball to reconstruct the metacarpophalangeal joint when the head of the metacarpale is damaged and fix the joint by Kirschner wire vertically. (e) Shorten the bone which is far from the osteoepiphysis to protect the joint when the patient is a child.

6.7.2.4 Repair of the Tendon

The opinions on how to repair the tendon are almost the same, which are using the proprius extensor of the index finger or the extensor carpi radialis longus to repair the extensor pollicis longus, and using the flexor digitorum superficialis of the ring finger to repair the flexor pollicis longus. The extensor and flexor tendon will be sutured to those of the adjacent fingers in parallel.

The common method of repairing the tendon: (a) Suture the tendon by the method of Kessler with the thread 3-0, put the line knot in the two ends of the tendon and then suture the extine with the thread 8-0. (b) Cut off the flexor digitorum superficialis when the damage is in the Zone II, and only repair the flexor digitorum profundus. (c) Repair the flexor pollicis longus by using the flexor digitorum superficialis of the ring finger by the method of Kessler. Repair the extensor pollicis longus by using the proprius extensor of the index finger or the extensor carpi radialis longus by the method of knitting stitch.

6.7.2.5 Reconstruction of the Blood Vessels

The palmar arteries of the thumb include the principal artery of thumb, the radial and ulnar volar artery. The occurrence rate of the principal artery of thumb is 93.7%, which goes through the transverse head and the caput obliquum of the abductor pollicis muscle and through the deep head of flexor pollicis brevis and then divides into branches at the deep side of the sheath of the flexor pollicis longus muscle tendon. Seventy-five percent divide into the radial and ulnar volar artery, 18.7% divide into the radial volar artery, the ulnar volar artery and the radial volar artery of the index finger. 6.3% will lack the principal artery of thumb. It will be easier for us to reconstruct the artery of the thumb by transferring the radial or ulnar volar artery of the index finger, the radial volar artery of the ring finger or the ulnar volar artery of the middle finger than using the vein graft. Before cut the arteries talked above, you should make sure whether the opposite artery is clear (Allen test), in case causing the necrosis of the finger.

There are three methods to reconstruct the blood vessels and nerves of the thumb. (a) Shorten the bone. (b) Use the vein and nerve graft. (c) Transfer the nerve and blood vessels from the neighboring fingers. If you just shorten the bone, you cannot cut off all the pathological blood vessels. Then it will cause the high rates of the thrombosis. Also, if you cut off too much of the bone, there will be no sense of replantation. Liangbingsheng thought that if you use the vein and nerve graft, you can leave the injured blood vessels and nerves and do not need to take more injure to the proximal tissues. If the difference of the diameter between the graft blood vessel and the taken site is big, you can (a) cut the thin vessel to the shape of slope 45°. (b) Cut some part of the wall from the thick vessel to shorten the diameter, and then anastomose them. (c) Cut the thin vessel into two parts like the mouth of the fish, and then anastomose them. Chengguoliang use the light microscope and scanning electron microscope to observe the vessels, and find out that the patency rate are 92%, 90% and 100% respectively with diameter ratio of 3.5:1.

6.7.2.6 Repair of the Nerve

In order to recover the best function of the fingers, we must repair the nerve. We usually use the nerve graft for the patient with nerve defect. Shake put the nerve end into the soft tissues to recover the pain function. Some authors anastomose the proximal of the ulnar proper nerve to the distal of the radial proper nerve and get the good results. The digital nerve are pure sensory nerve. The feeling function of the finger tip get well after the bridge connection with nerve graft. The two points discrimination is 2–5 mm. It will get good functions to transfer the artery, nerve and dorsal vein of the non-dominant side of the neighboring finger.

6.7.2.7 Management of the Vascular Crisis

The vascular crisis is one of the important reason that lead to the unsuccessful replantation. It is easy to manage by warming, lidocaine or heparin injection into the vein when the vascular crisis occurs during the operation. The arterial crisis often occurs after the operation because of the pain, mental stress, compression by the surrounding tissues, and the low temperature. The manifestations are pallor of the finger tip, the low skin temperature and the vanish of the capillary hyperemia reaction. The venous crisis often occurs because of the bad debridement, the low quality of the anastomosis and the tightness of the skin suture. The manifestations are the dark purple skin, swelling of the finger pulp and the time contraction of the capillary hyperemia reaction (<1 s). Fanqishen thought that the management of the vascular crisis is the main key to the replantation.

The anticoagulants and antispasmodic should be used after the replantation and reconstruction of the fingers routinely, Especially for those patients with hyperdactylia amputation injuries, bad anastomosis. Otherwise you do not need to uses them. For those who between the two above, you can use Dextran 40 and Danshen injection.

6.7.2.8 The Issues About Observing and Nursing After the Operation

The patient should be put in a quiet, clean, and comfortable room with fresh air. The smoking should be forbidden in case causing the vasospasm. The relative humidity should be 50–60%.The vital signs should be observed carefully after the surgery. A complete rest in bed should be taken for 72 h. The hand should be put on a soft pillow on or 10 cm above the level of the heart in order to make it easy for the backflow and relieving the swelling. The color, temperature, the time of the capillary hyperemia reaction and tension should be record regularly. The room temperature should be 25–28 °C. The hot lamps with the power of 60 W should be used 30–40 cm above the replanted finger in case burning the skin. The pain should be managed in case of the vascular crisis. The diazepam (10 mg) can be used IM. The suture should be taken out 2 weeks after the operation. The Ultrashort wave therapy can be used 3 weeks after the operation to accelerate the healing of the wound. Exercises should be taken 4–6 weeks after the operation. The Kirschner wire should be taken out 1.5–2 months after the operation. The patient can go back to normal life.

6.7.3 Replantation of Avulsed Amputated Finger

Both avulsion of amputated finger and rotated-avulsed-amputated thumb have the same traumatic mechanism, which is mostly because of operating high-speed rotating machine with gloves. The replantation method is the same as rotated-avulsed-amputated thumb. If transfer is impossible, but replantation can still be carried out, according to which finger it is and its post-replantation functional prognosis, by the way of transplantation of blood vessels and nerves.

In some conditions such as avulsion and draw-out of vessels and nerves as well as multiple fingers involvement, replantation should be given up. The reason is that it is usually severe and with various degree injury of finger bodies, vessels and nerves, and hard to transfer supplying blood vessels, nerves and tendons from neighboring fingers.

6.8 Severed Finger Reunion For Children

6.8.1 The Meaning and Current Situation of the Severed Finger Reunion for Children

On the grounds that children are naughty, active, lacking the safety awareness and prevention ability. However hands become the chief organ to touch the outside, so higher probability of trauma may come from hands. It shows no probability to proceed severed finger reunion for children before the microsurgical technique has not been applied in the clinic. Before this, the way of reunion is apical stitch in most hospitals, thus causes finger deformity when children were in their little age, also it caused a great impact on the children's growth, learning and life. With the continuous development of the microsurgical technique and severed finger reunion technique, it is easy to realize the reunion of finger termination of the children. The Academician Wang PengHuan was firstly and successfully proceeded the severed finger reunion for children, after that, Tamai reported one 20 months' baby case whose closer left phalangeal joints were amputated completely by pulley of the sewing machine. Academician Wang applied the microsurgical technique to mix two arteries, one dorsal digital vein, one side finger nerve, and to repair the finger flexion function, flexor tendon thus to make the finger relive. In the year of 1976, Kubo reported that one case-13 months' baby' one finger was completely amputated, but it just mixed 0.4 mm external diameter artery, not mixed the veins, then made it survive again by the way of pressing far-end finger. And in the year of 1980, O'Brien reported that 27 cases-the age between 13 and 14 months kids' severed finger, and the survival rate was 64.5%. And the case of little age was not through the finger reunion but got survival. And O'Brien reckoned that the veins of the children were slim, and it was more difficult to replant compared with the adults.

The severed finger reunion technique stared a little bit late in China, but it gained a greater improvement from the start. From the year of 1979 to 1985, the children age ranged from 10 to 14, total sum was 28 cases, 47 patients were proceeded the finger reunion, the failure case was just one, and the rest were survived, survival rate accounts for 97.7%. Thirty fingers which includes in 18 cases were in 4 years old, accounts for 73% in the total number, 29 fingers were survived again through the reunion, in that the smallest age is 14 months. After the operation, and through the follow-up in from 9 to 15 year, according to the stander which put forwarded by the International Association of Hand Surgery the good rate is 100%, the growth of the finger were good, the contour function was better compared with the adults.

6.8.2 The Features and Indications of the Replantation

The features of the replantation for children: (1) The children's finger are small and the blood vessels are slim, it is difficult to replant after being revered. (2) Capillary penetration and tissue reaction were a little intense, regeneration capacity was vigorous, the cicatrization speed is faster than the adults. (3) The children will get the deformity correction ability after fracture healing with growth. (4) As long as the external fixation moved away after the severed finger reunion for children, the children will start to use them freely, their functional recovery is better than adults. (5) Better plasticity. After being used for a long time, their fingers has been replaced the old ones. Children will forget their injury experience soon, not feel uncomfortable when they perceive that their fingers have once been served. However the functional recovery of the adults is comparably bad on the grounds that their fingers can't be practiced effectively. So, these reasons will result in atrophy of disuse.

The limits of indications of the severed finger reunion for children are larger than the adults. The traumatic amputation of fingers mostly comes from the accidents in the daily life. Also, Concis, Crush injury, machinery injury are the most reasons. Thus, the children' condition of their severed singers is better than the adults, only the finger contour has been saved completely and the ground injury is not obvious on the far and the bottle ends of the finger, most severed fingers of children are adopted to the replantation. With the development of the microsurgical technique, the severed finger reunion indications of children become larger, only finding the anastomosis of the blood vessels, no obvious flab injuries, if these conditions meet with the requirement, the fingers can be replanted.

The time limit of the severed finger reunion foe children: the time requirement is generally in 8 h, but after cooling the blood for 53 h, the replantation also achieves, thus makes long ischemia time is not the contraindication. Only the severed fingers through the appropriate safe keeping and refrigeration, in the normal situations, striving for the reconstruction of the blood circulation for the severed fingers in 24 h, thus most severed fingers can be survived through the replantation. If the fingers are refrigerated regularly, it can prolong the time limit of the ischemia of the finger, and if there is no quality to proceed the vascular anastomosis, it should be sewed up rigidly in the normal position. Also, it will gain the certain possibility to survive. Not all the hospitals can proceed the finger replantation for children, so if the children's fingers are mutilated by the trauma, the fingers should be refrigerated intermediately and send to the qualified hospital. The condition is same as adults that the severed fingers should avoid being soaked directly in NS, GNS, geramine even 75%alc …

6.8.3 The Bone and Joint Treatment

Three main points of the severed finger replantation for the infants: one is the epiphysis, the second is the vascular and nerve tissue is tiny and small. So it is difficult to operate. The third is the communication between doctors and patients is a little hard. The postoperative infants are unable to cooperate well with the treatment. On the grounds that the children's bones and joints are at the stage of growth, the way to handle it is difficult compared with the adults. Through the clinical practice and experience, we should abide by the following principles:

1. Try to protect the epiphysis. Epiphysis is the secondary ossification center which occurs in a different period after the children born. It is the growth area for the immature long bones of four limbs. Also it is the weakest and most vulnerable parts of the bone of children. After the epiphysis injury, it will cause vegetative disorder also result in limb shortening or joint deformities. So when shorten the epiphysis, it aims at the opposite diaphysis of the epiphysis.
2. The cripetura should not be so long. The bone cripetura between two ends of the bone is generally in the limit of 2–3 mm, the total cripetura is generally 5 mm, but when suffered from the serious contusion, we need to sew up the blood vessels, nerves, tendons and so on in the situation of tension-free, and at that time we need to prolong the cripetura.
3. Try to reserve joints. If we find there is disarticulation but the articular surface is complete during the operation, we can shorten the opposite diaphysis to reserve the joints on this side, but to avoid the arthrodesis. If the articular surface suffered from the damages, we should adopt the arthroplasty.
4. To make the fixation firmly. Because children have the comparatively worse self-control ability, the firm fixation is the basic safeguard. After the operation, through the X-ray on to check whether the bone position is right. Then, 3 weeks later, the patients can move the fixation away, they can do the functional activity.

6.8.4 The Problems that the Doctors Should Pay Attention to During the Operation

1. To find the main points of the blood vessels, to amplify the microscope, use the meticulous microinstruments carefully, and the priority is that doctors should be familiar with the anatomical position, to find the neurovascular bundle (NVB) along the both sides of the flexor tendon. Artery is located the lateral nerve, the relationship is constant. Because the walls are comparatively thin and deformed, so it is comparatively difficult to find the digital veins, and we should find them carefully. "Residual blood is the most valuable thing". The doctors can press the broken ends of fractured bone to confirm the position of the orifice.
2. Vascular anastomosis. The vascular anastomosis of children is not as difficult as we imagined. It is connected with the age-the more little age that the children is, the thinner blood vessel is, and the walls the same. So the patients who meet the requirement that the blood vessels are at the range of 0.3 mm, the doctors can proceed the severed finger reunion for children. But some following main points that the doctors should pay more attention to:
   (a) Noninvasive operation. The blood vessels of children are not only tiny but also the wall of the blood vessel is thin, then after peeling off the outer membrane, the vessel wall is almost transparent. So the surgeons should avoid pinching the walls directly, and when punctured the needle, the surgeons can use the sharp of the tweezers to pick up the blood vessel wall and make the needles reach the tissues vertically. The total action should be gently and the power of tying a knot should be moderate.
   (b) The choice of stitches. Try to choose noninvasive single nylon threads, and avoid using the needle threader to clip the stitches during the procedure. Before using the stitches, the surgeons should punctured from the tissues firstly to remove the foreign matter.
   (c) The number of stitches. External diameter 0.3–0.5 mm, the surgeons can punctured 4–6 stitches, 0.5–0.6 mm, 6–8 stitches, 0.7 mm above, 8 stitches. And the surgeons can add and reduce the number of stitches according to the current situation.
   (d) Flaccid suture. The children's blood vessels are endowed with good plasticity. Generally, if the children were fractured and the bones were shortened, then the surgeons can proceed the end to end anastomosis. Even if the damage degree is six times than the external diameter of the blood vessels. And if the damage degree is highly, the surgeons would rather adopt vasotransplantation than to proceed the anastomosis in the situation of tension.
   (e) The choice of vascular clamps. The vascular clamps that the surgeons choose, their clucking power should between 10 g. During the operation, the surgeons should choose and adjust the tightness of the vascular clamps according to the children's age, broken parts and the thickness degree of the blood vessels. For the occasion that the vascular clamps can't be used to fix the vessels, the surgeons can adopt the way to repair the vessels and wash them at the same time. Also the surgeons can choose to use Heparin Saline to wash the blood vessel damage on both sides then repair them at the filling state. The surgeons should avoid puncturing the opposite walls. Also they can use rubber tubing to interdict the blood flaw. But they should pay more attention to take the noninvasive principles.

6.9 Fingertip Replantation

Since 1988, Tian Wancheng firstly reported the case of fingertip replantation, thus made the finger surface come to the peak, however the damage of fingertip not only makes the appearance of finger get damaged, but also it can make the feeling function of the sensitive level of fingertips lose ever.

6.9.1 Fingertip Anatomy

The fingertip is the far apart of the roots of the nails; it is the special area for replantation. There are many nerves around the fingertips, and it is the most significant feeling part of the finger. If the fingertip gets damaged, it will bring the serious impacts on both the function and appearance of the fingers. Distal segment finger and the phalanges are surrounded with the most important arteries' final ends and the same arterial arches, also stretching five essential branches, which alongside with the surface of the volar curved tendon. Of the two sides, there is one comparatively artery (0.1–0.2 mm), and on the middle position, the third one is comparatively thick, and each artery is surrounding with each other, any one artery can be fitted. The initial point of the anatomy projection of this artery is located in the nail semilunar line. The vessels which on the dorsal part of the fingertips are comparatively tiny. The vessels on the dorsal part of the fingertips are closed to the under skin, and the walls are comparatively thin. And on the middle side of the nail surface, the vessels all can be fitted.

6.9.2 The Different Types of the Fingertips

The definition of the fingertips is not clear. Currently the most used one type is put forward by Yamano which being acknowledged during the clinical. And it classified the far-end fingertips as different sections, which defined the three sections beyond as severed finger. And it equals to the 1/2 far part of the distal segment finger. Also it can be inclined severed injury or sidewards injury.

6.9.3 The Injury Reason and the Indications

Stamping injuries and shearing injuries are taken the priority in fingertips tissues damages. For cutting and shearing will result in severed fingertips, the mutilation surface is comparatively smooth and the digit is also complete, the lacerated ends are with no obvious damages. So there will be many qualities to proceed the replantation or suture in suit. The coup injury also will result in the severed finger, for the severed part is resulted from the blunt force, the severed surface is damaged seriously, so there will be no chance to proceed the replantation or suture in suit.

For the severed fingertips which reserve the comparable smooth and no obvious damages on it also no comminuted fracture, vessel or nerve evulsion, for these fingertips, the surgeons should choose to replant. The priority to assure the survival is to control the indications of the replantation.

The indication of the fingertips is to estimate the survival rate after replantation. But how to estimate is not only through the visual inspection but the surgeons should use the surgery microscope to observe the level of the vessel damage. Then the surgeons can make a comparatively objective conclusion. Finger pulp has the comparably thick fat pats. When injured, the aortic arch of the fingers also the branches are under the certain protection of this fat, even there are many ecchymosis lying on the hyponychium. Sometimes the aortic arch and the branches can be in the good situation, so the surgeons cannot give up the fingertip replantation easily. Only if the finger body is complete, the patients ask for replantation, then the surgeons should try their best to proceed the fingertip replantation.

6.9.4 Operation Method

1. To narcotize the adults, the surgeons should use brachial plexus anesthesia or digital nerve block anesthesia. To narcotize children, they should use basic brachial plexus anesthesia or general anesthesia.
2. As for tourniquet, the surgeons usually choose to use the elastic to interdict the blood flow.
3. Routine debridement, the surgeons should scrub the wound 2–3 times, as for the separated damaged skin part, the surgeons should use disinfectant clean the wound. Before that, they should shorten the short proximal phalanx about 2 mm.
4. Neurovascular should be marked under the microscope. To loosen the tourniquet and then find the proximal arterial pulse points. Then to use a tourniquet, clean the arteries that close to the nerves, nerve artery is comparatively thick. When find it, to be marked. Try to find the veins under the Volar leather, the veins are thin also the walls are the same. So it is difficult to find it. If the surgeons cannot find them, they don't need to spend a lot of time, to leave them aside temporarily. To debride a little for the cross-end. According to position of the proximal artery to find the vessels, then try to make the positions for them.
5. To use the 0.8–1.0 mm Kirschner wire to proceed the internal fixation, do not remove bone gap away, making stump accurate reduction on both sides.
6. Sew up the skin and nails.
7. To use 3-0 silk to stretch the ends of the Palm-side skin margin, do not damage marked veins.
8. Under the microscope, use the 11-0 nylon to sew up 1–2 noninvasive neural, searching for the signs to identify the artery, to debride, loosen the tourniquet, confirming the proximal arteries are powerful, to press it and stop bleeding 3–5 min, use the tourniquet again. Cleaning the two broken ends of blood vessels, using noninvasive nylon thread and 4–6 needle 12-0, then use the line to sew up 1–2 veins, open a tourniquet, the severed finger will refresh the blood circulation, use salt warm water to clean it, and suture the skin, then the operation ends here.
9. If the veins cannot be found, after repairing artery, then loosen the tourniquet, it shows distal Palmar subcutaneous bleeding point is the vein, and then looking for the appropriate position of the proximal vein, then to repair it.

6.9.5 Warnings During the Operation

1. To control the indications seriously, any blunt force trauma cannot be replanted.
2. Two broken ends should debride a little under the microscope, the surgeons should pay attention to protect the vessels and nerves.
3. To use 0.8–1.0 mm Kirschner wire to proceed the internal fixation.
4. To use Tourniquet, <1 h each time.
5. To use 12-0 non-invasive in-line nylon thread suturing blood vessels, 11-0 sew up the nerves.

6.10 The Finger Displacement Replantation

6.10.1 The Definition

When we met the complicated avulsed fingers that can't be replanted or can it be in situ replantation but without any function, for example, pinch, clip and grasp, we should choose the minor fingers which were relatively intact to displace the more important fingers that can maximize the function of the reconstruction hand.

6.10.2 The Method of Finger Displacement Replantation

The thumb finger accounted for about 50% of our hand function and index finger has 20%. If the mutilation finger is the thumb finger at the same time without any advantage of in situ replantation, we should consider the order of our replantation. We always choose the relatively intact finger to replacement thumb finger, then the index finger, middle finger, ring finger and little finger.

If the replantation finger will narrow the first web place that affect the function of hand, you can consider first of the middle finger with the index finger stump by metacarpal head position to expand.

If the damage was in the palm of hand with the thumb survived, others were from the palm wrist, which displacement of fingers replantation in the basal parts of metacarpal, we should consider first the fingers that can pinch with thumb to rebuild the thumb opposing function. If the injury in wrist or wrist, palm that destroyed most of the fingers, the distal severed fingers with one or two intact that can be considered to the displacement of the wrist or anterior wall residual can rebuild the partial function of the hand, namely the emergency hand reconstruction.

6.10.3 The Notes of Surgery

The replacement replantation is the same as normal replantation surgery. But the former has the problems with the size of fingers and vessel caliber asymmetric.

The analysis and treatment in vessel caliber asymmetric of displacement replantation: different finger artery has different advantage side. The artery of thumb is thicker relatively than the other four fingers, at the same time, its' ulnar side is thicker than radial as well as the index and middle finger and opposite with ring and little finger.

Because of the different size of vessel caliber, we choose the ulnar artery of index and middle finger and the radial artery of ring and little finger to anastomosis conveniently with the same side of thumb finger. If conditions do not allow, can it only fit ulnar side blood vessels, we could cut the small diameter of the distal vascular oblique mouth after, in order to match each caliber. The vascular anastomosis process is easier between index and middle as well as ring and little finger replacement of replantation because of the relatively dimaster. When the replacement of finger is between index and middle and ring and little finger, we should choose the ulnar vessel to anastomosis. Because the caliber of blood just slightly thick and distal proximal relatively thin, we can use three needle set into laws, but also save operation time.

Referring to the finger body has different thickness: The thumb finger weeks diameter is the largest, the little finger weeks minimum diameter in the week of each finger size. When shifting after replantation, we often encountered is the diameter thin body shift de to the thick refers to the body (e.g., thumb). Skin anastomotic annular narrow can lead to blood vessels and nerve entrapment. Therefore, preoperative plan for detailed planning is necessary. Solutions are to make the plasty of "W" that can stitch to make the skin smooth transition.

6.11 Replantation with Tissue Defect

Finger amputated tissue defects often accompany treatment principle is still "missing much, much make up." When replanted according to the type of tissue defects, will be divided into the following sections are introduced:

6.11.1 Severed Finger with Skin, Vascular Defect

Replantation more common. Such as skin defects not associated with deep tissue exposed, it can be used to solve through skin graft. If accompanied by deep tissue exposed, you need to be covered with flaps. Meanwhile, the finger dorsal vein is often accompanied by soft tissue defects, palmar soft tissue defects often accompanied by finger artery defect. Should be used to select the optimum flap tissue defects according to the location, extent and function. Flap selection can be divided into two categories, pedicle flap and free flap.

6.11.1.1 Pedicle Flap

If accompanied by a vascular defect, surgery can be the first to take the free vein bridging vascular defect, then cover with a flap of skin defects. Optional pedicle flap are:

- Cross finger skin flap: for repair of finger volar skin defect. Be replanted fingers survived, after three weeks pedicle division If associated with vascular defects, finger flap can be used as a bridging vein in vascular repair arteriovenous defects.
- The dorsal metacarpal artery flap: is only suitable for nearly, the palm dorsal skin defect. Cut flap could undermine the back of hand, and the finger dorsal vein network, so when use the flap should be considered when developing refers to whether there is sufficient venous return.
- Adjacent finger dorsal vein island flap: especially suitable for nearly section in the soft tissue defect. According to the defects in neighboring refers to the size of the dorsal

design refers to the island flap of dorsal vein, only a proximal vein pedicle is linked together, through the subcutaneous tunnel transferred to the defect of severed fingers distal vein and vein anastomosis.

- Adjacent finger artery island flap: according to the size of skin defect in adjacent refers to the adjacent side, to take a flap refers to the proper palmar digital artery defects of the corresponding parts cut artery island flap, flap after open tunnel anterograde transferred to the defect in the area. If accompanied by artery defect, distal flap can be correspond to finger point to the proper palmar digital artery anastomosis, can repair the skin defect at the same time, restore the finger artery.
- Adjacent finger dorsal fascia flap repair: in adjacent refers to the corresponding parts for fascia flap, flap the anterograde transferred to open tunnel defect parts, pedicle dorsal skin graft, can repair the finger palm dorsal skin defect. Can also use fascia flap in the distal vein and the corresponding finger dorsal vein anastomosis, can repair the skin defect at the same time, restore the finger venous return. More commonly used with thumb radial side fascia flap and 2–5 finger dorsal fascia flap.

6.11.1.2 Free Flap

The use of some small or micro free flap to repair finger skin defect. To provide the skin flap blood supply and perception, and often have to sacrifice the finger artery and refers to the proper palmar digital nerves or refers to the dorsal nerve. In addition, you can use the blood vessels in free flap for bridging defects in the blood vessels and cover the wound at the same time, this also call flow-through technology. This can provide skin flap in the supply of blood at the same time, don't have to sacrifice a finger artery.

(a) Vein skin flap: superficial vein of forearm flap to repair. Can be made into physiological vein skin flap bridging refers to the dorsal vein, also can be made into vein was arterialized nonphysical flap bridging artery, can also be arteriovenous bridge together, flexible application. Can also solve the blood vessel and skin defects at the same time.

(b) Foot free flap, sort is various, including the dorsalis pedis flap, foot, toe artery island flap of medial flap, fu medial flap and plantar medial flap and so on. Suitable for different area of skin defect of finger, or circular skin defect. Especially in merger cases of arteriovenous defect, at this time can take advantage of the flap arteriovenous vessels of defects within the bridge repair, repair skin defect at the same time. Due to the quality of a material is the same, therefore, is good for the region of replantation repair skin defect. Defect is need two complex anesthesia and surgery area.

(c) The forearm free flap, including free interosseous dorsal skin flap, free wrist of ulnar artery skin flap. Apply to skin defect area is lesser, also need bridging artery, also can use flap of superficial vein bridge finger vein.

6.11.2 Severed Finger with Skin, Tendon Defect

Repair means has two kinds, one is the first phase of emergency repair tendon defect. The second is the survival phase ii tendon repair after replantation. The former good repair effect, but the high technical requirements. The latter treatment cycle is long, curative effect is poor, but relatively safe.

1. Contains the blood supply of tendon free composite tissue flap transplantation. Such as Tendon palmaris longus of vein skin flap and forearm with palm dorsalis pedis flap with toe long extensor tendon. At this time through free tissue flap transplantation can repairing tendons, skin, blood vessels, composite tissue defects at the same time. And tendons at this time to take the blood supply of the tendons, relatively free tendon without blood supply, this way of repairing tendon healing faster, shorter recovery time, curative effect is better.
2. Free tendon transplantation with skin flap grafting to repair. Use tendon palmaris longus or long extensor tendon free transplantation finger tendon repair, then using the foregoing method to repair skin defect.

6.11.3 Along with Skin, Bones Composite Tissue Defects

At this time should be according to the location of the defects of bone, size, make treatment decisions. Also hurt case is the important considerations, such as Chainsaw injury, less risk of infection. The meat grinder, ensilage machine injury, even if were carefully debridement and infection risk remains.

A finger backbone small defect often use short hand refers to the method, it can simplify the operation, reduce skin defect size. Long segment defect of replantation refers to the backbone, there are generally two kinds of processing way, one is the emergency repair, which often should be digit part free transplantation to repair. The need to carry phalanges. Because of the phalanges for belt blood supply, thus heal quickly. Also can use free iliac transplantation, flap coverage. But at the moment free bone block has a risk of infection. To reduce this risk, can adopt the second phase of bone reconstruction. That is, a period through the longitudinal Kirschner wire fixed and open defects of bone, maintain finger length, then the conventional reattach cover skin defect and using the above method. After being amputation survived, free ilium transplantation. This method is more safety, but the treatment cycle is long. Especially suitable for meat grinder, ensilage machines damage associated with high risk of infection.

Such as bone defect part in joint, choose more treatment. Such as the distal interphalangeal, due to the joint function is relatively minor, mostly choose joint fusion. If the proximal interphalangeal joint, to choose free toes small joint transplantation fusion or repair. Free toes joints graft repair can be done in the emergency issue, also can be done in phase ii, phase ii operation risk is relatively small. Near the metacarpophalangeal joint defect, if it is 2–5, often choose arthroplasty, such not only joint from simple operation can save a certain activity. Higher requirements for the patient, can choose the second phase of the free toes joints or artificial prosthesis replacement.

6.11.4 Special Composite Tissue Defects: Finger Ring Tissue Defect

At this time only flexor tendon is linked together, accompanied by circular soft tissue defects, including bilateral refers to the proper palmar digital artery and nerve, refers to the dorsal vein and extensor tendon defect.

Repair often use two ways, one is the ring width is narrower, the tissues of shortening phalange way may be used for repair. This is the simplest and most direct way. The second is the free toes segmental transplantation. If circular defect width wider, adopt the method of shortening of the finger can lead to obvious deformity or no function, so you will need to adopt the method of free toes graft. Usually by the second toe of defect size free composite tissue transplantation, the composite tissue including toe proper palmar digital artery and nerve, toe dorsal vein and extensor tendon, migrate to the area after toe proper palmar digital artery and nerve, toe distal dorsal vein and extensor tendon, and from the proper palmar digital artery and nerve of amputation, refers to the dorsal vein and extensor tendon anastomosis of the proximal and finger close off the proper palmar digital artery and nerve, refers to the dorsal vein and extensor tendon anastomosis, both rebuild the blood circulation, and repair the nerve, tendon and skin defect.

Advantages and disadvantages. Advantages of an operation is completed the finger replantation, and the corresponding tissue defect repair. Do not shorten the phalanx, can maximum limit to improve the function of the fingers and appearance. Defect is high operation requirements, operation risk is relatively large, in addition to taking the second toe will cause the second toe is missing its shortcomings.

6.12 The Late Reconstruction of Finger Function After Replantation

Because of the constraints, we always ensure the first period surgery live only with blood vessels except the tendons, joints, nerves, then we rebuild until a second period of the opposing palm and other functions, namely the late reconstruction of finger function after replantation.

6.12.1 The Reconstruction of Joints

When the joints injured that can't keep in the first period, we always perform the ankle arthrodesis or arthroplasty. If the patient's demand is higher, the second phase of reconstruction of finger joints can use the following method, the first is the free toes small joint transplantation and the second is the artificial joint transplantation.

The surgery method:

6.12.1.1 The Free Toes Small Joint Transplantation

The first step is thoroughly debridement, marking blood vessels, nerves and tendons standby, accurately measuring the length of the bone defect, the position of the joints, tendons, blood vessels and nerves for length and the area of the skin, etc. The donor site repairing: we design the donor site with the corresponding part of second toe according to the required for the length of the bone and skin defect. Mark the joint length and the area of the flap that is required on the skin surface and draw the bone away from the fault plane. Cutting skin at the proximal first dorsal of second digit incision line expose the subcutaneous vein, separate along the branch and ligate useless branches, free toe inherent artery and nerve on the bottom of the toe lateral, pay attention to protect well the near side branch of the toe joint. Free from the edge of the flap and cut the tendon in the high plane and pay attention to avoid the tendon from skin and bone. According to the preliminary design of bone cut from fault plane carefully, so in addition to the vascular pedicle is linked together, the rest of the group have been free and relax tourniquet for blood test. Tissue replantation: Breaking the pedicle of flap after 10 min blood go through and then transfer it to the recipient and the donor site cut toe or joint fusion processing. With the appropriate counterpoint of the joint, use the "ten" word wire or Kirschner fixation, half joint owners adopt joint capsule fixed-point suture, in case of rotating tendons start under the microscope after anastomosis of suture, nerve, the foot bottom inherent artery, nerve, and refers to the inherent artery, nerve anastomosis, toe back nervous and refers to the dorsal nerve anastomosis, toe dorsal vein in conformity with the refers to the dorsal vein.

Postoperative is the same with conventional replantation.

6.12.1.2 The Artificial Joint Transplantation

To avoid the formation of longitudinal skin scar's contracture and reduct adhesion of extensor tendon, we always perform the center of the back interphalangeal joint near side arc incision. Such as the extensor tendon ligament and the surrounding connection is complete, and the central extensor tendon is longitudinally splitted, and open both sides to expose the joint. Especially, if has the extensor tendon adhesion, we should release them sharpnessly and protect the intact of extensor tendon structure. To clear the central tendon bundle and lateral collateral ligament defect or complete, if defect, to rebuild in the section of the phalanx basal bone holes. At the same time, release the volar joint contracture. To protect the intact of the lateral collateral ligament. If we found the joints have osseous fusion or exist serious damage that should be cut include partial finger phalanx and articular cartilage surface that should be equal to the width of the prosthetic joint shaft.

We handle the marrow cavity to install prosthesis after cutting the section nearly phalanx head. To use the small size file at first, then gradually expand, until the joint prosthesis handle smoothly inserted as well as the middle finger phalanx. When the artificial joint module is appropriate, we insert the right swanson prosthesis in the flexion. St. George fill the bone cement after flushing out the bone debris in the medullary cavity and then dry it. We insert the distal prosthesis metal handle into the medullary cavity and polymer handle into the proximal medullary cavity with the joint and prosthesis in flexion.

Then straighten the joint and adjust the lines of force and the length of the fingers according to the condition of fingers when we wait for the bone cement solidification. While the bone cement is solidification, we clean up the bone cement and full stop bleeding after check the range of motion. Then close the tendons. To make sure the tendon is strong enough to get the good lateral stability and the relationship of the line, and to ensure that the joints have a certain range of motion. Interrupted suture the skin by 5-0 line and give the subcutaneous drainage.

We make no demand on the plaster in post operation. To exercise the joint after 2 days of operation and pay attention to the appropriate activity, not too hard. We often wear in front of the bone cement injection stitches to reconstruct the tendon. To exercise the joint after the tendon is healing. Usually we straight and fixat the joint after the operation and guide the patient to exercise. To move the joint under control after take off the external fixation third everyday, and mainly move the joint under control as well as actively move complementary after 1 week. Then 3 weeks later, to start active joints step by step and begin auxiliary strength training, until the best function recovery.

6.12.2 The Reconstruction of Thumb Opposing Function

If the plane of broken thumb is nearby the middle of fist metacarpal, then the function of thumb pinch is damaged inevitably, and perform this function weather in first period or second. There were variety of methods to reconstruct this function. We should choose it according the specific circumstance. Overall, the best method is still the transfer of the ECU tendon. The specific method introduce in other chapter.

6.13 Functional Assessment of the Replanted Finger

Hand surgery or disease always lead to the lose of hand function, for the light it causes the inconvenient of our life, and the serious lead to diminish the likelihood of independent living. Our work is to repair these wounds and residual hands maximally. So to have an objective evaluation of the injury degree and the result of function recovery before and after treatment is necessary. The aim of this evaluation is to explain the degree of damage, to make the patients being in the know, to compare the curative effect objectively before and after treatment and offer the objective and accurate standard to relevant department.

With the development of microsurgery technology, the live rate of replantation of finger become gradually higher, but this can't stand for the success of our surgery. We should try our best to recover the good appearance and function of our hands and to make this of our dream.

We have lots of function evaluations of postoperation after surgery, for example, the Japanese named Mimanhongzhi in 1997, Jones in 1982 and Zhongye or Yujing have put up their programs. They all have the same basic indicator with move, feeling and function. Miman, Zhongye and Yujing have come up with the same of patients' satisfaction for one of the most important standard.

We our country have put up the first evaluation of hand function in the magazine of hand surgery in 1989. But it isn't appropriate for our country, mainly evaluate from the appearance, anatomy, feeling and moving, and the same with swanson. Wangshuhuan has made the software of examing of hand damage in 1994. It is convenient to operate that offer facilities to doctors and come out an exact result.

We have a little of essay to evaluate the function of replantation of finger. Zengxianzheng has followed up 3 years with 59 patients during 1964 and 1983 in the Xijing Hospital of the Third PLA University according to the standard of Miman in 1986. The finger function were assessed as excellent in 24 cases, good in 23 cases, fair in 12 cases and poor in 0, and excellent and good rate was 79.6%. Pandade has followed up 6–8 months with 135 patients during 1978 and 1987 in the PLA of 401 hospital in 1987, among these patients, the thumbs are 212 cases, the finger function were assessed as excellent in 80 cases, good in 41 cases, fair in 17 cases and poor in 2, and excellent and good rate was 86.4%. The satisfactory patients has occupied 92.5%. 66.7% of patients have return to work (90 cases).for the standard of Miman, excellent in 99 cases, good in 30 cases, fair in 8 cases and poor in 3 cases, and excellent and good rate was 92.1% for the comparison, the standard of Miman is wider than others'.

The Hand Surgery Association of Chinese Medical Association have made the standard of functional evaluation during the seminar of upper extremity functional evaluation, which is the most polible and developed standard.

7 Replantation of Finger

Zengtao Wang

7.1 Preface

In china, there is a famous song written by Tao Xingzhi, in which the hands and brain are metaphorically referred as two human treasures with which we create what we want.

Finger amputation dramatically impairs the function of hand, affecting the victim's normal life. People tried to fix wood or metal fingers on the hand with amputated fingers in order to partially compensate for the lost finger functions. In the twentieth century, the sports function of myoelectricity hand makes the prosthetic hand better and better. In recent years, successful development of the brain electrical control-hands have made the function of prosthetic hand more and more similar to that of a real hand. However, even the most advanced brain-controlled mechanical hands are not compatible with real hands in sensory function or motor function. The patients who have lost their fingers would undoubtedly prefer a finger reconstructed with flesh and blood using the method of microsurgery.

The skills and methods of finger reconstruction are improving through the efforts of several generations of surgeons, greatly reducing the invasions caused by the surgery. Early methods of finger reconstruction include finger reconstruction by bone graft covered with pedicled flap, by bone allograft, artificial bone or other material covered with free flap, and finger stump elongation. Without joints and nails, the function and appearance of these fingers are far different from those of normal ones. Thumb reconstruction by the second toe transplantation which was performed by Yang Dongyue in 1966 was the first clinical success. In 1969 Cobbett accomplished the first thumb reconstruction by the great toe transplantation. In 1980 Morrison finished the first thumb reconstruction by the wrap-around flap. Foucher (1980) and Wei Fuquan (1980) respectively designed various types of surgery to reconstruct thumbs and fingers with toes. In 1979 at Shanghai Sixth People's Hospital, Yu Zhongjia reported reconstruction of two fingers on one hand by connecting titanium alloy artificial bone and bilateral second digit free autograft to the forearm stump. In 1981, Yu Zhongjia wrapped hallux nail flaps around the ilium and second toe to successfully reconstruct two fingers. In 1985, he reconstructed all the five fingers of one hand using the hallux nail flap for the thumb and the 2nd and 3rd toes of bilateral feet for the rest fingers. In 1982, Huang Shuolin wrapped the hallux nail flap around the frozen allograft finger to reconstruct the thumb. In 1988 Fu-chan Wei moved some longitudinal part of the phalange of great toe and hallux nail flap and narrowed the toe pulp so as to make the appearance of reconstructed thumb more similar to the normal. In 2001, in order to create a normal shape of reconstructed thumb, Wang Zengtao widened the second toe with tissue flap. In 2002, Cheng Guoliang proposed the concept of finger modification reengineering, in which some part of the toe tissue is transplanted for repair of partial finger defects. In 2006, the concept of full finger reconstruction was proposed by Wang Zengtao who holds that the finger reconstruction involves not only toe to hand transplantation, but also replantation of the tissue flaps from different parts of the body (sometimes combined with allografts or artificial materials) to assemble a finger which is similar to a normal one in both appearance and function. This method not only reduces the damage to the foot, but also results in better shape and function of the reconstructed finger.

No matter what strategy we use, whether simple digital transplantation or full finger reconstruction, the ultimate goal is to reduce the side effects and improve the efficacy of the surgery, though body injuries caused by these surgeries are still unavoidable. Jean-Michel Dubernard in France in 1998 and Pei Guoxian in China in 1999 experimented with allograft reconstruction of hands and fingers, achieving preliminary success. We will devote a special section in this chapter to introduce their clinical experiments.

There are various methods for reconstruction of fingers. In this chapter we only deal with microsurgical reconstruction of hands, like simple digital transplantation and full finger reconstruction.

Z. Wang (✉)
Shandong Provincial Hospital, Jinan, Shandong, China
e-mail: 392056552@qq.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_7

Microscopic reconstruction of fingers and hands is one of the most complex surgeries nowadays. Reconstructive surgery is just the initial stage which should be followed by functional reconstruction, rehabilitation and plastic procedure to make the results of the surgery more ideal.

Microscopic reconstruction of hands and fingers is difficult and risky. Microscopic reengineering of hands and fingers is currently (or partly) "robbing Peter to pay Paul," because the transplanted parts are mostly taken from other parts of the patient. The function of reconstructed fingers cannot reach the normal level, and there are usually such complications as necrosis of skin flap or skin graft of the reconstructed fingers, vascular crisis, wound infection, osteomyelitis, unsatisfactory activities or sensation recovery of the reconstructed fingers, poor nail deformity, defective appearance, etc.

Allografts and tissue tissue-engineered fingers may be the future trends in finger reconstruction. Nowadays microscopic reconstruction of fingers is the mainstream.

7.2 Anatomy for Finger/Thumb Reconstruction

Since the foot is the major donor site for finger reconstruction, it is necessary to have a deep understanding of the anatomy of foot.

There are numerous new findings about the microanatomy of foot recently.

All the literature concerning classifications of the 1st dorsal metatarsal artery (FDMA) (including the classification by Gilbert in 1976) will refer to the type of FDMA passing within the 1st dorsal interosseous muscle. For this type, when the procedure needs to harvest FDMA, the 1st dorsal interosseous muscle must be cut to separate FDMA. This procedure is the most difficult, because if the 1st dorsal interosseous muscle is damaged by the procedure, function of the 2nd toe is damaged, and skin graft on the injured muscle has a higher failure rate, etc. It is disappointing that according to the past classifications, the intramuscular type of FDMA has the greatest proportion.

To minimize the damage to the 1st dorsal interosseous muscle, we have been carefully studying the course of the FDMA since 1996. We have found that FDMA of the intramuscular type runs beside the tibial origin of 1st dorsal metatarsal muscle and then between the 1st dorsal metatarsal muscle and the 1st metatarsal bone, rather than within the muscle. We have performed anatomic study in 50 adult foot specimens to investigate FDMA.

The first dorsal interosseous muscle has two heads, the medial head adhere to the first metatarsal bone, and the lateral head adhere to the second metatarsal bone. The muscle bellies of the two heads mixed together at the distal end. It then passes through the dorsal side of the deep transverse ligament and infixes into the base of the dorsal digital aponeurosis and the proximal phalanx of the second toe. The medial head on the first metatarsal is a thin and tendinous structure, which is the only connection between the first dorsal interosseous muscle and the first metatarsal bone. Besides the tendinous connection, the space between the first dorsal interosseous muscle and the first metatarsal bone is filled by loose connective tissue. The most course of FDMA is within this space (Figs. 7.1, 7.2 and 7.3).

The anatomic study of the 50 specimens reveals that FDMA arises from the dorsalis pedis artery in 44 specimens, from the deep plantar arch or from the same branch of the deep plantar arch together with the first plantar metatarsal artery in 4, and is too slender in 2 (the diameter of the artery is smaller than 0.5 mm and useless for anastomosis). In the 44 specimens whose dorsalis pedis artery is the origin of FDMA, the FDMA runs superficially to the muscle dur-

Fig. 7.1 The medial origin of the first dorsal interosseous muscle is a thin tendinous structure attached to the first metatarsal bone

Fig. 7.2 FDMA runs within the loose connective tissue between the first dorsal interosseous muscle and the first metatarsal bone

ing the whole course in 6 cases, and runs under the tibial head of the muscle and goes into the interspace formed by the muscle and the first metatarsal in 38. The vessels are surrounded by loose connective tissue, which is one of the landmarks for identification of FDMA during operation (Figs. 7.4, 7.5 and 7.6).

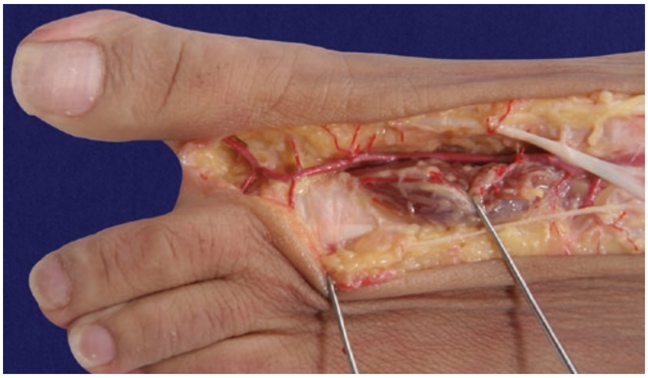


Fig. 7.3 FDMA runs within the loose connective tissue between the first dorsal interosseous muscle and the first metatarsal bone

7.2.1 Classification of FDMA

According to our cadaveric study, FDMA arises from the dorsalis pedis artery (44/50) or the deep plantar system (4/50); there are two types of FDMA course: the superficial type (6/50) and the type between the first metatarsal bone and the first dorsal interosseous muscle (38/50); FDMA can be too slender or absent (2/50). Therefore, we suggest the SIA classification system. FDMA can fall into 3 types: superficial, interspace and absent ones.

Type I (superficial): FDMA arises from the dorsalis pedis artery at the base and between the first and second metatarsals, and lies on the first dorsal interosseous muscle to the dorsal side of deep transverse ligament (Fig. 7.7).

Type II (interspace): FDMA goes under the tibial head of the muscle and courses into the interspace formed by the muscle and the first metatarsal. When it gets to the metatarsal head level, the artery runs superficially to the deep transverse ligament. In the cases of type I FDMA, the second toe transplantation can be performed with a long pedicle till the dorsalis pedis artery. A dorsalis pedis flap can be harvested

Fig. 7.4 The medial origin of the first dorsal interosseous muscle

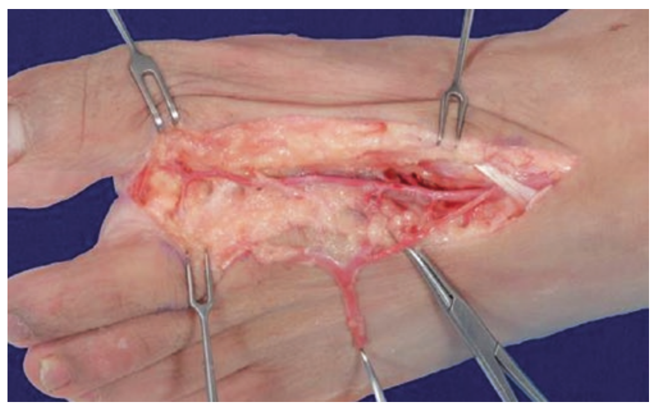


Fig. 7.6 The medial origin of the first interosseous muscle is dissected and pulled laterally, revealing FDMA between the muscle and the first metatarsal bone

Fig. 7.5 A vessel clamp is used to pull up the medial origin of the first interosseous muscle, revealing that FDMA passes beneath it

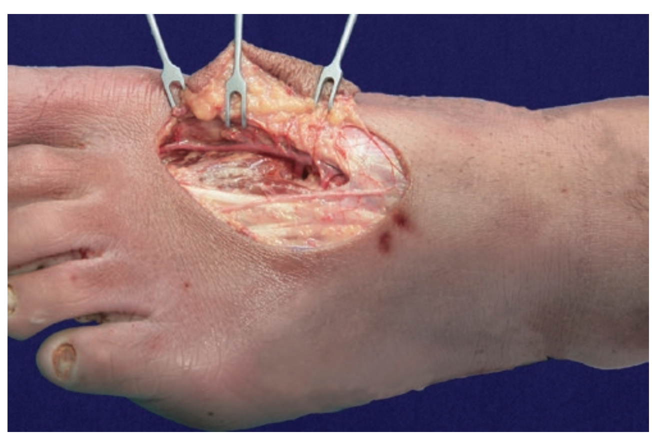


Fig. 7.7 FDMA lies on the first interosseous muscle

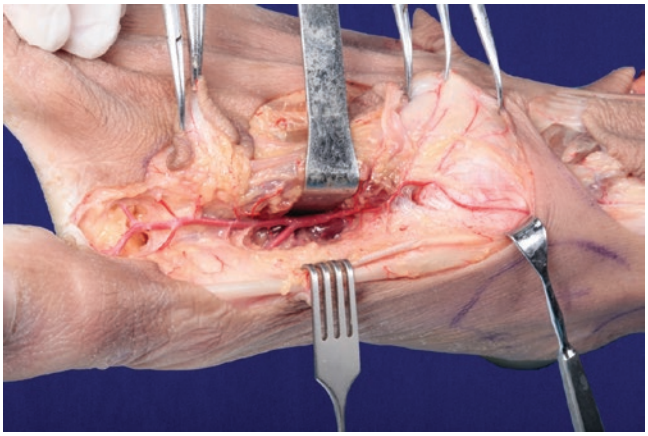


Fig. 7.8 FDMA arises from the deep plantar arch

Table 7.1 Classification of FDMA (n = 50)

	II		
Type I	II_a	II_b	III
Number 6 (12%)	38 (76%)	4 (8%)	2 (4%)

together with the pedicle, but this is impossible in the cases of type II because the FDMA may arise from the dorsalis pedis artery or from the deep plantar artery system. When FDMA arises from the deep plantar artery system, it is impossible to harvest a long pedicle and a dorsalis pedis flap. It is also helpful to classify type II into subtype IIa (FDMA arises from the dorsalis pedis artery) and subtype IIb (FDMA arises from the deep plantar artery system) (Fig. 7.8).

Type III: FDMA is absent or too slender for anastomosis. There is another situation in type III: the FDMA, which arises from the dorsalis pedis artery or the deep plantar artery system and runs between the first metatarsal and the first dorsal interosseous muscle, has no branch to the dorsal side of deep transverse ligament, but terminates in the interosseous muscle or to plantar side (Table 7.1).

Type I: FDMA lies on the first dorsal interosseous muscle.

Type II: FDMA goes between the first metatarsal and the first dorsal interosseous muscle. Type IIa: FDMA arises from the dorsalis pedis artery; Type IIb: FDMA arises from the deep plantar artery system.

Type III: FDMA is absent or too slender.

During operation, the type of FDMA can be identified as follows. First, observe if there is a FDMA dorsal to deep transverse ligament between the heads of the 1st and 2nd metatarsals. If the answer is no, it falls into type III. If the answer is yes, it falls into type I or II. Then it comes to type I or type II. If FDMA lies on the first dorsal interosseous muscle, it falls into type I; if FDMA goes between the first metatarsal and the first dorsal interosseous muscle, it falls into type II. If type II is ascertained, the origin of FDMA is identified to differentiate type IIa and type IIb.

According to the previous classifications, the intramuscular type is the most frequent. The procedure needs to dissect the first dorsal interosseous muscle to find FDMA. This is the difficult part, because the vessel is likely to get damaged and difficult to find. Some experts have described the skills to separate FDMA, advocating the dissection should be performed from ends to the middle. Some surgeons even harvest the entire the first dorsal interosseous muscle together with FDMA. These methods are safe enough but lead to great donor complications.

The major difference between our SIA classification and previous classifications is that the interposition type replaces the intramuscular type. The intramuscular type is a misunderstanding of the course of FDMA. It is actually the interposition type (type II) in SIA classification, also the most frequent type. We only need to divide the medial origin of the first dorsal interosseous muscle and pull the muscle laterally before we can easily expose FDMA.

Another typical example is the treatment of dorsal metatarsal artery of type III in the transplantation of the flap, bone, joint and hallux nail flap of the great toe and 2nd toe. The previous solutions are not appropriate. (1) Terminal branch of the dorsal metatarsal artery—the anastomosis of plantar perforator and plantar metatarsal artery or plantar digital artery. The dorsal metatarsal artery serves just as a bridge in this method. The method of transplanting a superficial vein can reserve the dorsal metatarsal artery and simplify the procedure. (2) Deputy 1st dorsal metatarsal artery. The deputy 1st dorsal metatarsal artery is thin. Although this blood vessel can ensure survival of the second toe, the toe may be cold and atrophic after surgery because of insufficient blood supply. (3) Continuous dissection of dorsal metatarsal artery—plantar perforator—1st plantar metatarsal arteries—common plantar digital artery—plantar digital artery. This method injures the intrinsic muscles of foot and increase the risk of necrosis of the great toe. It had some value when the micro-vascular anastomosis was immature. Nowadays when high quality vascular anastomosis can be finished in several minutes, anastomosis of toe-finger blood vessels or a bridge between plantar digital artery, plantar metatarsal artery and recipient blood vessels is better than continuous dissection in surgery time and surgery quality. (4) Transplantation of a vein to replace the first dorsal metatarsal artery. In this procedure, the dorsal metatarsal artery which is the same as the grafted vein plays a role in bridging the blood vessels. The grafted vein can be taken a little longer to connect the recipient blood vessel and the plantar digital artery. It can reduce the vascular anastomosis and reserve the dorsal metatarsal artery.

7.2.1.1 The Character of Skin of Foot

Foot is the only part that has similar skin with hand in aesthetic and functional aspects. For hand reconstruction, the foot has many advantages as the donor part of flaps compared with any other site.

The dorsal skin over foot and hand has similar characteristics: similar color and texture, little fat and high mobility. The palmar skin and the skin over the volar surface of the digits of foot and hand also have similar features. They are hairless, and have no sebaceous glands or pigment cells, but have dermatoglyph and a thick stratum corneum. That is why the flaps from foot are mostly used for hand reconstruction.

The nail, IP and MP joint of foot can be harvested to reconstruct same parts of hand.

7.2.1.2 Zones of Flap from Foot

The foot can be divided into 7 zones. (1) Ankle zone: Anterior malleolar flap, posterior medial malleolar flap, posterior lateral malleolar flap, and the posterior lateral flap can be expanded distally to be a lateral pedis flap. These flaps are around the ankle joint and seldom used as a choice for free flap. (2) Dorsal pedis zone: Dorsalis pedis flap, medial tarsal flap, and lateral tarsal flap. (3) Dorsal metatarsal zone: The 1st–4th dorsal metatarsal flaps which can be transferred to cover hallux or digit wounds, or harvested as free flaps to cover dorsal wounds of hand or finger. (4) Plantar zone: Medial plantar flap and lateral plantar flap which can be used as free flaps to cover wounds in palm or volar finger defects. (5) Plantar metatarsal zone: The 1st–4th plantar metatarsal flaps which can be used to cover hallux or digit wounds or as free flaps to repair wounds in palm or volar finger defects. (6) Digital web zone: The 1st–4th digital web flaps which can be used to repair wounds of digital webs in hand, and in the vascularized metatarsophalangeal joint transplantation to reconstruct the metacarpophalangeal joint. (7) Toe zone: Wrap-around flap, great-toe pulp flap, toe nail flap, great toe C-shape flap, lateral digital flap, digital pulp flap and dorsal digital flap which are mainly used as free flaps for digital wounds and in vascularized interphalangeal joint transplantation to reconstruct hand joints.

7.2.1.3 Vessel Anatomy of Foot

There are 3 main arteries in foot: dorsalis pedis artery, medial plantar artery and lateral plantar artery. Flaps in foot are supplied by the 3 vessels and their branches. The skin at the fibular ankle and lateral tibial side is also supplied by terminal branch of the peroneal artery and branches of the posterior tibial artery. Since the pedicles of flaps from foot have a diameter which is close to that of hand vessels, they are suitable for transplantation.

Posterior tibial artery gives off medial calcaneus artery at the medial ankle site to supply calcaneus and skin on medial side of the ankle. However, as posterior tibial artery and posterior tibial nerve pass through this area, the medial ankle area is not considered as a flap donor site. After the terminal branch of the peroneal artery converges with a branch from posterior tibial artery, it is renamed as the lateral calcaneal artery which passes to the lateral margin of the lateral ankle and foot. A posterior lateral ankle flap or lateral pedis flap can be harvested pedicled with the lateral calcaneal artery.

The dorsalis pedis artery gives off cutaneous branches at anterior ankle region where anterior malleolus flap can be harvested. The dorsalis pedis artery gives off medial anterior malleolus artery and lateral malleolus artery just below the ankle joint plane, and gives off medial tarsal artery and lateral tarsal artery proximal to the talonavicular joint. These branches can be the pedicles for associated flaps (medial anterior malleolus flap, medial tarsal flap, lateral anterior flap and lateral tarsal flap).

Lateral tarsal artery passes laterally beneath the extensor halluces brevis and extensor digitorum brevis to the dorsal lateral side of foot, and gives off branches to supply these muscles. Muscular branches of deep peroneal nerve accompany with lateral tarsal artery into extensor halluces brevis and extensor digitorum brevis. The extensor digitorum brevis can be harvested to form a muscular flap or a myocutaneous flap.

The first dorsal metatarsal artery passes on the surface of the first dorsal interosseous muscle or between the muscle and the first metatarsal bone. The first dorsal metatarsal flap can be harvested pedicled with FDMA. Occasionally the arcuate artery is large and gives off the second, third, and fourth dorsal metatarsal arteries, but in most cases the second, third and fourth dorsal metatarsal arteries arise from the deep plantar arch. After passing between the bases of metatarsals, the second, third and four dorsal metatarsal arteries give off descending branches to toe webs. The second to fourth dorsal metatarsal flaps can be harvested pedicled with associated metatarsal arteries (Fig. 7.9).

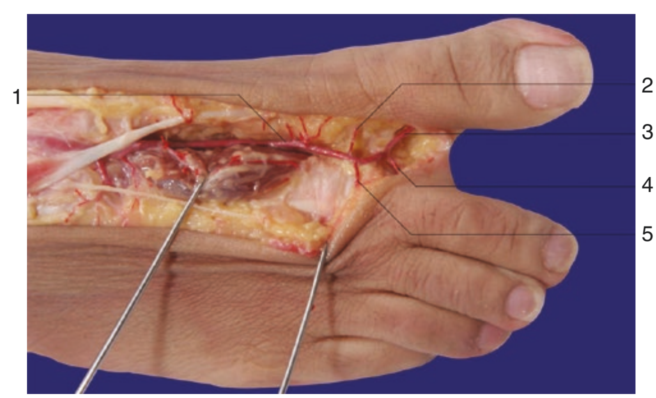


Fig. 7.9 The branch of 1st dorsal metatarsal artery. (1) First dorsal metatarsal artery. (2) Fibular dorsal digital artery of the great toe. (3) Fibular plantar digital artery of the great toe. (4) Tibial plantar digital artery of the second toe. (5) Tibial dorsal digital artery of the second toe

Dorsal metatarsal artery issues 2 dorsal digital arteries near the metatarsophalangeal joint respectively to the dorsal side of adjacent toe. It can be the pedicle of a dorsal toe flap, for it has a anastomosis with the common plantar digital artery in the transverse ligament of metatarsal head. It is divided into 2 plantar digital arteries to the neighbor side of adjacent toe. The dorsal metatarsal artery or common plantar digital artery can be the pedicle of a metatarsophalangeal joint flap. The distal part of dorsal metatarsal artery or common digital artery or plantar digital artery can be the pedicle of a toe pulp flap. When a toe pulp flap or toe lateral flap is harvested (including the fibular flap of the great toe), the plantar digital artery is the pedicle. The plantar digital artery is the pedicle of interphalangeal joint flap. 1st dorsal metatarsal artery or 1st common plantar digital artery and (or) plantar digital artery is designed to be the pedicle of hallux nail flap or toenail skin flap or simple toe nail flap (Figs. 7.10, 7.11 and 7.12).

Medial plantar artery at the origin issues a thin cutaneous branch to the medial side of foot sole which can be the pedicle of a medical plantar flap. The trunk of medial plantar artery goes through the deep abductor hallucis and walks distal to the space at the medial side of foot sole. It firstly sends out the deep branch of medial plantar artery and walks between the deep muscle at the foot sole and tarsal bone. It has an anastomosis with branch of the deep plantar arch at the distal (Fig. 7.13).

The medial plantar artery continues to walk distally, and then issues medial plantar metatarsal artery which accompanies with medial plantar metatarsal nerve. The medial plantar metatarsal artery has an anastomosis with the ascending

Fig. 7.10 The first dorsal interosseous muscle is pulled laterally to expose the FDMA. (1) Deputy 1st dorsal metatarsal artery. (2) Cutaneous branches from dorsalis pedis artery or first dorsal metatarsal artery (FDMA). (3) The medial origin of the first dorsal interosseous muscle. (4) Dorsalis pedis artery. (5) FDMA. (6) Dorsal digital artery of hallux. (7) Transverse hallucis artery. (8) Lateral plantar digital artery of hallux. (9) FDMA. (10) Dorsal digital artery of the 2nd toe. (11) Medial plantar digital artery of the 2nd toe

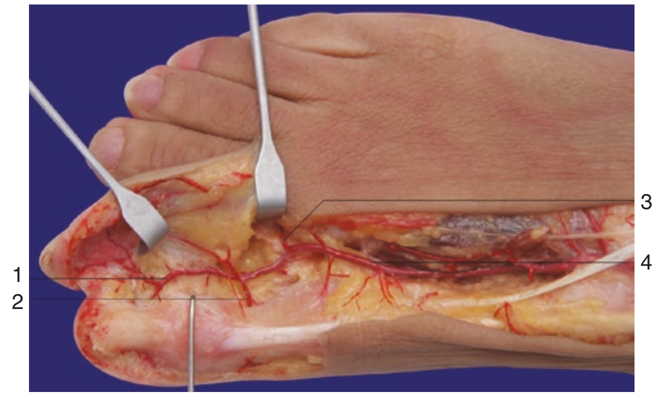


Fig. 7.11 Dissection of lateral plantar digital artery of hallux. (1) Lateral plantar digital artery of hallux. (2) Transverse hallucis artery. (3) Medial plantar digital artery of the 2nd toe. (4) FDMA

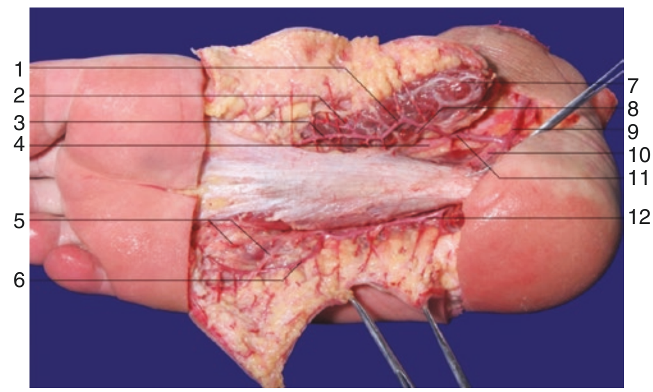


Fig. 7.12 The medial and lateral plantar space is dissected to draw away the flap, revealing both medial and lateral plantar arteries and nerves. (1) Superficial branch of medial plantar artery. (2) Medial plantar metatarsal artery. (3) Medial superficial arch branch of superficial branch of medial plantar artery. (4) Medial plantar nerve. (5) Common plantar digital nerves (lateral plantar nerve). (6) Proper plantar digital artery of little toe. (7) Abductor hallucis. (8) Deep branch of medial plantar artery. (9) Posterior tibial artery. (10) Lateral plantar nerve. (11) Medial plantar artery. (12) Lateral plantar artery

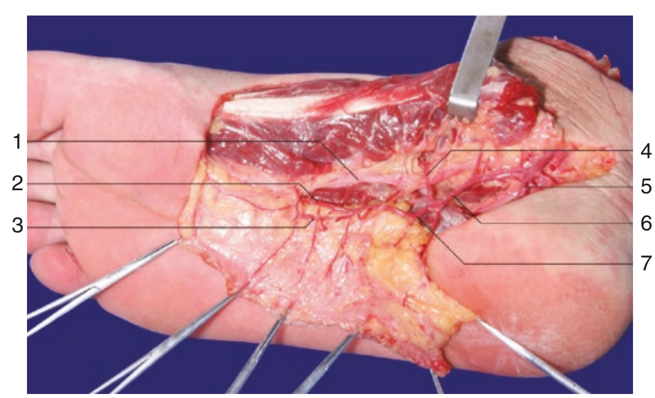


Fig. 7.13 Lateral traction of the flap, revealing the deep branch of medial plantar artery. (1) Medial plantar nerve. (2) Medial superficial arch branch of superficial branch of medial plantar artery. (3) Medial branch of superficial branch of medial plantar artery. (4) Deep branch of medial plantar artery. (5) Lateral plantar artery. (6) Medial plantar artery. (7) Superficial branch of medial plantar artery

branch of tibial branch of 1st plantar metatarsal artery at the distal. The medial plantar artery continues to go far and forms superficial plantar arch at the plantar metatarsal. The 1st–3rd plantar metatarsal arteries arise from the arch and accompanies with 1st–3rd common plantar digital nerves. The 1st–3rd plantar metatarsal arteries have an anastomosis with 1st–3rd plantar metatarsal arteries at the distal. The medial plantar artery and the medial plantar artery issue the cutaneous branches in the medial plantar space. They can be the pedicle of a medial plantar flap. Medial plantar artery and nerve send out some branches to abductor hallucis and flexor pollicis brevis during the course. The branch of medial plantar artery and nerve can be the pedicle of an abductor hallucis flap and a flexor pollicis brevis flap. The plantar metatarsal artery issues superficially the ascending branch and the descending branch in the metatarsal neck. The ascending branch is thin and has an anastomosis with plantar metatarsal artery of the same name; the descending branch is thick and continues for common digital artery. The plantar metatarsal artery and common digital artery are the pedicle of a plantar metatarsal flap (Figs. 7.14, 7.15, 7.16, 7.17 and 7.18).

Lateral plantar artery walks through the deep flexor digitorum brevis to the lateral plantar space. It issues some cutaneous branches and can be the pedicle of a lateral plantar flap. Lateral plantar artery divides into the deep branch and the superficial branch. The deep branch walks to the medial side of foot sole between the muscle of foot sole and interosseus. It and the deep branch of dorsal pedis artery make up the deep plantar arch. Plantar metatarsal arteries arise from the arch in the metatarsal neck (Figs. 7.19 and 7.20).

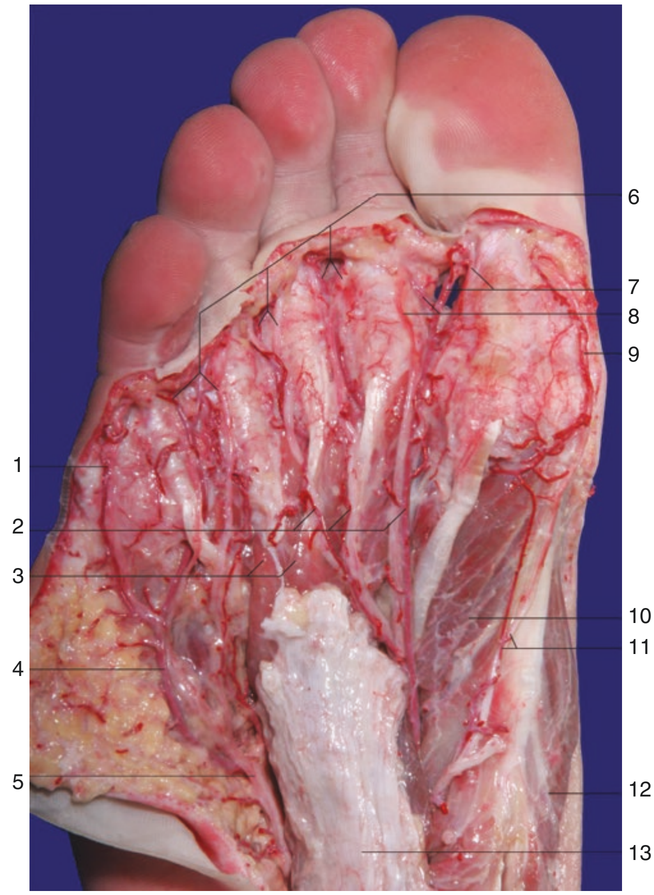


Fig. 7.14 Removal of plantar skin and fascia, revealing superficial plantar vessels and nerves. (1) Lateral proper plantar digital artery and nerve of little toe. (2) 1st–3rd plantar metatarsal arteries (superficial arch branch of medial plantar pedis artery). (3) Flexor digitorum brevis. (4) Superficial branch of lateral plantar artery. (5) Lateral plantar nerve. (6) Proper plantar digital arteries and nerves. (7) Lateral plantar digital artery and nerve of hallux. (8) Medial plantar digital artery and nerve of the 2nd toe. (9) Medial plantar digital artery and nerve of hallux. (10) Flexor hallucis brevis. (11) Medial plantar metatarsal artery and nerve. (12) Abductor hallucis. (13) Plantar fascia

7.2.1.4 The Anatomy of Foot Veins

In the part beyond the ankle joint, the superficial veins are the primary venous return. The veins' blood flows from plantar to dorsal, and deep to superficial. The density of superficial vein net is high and its diameter is thick. The arteries in foot mostly have accompanying veins, but their diameters are fine. They are not the first choice for anastomosis in tissue transplantation. The accompanying veins near the metatarsophalangeal joint, whose diameters are thin, can be used as the alternative veins. The accompanying veins beyond the metatarsophalangeal joint, whose diameters are too thin, are not easy to dissect. Therefore, in flap transplants, there are 2 sets of veins for anastomosis at the proximal metatarsophalangeal joint. In the part beyond the metatarsophalangeal joint, only superficial veins can be dissected as the pedicle vein of a flap. Fortunately, the number of superficial veins is large and their diameters are thick enough in this place.

The toe veins are located in the dorsum of toe. They are superficial and easy to dissect. The dorsal digital vein collects the plantar digital vein from the lateral side of digit. It is collected in several dorsal metatarsal arteries. At the dorsal side of the metatarsophalangeal joint, metatarsal vein locates in the superficial fascia. It is deeper than the dorsal digital vein. In order to visit the vein, the surface fat has to be cut in obese patients. Dorsal metatarsal veins form the dorsal pedis venous arch in the metatarsophalangeal joint. The continuation of arch foot is great saphenous vein and small saphenous vein. The superficial plantar vein is thin. It is collected in the 2 ft of dorsal

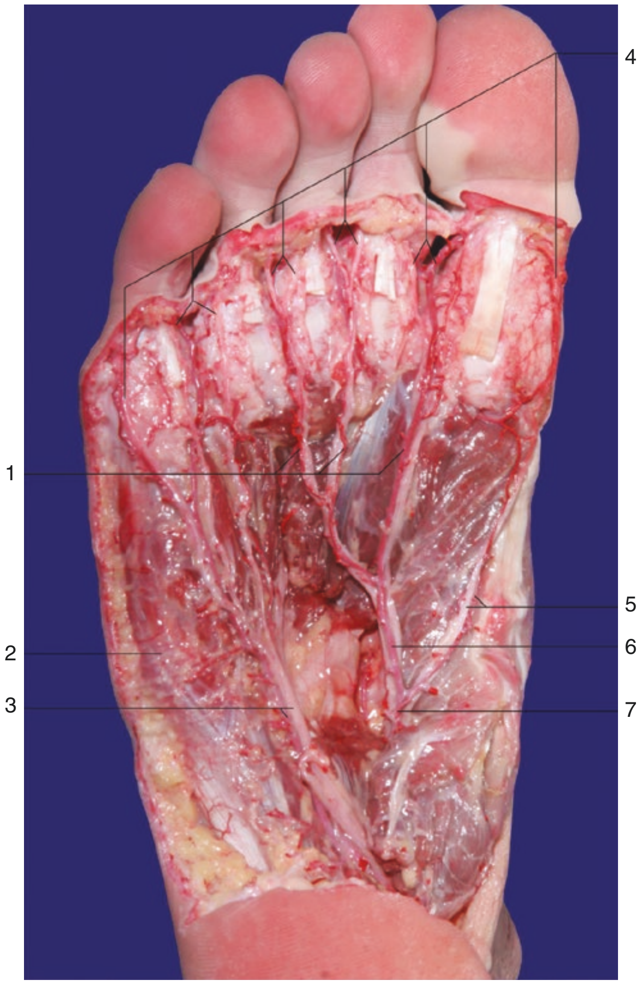


Fig. 7.15 Excision of tendons of flexor digitorum longus and flexor hallucis longus, revealing plantar vessels and nerves. (1) The 1st–3rd plantar metatarsal arteries and common plantar digital nerves. (2) Abductor digiti minimi. (3) Lateral plantar nerve and superficial branch of lateral plantar artery. (4) Proper plantar digital arteries and nerves. (5) Medial plantar metatarsal artery and nerve. (6) Medial superficial arch branch of medial plantar artery

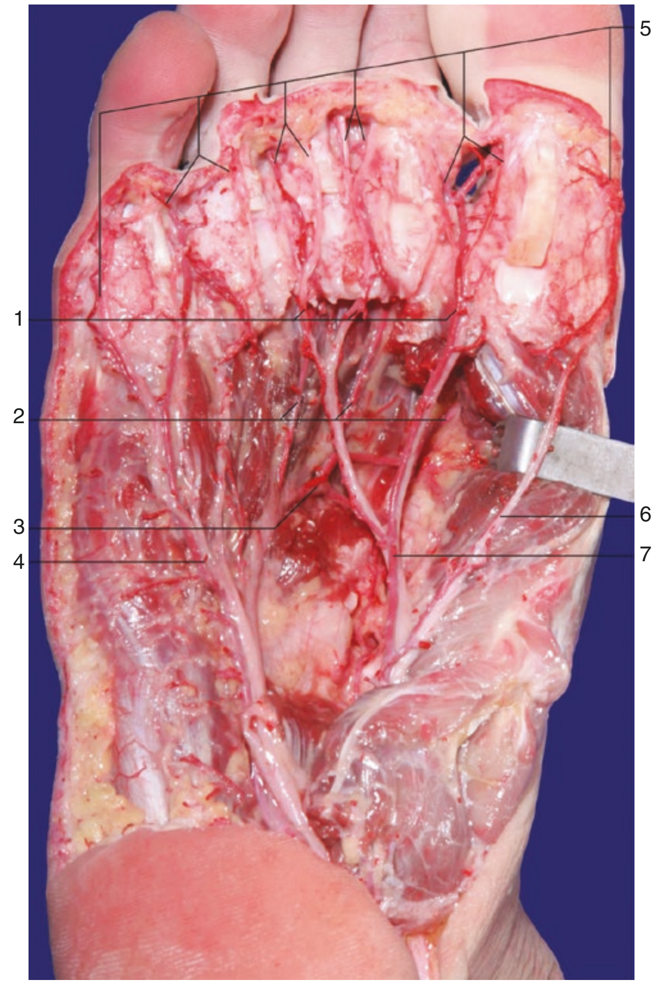


Fig. 7.16 Removal of plantar muscles, revealing deep plantar vessels and nerves. (1) 1st–3rd plantar metatarsal arteries and common plantar digital nerves. (2) Plantar metatarsal arteries. (3) Deep plantar arch and deep branch of lateral plantar nerve. (4) Lateral plantar nerve and superficial branch of lateral plantar artery. (5) Proper plantar digital arteries and nerves. (6) Medial plantar metatarsal artery and nerve. (7) Medial superficial arch branch of medial plantar artery

venous arch. It becomes the tributes of great saphenous vein and small saphenous vein (Figs. 7.21, 7.22, 7.23, 7.24 and 7.25).

7.2.1.5 Foot Nerve

Foot has five nerve sources: tibial nerve, superficial peroneal nerve, sural nerve, saphenous nerve and deep peroneal nerve. The terminal branch of the saphenous nerve only arrives at the medial side of ankle. Deep peroneal nerve only innervates the skin between 1st and 2nd metatarsals and the dorsal skin of toe web. At the recipient site of foot, tibial nerve, superficial peroneal nerve and sural nerve are the important ones. Tibial nerve is the main nerve of foot sole. Superficial peroneal nerve and sural nerve are the main nerves of foot dorsum.

Plantar area: After it sends out the heel branch at the ankle, the tibial nerve innervates the medial feeling of the heel. It divides into medial plantar nerve and lateral plantar nerve in the proximal part of flexor pollicis brevis. Both of them accompany the artery of the same name. The medial plantar nerve reaches the medial space of foot sole through the deep abductor hallucis. It sends out several branches to innervate abductor hallucis, flexor pollicis brevis and flexor digitorum brevis. In the middle area of foot sole, starting from the medial plantar pedis nerve, the medial plantar metatarsal never goes through the medial plantar intermuscular septum to the medial side of intermuscular septum. The nerve together with the arteriae recurrens of the same name reaches the medial side of first metatarsophalangeal joint. At this point, the medial plantar metatarsal never is named as tibial plantar digital nerve of the great toe. The trunk of

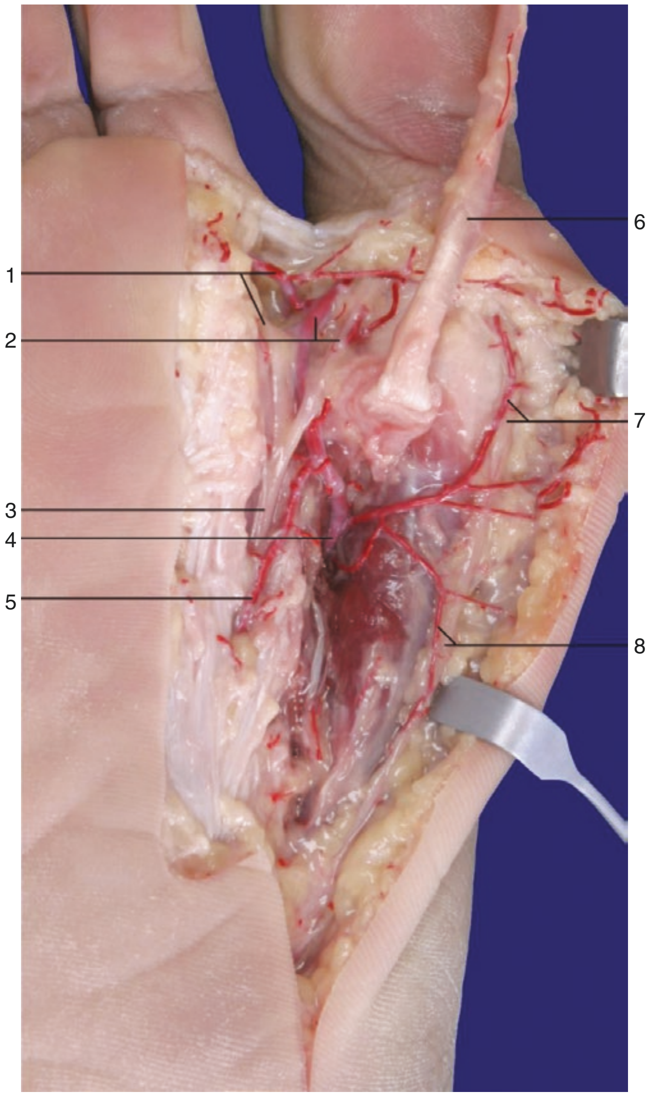


Fig. 7.17 The tendon of flexor hallucis longus is divided to expose deep structures. (1) Medial plantar digital artery and nerve of the 2nd toe. (2) Lateral plantar digital artery and nerve of hallux. (3) Common plantar digital nerve. (4) Plantar metatarsal artery. (5) Plantar metatarsal artery. (6) Tendon of flexor hallucis longus. (7) Medial plantar digital artery and nerve of hallux. (8) Medial plantar metatarsal artery and nerve

medial plantar pedis nerve keeps walking, and divides into 3 terminal branches which are 1st, 2nd and 3rd plantar metatarsal nerves. Plantar metatarsal never near the metatarsophalangeal joint divides into bilateral plantar digital nerves to adjacent toes. Medial plantar pedis nerve and medial plantar metatarsal never have scattered sensory nerves in the medial foot sole. When a medial plantar pedis flap is harvested, these thin sensory nerves should be dissected carefully. Had a branch-trunk separation with the trunk of medial plantar pedis nerve to an appropriate length, these thin sensory nerves merge into a thick bunch. It is easy for transfer and free transplantation. Lateral plantar pedis nerve

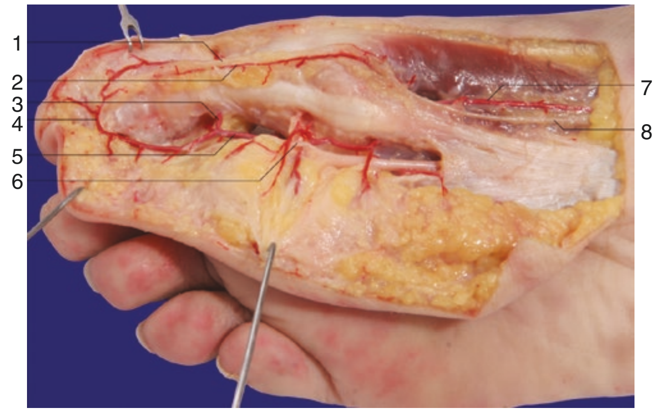


Fig. 7.18 Lateral traction of the flap, revealing both plantar digital arteries of hallux. (1) Medial plantar digital nerve of hallux. (2) Medial plantar digital artery of hallux. (3) Transverse hallucis artery. (4) Plantar digital artery arch of hallux. (5) Lateral plantar digital artery of hallux. (6) Lateral plantar digital nerve of hallux. (7) Medial plantar metatarsal artery. (8) Medial plantar metatarsal nerve

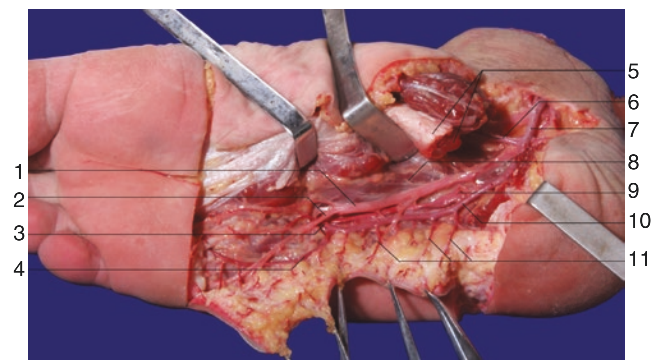


Fig. 7.19 The flexor digitorum brevis and abductor hallucis are divided to reveal the lateral plantar vessels and nerves. (1) Lateral plantar nerve. (2) Superficial branch of lateral plantar nerve. (3) Deep plantar arch. (4) Proper plantar digital artery of little toe. (5) Plantar fascia and flexor digitorum brevis. (6) Medial plantar artery. (7) Posterior tibial artery. (8) Flexor accessories. (9) Lateral plantar vein. (10) Lateral plantar artery. (11) Cutaneous branches of lateral plantar artery

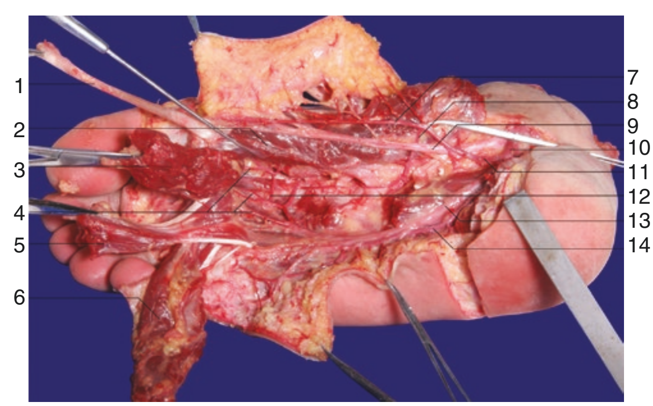


Fig. 7.20 The flexor accessories are divided to reveal deep plantar vessels and nerves. (1) Flexor hallucis longus. (2) Flexor hallucis brevis. (3) Oblique head of adductor hallucis. (4) Plantar metatarsal artery. (5) Flexor accessories and flexor digitorum longus. (6) Flexor digitorum brevis. (7) Superficial branch of medial plantar artery. (8) Deep branch of medial plantar artery. (9) Medial plantar nerve. (10) Posterior tibial artery. (11) Medial plantar artery. (12) Deep plantar arch. (13) Lateral plantar nerve. (14) Lateral plantar artery

Fig. 7.21 Removal of the skin on dorsal foot and anterior ankle, revealing superficial fascia. (1) Extensor digitorum brevis. (2) Dorsal vein arch of foot

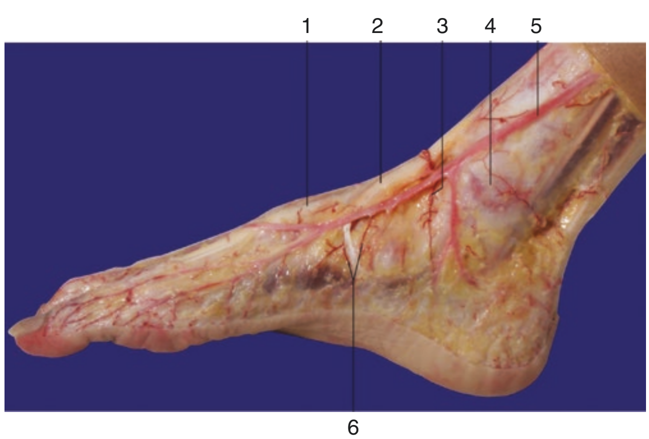


Fig. 7.22 Removal of superficial fascia, revealing vessels in the medial tarsal area. (1) Extensor hallucis longus. (2) Tibialis anterior. (3) Anterior medial malleolus artery. (4) Medial malleolus. (5) Great saphenous vein. (6) Medial metatarsal artery

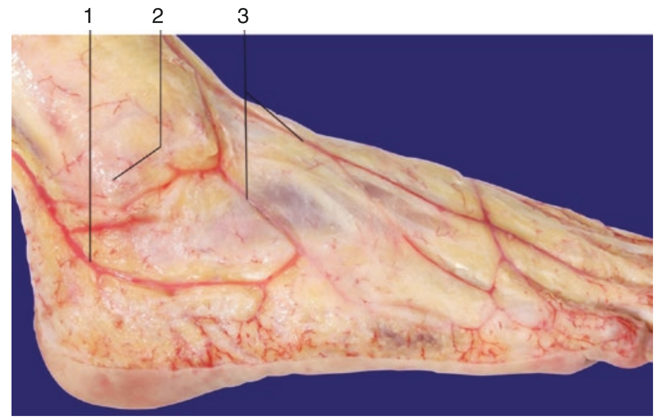


Fig. 7.23 Removal of surrounding tissue of small saphenous vein and its tributaries. (1) Small saphenous vein. (2) Lateral malleolus. (3) Dorsal veins of foot

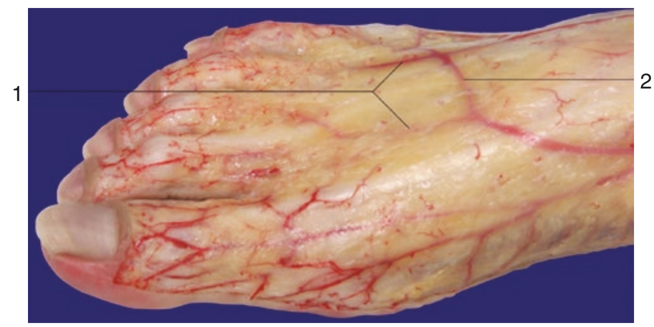


Fig. 7.24 Removal of the skin, revealing superficial fascia, thick dorsal metatarsal fascia particularly around the metatarsophalangeal joint, and dorsal metatarsal veins located in the superficial fascia. (1) Dorsal metatarsal veins. (2) Dorsal vein arch of foot

Fig. 7.25 Excision of the surrounding tissue, revealing dorsal veins of foot. (1) Dorsal vein arch of foot. (2) Dorsal metatarsal veins

accompanying lateral plantar pedis artery reaches the lateral plantar pedis space through the deep flexor digitorum brevis. In the course of walking distally, it sends out cutaneous branches to innervate the sense of lateral plantar pedis area. It divides into the superficial branch and deep branch in plantar metatarsal area. The deep branch walks between the metatarsal and interosseus. It sends out muscular branches to innervate interosseus and adductor pollicis, etc. The superficial branch divides into 2 branches: lateral plantar digital nerve of little toe and 4th plantar metatarsal nerve. The foot nerves almost accompany the arteries of the same names. It is very easy and convenient to dissect the foot nerves (Figs. 7.26 and 7.27).

Dorsal pedis area: superficial peroneal nerve in the ankle divides into two terminal branches. One is the dorsal pedis middle cutaneous nerve, which innervates the sense of dorsal pedis area and the middle dorsal metatarsal area. It is the main sensory nerve of a dorsal pedis flap. Sural nerve walks into dorsum pedis from the posterior side of lateral ankle. It innervates the sense of lateral region of dorsum pedis. This nerve is used in a lateral pedis flap and a lateral tarsus flap. The terminal branch of deep peroneal nerve is located in 1st toe web, and used in 1st toe web flap (Figs. 7.28, 7.29 and 7.30).

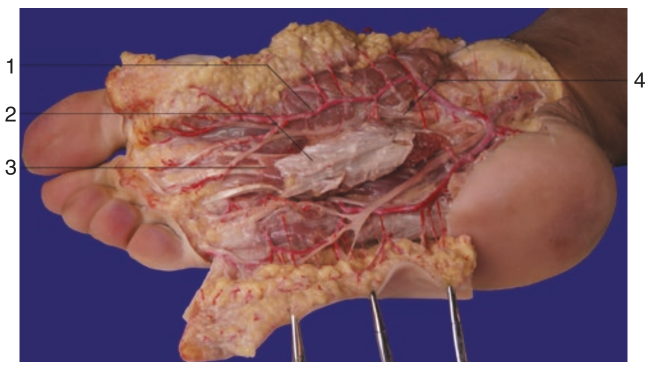


Fig. 7.26 Dissection of the distal part of the plantar fascia, revealing the flexor digitorum brevis. (1) Medial superficial arch branch of medial plantar artery. (2) Plantar fascia. (3) Flexor digitorum brevis. (4) Medial plantar nerve

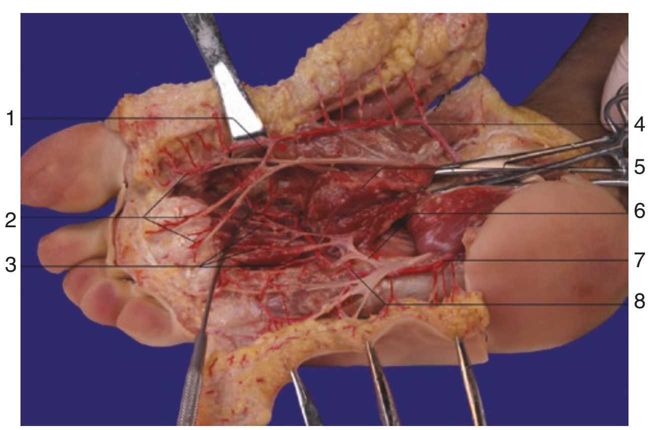


Fig. 7.27 Excision of the transverse head of adductor pollicis muscle, stripping the surface of the interosseous muscle sarcolemma to reveal deep plantar metatarsal arteries issued from the deep plantar arch. (1) Superficial plantar arch. (2) Common plantar digital arteries. (3) Plantar metatarsal arteries. (4) Superficial branch of medial plantar artery. (5) Oblique head of adductor hallucis. (6) Deep branch of lateral plantar nerve. (7) Lateral plantar artery. (8) Deep plantar arch

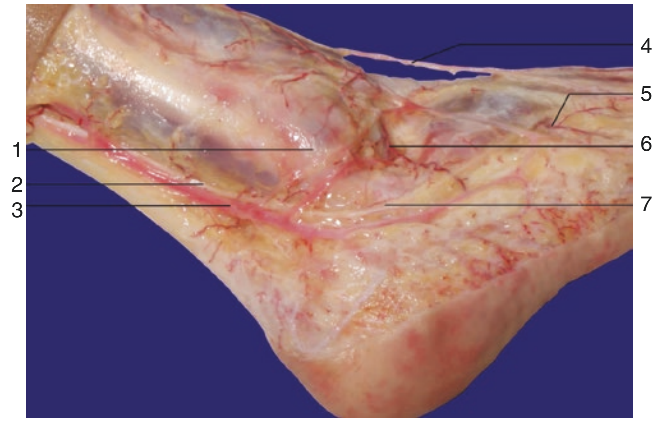


Fig. 7.28 Resection of superficial fascia, exposing small saphenous vein and sural nerve. (1) Lateral malleolus. (2) Sural nerve. (3) Small saphenous vein. (4) Intermediate dorsal cutaneous nerve of foot. (5) Cutaneous branches of lateral tarsal artery. (6) Anterior lateral malleolus artery. (7) Lateral dorsal cutaneous nerve of foot

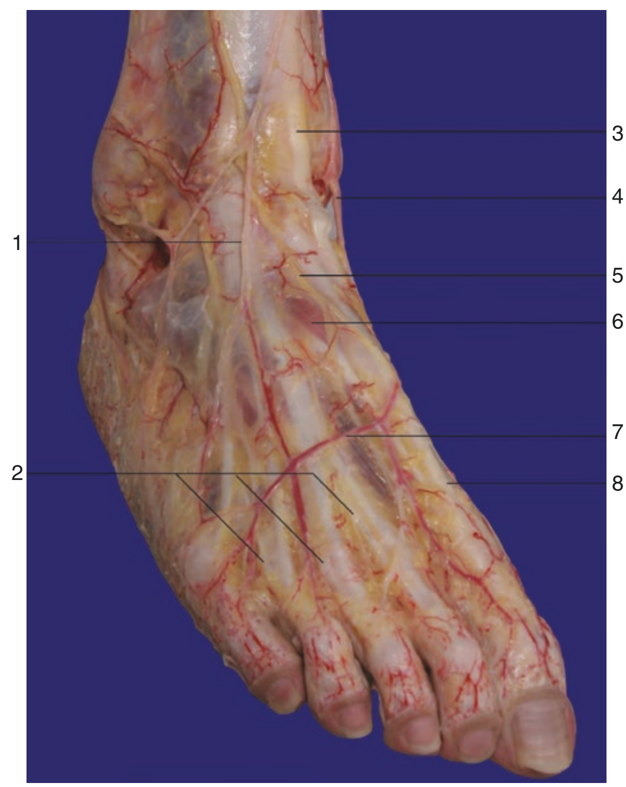


Fig. 7.29 Dissection of vessels and nerves in dorsal foot and anterior ankle. (1) Intermediate dorsal cutaneous nerve of foot. (2) Extensor digitorum brevis. (3) Tibialis anterior. (4) Great saphenous vein. (5) Medial dorsal cutaneous nerve. (6) Extensor hallucis brevis. (7) Dorsal vein arch of foot. (8) Extensor digitorum longus

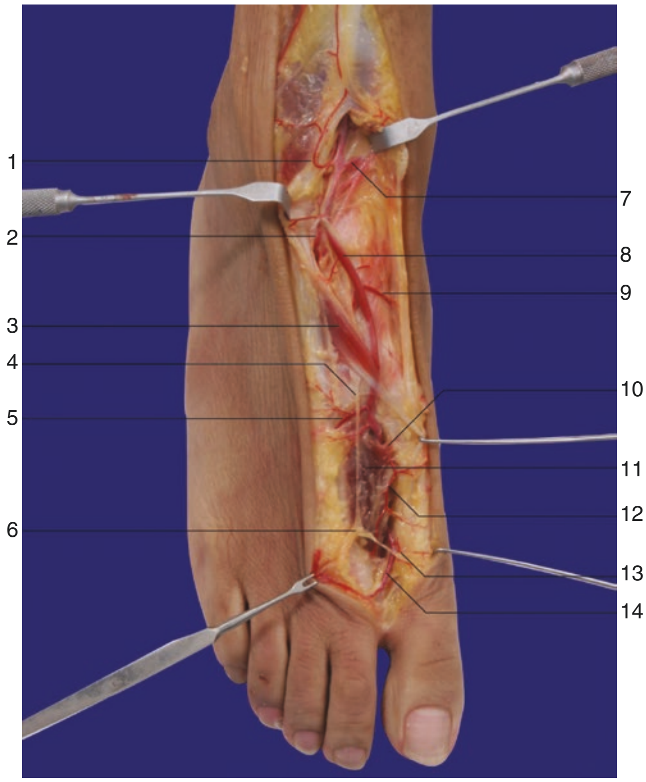


Fig. 7.30 Removal of the superficial fascia of the dorsal metatarsal area, revealing the 1st dorsal interossei. (1) Lateral anterior malleolar artery. (2) Lateral metatarsal artery. (3) Flexor halluces brevis. (4) Deep peroneal nerve. (5) Arcuate artery. (6) Terminal branch of deep peroneal nerve. (7) Medial anterior malleolar artery. (8) Dorsalis pedis artery. (9) Medial metatarsal artery. (10) Medial origin of the first dorsal interosseous muscle. (11) The first dorsal interosseous muscle. (12) Deputy 1st dorsal metatarsal artery. (13) A cutaneous branch of FDMA. (14) FDMA

7.3 The Second Toe Transfer for Thumb Reconstruction

The thumb can pinch with the remaining four fingers and perform rubbing action after pinch is mainly done by the thumb. The accurate proportion of the thumb in total function of the hand is not easy to calculate, but the previous literature has estimated it at 40% of hand function. Even if the statement is not accurate, it also shows the importance of the thumb and necessity for thumb reconstruction.

Since Yang Dongyue first reported the second toe transfer for reconstruction of thumb in 1966, a microscopic finger reconstruction era has come. Although we have now many methods for thumb reconstruction, the most widely used and the most classic is the second toe transplantation.

Thumb deficits are currently classified into six degrees:

- Degree I: The part beyond the interphalangeal joint is missing.
- Degree II: The thumb stump is located in the interphalangeal joint area.
- Degree III: The thumb stump is situated between the interphalangeal joint and the metacarpophalangeal joint.
- Degree IV: The thumb stump is located in the metacarpophalangeal joint area.
- Degree V: The thumb stump is situated between the metacarpophalangeal joint and the carpometacarpal joint.
- Degree VI: The thumb stump is located in the carpometacarpal joint area.

7.3.1 Indications

Patients with thumb defects require reconstruction and are physically and mentally capable of tolerating surgery.

7.3.2 Surgical Design

(1) Length: The length of the second toe should be designed according to the defective length of the thumb. (2) Bone and joints: The length should be designed by the defect length of the thumb. Arthrodesis should be considered for distal interphalangeal joint of the second toe. (3) Skin: The flap should be designed in the proximal of the toe or in the dorsal metatarsal or in the dorsal pedis by the thumb stump. (4) The artery and vein: We can use the plantar digital artery, plantar or dorsal metatarsal artery, or dorsal pedis artery as the vascular pedicle according to the recipient site while the plantar digital vein, dorsal metatarsal or dorsal pedis vein is chosen. (5) Nerve: The bilateral plantar digital nerves or unilateral one is used. If a longer nerve is needed, the whole plantar metatarsal nerve or its branch to the second toe can be chosen.

7.3.3 Surgical Methods

1. Recipient site dissection: Cut thumb stump and dissect artery, superficial vein and nerve. If vascular condition is not good enough, dissect to reveal dorsal finger artery and vein, or the radial artery and cephalic vein at the snuffbox.
2. Harvest of the second toe: (1) Dorsal plantar neurovascular dissection: Incise the skin in the gap at the dorsal side between the first and second metatarsals according to design, dissect the superficial dorsal metatarsal vein in superficial fascia. Dissect and reveal deep peroneal nerve in the deep side of dorsal metatarsal vein. Dissect and reveal the first dorsal metatarsal artery in the deep side of peroneal nerve. If the first dorsal metatarsal artery is on the interosseous muscle surface or in the gap, dissect it in the dorsal and proximal of the first metatarsophalangeal joint, retrogradely and proximally along the vascular anatomy to an appropriate length. Dissect distally to web space, revealing the distal first dorsal metatarsal artery

and its anastomosis with common plantar digital artery and the beginning of fibular side artery of great toe and tibial side artery of second toe after anastomosis. Dorsal metatarsal vein, deep peroneal nerve, the first dorsal metatarsal artery are parallel to each other from superficial to deep in the gap at the dorsal side between the first and second metatarsals. If the first dorsal metatarsal artery is of the third type, dissect the first plantar digital artery to a proper length in the plantar side and use it as the vascular pedicle. (2) Dissection of neurovascular structure and tendon in plantar metatarsal area: Incise the skin in the plantar metatarsal area as designed. Dissect the first common plantar digital artery and the first plantar metatarsal nerve in the gap at the plantar side between the first and second metatarsals to a proper length if needed. Dissect the second common plantar digital artery and the second plantar metatarsal nerve in the gap at the plantar side between the second and third metatarsals to a proper length as needed. Incise the flexor tendon sheath at the plantar side of the second metatarsal, reveal the flexor tendon of the second toe and cut it off at a proper length. (3) Processing of the second metatarsal and extensor tendon: Cut off the extensor tendon and saw the metatarsal in a proper place according to the need of recipient site. (4) The second toe freed: Lift the second toe and cut off its interosseous muscle, to form a free second toe with the pedicle of the first dorsal metatarsal artery and dorsal metatarsal superficial vein. If a longer vascular pedicle is needed, the proximal vessel is dissected to form a free second toe with the pedicle of a dorsal pedis artery, dorsal pedis superficial vein or saphenous vein.

3. The donor site is usually sutured directly. If the wound is large, it can be repaired by flap or skin grafting.
4. Transplantation: Transplant the second toe to the thumb stump. The bone is fixated with Kirschner wire or other fixators. Repair flexor and extensor tendon, with vascular and nerve anastomosis. Suture the skin. The transplanted toe is maintained in pronation.
5. Notes: (1) Extensor tendon tension should be larger, otherwise the interphalangeal joint fusion is performed in order to avoid possible postoperative deformity of vertical toes because the second toe has a distal interphalangeal joint. (2) In reconstruction of defects of degrees IV to VI, osteotomy should be carried out to make appropriate adjustments of the motion of the metatarsophalangeal joint according to the motion range of contralateral thumb metacarpophalangeal joint. (3) Although an appropriate length can be achieved in the second toe transfer for reconstruction of thumb, there is still a big difference between the shapes of thumb and toe, leading to unsatisfactory appearance of the reconstructed thumb (Figs. 7.31, 7.32, 7.33, 7.34, 7.35, 7.36, 7.37, 7.38, 7.39, 7.40 and 7.41).

Fig. 7.31 Incise the skin in the gap at the dorsal side between the first and second metatarsals according to design, and dissect the dorsal metatarsal vein and deep peroneal nerve in superficial fascia. (1) Dorsal metatarsal vein. (2) Deep peroneal nerve

Fig. 7.32 Dissect and reveal the first dorsal metatarsal artery in the deep side of peroneal nerve. (1) Common plantar digital artery. (2) First dorsal metatarsal artery. (3) Deep peroneal nerve. (4) Dorsal metatarsal vein. (5) Fibular side plantar artery of great toe. (6) Tibial side plantar artery of second toe

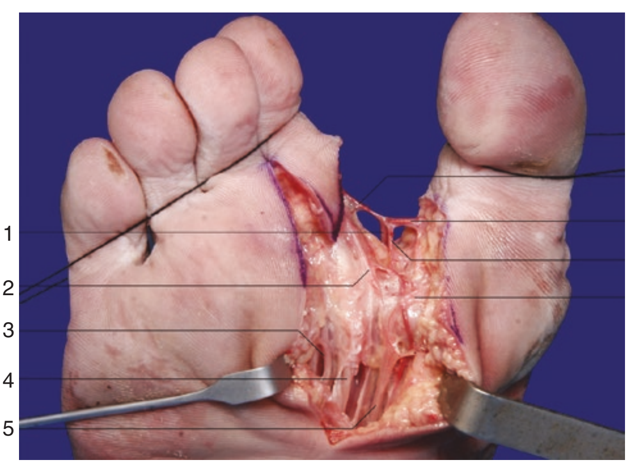


Fig. 7.33 Incise the skin in plantar metatarsal area as designed, and dissect the first common plantar digital artery and the first plantar metatarsal nerve. (1) The first dorsal metatarsal artery. (2) Tibial side plantar nerve of second toe. (3) Common plantar nerve of the second toe. (4) Flexor tendon of the second toe. (5) The first common plantar nerve. (6) Tibial side plantar artery of the second toe. (7) Fibular side plantar artery of great toe. (8) The first common plantar artery. (9) Fibular side plantar nerve of great toe

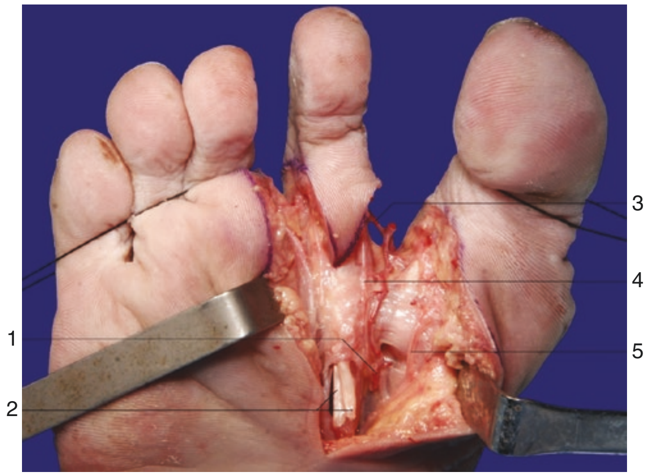


Fig. 7.34 Incise the flexor digitorum longus tendon, flexor digitorum brevis tendon, fibular side plantar artery of great toe, tibial side plantar artery and nerve of the second toe. (1) The first plantar metatarsal artery. (2) Flexor digitorum longus tendon and flexor digitorum brevis tendon. (3) Tibial side plantar artery of second toe. (4) Tibial side plantar nerve of second toe. (5) Fibular side plantar nerve of great toe

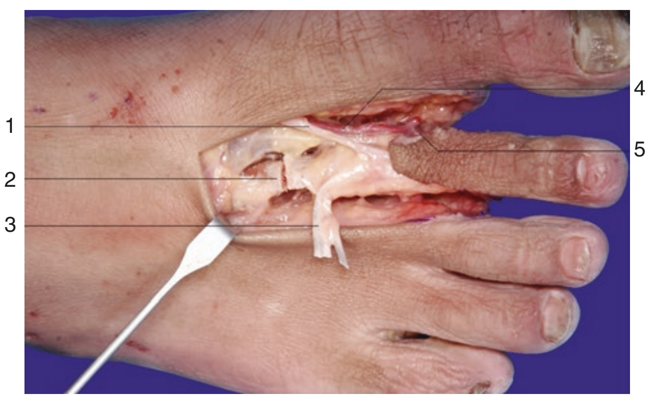


Fig. 7.35 Incise the metatarsal bone and extensor tendon. (1) Dorsal metatarsal vein. (2) The second metatarsal bone. (3) Extensor digitorum tendon. (4) The first dorsal metatarsal artery. (5) Tibial side plantar artery of the second toe

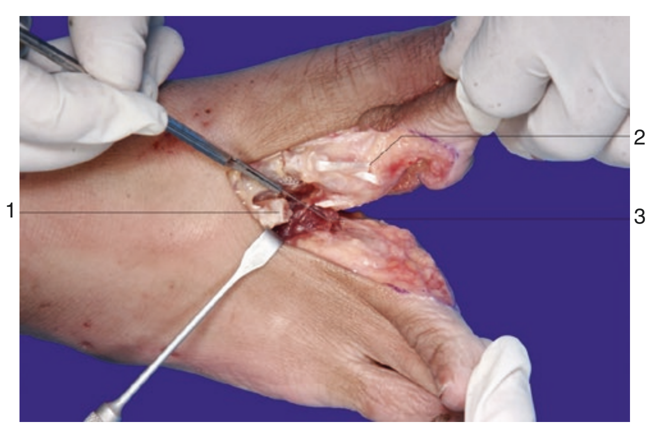


Fig. 7.36 Lift the second toe and incise the interosseous muscle. (1) The second metatarsal bone. (2) Extensor digitorum tendon. (3) Interosseous muscle

Fig. 7.37 Formation of the free second toe with the pedicle of the first dorsal metatarsal artery and dorsal metatarsal superficial vein. (1) Dorsal metatarsal vein. (2) The first dorsal metatarsal artery. (3) Flexor digitorum tendon. (4) The second metatarsal bone. (5) The first plantar metatarsal artery

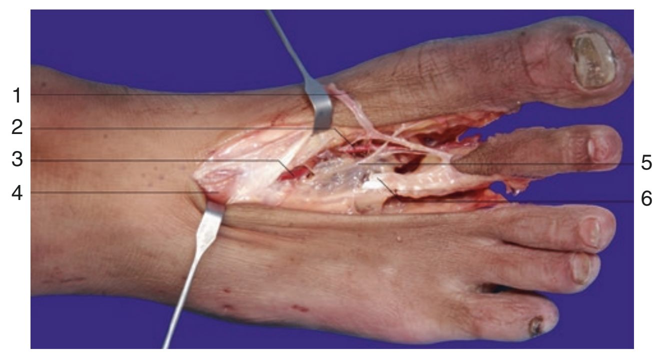


Fig. 7.38 If a longer vascular pedicle is needed, the proximal part can be dissected. (1) Dorsal metatarsal vein (incised). (2) The first dorsal metatarsal artery. (3) Dorsal pedis artery. (4) Extensor digitorum brevis tendon. (5) Deep peroneal nerve. (6) Extensor digitorum longus tendon. (7) The first dorsal interosseous muscle

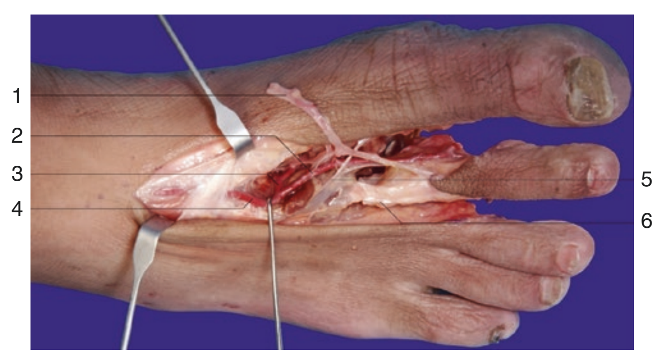


Fig. 7.39 Incise the tibial side of the first dorsal interosseous muscle, and dissect the branches of dorsal pedis artery. (1) Dorsal metatarsal vein. (2) The first dorsal metatarsal artery. (3) Anterior perforating branches. (4) Dorsal pedis artery. (5) Deep peroneal nerve. (6) Extensor digitorum tendon

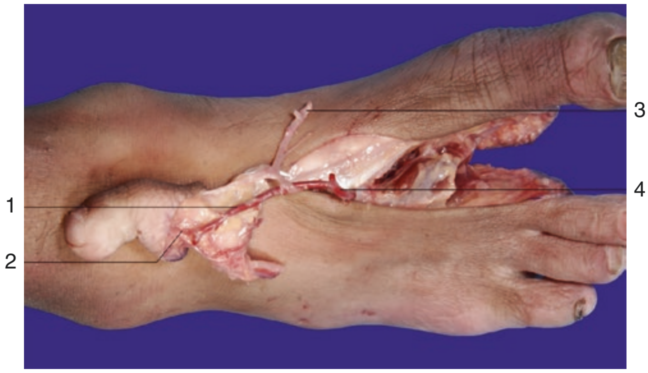


Fig. 7.40 Incise the anterior perforating branches to form the free second toe with the pedicle of dorsal pedis artery. (1) The first dorsal metatarsal artery. (2) Tibial side plantar artery of second toe. (3) Dorsal pedis vein. (4) Dorsal pedis artery

Fig. 7.41 Close the donor site

Fig. 7.42 Preoperative picture

Fig. 7.43 Preoperative picture

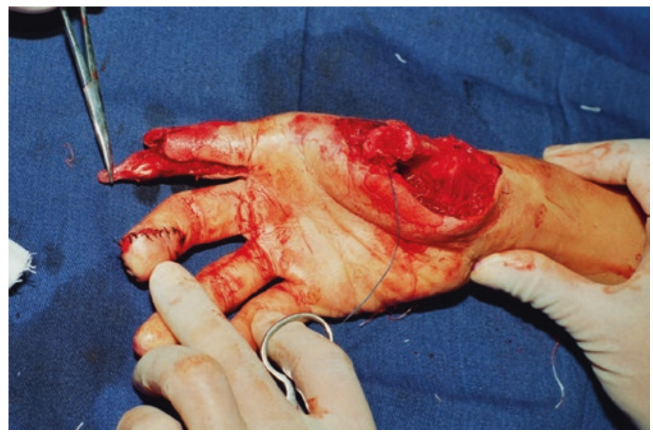


Fig. 7.44 Debridement

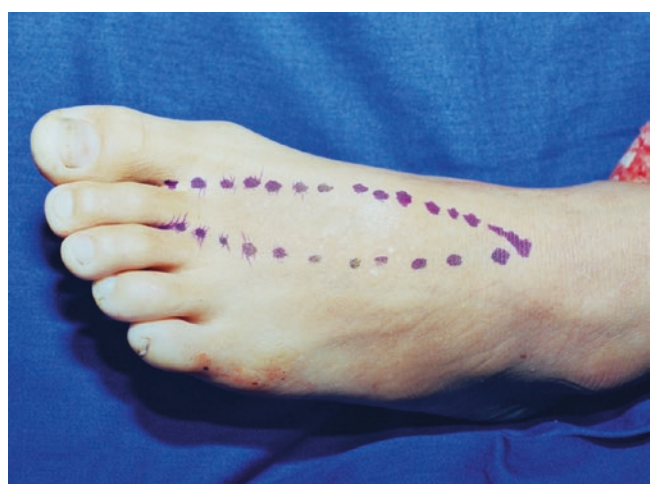


Fig. 7.45 Design of the donor site

7.3.4 Clinical Case

See Figs. 7.42, 7.43, 7.44, 7.45, 7.46, 7.47 and 7.48.

Fig. 7.46 The second toe incised

Fig. 7.47 Recovery of the hand

Fig. 7.48 Recovery of the hand

7.4 Toe to Hand Transplantation for Finger Reconstruction

At the beginning of the second toe transfer to hand in the 60s of the last century, digital reconstruction was only for the thumb because it is more important than anyone of the other fingers. However, there are victims who own a full thumb but miss the other four fingers. Surgeons began to transfer toes to hand for reconstruction of one to even four fingers. Generally, the second toe is used for one homolateral finger reconstruction. The vascularized second and third toes or the bilateral second toe are harvested to reconstruct two digits. The donor sites for reconstruction of three fingers are the homolateral second toe and the contralateral second and third toes. The bilateral second and third toes are used to reconstruct four digits. The most impressive toe-to-hand transplantation was performed by Yu in 1985 who reconstructed all the five fingers in one hand. With the improvement of microsurgical techniques, partial toe transplantation in which the pedal digital artery is anastomosed with the finger artery can successfully reconstruct part of a finger. Reconstruction of one single or multiple fingers is also widely carried out. Because of the great difference in phalanx length between toes and fingers, defects above grade IV are not suitable for toe to hand transplantation.

7.4.1 Grading of Finger Defects

There are various systems to grade finger defects, but the following is the mostly used.

- Grade I: The part beyond the distal interphalangeal joint is lost.
- Grade II: The finger stump is located in the area of distal interphalangeal joint.
- Grade III: The finger stump is located between the area of distal interphalangeal joint and proximal interphalangeal joint.
- Grade IV: The finger stump is located in the area of proximal interphalangeal joint.
- Grade V: The finger stump is located between the area of proximal interphalangeal joint and metacarpophalangeal joint.
- Grade VI: The finger stump is located in the area of metacarpophalangeal joint and proximal to this joint.

7.4.2 Indications

1. Single middle finger defects of Grade I to III
2. Index, ring and little finger defects of grade I to IV
3. Loss of 2 to 5 fingers, finger defects of grade I to VI

7.4.3 Design

1. One single second toe or bilateral ones are harvested to reconstruct finger. (1) Length: The length of the harvested single or bilateral second toes is corresponding to the length of single finger defect. (2) Bone and joint: The distal interphalangeal joint of the second toe can be fused. (3) Skin: The flap is designed on the proximal end of toe, dorsal metatarsal and dorsum of foot (4) Artery and vein: The proper plantar digital artery, dorsal metatarsal artery or common plantar digital artery, and dorsalics pedis artery are the vessel pedicle. The dorsal digital vein, dorsal metatarsal or dorsalics pedis veins are used. (5) Nerve: The single or bilateral plantar digital nerves, and if necessarily, the total plantar metatarsal nerve or the tract of second toe from plantar metatarsal nerve can be carried.
2. The second and third toes in one or two feet are harvested to reconstruct more than two fingers. The vessel pedicle is the 1st dorsal metatarsal artery or common plantar digital artery and dorsalics pedis artery. The two toes are carried with the same pedicle. The plantar digital nerve of one single finger or dorsal metatarsal nerve is harvested. The osteotomy level is based on the finger stump. Unlike one single toe to hand transplantation, the third toe is shorter than the second one. For this reason, the second is designed on the middle finger or near this finger while the third toe is designed far away from the middle digit.
3. When multiple toes with their independent pedicles are transferred, the design is the same as for the simple second toe transplantation. The only difference is that the plantar digital artery of the second toe or the 2nd or 3rd dorsal metatarsal artery, the dorsal digital vein of the second toe or dorsal metatarsal artery and the plantar digital nerve of the second toe or the 2nd or 3rd plantar metatarsal nerve are carried in the third toe.

7.4.4 Procedure

1. Preparation of recipient site
   After the finger stump is incised, the artery, superficial vein and digital nerve are dissected. When these blood vessels are not healthy enough, the common digital artery or radial artery, ulnar artery and dorsal metacarpal vein or cephalic and basilic veins are dissected.
2. The second toe harvest
   (a) Harvest of one single toe
      (I) Dissection of the blood vessel and nerve at the dorsal metatarsal side
         Make an incision at the dorsal side of the space between 1st and 2nd metatarsals. The dorsal metatarsal vein is dissected at the fascia superficialis level. In the depth of the dorsal metatarsal vein, the deep peroneal nerve is dissected. The 1st dorsal metatarsal artery is dissected under the depth of the peroneal nerve. If the 1st dorsal metatarsal artery is located on the surface of interosseus or interosseus, this artery is dissected first at the dorsal and proximal side of the metatarsophalangeal joint, and then dissected conversely following the course of the blood vessel till an appropriate length. At the toe web, the distal part of the 1st dorsal metatarsal artery, the anastomosis with the 1st dorsal metatarsal artery and common 1st plantar digital artery, the fibular plantar digital artery of the great toe and the origination of tibial plantar digital artery of the second toe are exposed. At the dorsal side between the 1st and 2nd metatarsals, dorsal metatarsal vein, deep peroneal nerve and the 1st dorsal metatarsal artery are arranged vertically. From superficial to deep, the superficial is dorsal metatarsal vein, the deep is the 1st dorsal metatarsal artery and the middle is deep peroneal nerve.
      (II) Dissection of the blood vessel and nerve at the plantar metatarsal side
         The skin of the plantar metatarsal area is incised. The 1st common plantar digital artery and the 1st plantar metatarsal nerve are dissected in the deeper subcutaneous tissue between 1st and 2nd metatarsals. If the 1st common plantar digital artery and the 1st plantar metatarsal nerve are used as the pedicle, they are dissected proximally and ligated at an appropriate length. In the superficial of the 2nd metatarsal, flexor tendinous sheath is open and the flexor tendon of the second toe is exposed and ligated at an appropriate length.
      (III) Management of the 2nd metatarsal and extensor tendon
         According to the need of the recipient site, extensor tendon of the toe and the metatarsal is cut at a proper site.
      (IV) Harvest of the second toe
         The second toe is lifted and its interosseus is cut. The free second toe is harvested and its pedicle is the 1st dorsal metatarsal and the superficial dorsal metatarsal vein. If a longer pedicle is needed, the blood vessel is dissected proximally so that the dorsalis pedis artery, the superficial vein of dorsum of foot or the great saphenous vein is the pedicle.
   (b) Harvest of the 2nd and 3rd toes with the same pedicle
      The dissection of blood vessels is the same as for the single toe harvest. Additionally, when the toes are

harvested, dissect the plantar digital nerve or plantar metatarsal nerve of the third toe, and cut the flexor tendon, extensor tendon and phalanx or metatarsal at an appropriate length.

(c) Harvest of multiple toes with independent pedicles

Harvest of the second toe is the same as that of one single toe. Harvest of the third toe is the same as that of the second toe. The vein is the dorsal digital vein or dorsal metatarsal vein or even dorsalis pedis vein. The artery is the dorsal digital artery of the third toe, the dorsal metatarsal artery of the second toe or the plantar metatarsal artery. The nerve is the plantar digital nerve or the plantar metatarsal nerve.

3. Management of the donor site

When only one toe is harvested in each foot, the donor wounds are sutured directly. When two toes are harvested in one foot, if only part of the toe is harvested, the stump of the donor foot is also sutured directly. If the metatarsophalangeal joint, the metatarsal or the larger pedis dorsalis flap, or dorsal metatarsal flap is harvested, the donor site should be covered by flaps or skin grafts.

4. Transplantation

The harvested toe is transferred to the stump of finger. Kirschner wire, plate or wire is used to fix the bone and the tendon. Blood vessels and nerves are anastomosed. If the blood vessel in finger is unhealthy, the ulnar or radial artery is used for anastomosis, especially in the multiple toe transplantation. If the blood vessels in the recipient site are not enough, a focal vein graft is necessary.

5. Notices

(a) In the second toe, the median and distal phalanxes are always set at flexion. The excessive tension of the extensor tendon needs to be adjusted in operation or the distal interphalangeal joint of toe is fused so as to improve the appearance of the reconstructive finger.

(b) Because the median and distal phalanxes are shorter, we prefer to slightly shorten the finger in the finger reconstruction of defects of grades IV and V. What we do can avoid the incongruous appearance and function in the recipient hand.

(c) In the reconstruction of grade VI defects, osteotomy is performed to ensure the movement range of metatarsophalangeal joint.

7.4.5 Case Report

See Figs. 7.49, 7.50, 7.51, 7.52 and 7.53.

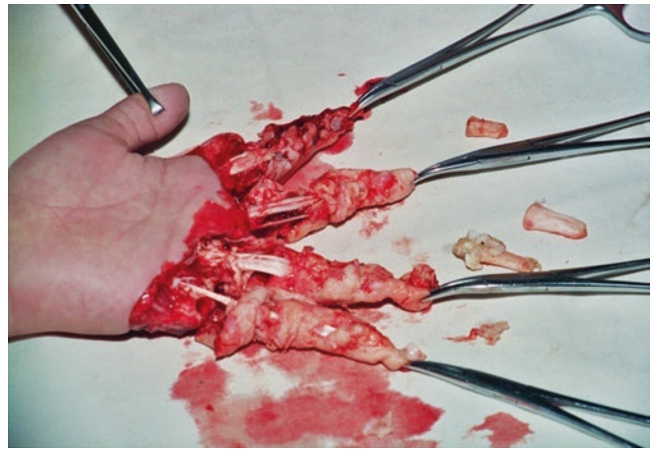


Fig. 7.49 The injury before operation

Fig. 7.50 Appearance of the recipient hand after operation (palmar view)

Fig. 7.51 Appearance of the recipient hand after operation (dorsal view)

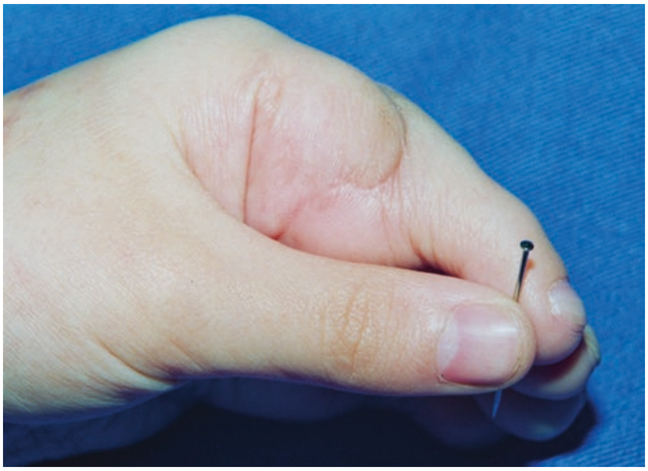


Fig. 7.52 The recipient hand picks up a fine object

Fig. 7.53 The patient holds a large bottle object after reconstruction of 4 fingers

7.5 Transfer of the Reshaped Second Toe for Reconstruction of Thumb/Fingers

Toe graft is the most common and most effective of all the methods of thumb/finger reconstruction. Its transplant survival rate is close to 100%, and reconstructed fingers restore most of the functionality of the original ones. However, there is a great difference in the appearance between toes and fingers. The great toe is too thick, and the other toes and fingers are too thin. A toe is a toe after all, still like a toe after transfer to the hand. Thus the appearance of reconstructed thumb/fingers is still unsatisfactory.

In 1980, Wei FC designed resection of the tibial part of the great toe which made the great toe thinner and thus closer to a normal thumb in appearance. In 1998, Wang ZT began using tissue flaps to make the transferred second toe closer to the appearance of the finger. He put forward the concept of cosmetic reconstruction of digits in 2002. There are many ways to modify the shape of reconstructed digits, including tissue flap transfer to reform the second toe blunt end and a small section of the finger shape. A representative surgical procedure is embedding a fibular flap of the great toe to the second toe for reconstruction of thumb/fingers, making the reconstructed digit closer to a normal one in shape. This section illustrates a typical example of the surgical procedure.

7.5.1 Surgical Indications

Thumb missing, finger defects of degrees II to V, and entire finger missing.

7.5.2 Applied Anatomy

Refer to Sect. 7.2 of this chapter.

7.5.3 Surgical Methods

1. Design: According to the appearance of the second toe, a vascularized elongated flap pedicled on the lateral plantar digital artery of the great toe is designed on the fibular side of the great toe.
2. Harvest: At the first web space, the first dorsal metatarsal artery or the lateral plantar digital artery of the great toe is dissected. Reveal the intersection of the first dorsal metatarsal artery, the first common plantar artery, the fibular plantar digital artery of the great toe, and the tibial plantar digital artery

of the second toe. Dissect the lateral plantar digital artery from the intersection to the distal end with the digital nerve. Cut off and ligate the transverse hallucis artery from the beginning. According to the lines designed on both sides of the great toe, incise the fibular flap and deep subdermal tissue. From the point between the dermis and superficial fascia on both sides, dissect for 5–10 mm before the flap is elevated. On both sides of the flap 5–10 mm wide fascia tissue is kept from the distal to proximal, to form a great toe fibular flap with wing-like fascia on both sides. Routinely dissect the second toe, carefully protecting the toe end anastomosis of the great toe fibular artery and the second toe tibial artery. According to the desired length, intercept the second toe, make a median longitudinal incision at the plantar side of the second toe, and cut from the proximal toe to the toe stripes belly point (plantar side). Along with the periosteal surface, dissect the tendon sheath from the second toe on both sides of the skin, so that a potential central cavity between the second toe on both sides of the skin and phalanges is made. In the proximal second toe, make a subcutaneous tunnel, connecting the proximal end of the second toe and the middle section of the second toe on the plantar side incision. The great toe fibular flap is introduced into the incision from the subcutaneous tunnel; the wing carried by the fascia fibular flap of the great toe is inserted between the skin and bone on both sides of the second toe. Modify the concave shape of the second toe on both sides, and make it flat. The vascularized composite tissue is transferred to the finger defect on the recipient hand.

Pearls and Pitfalls

1. Pearl: The modified second toe looks more like a normal finger after transfer.
2. Pitfall: Surgical operation is relatively simple but the second toe transplantation difficult.

7.5.4 Attention

After the fibular flap of great toe is fitted to the second toe, avoid twisting or folding the pedicle, and subject the pedicle to no tension or pressure.

7.5.5 Typical Cases

Transfer of the second toe with embedded great toe fibular skin flap for thumb reconstruction (Figs. 7.54, 7.55, 7.56 and 7.57).

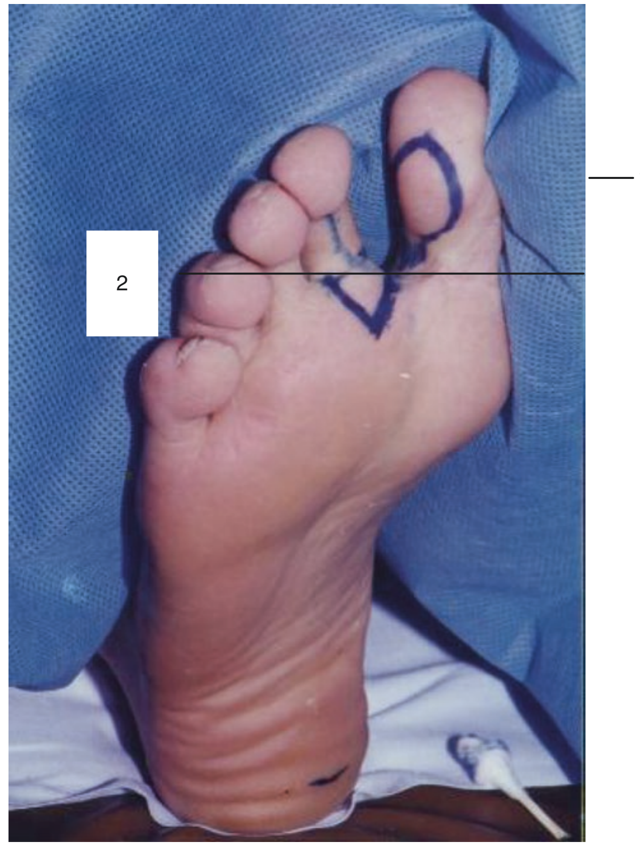


Fig. 7.54 Donor site design. (1) Fibular flap of the great toe. (2) Incision of the second toe

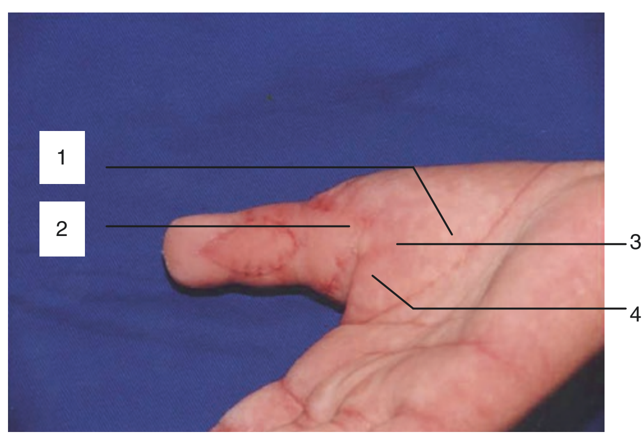


Fig. 7.55 Postoperative appearance. (1) Appearance of the thumb after reshaping reconstruction. (2) The second toe. (3) Fibular flap of the great toe embedded into the second toe. (4) The fascia wing carried by the fibular flap of the great toe was inserted into the second toe, making it flat

Fig. 7.56 Postoperative appearance. (1) Reconstruction of the thumb. (2) The fibular flap of the great toe embedded into the second toe

Fig. 7.57 Contrast between the thumb after reshaping reconstruction and the second toe in appearance

7.6 The Great Toe Wraparound Flap Combined with Bone of the Second Toe to Reconstruct Fingers

The great toe wraparound flap refers to a composite flap of the big toe containing nail and skin. It is different from a nail flap of the great toe in that it carries not only the nail and affiliated tissues but also more skin. It is used more to repair degloving injury of the thumb and fingers, and also to reconstruct fingers combined with bone/tendon of the second toe.

7.6.1 Surgical Indications

Defects of 1 or 2 fingers, and the thumb as well.

7.6.2 Applied Anatomy

Refer to Sect. 7.2 of this chapter.

7.6.3 Surgical Methods

1. Design

   According to the digital defect and the corresponding digit of the contralateral hand, a vascularized composite tissue graft (including bone, nail and skin) is designed on the fibular side of the great toe. As a hallux nail is generally bigger than a fingernail, we can only cut part of the nail on the lateral side of the great toe according to the size of the fingernail. The vascularized PIP joint of the second toe is harvested based on the plantar digital artery together with a lateral-sided tongue-shaped flap, with or without skin.
2. Harvest
   (a) Harvesting the vascularized composite tissue graft from the great toe: The dorsal veins are dissected out first and divided proximally at an appropriate length. At the first web space, the lateral plantar digital artery of the great toe is dissected out. After the skin flap is elevated, the dissection continues to the bone on the lateral side of the great toe. The periosteum is incised on the medial side of the nail, and an osteotome is used to open the cortex. The flap is elevated above the extensor tendon up to the distal part of its insertion. An osteotome is then used to cut the dorsal and medial cortex of the distal phalanx. After the dorsal lateral part of the bone is separated from the rest of the distal phalanx, it is included in the composite tissue flap together with a part of the nail and a skin paddle. The lateral plantar digital artery and nerve are divided proximally at appropriate lengths. The nerves of the vascularized composite tissue graft from the great toe have multiple sources: the medial dorsal cutaneous nerve, terminal branches of the deep peroneal nerve, and the lateral plantar digital nerves. Generally, the deep peroneal nerve or the lateral plantar digital nerves are chosen as the sensory nerve of the vascularized composite tissue. The nerves are divided proximally at appropriate lengths.
   (b) Harvesting the vascularized PIP joint of the second toe: By design, cut the dorsal skin of the second toe first, from medial to lateral side of the second toe, carefully protecting the dorsal vein. Stir up the toenail area on the distal dorsal surface from the bone to

the lateral side. Dissect the flap to lateral side of the second toe on the surface of the bone and tendon so that the lateral plantar artery and nerve remain on the second toenail flap. Then at the lateral plantar toe, dissect the flap under the corium cutis with medial plantar artery and nerve on the joint, and then continue to dissect the flap along the tendon sheath on the bottom surface to the lateral side of the toe. Continue to dissect the flap, and converge the lateral surface to form the toe nail flap pedicle, with the lateral plantar digital nerve/artery of the second toe and the medial plantar digital artery/nerve remaining on the toe. According to the design, cut the toe extend/flex tendon, and cut off the bone to form the flap of the second toe pedicled on the medial plantar digital artery/nerve and dorsal superficial vein.

(c) Composite vascularized tissues: (1) Common vascular pedicle: Dissect proximally at an appropriate length of the first dorsal metatarsal artery or the first plantar digital artery and dorsal metatarsal or dorsal superficial vein. Form a common pedicle of the first dorsal metatarsal artery (or the first plantar digital artery) for the wraparound flap and the second toe flap. Combine the wraparound flap and the second toe flap to form a new thumb or finger. (2) Separate vascular pedicles: Although the number of anastomosis and the surgical difficulty may be reduced when the wraparound flap and the second toe flap share a common vascular pedicle, blood circulation crisis is likely to happen because the combined partial blood vessels and nerves crossing from one side to the other side are easy to reverse and oppress one another. In fact, the wraparound flap and PIP joint flap can use separate independent vascular pedicles. Transfer the vascularized PIP joint of the second toe to the thumb or finger stump first, and then transfer the vascularized tissue of the great toe to wrap the second toe PIP joint flap. Respectively, the blood vessels, nerves, and tendon are anatomized with those of the reconstructed finger. This surgery needs more vascular anastomoses, but is simpler. For surgeons good at vascular anastomosis, we recommend this surgery.

3. Resurfacing the donor site wound

   The donor site can be covered with a full-thickness skin graft. It can also be covered with free flap or local pedicle flap.

4. Transfer

   The vascularized composite tissue is transferred to repair the finger defect on the recipient hand. A longitudinal K-wire is used for bone fixation. The extensor and flexor tendons are repaired with 4-0 nonabsorbable suture. Finally, the arteries, veins, nerves of the vascularized composite tissue are anastomosed respectively.

Pearls and Pitfalls

1. Pearls
   (a) Since the great toe nail is larger than a normal fingernail, it should be trimmed according to the shape of the fingernail. A better shape of the reconstructed fingers can be achieved after the modification.
   (b) The vascular pedicle is relatively constant, and easy to dissect.
   (c) The reconstructed finger can obtain sensation.
   (d) Since the diameters of the vessels and nerves are similar, anastomosis becomes easy.
2. Pitfalls

   Since the operation is more complex and risky, only the thumb or two fingers can be reconstructed.

7.6.4 Attentions

1. When the vascularized tissues are combined, care should be taken not to reverse the vascular pedicle compression.
2. Since a portion of the hallux nail ditch fits more to the deep and the skin in deep ditch is thin, they are easy to be cut through when the tissues close to the periosteal surface are dissected.
3. As it is difficult for a skin graft to the toenail donor site wound to survive, it is better to cover the wound by a flap.
4. The skin island in the vascularized second PIP joint has two roles. One is for observation of the vascularized second PIP joint. The other is for avoiding intolerance between the nail flap and the second toe joint. Some experts do not support the idea that the second toe joint with a skin flap is used to get a nice shape of the reconstructed thumb or finger.

7.6.5 Typical Cases

See Figs. 7.58, 7.59, 7.60, 7.61, 7.62, 7.63, 7.64 and 7.65.

Fig. 7.58 Thumb defect preoperatively

Fig. 7.59 Design of the donor site during surgery

Fig. 7.60 Design of the donor site during surgery

Fig. 7.61 Harvest of the vascularized composite tissue graft

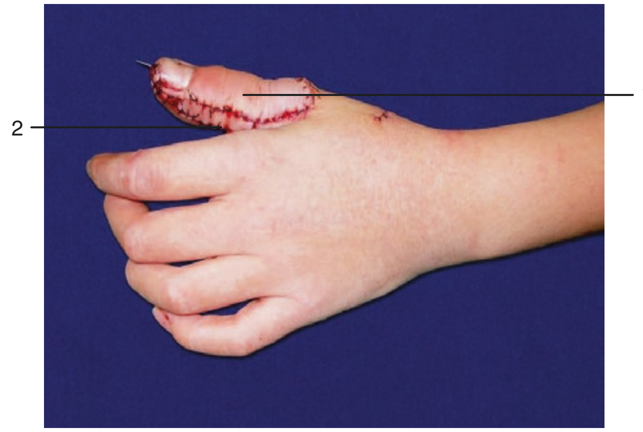


Fig. 7.62 Appearance of the reconstructed thumb. (1) Wraparound flap. (2) Island flap with the vascularized PIP joint of the second toe

Fig. 7.63 Appearance of the reconstructed thumb

Fig. 7.64 Repair of the donor site of the great toe by the toenail flap of the second toe. (1) Flap in the medial of the great toe. (2) Toenail flap of the second toe

7.7 Reconstruction of Finger Tip Defects

The distal part of toe or finger is called finger/toe tip. Replantation of finger tip was reported first by Tian in 1991. It is the same specialty as finger replantation. In general, the dorsal digital vein, or even the dorsal metatarsal vein or the thick dorsalis pedis vein, is used in finger reconstruction. However, in finger tip reconstruction, the subcutaneous superficial vein at the dorsal side is absent because of the existence of nail. Although the dorsal digital vein is anastomosed according to the continuity of palmar digital vein and dorsal digital vein, it is still very difficult to dissect.

Fig. 7.65 Appearance of the donor site. (1) Flap in the medial of the great toe. (2) Toenail flap of the second toe

7.7.1 Indications

Patients with finger tip defects who seek for perfect appearance and function of hand.

According to the size of toe and finger nail and the patient's requirement, the great toe or the second toe can be used as donor site which have their own advantages and disadvantages. In this section, these two surgical methods are described.

7.7.1.1 Donor Site 1: The Great Toe

Design

The composite flap that carries partial phalanx is designed on the lateral side of the great toe tip. Because the size of the great toe tip is larger than the finger's, a tongue-shaped flap is reversed at the medial side and tip of the great toe to diminish the circumference of the reconstructed finger tip. This tongue-shaped flap is used to cover the donor site of great toe tip. The nail in the great toe is larger than that in a finger. The nail which is harvested on the medial side of the great toe tip is corresponding to the defective size of the finger nail. The real composite tissue flap should contain the end of the distal phalanx. The pedicle of the flap is the superficial vein in the hallux pulp, or the superficial fibular dorsal digital vein of the great toe, and the tibial plantar digital artery and nerve of the great toe.

Flap Harvest

The dorsal veins are dissected out and divided at an appropriate length. The tip is then dissected out towards the fibular side of the great toe tip. The dorsal metatarsal artery, common plantar digital artery and fibular plantar digital artery of the great toe are dissected in the first web space. The fibular plantar digital artery and nerve of the great toe are carefully dissected out to the fibular side line in the great toe tip and the transverse hallux artery is cut and ligated. The skin is incised on the hallux pulp. The superficial veins of 1–2 cm are dissected for anastomosis. The periosteum is incised on the tibial and proximal side of the nail. Osteotomy is performed on the phalanx before the broken bone is lifted. The fibular plantar digital artery and nerve of the great toe are divided at sufficient lengths.

Resurfacing the Donor Site Wound

An osteotomy is conducted at the distal phalanx stump of the great toe. The remnant of a small nail is removed, and the reserved nail bed combined with the hallux triangle flap at the tibial side is turned to the tip. After the skin is advanced in the hallux pulp, the tip skin is sutured.

Preparation of the Recipient Site

Chronic injury: The scar tissue is excised. The nail stump is smoothed with a sharp knife; the bone at the tip of stump is removed with a rongeur until the normal bone marrow cavity or cancellous bone is seen. Bilateral digital arteries and nerves are carefully dissected out, and occluded arteries are removed until the blood in these arteries is spurting out. The neuroma at the end of severed nerves is resected and an appropriate length of nerve is dissected out for anastomosis. A 10 cm curvilinear incision is made on the dorsal aspect of the middle phalanx of the finger or on the proximal phalanx of the thumb; 1 or 2 dorsal superficial veins are dissected out for anastomosis.

Acute injury: After a routine debridement, surgeons deal with phalanges and nail stump. A 1 cm curvilinear incision is made on the dorsal aspect of the middle phalanx of the finger or on the proximal phalanx of the thumb; 1 or 2 dorsal superficial veins are dissected out for anastomosis.

Composite Tissue Transfer

The tuberositas unguicularis at the toe tip is pruned so that the diameter of phalanx is thinner. The bone is fixed with Φ 0.8 mm K-wire, and the nails from the finger and toe are matched exactly. If they do not match because of different radians of the nail plate, the nail plate should be removed. The nail bed is repaired with 5-0 nylon suture. Plantar digital artery and nerve of the toe tip are anastomosed with the digital artery and nerve of the finger; dorsal digital veins of the recipient and donor sites are anastomosed. The toe pulp vein is connected with the metacarpal digital vein.

7.7.1.2 Donor Site 2: The Second Toe

Design

The toe nail flap that carries partial distal phalanx is designed on the second toe beyond the nail wall. A triangle-shape flap is designed on the tibial side of the second toe tip, and a tongue-shaped flap is designed on the fibular side. The artery of the composite flap is the tibial plantar digital artery of the second toe. The vein is the thin superficial vein located in the toe pulp, or the dorsal digital vein which is regarded as the flap pedicle is dissected out along the course of the superficial vein.

Flap Harvest

The dorsal digital vein of the second toe is dissected out proximally and divided at an appropriate length. Then, along the vein branch the tip is dissect out towards the 2nd web space. The first dorsal metatarsal artery, the first common plantar digital artery and medial plantar digital artery and nerve of the second toe are dissected in the first web space. The tibial plantar digital artery and nerve of the second toe are carefully dissected out to the fibular side line. Following the design line, the skin is incised on the fibular and proximal side of the nail. The tibial and proximal edges of the flap are incised in the toe pulp. A mastectomy is performed on the phalanx before the broken bone is lifted. The tibial plantar digital artery of the second toe and nerve are divided at sufficient lengths.

Resurfacing the Donor Site Wound

A tongue-shaped flap on the fibular side of the second toe tip is turned to the tibial side. After the skin in the second toe pulp is advanced, the tip skin is sutured.

Composite Tissue Transfer

The composite tissue flap is transferred to the hand. The bone is fixed with Φ 0.8 mm K-wire. Tibial plantar digital artery and nerve from the toe tip are anastomosed with the proper palmar digital artery and nerve on the finger, and dorsal digital veins from the hand and foot are anastomosed.

Postoperative Management

The k-wire is removed 4 weeks after surgery. At the same time, the patient starts to do exercises. If the patient is not satisfied with the finger appearance, another surgery can improve it.

Notices

1. Apparently, the second toe is different from a finger in appearance. (1) The volume of the second toe is smaller than a finger's, but its tip is larger. In operation, a lateral longitudinal incision on the metacarpal side of the second toe is made to remove partial skin and subcutaneous tissue. In this way, the volume of the toe tip is diminished and the shape is changed to be more like a fingertip. (2) The nail of the second toe is smaller than a finger's, and the same is with the width and length of the second toe. The length of the nail bed in the second toe is much shorter than a finger's. When the defect is at the proximal part of the middle finger nail, transplantation of the second tip cannot produce a normal length of the finger's nail bed or perfect appearance.
2. The volume of the great toe is large, and the same is with the nail bed of the great toe. Reconstruction of a finger just needs a part of the nail from the great toe. The toe can be divided into two parts. One is used for finger tip reconstruction, and the other is reserved in the great toe in order to maintain the appearance and function of the great toe. Compared with reconstruction with the second toe, transplantation of the great toe may lead to fewer complications regarding the appearance and function of the donor foot. The reconstructive finger is more lifelike.

7.7.2 A Case Report

See Figs. 7.66, 7.67, 7.68, 7.69, 7.70, 7.71, 7.72 and 7.73.

Fig. 7.66 The defect at the ring finger tip

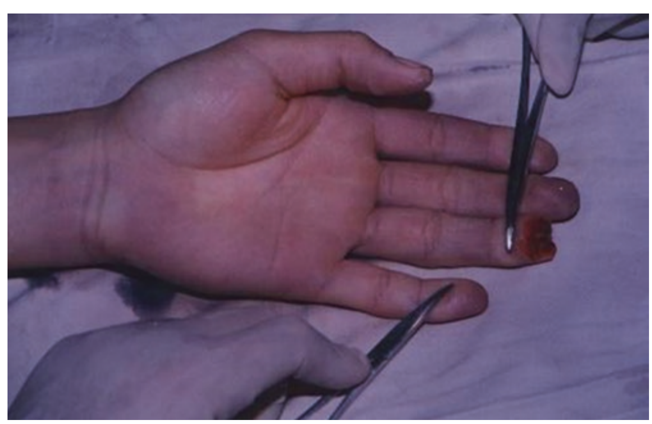


Fig. 7.67 The defect at the ring finger tip

Fig. 7.68 Transplantation of partial tip of the great toe is designed to reconstruct the ring finger tip

Fig. 7.69 Transplantation of partial tip of the great toe is designed to reconstruct the ring finger tip

Fig. 7.70 Appearance of the ring finger tip 8 months after surgery

Fig. 7.71 Appearance of the ring finger tip 8 months after surgery

Fig. 7.72 Appearance of the ring finger tip 8 months after surgery

Fig. 7.73 The appearance of the donor site 8 months after surgery

7.8 Special Reconstructions

In general, the concept of toe-to-hand reconstruction is that the distal/full part of a toe is harvested and transferred to hand for reconstruction of the distal/full defect of the finger.

Although some surgical methods are described as finger reconstruction, they are somewhat different from conventional finger reconstruction.

7.8.1 Decorative Digital Reconstruction

The concept was proposed first by Cheng in 2005. Composite tissue defects located at the lateral, dorsal and metacarpal side of the distal plantar or the finger body are repaired by lateral nail flap, dorsal nail flap, toe pulp flap or composite tissue flap of partial toe. The function and appearance of the finger repaired by the above methods are very close to those of a normal finger.

The surgical object is not the length of defective finger but the transverse tissue defect. Compared with such conventional methods as adjacent finger flap, forearm flap, pedicle abdominal flap, and vascular island flap, decorative digital reconstruction has the advantages of cosmetic appearance, full length, excellent sensation and function and reconstruction of the nail and finger pulp thread. This is a reconstruction at a different level. This section will introduce decorative digital reconstruction of the defect at the tip and nail.

7.8.2 One Decorative Reconstruction of Partial Nail Defect

For recovery of normal appearance and function, the toe nail and its surrounding tissue can be used to repair a partial nail defect of finger. Compared with other toes, the great toe has a larger nail, thicker phalanx and more skin and subcutaneous tissues. After the composite tissue flap is harvested from the great toe, the length and appearance of the great toe can be maintained at the donor foot. Therefore, the great toe has been the most common donor site.

7.8.2.1 Indication

Partial nail defect of a finger.

7.8.2.2 Anatomy

See Sect. 7.2.

7.8.2.3 Procedures

1. Design

   The hallux toenail flap is designed based on the defect of the nail, nail wall, tissue and phalanx.

2. Flap harvest

   At the first web space, several dorsal metacarpal veins are dissected till the toe pulp flap or the dorsal side of the great toe. The vein is also dissected in the skin incision and proximally cut at an appropriate length. The medial and proximal edges of the flap are incised, and the free flap is dissected from the tibial side to the fibular side, and from the proximal to the distal. The fibular plantar digital artery of the great toe and its accompanying nerve are dissected carefully. If there is a large arterial absence, the artery is dissected to the proximal of the hallux transverse artery or even the first dorsal metatarsal artery or the first common plantar digital artery. The deeper level of the medial toe pulp flap is dermis tissue which is reserved in the great toe in order to diminish the possibility of injuring the medial plantar digital artery of the great toe. Bone exposure should be avoided to decrease a possible failure of the skin graft at the donor site. The fibular plantar digital artery of the great toe is included in the flap. If the dorsal digital vein is not good enough, the first or second superficial plantar digital vein can be dissected and used for anastomosis. A goose saw or rongeur is used to cut the phalanx. After partial phalanx is harvested, the tibial and fibular edges of the flap are joined together. The harvest of the composite tissue flap is finished.

3. Transfer and management of donor site

   The proper digital artery and nerve are dissected at the recipient site. Transfer the flap to hand and then fix the bone. The fibular plantar digital artery is anastomosed with finger artery. Superficial dorsal metatarsal (or plantar) vein is anastomosed with the superficial dorsal digital vein. The plantar digital nerve is anastomosed with the proper digital nerve. The recipient site can be sutured directly or repaired by skin graft or flap.

Pearls and Pitfalls

1. Pearls
   (a) Since the nail of the great toe is larger than a finger's, excellent appearance of the recipient site can be achieved after the nail is harvested according to the corresponding shape of the normal finger.
   (b) The pedicle of the flap is eternal and easy to harvest.
   (c) The nerve is carried in the flap.
   (d) The diameters of blood vessels at both the recipient and donor sites are similar.
2. Pitfalls

   This surgery is complicated and highly risky. Because the tissue defect at the finger tip is at a very limited scale, design of the surgery is very difficult. The veins are hard to harvest but easy to injure.

Notices

1. The vein should be harvested carefully under a microscope.
2. The deeper skin of the nail groove is thin and easy to break. The skin should be dissected on the surface of periosteum closely.
3. It is likely to fail to use a skin graft at the toe nail. The best method is to use the flap to cover the donor site.

7.8.2.4 Case Report

See Figs. 7.74, 7.75, 7.76, 7.77, 7.78, 7.79, 7.80, 7.81, 7.82, 7.83 and 7.84.

Fig. 7.74 The defect of right middle finger before operation (dorsal view)

Fig. 7.75 The defect of right middle finger before operation (palmar view)

Fig. 7.76 The defect of right middle finger before operation (lateral view)

Fig. 7.77 Harvest of the fibular hallux flap

Fig. 7.78 Transfer of the fibular hallux flap to the middle finger (palmar view)

Fig. 7.79 Transfer of the fibular hallux flap to the middle finger (lateral view)

Fig. 7.80 Transfer of the fibular hallux flap to the middle finger (lateral view)

Fig. 7.81 Transfer of the fibular hallux flap to the middle finger (dorsal view)

Fig. 7.82 Follow-up after operation (dorsal view)

Fig. 7.83 Follow-up after operation (lateral view)

7.8.3 Two Parasitic Transplantation of the Hallux Pulp Flap and the Second Toe

Sometimes adjacent fingers are injured, resulting in one digital defect and one digital palmar skin defect. If the tissues such as proximal blood vessels in one finger are injured so severely that they cannot be used for anastomosis, a combination transfer of the hallux pulp flap and the second toe is used. In this situation, the proximal pedicle is only anastomosed with the blood vessel which is not damaged seriously. The second toe and hallux pulp flap are used respectively to reconstruct the finger defect and to repair the palmar side skin of the other finger. Transplantation of the hallux toe pulp flap and the second toe, which is parasitic in the other one, is described as parasitic transplantation.

7.8.3.1 Indication

The injury of adjacent fingers, one is digital defect and the other is digital palmar skin defect.

Fig. 7.84 The appearance of both hands after operation

7.8.3.2 Anatomy

See Sect. 7.2.

7.8.3.3 Procedures

1. Design

   The second toe and hallux pulp flap are designed according to the specific digital injuries of the hand.

2. Harvest

   At the first web space, several dorsal metacarpal veins are dissected till the hallux pulp flap or the proximal side of the second toe and ligated at an appropriate length. The junctions of the first dorsal metatarsal artery, the first proper plantar digital artery, fibular hallux artery and tibial digital artery of the second toe are exposed. Following the course of the fibular plantar digital artery of the great toe at the junction site, the accompanying nerves and blood vessels are dissected till the origin of the hallux transverse artery. The hallux transverse artery is cut and ligated. The fibular edge of the hallux pulp flap is incised, and the superficial vein is protected carefully. In the deeper of the fibular plantar digital artery of the great toe, the hallux transverse artery is cut and ligated so that the flap is turned to the hallux pulp side. The dissection stops when it is near the middle line of the hallux pulp. The tibial and proximal edges of the flap are incised and the free flap is dissected from the tibial side to the fibular side. The deeper level of the medial side of the toe pulp flap is dermis tissue which is reserved in the great toe in order to diminish the possibility of injuring the tibial plantar digital artery of the great toe. Bone exposure should be avoided to decrease the risk of skin graft failure at the donor site. When harvest is carried on near the fibular side of the flap, the dissection level should be deeper so that the fibular plantar digital artery of the great toe is included in the flap. If the dorsal digital vein is not good enough, the first or second superficial plantar digital vein can be dissected. After the tibial and fibular edges of the flap are joined together, the harvest of the composite tissue flap is finished. The second toe is dissected in the conventional way. The anastomosis between the fibular plantar digital artery of the great toe and the second tibial plantar digital artery is protected carefully. The second toe is dissected at a proper length needed. Raise the second toe and the hallux pulp flap together to finish the composite tissue flap the pedicle of which is the first dorsal metatarsal artery. If the first dorsal metatarsal artery is of type III, the second common plantar digital artery is the pedicle of flap. If the artery is good, the fibular plantar digital artery of the great toe and the second plantar digital artery can be the pedicle.

3. Transfer

   After the composite tissue is transferred to the hand, dissect the proper digital artery or common palmar digital artery in a finger which is in relatively good condition. The dorsal metatarsal artery is anastomosed with the digital artery or common palmar digital artery. The superficial dorsal metatarsal vein is anastomosed with the superficial dorsal digital/metacarpal vein. The plantar digital nerve of the hallux pulp flap and the plantar digital nerve of the second toe are anastomosed respectively with the proximal proper digital nerves in two fingers. If the proper digital artery in the chosen finger is healthy, the fibular plantar digital artery of the hallux pulp and the digital artery of the second toe are anastomosed respectively with the bilateral proper digital arteries in one finger. In this way, it is easier to adjust the site of flap and the fingers do not appear fat after operation. If there is only one healthy proper digital artery, one of the two plantar digital arteries in the second toe is anastomosed with the proper digital artery, and the other one is anastomosed with the fibular plantar digital artery of hallux pulp flap. The blood supply to the hallux pulp flap is provided by the connection of bilateral plantar digital arteries of the toe.

Three weeks after operation, the pedicle is cut and the adjacent 2 fingers are separated.

Pearls and Pitfalls

1. Pearls

   When the unhealthy proximal blood vessel in one finger is not used for transplantation, the blood vessel in the adjacent finger can be used for it.

2. Pitfalls

   Another operation is needed to cut the pedicle.

Notices

1. If the composite flap carries too much tissue, the finger will appear too fat after operation.
2. When the pedicle of the flap is cut, the plantar digital artery of the hallux pulp flap is parasitized in the adjacent finger or the plantar digital artery of the second toe is reconnected with the blood vessel in the recipient finger. This step aims to recover fine blood supply to the injured fingers.

7.8.3.4 Case Report

See Figs. 7.85, 7.86, 7.87, 7.88, 7.89, 7.90 and 7.91.

7.8.4 Three Parasitic Transplantation of the Second Toe and the Hallux Nail Flap

The second toe and the hallux nail flap which have the same pedicle are transferred to reconstruct one defective finger and to repair the injury of the other adjacent finger. One component of this composite tissue graft is parasitized temporar-

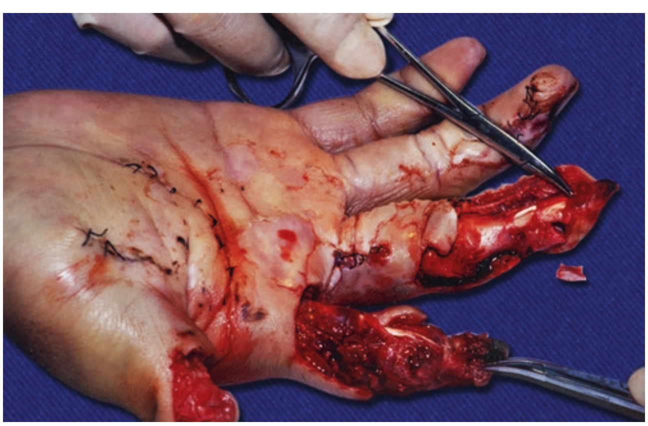


Fig. 7.85 The defect in the index and middle fingers

Fig. 7.86 Design on the left foot

Fig. 7.87 Design on the left foot

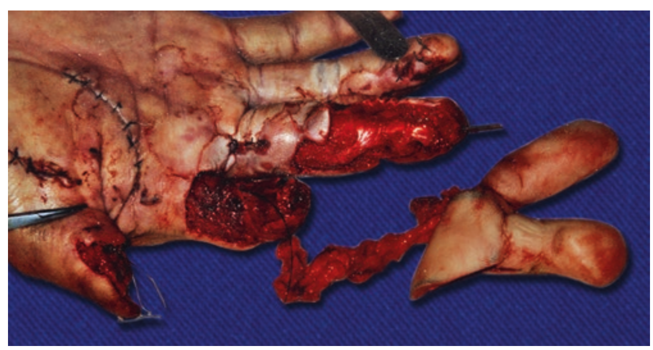


Fig. 7.88 Harvest of the composite tissue flap

Fig. 7.89 The recipient hand after operation (before pedicle cutting)

Fig. 7.90 The appearance of the recipient hand after pedicle cutting

Fig. 7.91 The flexion of the fingers in the recipient hand after pedicle cutting

ily on the other one or on the adjacent injured finger. When the blood vessel in the recipient finger is unhealthy or the general condition of the patient does not allow prolonged surgery, parasitic transplantation of the second toe and the hallux nail flap is performed to increase the successful rate of the operation and shorten the surgery time.

7.8.4.1 Indication

Adjacent fingers are injured, resulting in one digital defect and one digital palmar skin defect.

7.8.4.2 Anatomy

See Sect. 7.2.

7.8.4.3 Procedures

1. Design

   The second toe and hallux nail flap are designed according to the specific digital injury.

2. Harvest

   At the first web space, several dorsal metacarpal veins are dissected till the hallux pulp flap or the proximal side of the second toe and ligated at an appropriate length. The junctions of the first dorsal metatarsal artery, the first common plantar digital artery, fibular hallux artery and tibial digital artery of the second toe are exposed. The tibial edge of the hallux nail flap is incised based on the design line. The deep nail bed and onychostroma are dissected and the hallux nail flap is lifted from the tibial side to the fibular side. The tibial and proximal edges of the flap are incised in the toe pulp and the flap is dissected from the tibial side to the fibular side. The deep level of the medial side of toe pulp flap is dermis tissue which is reserved in the great toe in order to diminish the possibility of injuring the tibial plantar digital artery of the great toe. Bone exposure should be avoided to decrease the risk of the skin graft failure at the donor site. When harvest is carried on near the fibular side of the flap, the dissection level should be deeper so that the fibular plantar digital artery of the great toe is included in the flap. After the tibial and fibular edges of the flap are joined together, harvest of the composite tissue flap is finished. The second toe is dissected in the conventional way. The anastomosis between the fibular plantar digital artery of the great toe and the tibial plantar digital artery of the second toe is protected carefully. The second toe is cut off at a proper length needed. Raise the second toe and the hallux pulp flap together to finish the composite tissue flap whose pedicle is the first dorsal metatarsal artery. If the first dorsal metatarsal artery is of type III, the second common plantar digital artery is the pedicle of flap. If the artery is healthy, the fibular plantar digital artery of the great toe and the second plantar digital artery can be the pedicle.

   After the composite tissue is transferred to the hand, a finger which is in relatively good condition is chosen to dissect the proper digital artery or common digital artery. The dorsal metatarsal artery is anastomosed with the digital artery or common digital artery. The superficial dorsal metatarsal vein is anastomosed with the superficial dorsal digital/metacarpal vein. The plantar digital nerves of the hallux nail flap and the second toe are anastomosed respectively with the proximal proper digital nerves in two fingers. If the bilateral proper digital arteries in the chosen finger are healthy, the fibular plantar digital artery of the hallux nail flap and the plantar digital artery of the second toe are anastomosed respectively with the bilateral proper digital arteries in one finger. In this way, it is easier to adjust the site of flap and the appearance of repaired finger is not too fat after operation. If there is only one healthy proper digital artery, one of the two plantar digital arteries in the second toe is anastomosed with the proper digital artery, and the other one is anastomosed with the fibular plantar digital artery of hallux nail flap. The blood supply to the hallux nail flap is provided by the connection of bilateral plantar digital arteries of the toe.

Three weeks after operation, the pedicle is cut and the adjacent two fingers are separated.

Pearls and Pitfalls

1. Pearls

   When the unhealthy proximal blood vessel in one finger is not suitable for transplantation, the blood vessel in the adjacent finger can be used for it.
2. Pitfalls

   Another operation is needed to cut the pedicle.

Notices

1. If the composite flap carries too much tissue, the finger repaired will appear too fat after operation.
2. When the pedicle of the flap is cut, the plantar digital artery of the hallux pulp flap is parasitized in the adjacent finger or the plantar digital artery of the second toe is reconnected with the blood vessel in the recipient finger.

7.9 Cosmetic Reconstruction

Loss of a thumb or finger can dramatically affect a person's work and life. For many years, doctors have been seeking methods to repair defective digits. However, there is no perfect procedure for thumb and finger reconstruction in functionality and cosmetics. The two major challenges are: (1) Loss of one or multiple toes from the donor foot. During conventional toe-to-hand transfer, a surgeon harvests a toe according to the length of the damaged thumb/finger. This procedure causes significant damage to the foot and toe that sometimes outweighs the benefit of reconstructed thumb/finger. Such reconstructive procedures sometimes require sacrifice of multiple toes. Consequently, unacceptable damage to the foot is created when multiple thumb/finger reconstructions are performed. (2) Despite some similarities between thumb/fingers and toes in appearance and function, there are dramatic differences in length, joint, and diameter. Reconstructed digits still look like toes, which is especially noticeable when a long digit is reconstructed.

A hand is not only an indispensable tool but also a part of a person's general appearance. Therefore, a digital defect not only impairs a patient's daily living and work activities but also affects the patient's self-image and willingness to socialize. Patients often feel embarrassed when showing a digit reconstructed by traditional toe-to-hand transfer. Current digital reconstruction has been focusing on producing a thumb/finger that closely resembles a normal digit and has good function. At the same time, we have tried to preserve foot/toe function and appearance as much as possible. However, the above-mentioned goals are difficult to achieve through conventional toe-to-hand transfer.

In 1998, we started to modify the toe-to-hand transfer to produce aesthetic reconstruction of a thumb/finger.

Cosmetic reconstruction of hand digits means taking different types of graft from various parts of the body to build a thumb/finger that closely resembles a normal digit.

Cosmetic reconstruction is just a new theory and operation conception that we can design. It incorporates various operation styles in one case. Its main goals include: (1) A reconstructed digit closely resembles its corresponding contralateral digit in diameter and length. (2) A reconstructed digit closely resembles its corresponding contralateral digit in lengths of different phalanges, size of nail, and texture of skin. (3) Surgery produces less damage to the donor foot than previous approaches. Digits can be reconstructed by sacrificing only one toe, or even no toe at all.

7.9.1 Reconstruction for Grade I Defects

1. Design

   According to the finger defect, a vascularized composite tissue graft including partial nail, dorsal part of the distal phalanx, and a skin flap is taken from the lateral side of the great toe. A tongue-shaped flap is lifted on the medial plantar side of the great toe. Venous return of the harvested flap is through the plantar or dorsal side superficial veins. The lateral plantar digital artery and nerve are used as pedicle for the composite tissue graft.
2. Flap Harvest

   The dorsal veins are dissected out proximally and divided at an appropriate length. They are then dissected out distally towards the lateral tip of the great toe. The dorsal and palmar arteries are dissected in the first web space. The lateral plantar digital artery and nerve are carefully dissected out to the proximal edge of the flap before the transverse hallux artery is cut. The skin is incised on the plantar side of the great toe. The plantar superficial veins of 1–2 cm in length are dissected for anastomosis and divided until the lateral side of phalanx. The periosteum is incised on the interior and proximal side of the nail. A small drill is used to open the cortex on the dorsal and lateral sides of the distal phalanx, and an osteotome is used to separate the lateral cortex from the medial cortex. The partial nail and skin flap are harvested together with the bone based on the same vascular pedicle. The lateral plantar digital artery and nerve are divided at sufficient lengths.

3. Resurfacing the donor site wound

   Most donor site wounds can be repaired by a local advanced flap. However, if the wound is too large, a local advancement flap, in combination with a plantar metatarsal flap, a dorsal metatarsal flap, or a medial-sided flap of the second toe, can be used to resurface the donor site wound.

4. Preparation of the recipient site: (1) Chronic injury: The scar tissue is excised. The nail stump is smoothed with a sharp knife; the bone at the tip of stump is removed with a rongeur until the normal bone marrow cavity or cancellous bone is seen. Bilateral digital arteries and nerves are carefully dissected out, and occluded arteries are removed until the blood in these arteries is spurting out. The neuroma at the end of severed nerves is resected and an appropriate length of nerve is dissected out for anastomosis. A 10 cm curvilinear incision is made on the dorsal aspect of the middle phalanx of the finger or on the proximal phalanx of the thumb; 1 or 2 dorsal superficial veins are dissected out for anastomosis. (2) Acute injury: After a routine debridement, surgeons deal with phalange and nail stump. A 1 cm curvilinear incision is made on the dorsal aspect of the middle phalanx of the finger or on the proximal phalanx of the thumb; 1 or 2 dorsal superficial veins are dissected out for anastomosis.

5. Composite tissue transfer

   The vascularized composite tissues from the great toe that wrap the phalanx and are reorganized to the shape of the original missing finger is transferred to the site of the finger or thumb. The bone is fixed with K-wires, and the nail and nail bed are repaired with 6-0 polydioxanone suture II. Plantar digital artery and nerve from the toe are anastomosed with the digital artery and nerve on the finger; both dorsal and volar superficial veins are anastomosed.

Pearls and Pitfalls

Owing to the large size of the great toe, only a part of the nail is needed for grade I defect reconstruction. The rest of the nail can be left in situ to preserve the appearance and function of the great toe. Compared with transfer of the second toe to reconstruct the fingertip, a vascularized composite tissue graft from the great toe produces less morbidity on the foot in terms of cosmetic appearance and function. The reconstructed thumb or finger appears and functions as similarly as the missing thumb or finger.

The most difficult part of the procedure is dissection of the veins. As no dorsal skin is included in the composite tissue graft, we cannot use the dorsal veins directly for anastomosis. One of the following three methods can be used to address this problem. (1) The plantar superficial veins can be used for anastomosis. (2) The dorsal veins on the great toe are identified proximally and dissected distally to the edge of the composite tissue graft. (3) A lateral triangular skin paddle can be included in the composite tissue graft, and the veins in the triangular flap can be used for anastomosis with the dorsal veins on the thumb or finger.

Case 1 A combined flap of hallux nail, skin and bone is transferred to treat the hook nail deformity (Figs. 7.92, 7.93, 7.94, 7.95 and 7.96).

Case 2 Treatment of the Grade I defect on the index finger (Figs. 7.97, 7.98, 7.99, 7.100 and 7.101).

Fig. 7.92 Grade I defect on the ring finger

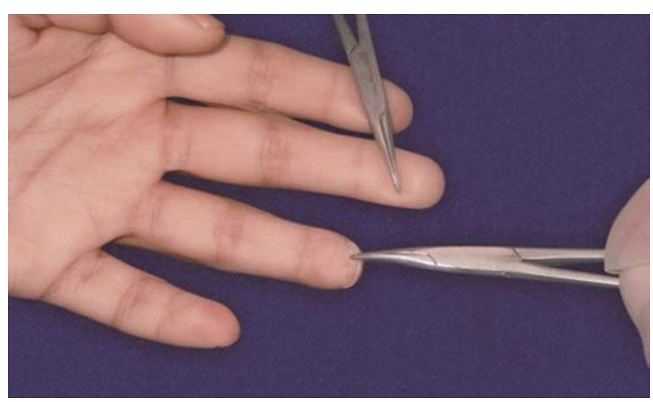


Fig. 7.93 Grade I defect on the ring finger (palmar view)

Fig. 7.94 Design of the flap

Fig. 7.95 Appearance of the ring finger after operation (dorsal view)

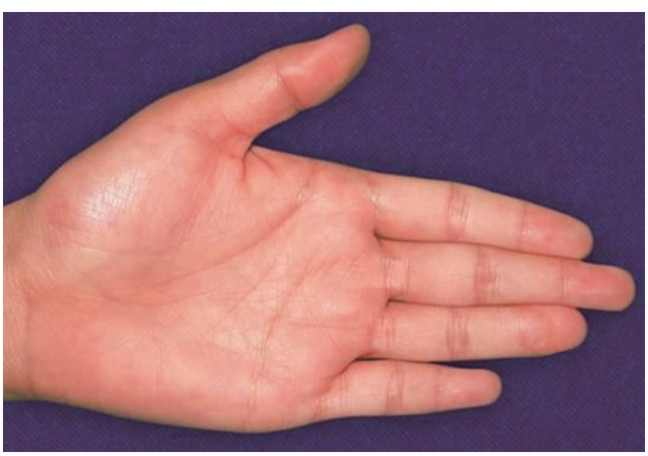


Fig. 7.96 Appearance of the ring finger after operation (palmar view)

Fig. 7.97 Grade I defect on the index finger

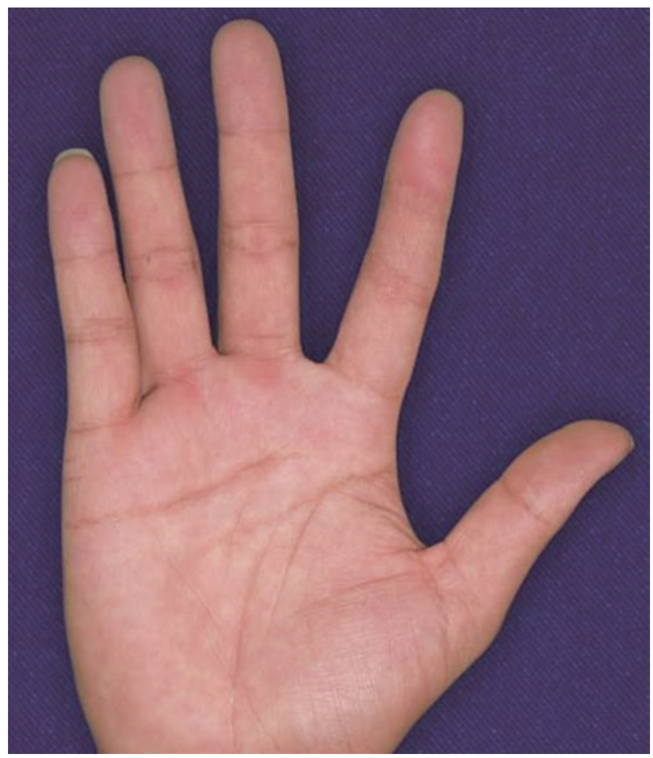


Fig. 7.98 Appearance of the index finger after operation (palmar view)

Fig. 7.99 Appearance of the index finger after operation (dorsal view)

Fig. 7.100 Appearance of the donor foot after operation

7.9.2 Composite Tissue Flaps from Bilateral Great Toes

In addition to the method described above, for grade I defect, we also combine two halves of the halluces harvested from both feet to fabricate a thumb or finger which is then transferred to the defective stump.

Fig. 7.101 Appearance of the donor foot after operation

1. Design

   We design the composite tissue graft from bilateral great toes including partial distal phalanx after we measure the length and circumference of defective finger and the length and width of the nail carefully according to the severity of finger defect. The width of the harvested toe nail is just half of that of the thumb or finger to be reconstructed. The flap from the foot or other part of the body is transferred/transplanted to repair the donor site. The designed incision lines are marked at the donor and recipient sites.
2. Flap harvest

   Make an incision on the fibular side of the great toe and first toe web. The dorsal veins are dissected out from the distal to the proximal and divided proximally at an appropriate length. On the dorsal side of great toe, the extensor hallucis longus tendon insertion is dissected and exposed. On the palmar side, the flap is dissected to fibular side, carrying a proper thickness of subcutaneous tissue and including the lateral plantar digital artery and nerve. Beyond the extensor hallucis longus tendon insertion, transect half side of the phalanx with a special rongeur or mini swing saw in order to receive the bone we need. Then, the nail and partial phalanges are cut longitudinally. The composite flap whose pedicle is the lateral plantar digital artery and nerve of great toe is formed. The lateral plantar digital artery and nerve of great toe are dissected distally at appropriate lengths. The transverse hallux artery is cut at 0.5 cm away from the starting point. Keep the continuity of the first dorsal metatarsal artery and the second plantar digital artery on the medial side and palmar metatarsal artery till the proximal plantar digital artery of the great toe. The flap harvest is finished at this time. The contralateral flap is harvested in the same manner.

3. Transfer to the hand

   The nail, tissue and phalange of the bilateral composite flap are pruned under a microscope. This step can make sure the components above match exactly. Suture the nail bed and fix the phalanges with K-wire, transversely or by binding. The distal artery arches or the transverse hallux arteries from bilateral flaps are anastomosed. After preparation of the recipient site, the reconstructive digit is washed with warm water and transferred to the recipient site. Fix the bone with K-wire and put the reconstructive digit in a right position. The plantar digital artery and nerve from the toe are anastomosed with the digital artery and nerve on the finger; the two dorsal metatarsal veins from the composite flap are anastomosed with dorsal digit veins.

4. Donor site wound resurfacing

   The secondary wound on the great toe is covered by a pedicled local flap transfer. Dorsalis pedis flap, dorsal metatarsal flap, lateral tarsal flap, plantar metatarsal flap, or even a free groin flap can be transferred.

   This method is used to repair not only grade I defects but also Grade II–III defects. The reconstructive digit is very similar to a normal finger in appearance and function.

Case 3 Reconstruction of the index finger with bilateral composite flaps (Figs. 7.102, 7.103, 7.104, 7.105, 7.106, 7.107, 7.108, 7.109, 7.110, 7.111, 7.112, 7.113, 7.114, 7.115 and 7.116).

Fig. 7.102 Defect on the right index finger

7.9.3 Reconstruction of Grades II and III Defects

1. Design

   According to the digital defect, a vascularized composite tissue graft (including bone, nail, and skin) is designed on the fibular side of the great toe. As the dorsal skin is included in the composite tissue graft, its dorsal veins are used for anastomosis.

2. Surgical procedures

   The dorsal veins are dissected out first and divided proximally at an appropriate length. At the first web space, the first dorsal metatarsal artery, the first common plantar digital artery and the lateral plantar digital artery of the great toe are dissected out. The lateral plantar digital nerve is also carefully dissected out together with the digital artery. The transverse hallux artery is cut off. Incision is made according to the designed line on the palmar side of phalanx. The skin flap is elevated, and the dissection is carried on to the bone on the lateral side of the great toe. The periosteum is incised on the medial side of the nail, and an osteotome is used to open the cortex. The flap is elevated above the extensor tendon up to the distal part of its insertion. An osteotome is then used to cut the dorsal and medial cortex of the distal phalanx. The dorsal lateral part of the bone is separated from the rest of the distal phalanx. A part of the nail and a skin paddle are included in the composite tissue flap. The lateral plantar digital artery and nerve are divided proximally at appropriate lengths. The length of the bone in the composite tissue is measured. An iliac crest bone graft (ICBG) or bone allograft is used if a greater length is needed. A vascularized proximal interphalangeal (PIP) joint from the second toe can be used to reconstruct the distal interphalangeal (DIP) joint in the reconstructed finger if necessary.

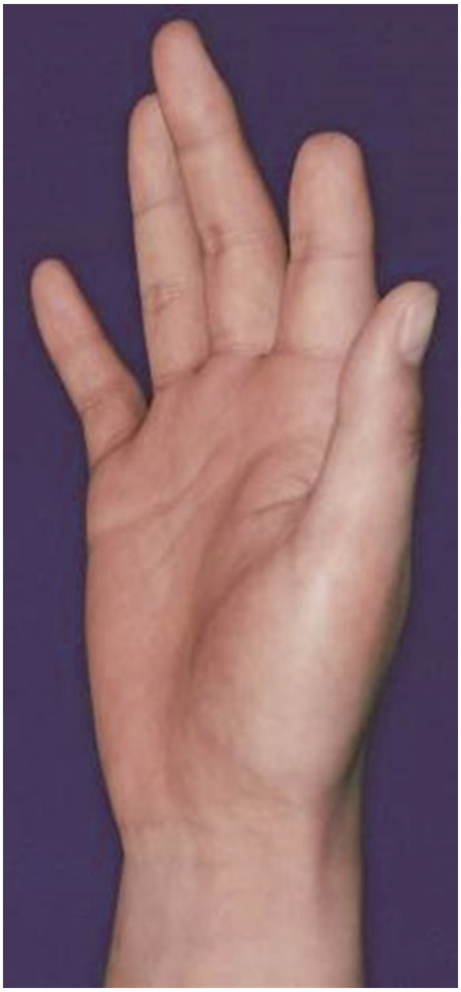


Fig. 7.103 Defect on the right index finger

Fig. 7.104 Flap design on the right foot

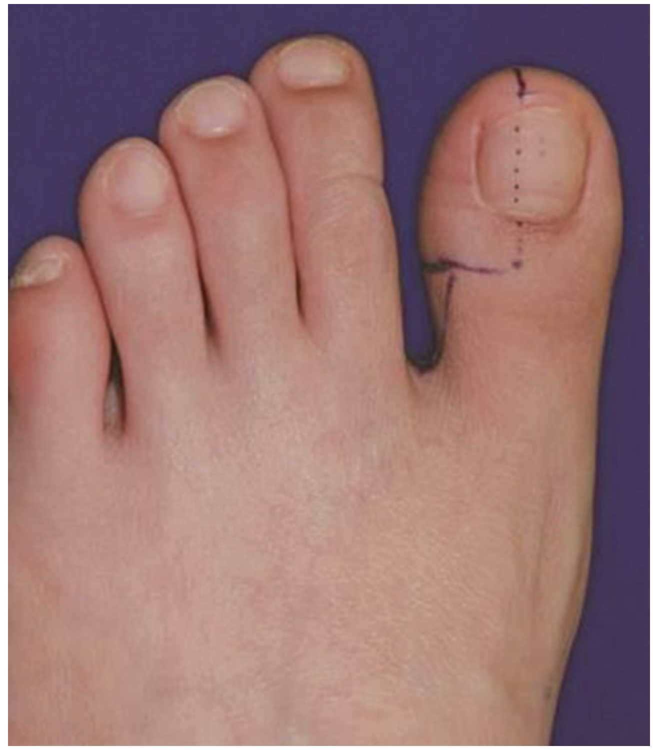


Fig. 7.105 Flap design on the left foot

Fig. 7.106 Harvest of the bilateral composite flaps

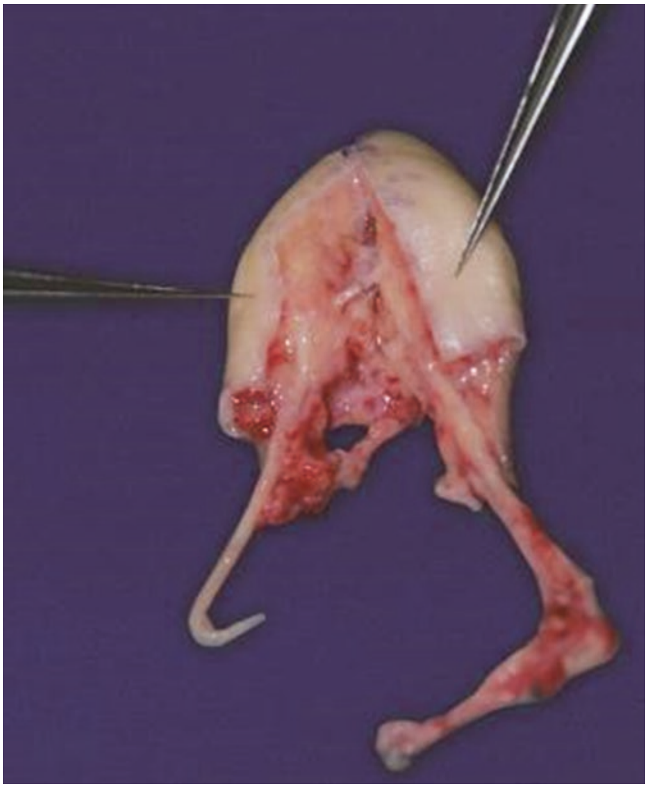


Fig. 7.107 Assembly of the flaps

Fig. 7.108 Assembly of the flaps

Fig. 7.109 Transplantation of the assembled flap to the right index finger

Fig. 7.110 Appearance of the recipient finger after operation (dorsal view)

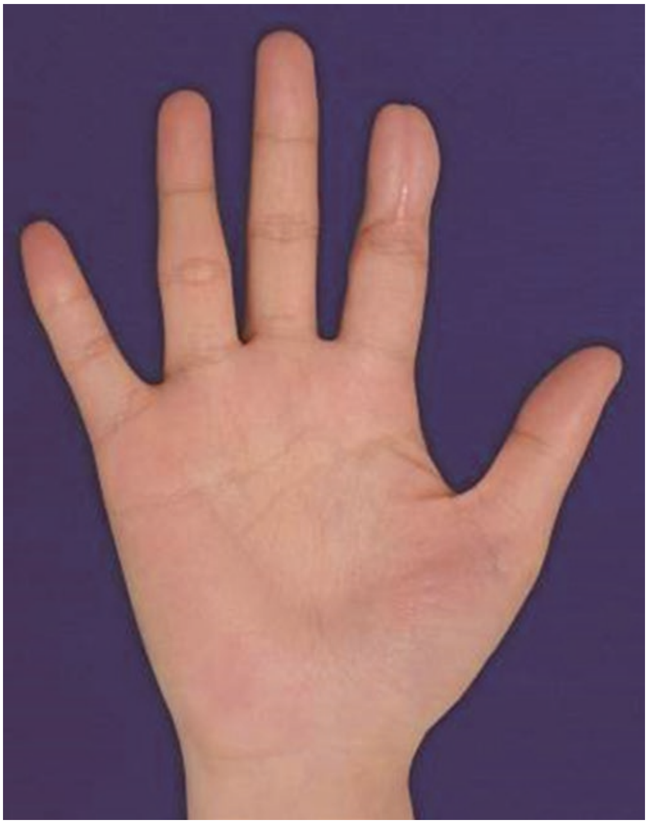


Fig. 7.111 Appearance of the recipient finger after operation (palmar view)

3. Resurfacing donor site wound

   The secondary wound on the great toe is covered by a pedicled local flap transfer, like plantar metatarsal flap, dorsal metatarsal flap, and/or tibial side flap from the second toe. A free groin flap transfer can also be used.
4. Transfer to the hand

   The vascularized composite tissue flaps wrapping the phalanx are assembled according to the original shape of the defective finger. For some defects of grades II and III, the length of phalanx in the composite flap is not enough. A longitudinal K-wire is used to fix it with iliac bone together and then the reconstructive digit is fixed to the recipient finger stump. The PIP joint from the second toe can be included in the composite tissue graft to reconstruct the DIP joint of the finger. A conventional iliac bone graft is inserted for additional length requirement. Plantar digital artery, nerve and dorsal digital vein in the composite flap are anastomosed with proper digital artery, nerve and dorsal digital vein in the recipient finger.

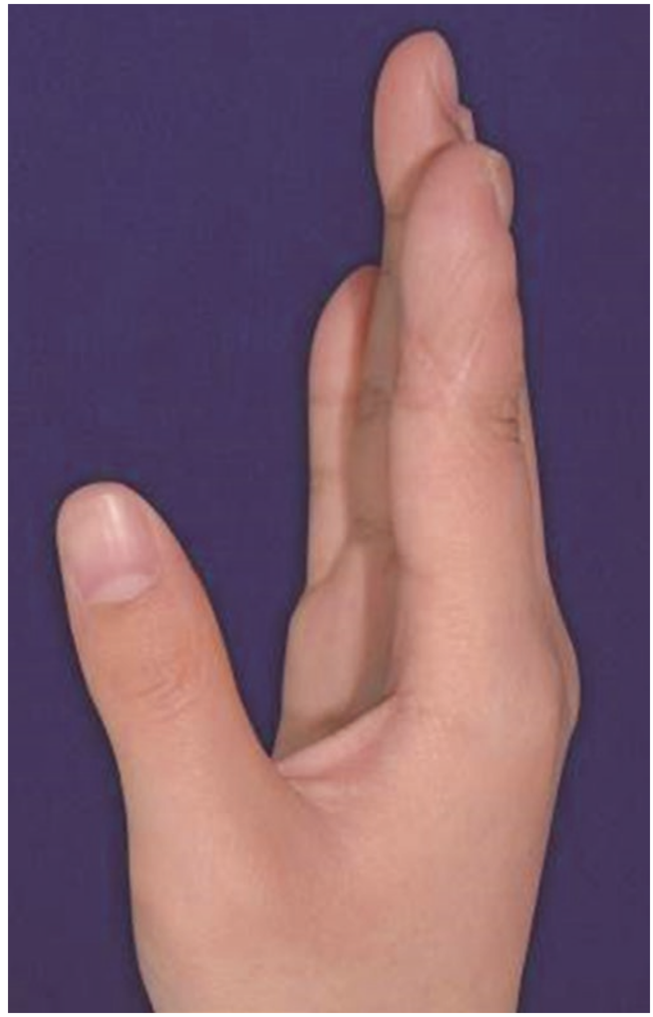


Fig. 7.112 Appearance of the recipient finger after operation (lateral view)

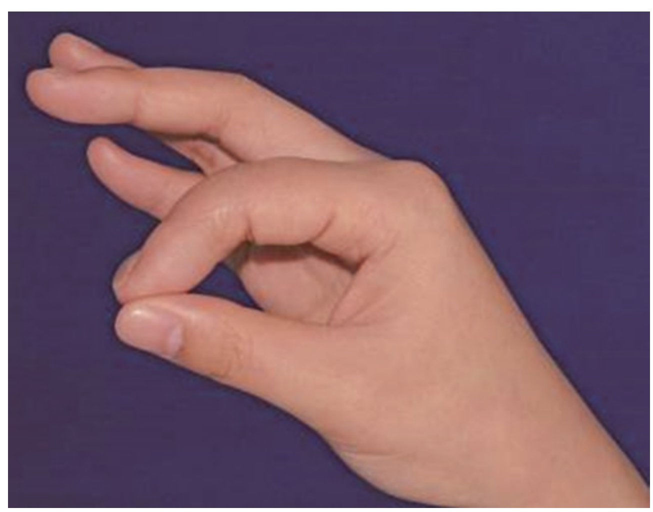


Fig. 7.113 Finger opposition

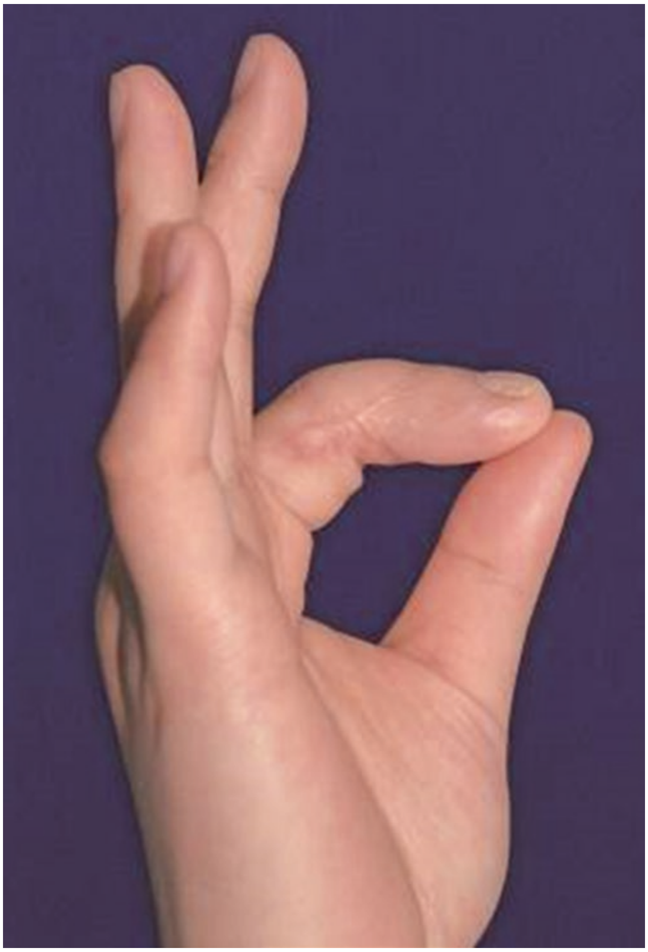


Fig. 7.114 Finger opposition

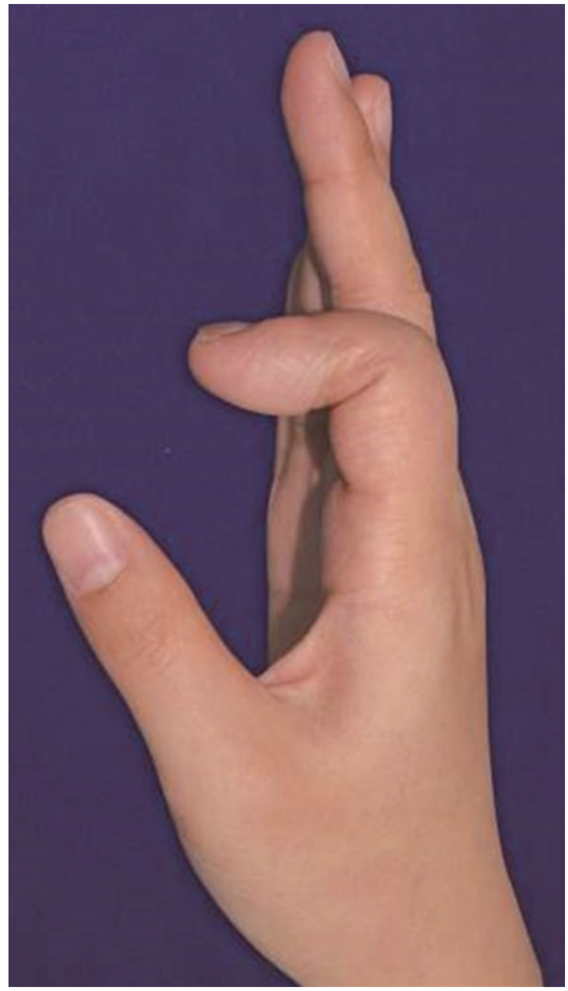


Fig. 7.115 Maximal proximal interphalangeal (PIP) joint flexion

Pearls and Pitfalls

1. The skin and nail are usually enough in the vascularized composite tissue graft from the great toe for reconstruction of digital defects of grades II and III. However, because of a short length of phalanx from the toe, a conventional iliac bone graft may be needed to restore the length of reconstructed finger.
2. The secondary wound at the donor site can be covered by a local pedicle skin flap. However, a skin graft is needed to cover the additional wound from the local pedicle skin flap. At this point, it is valuable to transplant a free groin flap to cover the donor site. Our experience is to use a groin flap.
3. Theoretically, fingers may have better function with motion of the DIP joint. However, the DIP joint function in the following three cases of ours was not satisfactory. Reconstruction of this joint makes surgery much more difficult, leading to longer operation time, higher risk and repeated operations. This is a great challenge that needs to be resolved in the future.

Fig. 7.116 Appearance of the donor feet after operation

Fig. 7.117 Grade III defects on the right index and middle fingers

Case 4 Reconstruction of defects of grades II and III (Figs. 7.117, 7.118, 7.119, 7.120, 7.121 and 7.122).

7.9.4 Reconstruction of Defects of Grades IV and V

1. Design

   Preoperative Doppler and computed tomographic (CT) examinations reveal the condition of the first dorsal metatarsal artery on the donor foot and the artery on the recipient hand. The length, diameter, and location of the joints and the nail size on the reconstructed digit are determined by measuring those of the contralateral hand. Based on these measurements, the great toe composite flap and second toe PIP joint transfer are designed on the donor foot. The diameter of the reconstructed thumb is designed 0.5 to 1 cm larger than the contralateral one, because the reconstructed thumb will become smaller because of atrophy.
2. Preparation on the recipient digit

   Make a middle incision at the tip of recipient finger. After the stump of proximal phalanx is exposed, the bone at the tip of stump is removed until the normal bone marrow cavity is seen. Extend incision proximally, and dissect flexor digitorum tendon, extensor digitorum tendon, bilateral proper digital arteries and nerves, palmar or dorsal superficial vein for anastomosis.
3. Flap harvest

   Designed incisions are made on the great toe and the second toe of the donor foot. Superficial veins on the dorsal side of metatarsal are exposed and dissected out distally towards the great and second toes. Deep peroneal nerve, the first dorsal metatarsal artery, the first common plantar digital artery, the lateral plantar digital artery and nerve of the great toe, and the medial plantar digital artery and nerve of the second toe are all carefully dissected out. If the first dorsal metatarsal artery is absent or too small, a greater length of the first common plantar digital artery is dissected out as the pedicle. Extensor digitorum longus (EDL) and flexor digitorum brevis tendons (FDB) to the second toe are harvested according to the defect size on the recipient site. The nail on the great toe is harvested according to the predesigned size. Osteotomy of the toe is performed from the proximal to the nail root. The lateral half is harvested in the flap. The vascularized PIP joint of the second toe is harvested based on the plantar digital artery with a lateral-sided tongue-shaped flap, with care to protect the dorsal vein and lateral plantar digital artery of the second toe.
4. Harvest of ICBG and skin graft

   According to the size of bone defect on the recipient digit, a 2 × 2 cm bicortical iliac bone graft is harvested from the iliac crest with 3 cm in width which is located about 4 cm in the back of the anterior superior iliac spine. After complete hemostasis, the iliac crest will be restored in situ, and the periosteum and subcutaneous tissue will be sutured respectively. If necessary, a full-thickness skin graft is harvested according to the skin defect on the donor foot before suturing the skin.
5. Vascularized composite tissue transfer

   The vascularized PIP joint from the second toe is wrapped with the composite tissue graft from the great toe. If the flap pedicle is not long enough, dissect the medial side of plantar digital artery from the second toe to solve this problem. If the joint from the second toe cannot be wrapped with the composite graft, the medial side of plantar digital artery can be cut off near the original site. After the joint is wrapped, the plantar digital artery from the second toe and artery from the composite tissue graft are connected respectively to the two digital arteries of the recipient digit. The joint position and length of different phalanges are adjusted according to the PIP joint and phalanges on the corresponding contralateral finger. An appropriately sized ICBG can help adjustment of the position of PIP joint and the lengths of phalanges. K-wires, screws, or a plate can be used for bone fixation, and fluoroscopy is used to check the PIP joint position

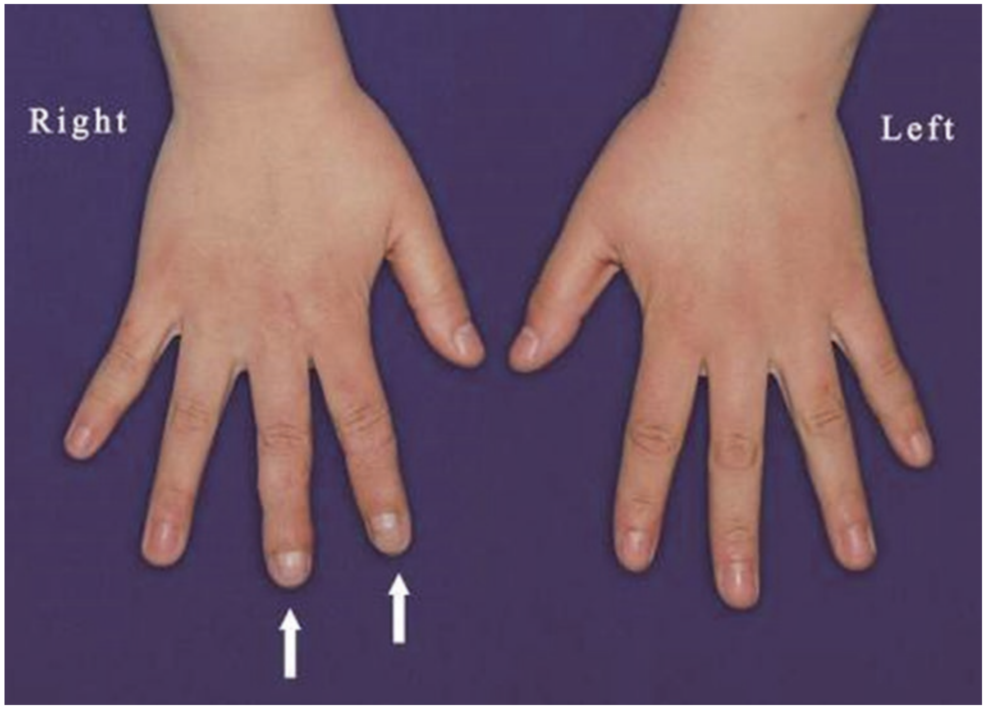


Fig. 7.118 Appearance of the right index and middle fingers after operation (dorsal view)

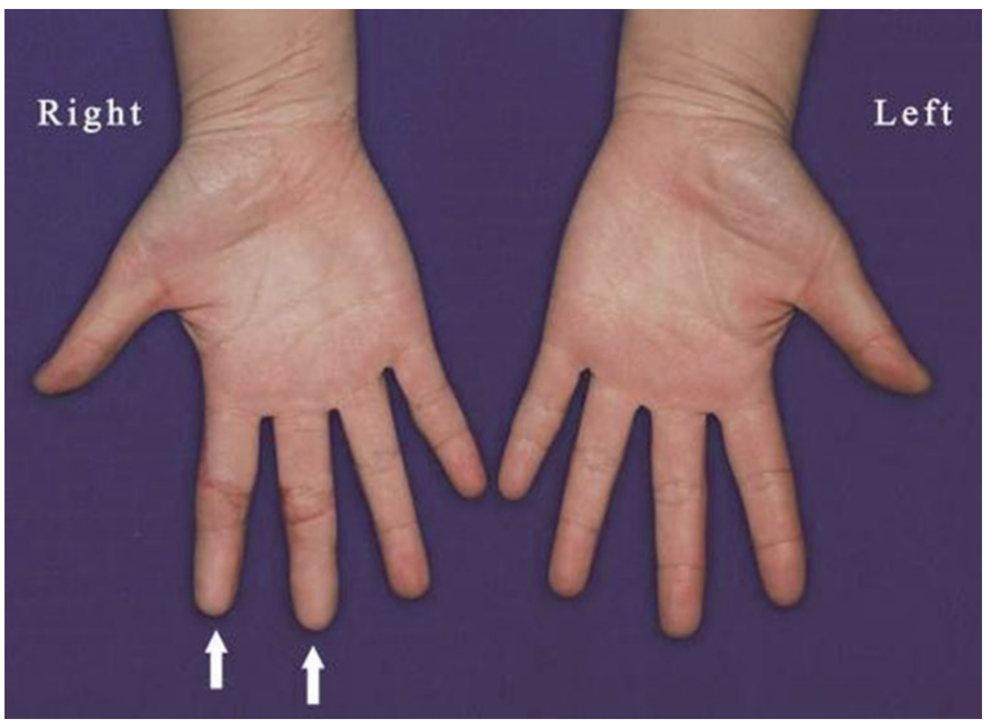


Fig. 7.119 Appearance of the right index and middle fingers after operation (palmar view)

and bone fixation. The extensor and flexor tendons are sutured. If the composite tissue graft from the great toe and the vascularized PIP joint which is harvested with a small skin flap lateral to the joint and the flexor and extensor tendons from the second toe share the same pedicle, the pedicle is anastomosed with the digital artery of the recipient finger. If they have separate vascular pedicles, the two pedicles can be anastomosed with digital arteries of the finger. The dorsal and volar superficial veins are anastomosed next. Finally, the lateral digital nerve from the great toe and the medial digital nerve from the second toe are sutured to digital nerves of the finger. Pink color, good capillary refill, and active bleeding from the skin edge should be all present in the nail and flaps from the

Fig. 7.120 Flexion of the reconstructed and contralateral hands

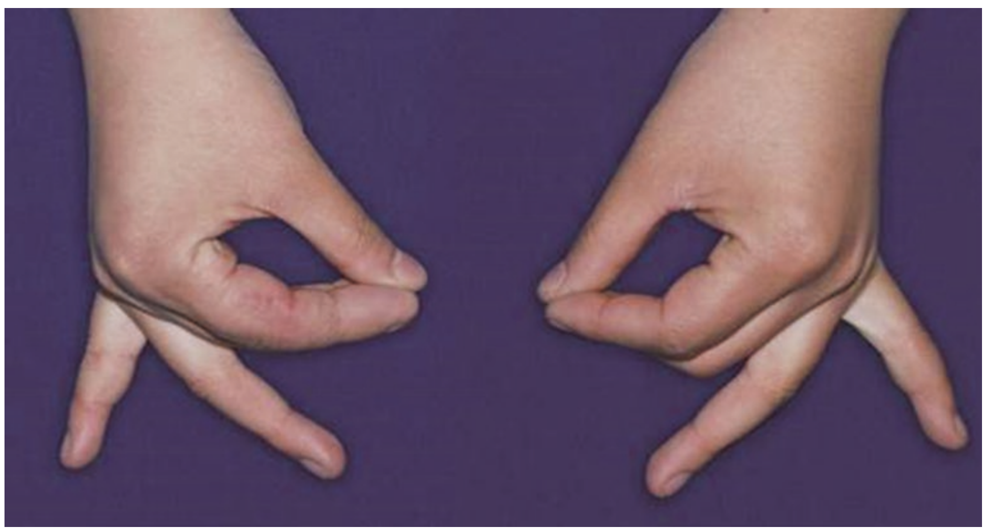


Fig. 7.121 Flexion of the reconstructed and contralateral hands

great toe and second toe. After meticulous hemostasis, the skin is closed.

6. Resurfacing the donor site wound

   The remaining part of the second toe, including nail and skin flap, is fixed to the distal phalanx stump of the great toe with a K-wire. The wound still left on the dorsal aspect of metatarsals can be covered with a full-thickness skin graft from the groin area. The wound on the donor site after the great toe wraparound flap is harvested can also be covered with a free groin flap, a local pedicle flap, or a lateral tarsal flap. The bone defect at the donor site after the second toe PIP joint is harvested can be filled with ICBG and fixed with a K-wire.

Pearls and Pitfalls

Reconstruction of defects of grades IV and V is challenging because of the small size of toes compared to fingers. Simple second-toe-to-hand transfer cannot achieve a satisfactory cosmetic appearance. The PIP joint of the second toe is used to reconstruct the PIP finger joint and ICBG to adjust the position of the PIP joint and length of phalanges. The reconstructed finger has good function and excellent cosmetic appearance. The disadvantage of this procedure is its complexity which requires meticulous microsurgical techniques.

Case 5 Grade V defect on the left index finger (Figs. 7.123, 7.124, 7.125, 7.126, 7.127, 7.128 and 7.129).

Fig. 7.122 Appearance of the donor feet after operation

Fig. 7.123 A hand with grade V defect on index finger (B)

Fig. 7.124 Design of a wraparound flap from the great toe and a vascularized PIP joint from the second toe

7.9.5 Reconstructions for Grade VI Defects

1. Design

   Preoperative Doppler and computed tomographic (CT) examinations reveal the condition of the first dorsal metatarsal artery, plantar metatarsal artery and plantar digital artery on the donor foot and the artery on the recipient hand. The length, diameter, and nail size of the reconstructed finger are determined by measuring the corresponding contralateral finger. Based on these measurements, the great toe composite flap and second toe PIP joint transfer are designed on the donor foot. The composite tissue graft includes part of the distal phalanx,

Fig. 7.125 Appearance of the recipient finger after operation

dorsal metatarsal artery flap and plantar metatarsal artery flap. The diameter of reconstructed finger is designed 0.5 to 1 cm larger than the contralateral one. The metatarsophalangeal joint from the second toe is used to reconstruct the metacarpophalangeal joint in the recipient hand. The interphalangeal joint from the second toe is used to reconstruct the PIP joint in the recipient hand. When the defect is on the index/middle finger, the great/second toe on the contralateral side is the donor site. However, the homolateral foot is the donor site in cases of ring finger defects.

2. Preparation of the recipient digit

   Make a middle incision at the tip of recipient finger. The stump of proximal phalanx is exposed, and the bone at the tip of stump is removed until the normal bone marrow cavity is seen. Extend incision proximally, and dissect flexor digitorum tendon, extensor digitorum tendon, proper digital arteries and nerves or common palmar digital artery, palmar or dorsal superficial veins for anastomosis.

3. Harvest of composite tissue graft

   Incisions are made on the great and second toes. After a dorsalis pedis flap and a dorsal metatarsal flap are elevated, the dorsal superficial veins are dissected out for anastomosis. The deep peroneal nerve, the first dorsal and plantar metatarsal arteries, the lateral plantar digital artery and nerve of the great toe, and the medial plantar digital artery and nerve of the second toe are all dissected out. If the first dorsal metatarsal artery is absent or too small, a greater length of the first common plantar digital artery is dissected out as the pedicle. EDL and FDB from the second toe are harvested. A wraparound flap from the great toe is harvested with part of the fibular distal phalanx. Osteotomy is conducted from the proximal to the nail. Dissect the composite tissue graft carefully so that the total proximal phalanx, middle phalanx and PIP from the second toe can be included in the flap. A tongue-shaped flap on the tibial side of the second toe is included. Care is taken to protect the lateral plantar digital artery of the second toe. The distal phalanx of the second toe is left *in situ*.

Fig. 7.126 Appearance of the recipient finger after operation

Fig. 7.127 Appearance of the recipient finger after operation

Fig. 7.128 Appearance of the donor site after operation

4. Harvest of ICBG and skin graft

According to the size of bone defect on the recipient digit, an appropriate graft of bicortical iliac bone is harvested from the iliac crest with 3 cm in width which is located about 4 cm in the back of the anterior superior

Fig. 7.129 Appearance of the reconstructed finger 17 months after operation

iliac spine. After complete hemostasis, the iliac crest will be restored in situ, and the periosteum and subcutaneous tissue will be sutured respectively. If necessary, a full-thickness skin graft is harvested according to the skin defect on the donor foot before suturing the skin.

5. Transfer to the hand

If the vascularized PIP joint from the second toe cannot be wrapped with the composite tissue graft from the great toe because the flap pedicle is too short, cutting off the lateral side of plantar digital artery from the great toe near the original site to solve this problem. After the vascularized PIP joint is wrapped, transplant a vein to connect the broken artery or anastomose the first common plantar digital artery and the artery from the composite tissue graft. K-wires can be used to fix the PIP from the second toe, and the ilium and part of the distal phalanx from the composite flap. The metatarsophalangeal joint is fixed at extension position in order to increase the range of flexion of the reconstructed metatarsophalangeal joint. Beyond the metacarpus and PIP joint, the length and joint position can be adjusted according to bone grafting. Fluoroscopy is used to check the joint position. The extensor and flexor tendons are sutured. Dorsal metatarsal artery is anastomosed with common palmar digital artery or proper digital artery and radial artery. Connect the dorsal metacarpal vein from foot with the dorsal metacarpal vein from hand. The proper digital nerves from finger and toe are anastomosed together. After active bleeding appears from the skin edge, the skin is closed.

6. Resurfacing secondary wounds on the donor foot

The residual tissues from the second toe, including nail, bone, and flap, are fixed to the residual tissues from the great toe with a K-wire. The wound is closed as much as possible. The remaining wound on the dorsal foot is covered with a full-thickness skin graft from the groin area or medial plantar area.

Pearls and Pitfalls

Reconstruction of a lengthy digital defect of grade VI is challenging. A conventional second-toe-to-hand transfer produces a small digit with poor cosmetic appearance. We use the MTP and PIP joints of the second toes to reconstruct the MCP and PIP joints of the defective finger. ICBG or second-stage bone lengthening is used to lengthen the proximal phalanx of the reconstructed finger. A finger with good joint position can be reconstructed by this method. The disadvantage of this method is complexity which calls for meticulous preoperative design and delicate surgical techniques, especially microsurgical techniques.

Case 6 A grade VI defect on the right index finger (Figs. 7.130, 7.131 and 7.132).

Fig. 7.130 Right index finger amputation at the proximal metacarpal level combined with middle finger deformity

Fig. 7.131 Radiograph before surgery

Fig. 7.132 The reconstructed right index finger after operation

7.9.6 Coverage of the Donor Site

1. Dorsalis pedis flap

   A transverse or longitudinal flap is designed. The medial side of the flap is first elevated above the peritenon, including the dorsalis pedis artery and its accompanying veins. The cutaneous nerve branches are identified and protected, and the proximal end of the pedicle is divided and ligated. The flap based on the deep plantar branch of the dorsalis pedis artery is rotated to cover the wound on the great toe. If there is communication between the first dorsal metatarsal artery and the first plantar metatarsal artery or the medial plantar digital artery in the first web space, it can also be used as the pivot point for flap rotation.

Case 7 Donor site is repaired by a dorsalis pedis flap (Figs. 7.133, 7.134, 7.135, 7.136, 7.137, 7.138, 7.139 and 7.140).

2. The First Dorsal Metatarsal Flap

   This type of flap can be used when there is a communication branch between the first dorsal metatarsal artery and the first plantar metatarsal artery or the medial plantar digital artery of the second toe. The flap is designed on the dorsal aspect of the first and second metatarsals. The flap is elevated above the peritenon and the interosseous muscle. The dorsalis pedis artery, its deep plantar branch, the first plantar metatarsal artery, and their concomitant veins are all dissected out. The cutaneous branches are identified and protected. The dorsalis pedis artery and its concomitant veins are divided proximally and ligated. The flap is rotated on the communicating branch in the first web space to cover the wound on the great toe.
3. The Second Dorsal Metatarsal Flap

   This flap is used when the first dorsal metatarsal artery is absent or the communicating branch in the web

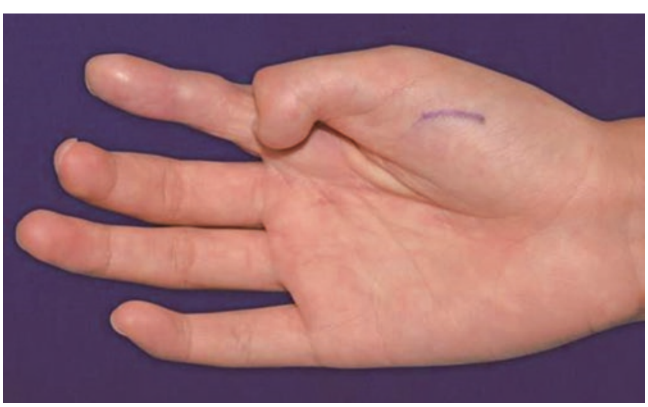


Fig. 7.133 A hand with multiple digital deformities

Fig. 7.134 Design of the flaps

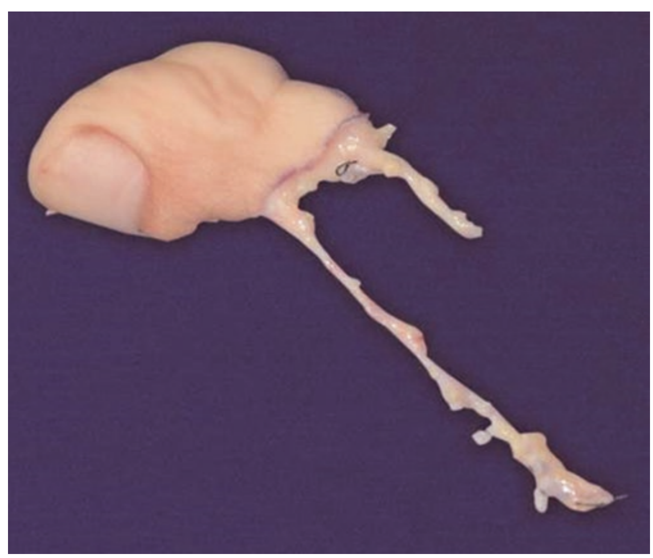


Fig. 7.135 Harvest of the vascularized composite tissue flap from the great toe

Fig. 7.136 The thumb reconstructed with transfer of the vascularized nail flap with part of distal phalanx of the great toe

Fig. 7.137 Design of the dorsalis pedis flap to cover the donor site

Fig. 7.138 Donor site repaired by the dorsalis pedis flap

Fig. 7.139 Appearance of the foot after flap transfer

Fig. 7.140 Appearance of the foot 6 months after operation

space has been taken with the great toe wraparound flap. The flap is designed on the dorsal surface of the second and third metatarsals. The flap is elevated above the peritenon and the interosseous muscles. The second plantar artery and its concomitant veins are dissected out, with care to protect their cutaneous branches. In the second toe web space, the communicating branch between the second dorsal metatarsal artery and the second plantar metatarsal artery is dissected out. This branch can be used as the pivot point of the flap to cover the wound on the great toe.

4. Anterior Ankle Flap

   This type of flap is used when the first dorsal metatarsal artery is absent or has been taken with the great toe wraparound flap. The flap is designed in the anterior aspect of the ankle and elevated above the extensor retinaculum from one side. The anterior malleolus cutaneous branch of the anterior tibial artery is dissected, and the extensor retinaculum is opened. Then the anterior tibial artery and its concomitant veins are dissected out. The flap is then elevated from the other side. The anterior tibial artery is divided and ligated proximally. The flap is rotated on the deep plantar branch of the dorsalis pedis artery to cover the wound on the great toe.

5. Lateral Tarsal Flap

   The flap is harvested from the lateral aspect of the foot and elevated on the medial side first above the surface of the extensor digitorum brevis (EDB) and then up to its lateral border. The cutaneous branch of the lateral tarsal artery is identified and protected. The EDB is retracted, and the lateral tarsal artery and its concomitant veins are dissected out. The flap is then continuously elevated on the lateral side. The dorsalis pedis artery is ligated proximally to the origin of the lateral tarsal artery. The flap is then transferred based on the deep plantar branch of the dorsalis pedis artery to cover the great toe.

6. Medial Tarsal Flap

   The flap is designed on the medial aspect of the dorsal foot. An incision is made in the anterior aspect of the ankle. The dorsalis pedis artery is exposed first, and then the medial tarsal arteries and the concomitant veins are identified and dissected out. The flap is elevated on the surface of the abductor pollicis towards the dorsal aspect of the foot. The cutaneous branches of the dorsalis pedis artery are identified, with care to protect the vessels when dissecting them underneath the EPL and the anterior tibialis tendon. After flap elevation, the dorsalis pedis artery is ligated proximally to the origin of the medial tarsal artery. The flap is transferred based on the deep plantar branch of the dorsalis pedis artery to cover the wound on the great toe.

7. Plantar Metatarsal Flap or Medial Plantar Flap

   The plantar metatarsal flap is based on the communicating branch between the first dorsal metatarsal artery and the plantar metatarsal artery or the medial plantar digital artery of the second toe. The medial plantar flap is based on the communicating branch between the medial plantar digital artery of the great toe and the medial plantar metatarsal artery. When the plantar metatarsal flap is harvested, we usually first expose the plantar metatarsal artery and its concomitant veins in the first web space and dissect them out proximally. The proximal end of the artery is then divided and ligated. The communicating branch between the plantar metatarsal artery, the common plantar metatarsal artery, and the medial plantar digital artery of the great toe at the neck of the first metatarsal is dissected out. Care is taken to protect the concomitant veins.

Case 8 Donor site repaired by a medial plantar flap (Figs. 7.141, 7.142, 7.143, 7.144, 7.145, 7.146, 7.147 and 7.148).

8. Lateral or Medial Side Flap of the Second Toe
   A lateral flap of the second toe is used to cover a small wound on the great toe after fingertip reconstruction. The lateral flap of the second toe is the residual flap after combined transfer of the great toe wraparound flap with the PIP joint from the second toe. The medial flap of the second toe is designed on the medial side of the pulp and pedicled with the medial plantar digital artery and its concomitant veins. The donor side after such a small flap is harvested from the second toe can usually be closed directly. A full-thickness skin graft is used to cover the wound if a small wound is left.

Fig. 7.141 A defect on the left index finger

Fig. 7.142 Design of the flap from the great toe

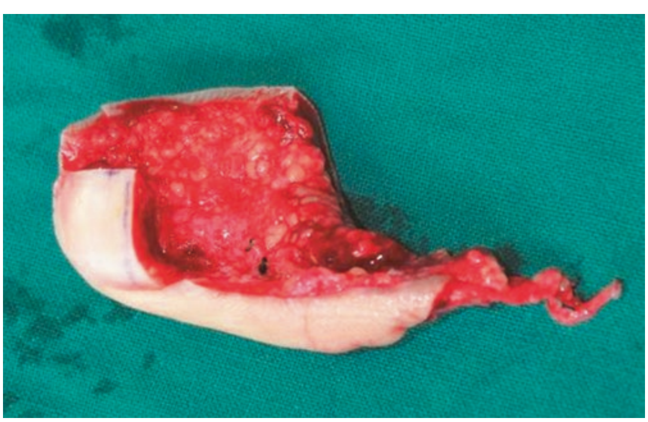


Fig. 7.143 The flap harvested

Fig. 7.144 A reconstructed finger with the flap from the great toe

Fig. 7.145 Harvest of the medial plantar flap

Fig. 7.146 The donor site covered with the medial plantar flap

Fig. 7.147 Flap coverage of the donor site after surgery (dorsal view)

Fig. 7.148 Appearance of the donor site after operation

9. Flaps from the Lower Two-Thirds of the Leg

   We use local flaps based on either anterior tibial artery or peroneal artery to cover donor site defects in some cases. The flaps are designed on the anterolateral or lateral aspect of the leg according to the area to be covered in the great toe. After being dissected distally at an appropriate length, they are rotated to cover the wound on the great toe.

10. Free Vascularized Flaps

    A free vascularized groin flap is used in most of our cases. An anterolateral thigh flap, a saphenous artery flap and a perforator flap from the medial leg are also used. The free groin flap is designed on the inguinal region. An incision is made on the skin proximal to the femoral artery and superficial circumflex iliac artery. Seek for superficial circumflex iliac vein, superficial circumflex iliac artery and its accompanying vein. The flap is elevated and harvested on the deep fascia. The anterolateral thigh flap, saphenous artery flap and perforator flap from the medial leg are designed on the thigh, the upper part of the leg and the middle part from the medial leg according to the results of preoperative Doppler examination.

    These flaps are based on the descending branches of lateral circumflex femoral artery, saphenous artery, perforators of posterior tibial artery and their accompanying veins (or superficial veins).

Key Points

Patients with a finger defect or defects due to injury or congenital deformity all dream of owning a normal finger or fingers and complete toes. Our major efforts over the past decade were to improve the cosmetic appearance of reconstructed digit(s) and to preserve foot function, all the toes, and the cosmetic appearance of the foot. To achieve these goals, we need to address the following technical aspects:

1. Some surgeons use a skin graft (preferably from a concealed area such as the groin) to resurface the wound on the great toe after harvesting the wraparound flap. However, as this approach often requires the great toe to be shortened, it does not meet the goal of ours that the length and cosmetic appearance of the great toe should be preserved.
2. Although various flaps can be used for soft tissue coverage at the donor site, preoperative planning is important. We now mainly use a plantar metatarsal flap and a free groin flap to cover wounds on the great toe after harvesting the wraparound flap. However, as resurfacing the donor site wound on the great toe is challenging, many surgeons do not usually bother with this additional procedure. The choice of flaps should be based on the wound condition, patient's requirement, and proficiency of surgeons. Decisions should be made on a case-by-case basis. Preoperative Doppler is required to detect the pedicle when a perforator flap on the medial side of the leg and a free saphenous artery flap are used. Use of the perforator flap from the medial side of the leg is limited by great variations of the pedicle. Since the groin flap has a concealed donor site and its vascular anatomy is constant, a large flap can be harvested with little donor site morbidity. Limitations of the groin flap include its thick fatty tissue, easy pigmentation after sun exposure, and lack of good sensation. In addition, we have to defat these flaps after transfer.
3. For adequate restoration of digital cosmetic appearance, surgical design is very important in combined transfer. A variety of possible designs are given in the illustrative cases mentioned above.
4. All the reconstructed digits we described and summarized here have survived. All the transfers of toe and other vascularized tissue were performed by highly experienced surgeons, which is an important factor for our high success rate. It typically takes 6–8 h to complete one surgery, with one team for the donor site and the other for the recipient site. Sometimes, we had to anastomose arteries

or veins with very different diameters together, or even vein grafts. However, we saw vascular crisis in a small percentage of the patients. An extreme example is that we had to explore the causes and continue working on vessels in 6 surgeries on 6 consecutive nights for one case. We take extremely active measures for such cases through timely exploration and reanastomosis by a team of surgeons, including performing a vascular graft. Without such extraordinary efforts, we would have been reporting much more failed surgeries.
5. Tenolysis is sometimes required to improve digital joint motion of the hand. Defatting is sometimes a necessary secondary procedure to improve the appearance of the reconstructed finger. Vascularized joint transfer restores the function of the joint. Often the joint can achieve limited recovery of motion.
6. Compared with conventional reconstruction methods, finger reconstruction approaches described above yield better cosmetic appearance, but require a higher level of microsurgical expertise. Therefore, we recommend that only medical units with enough skillful microsurgeons choose the methods to reconstruct fingers.

We have incorporated multiple free vascularized composite tissue transfer into conventional vascularized toe transfer or toe flap transfer for thumb and finger reconstruction. Appearance of the thumb and fingers reconstructed this way is more cosmetic and complications of the donor site are fewer. We acknowledge that technically the surgeries illustrated above are challenging and demanding. However these methods we mentioned above can improve both the cosmetic appearance and function of the recipient hand. These surgeries can also greatly improve the quality of life of patients. We expect that the concept of cosmetic reconstruction of the hand digits by composite tissue grafting can be well realized in clinical practice.

8 Skin Flap and Myocutaneous Flap

Shi-Min Chang, Ying-Qi Zhang, and Xiao-Hua Li

8.1 General Description of Flaps

Flaps, or more accurately and standard termed Surgical Flaps, is a viable tissue block that has its own blood circulation and can survive by itself.

What distinguishes a flap from a graft is an intrinsic blood supply that is responsible for a flap's viability; a graft must rely on diffusion until its vascularity becomes re-established. An intrinsic vascularity confers tremendous flexibility and potential, allowing a flap to supply critical vascularized coverage to complex defects and to restore form and function in nearly unlimited ways.

If the tissue block has cutaneous tissue, it is called skin flap or cutaneous flap. In surgery, flaps are used to repair wound, to reconstruct function, and to restore aesthetic appearance.

Surgical flaps can be classified by it composition, such as skin flaps, fascial flaps, muscle flaps, tendon flaps, bone flaps, periosteal flaps, and composite flaps and combined flaps [1–8].

In terms of structure, every flap is consisted of three parts, i.e. flap base, flap pedicle, and flap proper (Fig. 8.1). The flap proper is the tissue to be transferred, which is the aim of the operation. Flap pedicle is the lifeline of flap proper, which is the metabolic route of flap survival in early stage, and usually composed by artery, veins, nerves and lymphatics. Flap base is the connection site where flaps attached to donor site of the mother body, it is the origin of blood supply.

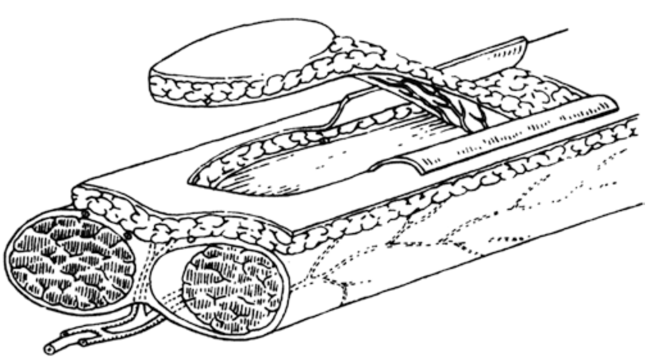


Fig. 8.1 Schematic drawing to show the structure of a skin flap

8.2 Vascular Anatomy of Skin Flaps

The integument of the human body is consisted of cutaneous, subcutaneous adiposal, and deep fascial tissues. Integument vasculature is from the deep segmental source artery. The pathway of integument vascularisation can be simply divided into four origins: (1) direct skin vessels, (2) septocutaneous perforators, (3) musculocutaneous perforators, (4) accompanying vessels of some specific structures in the subcutaneous tissue (e.g. cutaneous sensitive nerve and superficial veins) (Fig. 8.2).

8.2.1 The Direct Cutaneous System of Vessels

This kind of cutaneous vessels is located in certain specific areas such as anatomical fossa, usually accompanied by veins, which run in the subcutaneous fat parallel to the skin surface. These direct cutaneous arteries tend to run in a linear direction for some considerable distance, and when incorporated in a skin flap allow much greater length of survival, and traditionally known as axial pattern flaps (Fig. 8.3).

8.2.2 The Musculocutaneous System

The musculocutaneous flap is a compound flap in which muscle, fascia, subcutaneous fat and skin are combined as one unit of tissue based on one or more vascular pedicle. The blood supply to this unit comes primarily from the supply to the muscle and reaches the skin by vessels which pierce the surface of the muscle, pass through the deep fascia and the

S.-M. Chang (✉) · Y.-Q. Zhang · X.-H. Li
Department of Orthopaedics, Yangpu Hospital, Tongji University, Shanghai, China
e-mail: Shiminchang11@aliyun.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_8

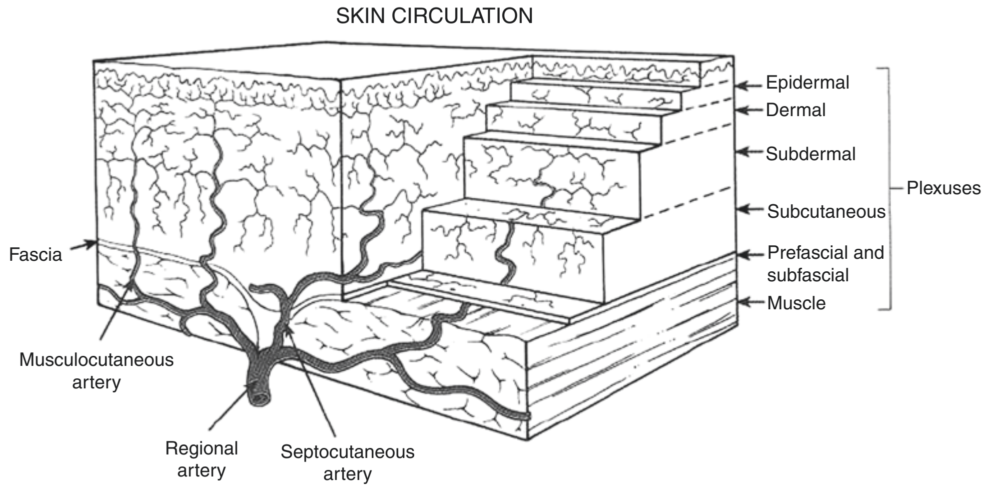


Fig. 8.2 Schematic drawing to show the vasculature of the integument

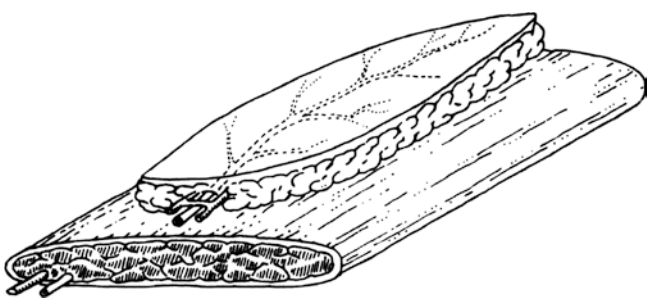


Fig. 8.3 Direct cutaneous vessel and its distribution

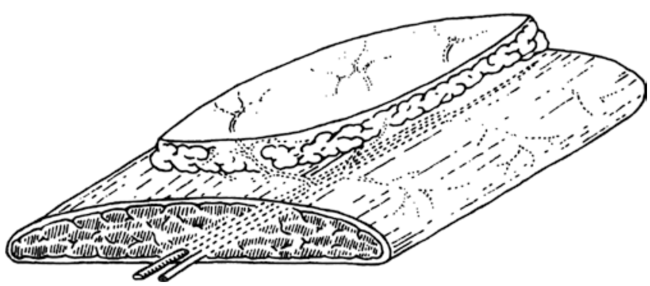


Fig. 8.4 Musculo-cutaneous perforators and their distribution

spread out in the overlying subcutaneous tissue, i.e. musculocutaneous perforators (Fig. 8.4).

8.2.3 The Septo-Fasciocutaneous System

The main blood vessels travel between the slender muscles, branching septa-fascio-cutaneous perforator which nourish deep structures (muscles, bones, nerves, etc.) and the overlying skin. The blood vessels pass through the fascia from the deep to the shallow and distal side, emitting the thick descending branch, the small ascending branches (recurrent branches) and transverse branch (or horizontal branch). There is a rich plexus on the deep fascial surface (Fig. 8.5). The septa-fascio-cutaneous perforator in the proximal side of the limbs reach the shallow layer after traveling a long distance where the intercompartmental septum and intermuscular septum are thick as the main vessels are located deeply. Therefore, there are fewer perforating vessels in the proximal limbs while the caliber is large (sometimes more than 1 mm). On the distal side of the limbs, due to the superficial main blood vessels and thin intermuscular septum, the perforating vessels are closer to the skin. Therefore, the number of perforating vessels is more and the caliber is smaller (mostly below 1 mm). The septa-fascio-cutaneous perforator mainly exists in the limbs. The lifting plane of septocutaneous flap (fasciocutaneous flap) is in the deep fascia, which is the surgical plane where we harvest the flap.

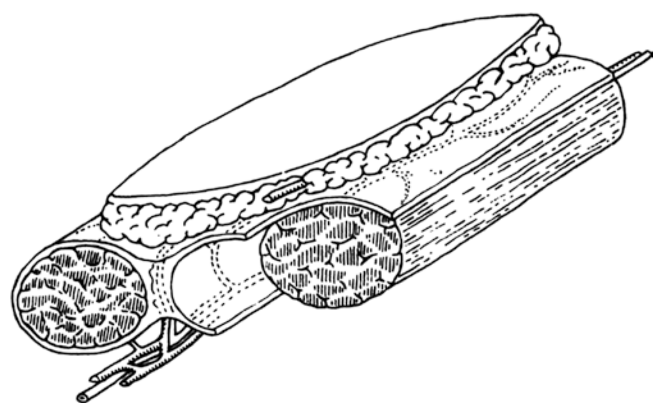


Fig. 8.5 Septo-fascio-cutaneous perforators and their vascular plexus

8.2.4 Paraneural and Perivenous Plexuses

If the integument tissue incorporates some special structures, such as cutaneous sensitive nerve and superficial veins. These structures have their own nutrient vessels which form a rich paraneural plexus and perivenous plexus. These nutrient vessels also give branches to tegumental tissue. These longitudinal vascular plexuses provide the anatomical basis for harvesting large-scale superficial vein in neurocutaneous vascular flaps.

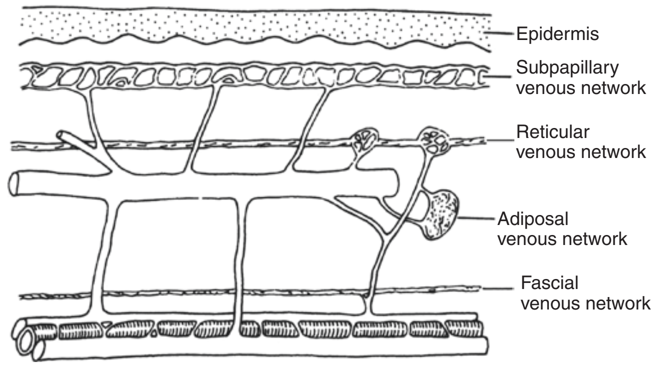


Fig. 8.6 Venous structure of integument

8.2.5 Venous Drainage

Historically, venous drainage of the integument has gained much less attention than it deserves, given that flap failure caused by venous compromise is not uncommon. Venous drainage of the skin and subcutaneous tissue, in anatomical terms, consists of two systems that are interconnected by veins without valves called oscillating veins or bidirectional veins. The first system if the superficial veins from longitudinal subdermal venous plexus. These are large subcutaneous vessels, such as cephalic, basilic, small and large saphenous veins. Their functions are involved with thermoregulation. These superficial systems travel for long distances parallel to the skin surface and are interconnected by avavular channels, pierce the deep fascia near joints, and sometimes connected to the deep veins by venae communicators, which may or may not be accompanied by cutaneous arteries. Superficial venous system often accompanies the cutaneous sensitive nerves. The second system of integument veins is the deep one, which is vertical stellate shaped venae comitantes, accompanies the cutaneous arterial perforators, also called venous perforators (Figs. 8.6 and 8.7).

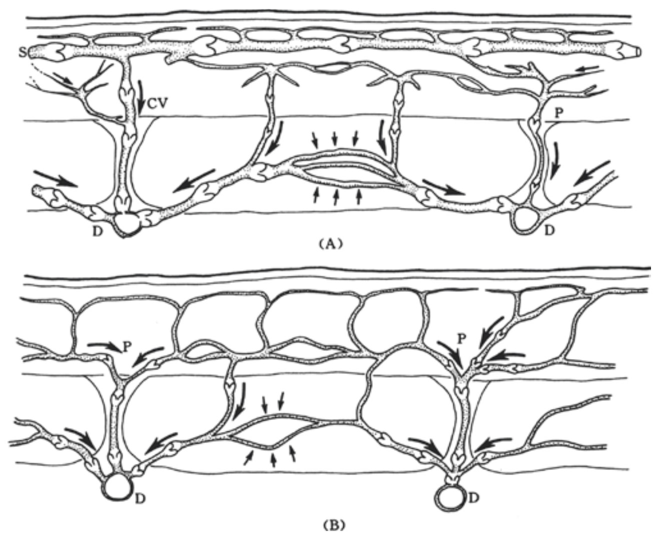


Fig. 8.7 Venous drainage of integument. *A* site with large superficial vein, *B* site without large superficial vein, *S* superficial large vein, *D* deep vein, *P* perforating vein, *CV* venous communicator

8.3 Flap Classification

Classification is a logical method in philosophy and is based on comparison. There are a lot of classifications for surgical flaps, for example based on different vessel types, tissue structures, transportation methods and distances, flap geometric shapes and so on. However, the most important classification is based vessel anatomy, as vascularization is the vital element for flap survival [1–6].

A thorough flap classification can be summarized by six "C": (1) circulation, physiologic or nonphysiologic flap? (2) constituent, which means the tissue composition, myocutaneous or fasciocutaneous, (3) construction, type of pedicle, pedicled transportation or microsurgical free transfer, orthograde flow or retrograde flow, (4) conformation, which means the geometry configuration, triangle shape or ellipsical shape, (5) contiguity, the relationship between the donor site and the wound, local, regional or a distant flap, (6) conditioning, is there any pre-management, for example, delay or skin expansion.

8.3.1 Classification Based on Vascular Anatomy

Based on skin vessel caliber, distribution and the perfusion area, McGregor and Morgan in 1973 proposed a anatomical classification with surgical implications. They categorized skin flaps into two kinds, one is axial-pattern and the other is random-pattern. They also pointed out that a flap survival area depends not only on the vascular anatomic territory, but also on the haemodynamic territory, which is influenced by the law of dynamic pressure equilibrium.

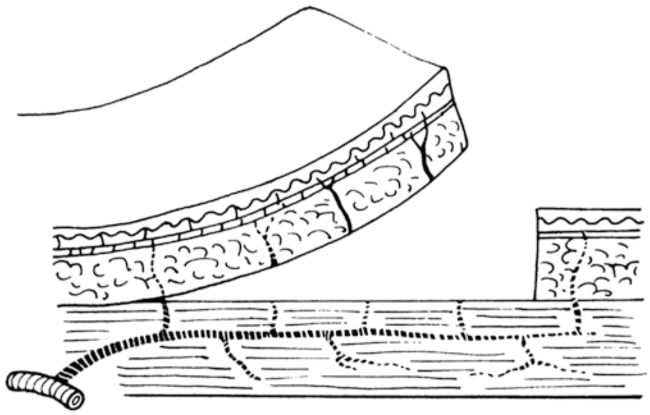


Fig. 8.8 Schematic drawing to show a random-pattern flap vascularization

The random-pattern flap: which is supplied by some dispersed small vascular branches, the design determines its survival, which consists a wide base and less than 2:1 length-to -width ratio of the flap (Fig. 8.8).

The axial-pattern flap: that is nourished by a big isolated artery, for which it can survive in a large scale with smaller pedicle such as vascular bundle, and can be transplanted with microsurgery freely (Fig. 8.9). Currently, there are three types axial-pattern flaps in surgical applications, which are based on direct cutaneous artery, myocutaneous artery, septocutaneous artery, respectively [9–12].

With the further development of flap microsurgery, some new flap transplants have emerged, such as (1) fasciocutaneous flaps which was harvested along the axial longitudinals of the limbs, and (2) (neuro-fasciocutaneous flap, veno-fasciocutaneous flap, neuro-veno-fasciocutaneous flap) (3) (neuro-adipofascial flap, veno-adipofascial flap, neuro-veno-adipofascial flap), these flaps survive with the length to width ratio of more than 5:1, and there is no axial artery in the pedicle. It is necessary to retain a certain width of the subcutaneous fascia pedicle. Chang Shimin et al. discovered the chained anastomotic vascular network between fascial and skin through microsurgical anatomy. In 1994, the concept of link-pattern flap was proposed by him.

On the extremities, the direction of the muscle interval, the fiber direction of deep fascia, and the distribution direction of the cutaneous nerve and superficial vein are all longitudinal along the deep main artery, so the anastomosis between ascending and descending branches of the adjacent perforating artery is abundant and obvious. A chain-linked longitudinal anastomoses exists on the surface of the deep fascia, around the superficial cutaneous nerve and the lower dermis, directing the blood supply channel of local fascia and skin. The direction is as follows: it is longitudinal in the limbs, transverse or oblique in the torso, and radial in the Head and Neck (Fig. 8.10).

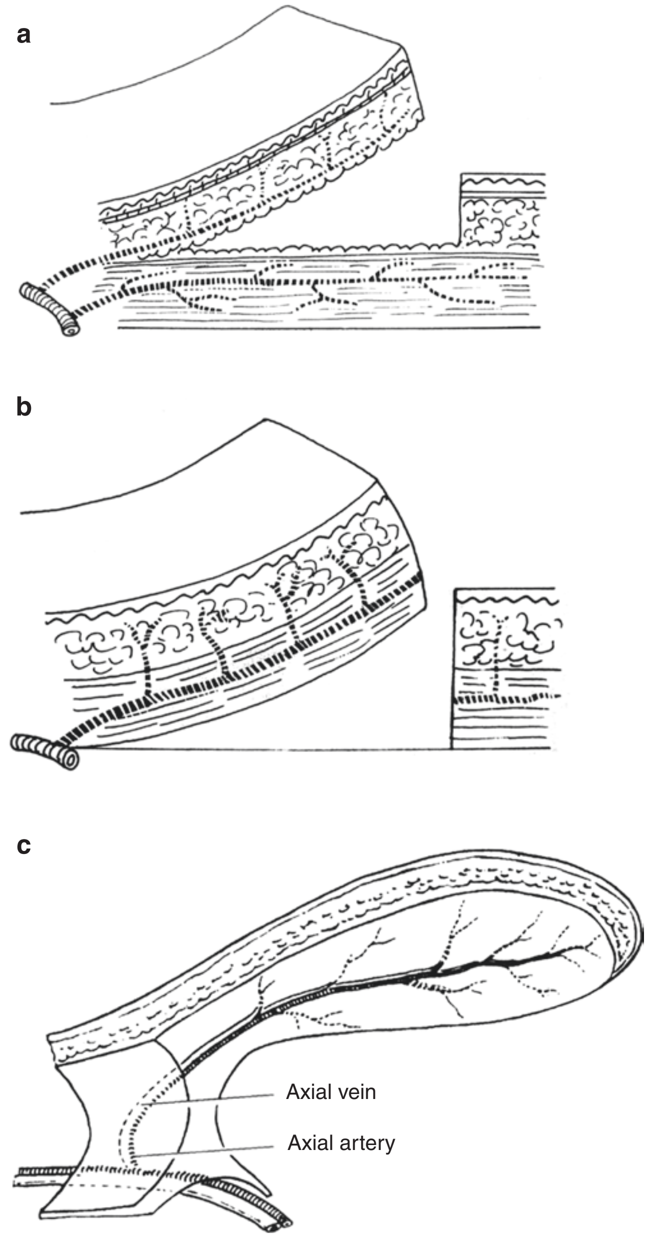


Fig. 8.9 (**a**) Direct skin artery flap; (**b**) myocutaneous artery flap; (**c**) septo-fasciocutaneous artery flap

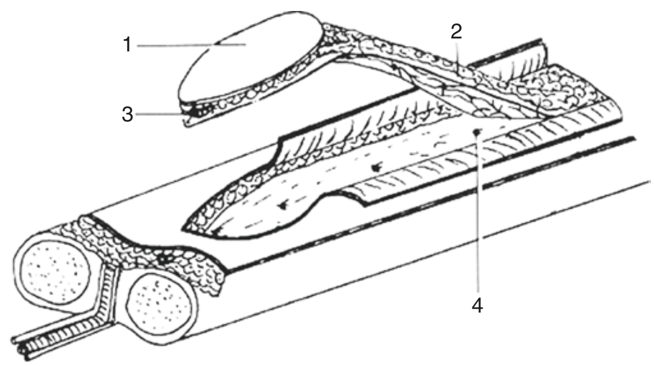


Fig. 8.10 Schematic drawing to show chain-linked vascular plexus and link-pattern fasciocutaneous flap. *1* flap, *2* adipofascial pedicle, *3* cutaneous nerve and vein, *4* perforating vessel

Table 8.1 Comparative characteristics of three types of flaps

	Axial-pattern flap	Link-pattern flap	Random-pattern flap
Vascular basis	Axial single artery	Chain-linked directional vascular plexuses	Random vascular networks
Distributed territory	Vast	Small-medium, potentially enlarged by pressure equilibrium through chain-linked plexuses	Small
Flap size	Large	Medium	Small
Donor site	Specific	Distal extremities	Ubiquitous
Flap axis	Yes	Yes	None
Pedicle axis	Yes	Yes	None
Pedicle width	Narrow, only vascular bundle	At least 3–4 cm to incorporate chain-linked plexuses	Restricted by flap length
Flap length/ pedicle width ratio	On surgeon's will	3~5:1	1.5~2:1
Transposition mode	On surgeon's will, including free	Pedicled, for local and regional defects	Pedicled, for local defects

It can be considered as an intermediate one between axial and random (Table 8.1), which explains the contradiction between the large length-to-width of the flaps and lacking axis vessels in the pedicle.

8.3.2 Classification According to Flap Proper Component

Flap proper is the aim of operation. There are three major types of flaps, subcutaneous-based system, fasciocutaneous-based system, and musculocutaneous-based system.

There are several kinds of flaps with different layers of the integument tissues. From surface to deep, there may be: subdermal vascular plexus flap, also called superthin flap, subcutaneous flap, fasciocutaneous flap, neurocutaneous flap, venocutaneous flap, musculocutaneous flap, tenocutaneous flap, osteocutaneous flap. There are also flaps without the overlying skin, for example, adipofascial flap, fascia-fat flap, fascial flap, myofascial flap, osteo-myo-fascial flap, fascio-periosteal flap, fascio-tendon flap, and etc.

8.3.3 Classification According to the Pedicle

Pedicle is the lifeline and provides vascularization of a flap. There are several types of pedicle according its structure, for example, (1) the axial vascular pedicle, which is the most common for flap surgery, (2) the vascular plexus pedicle such as adipofascial pedicle, cutaneous sensitive neurovascular axis pedicle, and subcutaneous pedicle.

8.4 Clinical Principles of Surgical Flap

Carefully preoperative planning, including the design of flap, may be more important than the actual operation. The selection of the ideal flap is imperative, as otherwise, if chosen incorrectly, the entire reconstructive endeavor may be doomed to failure, no matter how meticulous the surgical execution. Currently, although an overwhelming number of alternative flaps are available, a thorough appreciation of the attributes of different flaps and their usages is critical to deciding which flap is most appropriate for a given defect. Mostly, the candidates are among a limited number of workhorse flaps.

8.4.1 Principles for Choosing a Flap

Clinically, choosing a flap in practice should consider three aspect factors: donor site, the recipient site and the surgeon. Acceptance of morbidity at the donor site must always be tempered by considerations necessary to satisfy the needs of the recipient site.

The following principles should be followed in clinical flap selection:

1. repair the important tissue by less important one,
2. use pedicled flap firstly and free flap secondarily,
3. use branch vessels primarily and trunk vessels secondarily,
4. simple method firstly and complex method secondarily,
5. pay emphasis on donor site cosmetics and functional preservation.

Currently, the changes in the reconstructive ladder are evident. With the widespread success of microsurgery, many defects are reconstructed with the most complex free tissue transfers as the primary option, i.e. jumping straight to the top of the ladder, or directly by elevator [13].

8.4.1.1 The Recipient Requirement

The recipient needs include the wound position, aetiology, size, specific on sensation and muscle strength.

1. Choose adjacent flaps firstly, as they are matching in color, thickness, and simple transposition.
2. Repair with like-to-like. In practice, almost 80% flaps are used to repair simple superficial wounds without deep

osteomyelitis or dead space, so axial-pattern flaps including perforator flaps are most suitable.
3. Design the flap a little bit larger than the defect. As the wound will enlarge after debridement, and the flap will shrink after elevation, the harvested flap should 20% larger than the primary wound.
4. The final design of the flap should occur only after the defect is completely defined. When tumor exposure or wound debridement is required, the defect is often much larger and deeper than initially anticipated. By final design of the flap after debridement, costly errors in inadequate coverage can be avoided.
5. Pay attention to flap sensation reconstruction and functional muscle transfer. For some specific recipient site, for example finger pulp and weight-bearing heel, restoration of flap sensation is essential. For these areas, flap containing a sensory nerve is important and the superficial sensory nerve should be neurorhaphied to a recipient branch to allow axional regeneration into the flap. For muscle dynamic reconstruction, neurovascular myocutaneous flap should be transferred and motor branch neurorrhaphy performed.

8.4.1.2 The Donor Site Consideration

An equally important objective must be to minimize any potential morbidity at the donor site of the selected flap. An ideal donor site should meet the following conditions:

1. The donor skin or muscle is healthy. Excluding previous operation site, radiotherapy site or inflammatory site.
2. There should be minimal donor site sequlea on cosmetics and function. Hidden donor site is of choice.
3. Choose flap donor site with minimal variation on vascular anatomy. Frequent vascular variation increases the surgical difficulty and the risk of failure.

8.4.1.3 Mode of Flap Transplantation

There are two reconstructive options for flap selection and transplantation: climbing ladder or taking elevator (Figs. 8.11 and 8.12). For most wounds, simple and pedicled flap may be an easy and effective method. For specific wound, for example the finger pulp, neurovascular partial toe flap with microsurgical anastomosis may be the best method for functional restoration [13].

8.4.2 Principles in Flap Design

Proper and correct flap design determines the success or failure of the operation. There are four points for correct flap design: pivot, axis, area, and arc [14].

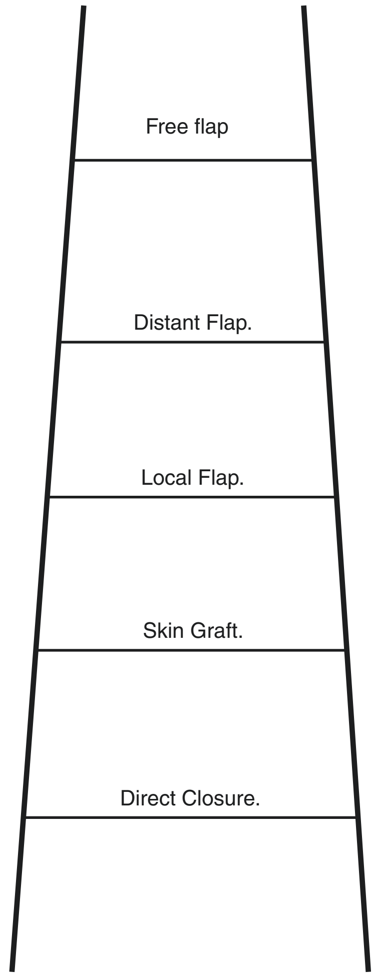


Fig. 8.11 Principle on flap selection: climbing the ladder step by step

1. Pivot point, which is point the vessels enter the flap in anatomy, and the flap rotation site in surgery. Some flaps have two pivot points, proximal and distal, which means the flap can be transferred to proximal or distal recipient site.
2. Axis, which is the vascular axial line in anatomy, and the flap orientation in surgery. Flap should be designed along the vascular axis, or the vascular plexus axis to have a greater survival length.
3. Flap area, which is the vascular supplying area in anatomy and the largest survival size in surgery. Flaps survival area is determined by anatomical vascular angiosome and hemodynamic pressure equilibrium. Flap elevation plane also affects its survival area, for example fasciocutaneous flap has a longer survival than subcutaneous flap from the some donor site.
4. Arc, which means rotation arc in surgery to reach the recipient site. Every wound within this arc can be covered by rotation of this flap. The smaller the rotated torsion on vascular pedicle, the safer the blood supply to the flap.

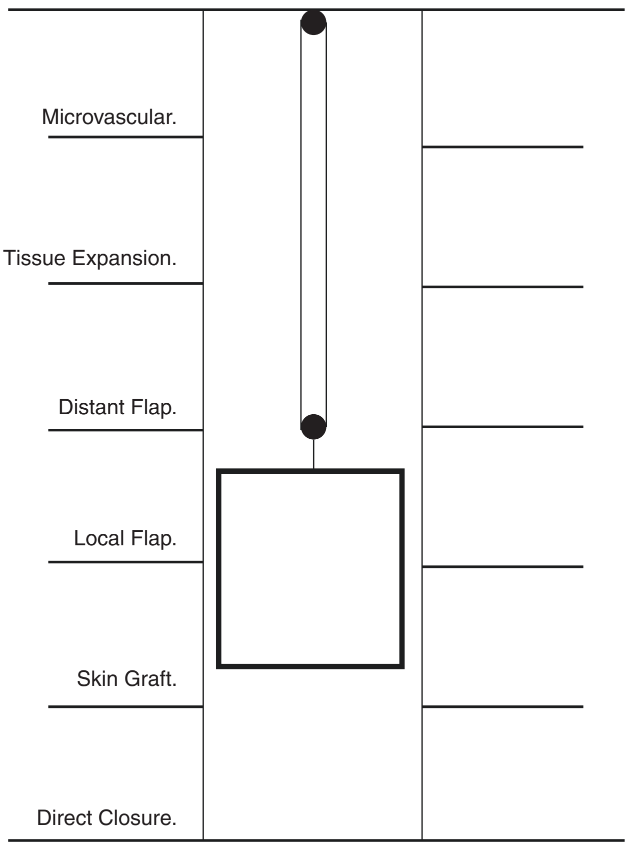


Fig. 8.12 Principle on flap selection: taking elevator

8.4.3 Musculocutaneous System Versus Fasciocutaneous System

Selection of the most appropriate reconstructive method can be difficult. Careful consideration must be given to all the possible methods of repair and the advantages and disadvantages of each technique must be weighed accordingly.

Musculocutaneous flap system and fasciocutaneous flap system are two major flap categories used frequently in orthopaedic microsurgery. Their advantages and disadvantages are compared in the following Table 8.2.

8.5 Techniques in Flap Transfer

The reliability of any surgical flap depends on the maintenance of an adequate blood circulation. There are two options to keep blood flow in continuity: by an uninterrupted vascular pedicle, which is called pedicled flap, local flap, or island flap; or by microsurgical anastomosis after vascular interruption, which is called free flap or microsurgical flap.

8.5.1 Donor Site Preparation

Wounds can be classified into 4 types, new wound after injury, chronic wound with bone or tendon exposure, wounds

Table 8.2 Comparison between musculocutaneous and fasciocutaneous flaps

	Muscle and musculocutaneous flaps	Fascial and fasciocutaneous flaps
Advantages	1. The vascular pedicles are specific and reliable 2. The vascular pedicle is often located outside the surgical defect, which can be particularly important for wounds with an extensive zone of injury beyond the actual wound (e.g., after irradiation, trauma) 3. The muscle provides bulk for deep, extensive defects and protective padding for exposed vital structures (e.g. tendons, nerves, vessels, bones, and prostheses) 4. Muscle is malleable and can be manipulated (e.g. folded on itself) to produce a desired shape or volume 5. Well-vascularized muscle is resistant to bacterial inoculation and infection 6. Reconstruction by use of muscle or musculocutaneous flaps is often a one-stage procedure 7. Restoration of function, whether motor or sensory, is possible with certain flaps 8. The reliability and availability of muscle and musculocutaneous flaps make them an excellent alternative means of reconstruction when the closure method of choice for a particular defect is unavailable or inadequate	1. Thin and pliable 2. Blood supply is reliable and robust 3. Donor site morbidity is minimal in regard to function 4. Muscle sparing 5. Have the ability to restore sensation 6. Many potential donor sites
Disadvantages	1. The donor defect may lose some degree of function 2. The donor defect may be aesthetically undesirable 3. Reconstruction with muscle or musculocutaneous flaps may provide excessive bulk, leaving an aesthetically unacceptable result 4. Muscle or musculocutaneous flaps may atrophy over time and thus fail to provide adequate coverage 5. Removal of the muscle or musculocutaneous flap may result in contour deformities at the donor site	1. Lack bulk for deep defects 2. Technically more challenging (pedicle dissection; many require microvascular anastomosis) 3. Size limitations 4. The arc of rotation is limited 5. Donor site may require skin graft closure, resulting in donor site deformity

as sequlea of surgery such as after tumor resection, and lastly complex wounds with deep structure problems such as osteomyelitis, bone non-union. The former three types wounds are easy to manage.

For the chronic and complex wound, complete debridement is essential prior to flap reconstruction, including infected tissue, sinus, dead space, scare, bone sequestration. The aim is to get a relatively healthy recipient bed for flap.

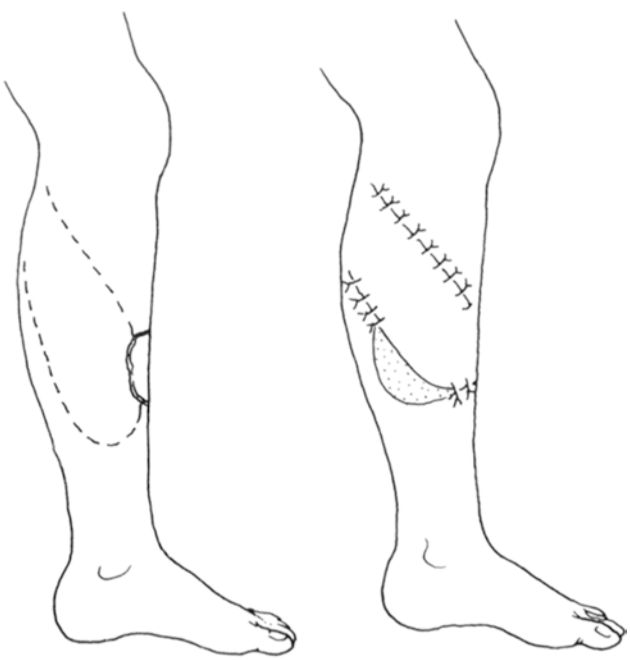
8.5.2 Flap Harvest

Correct flap design depends on several factors, for example, the anatomic knowledge of the vascular pedicle, preoperative ultrasonic Doppler probe and Duplex scanning.

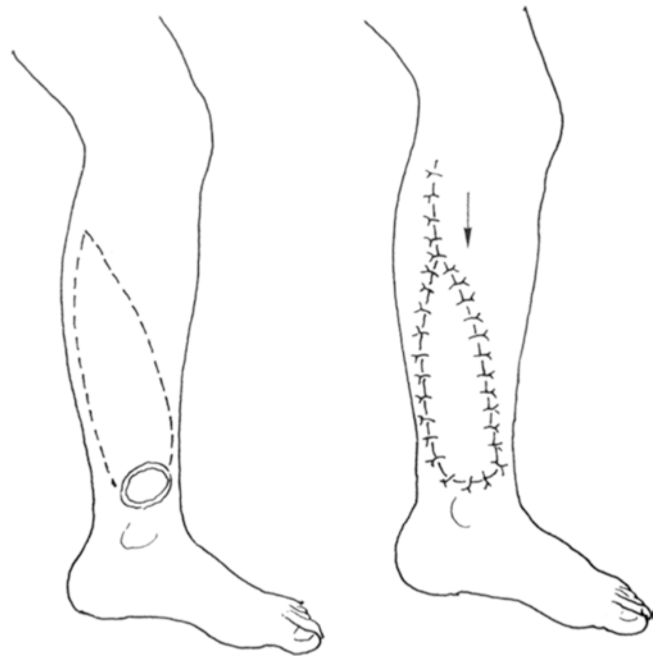
Harvest the flap can be carried out in orthograde fashion (from vascular trunk to perforator branch) or retrograde fashion (from perforator branch to deep trunk).

8.5.3 Flap Transfer

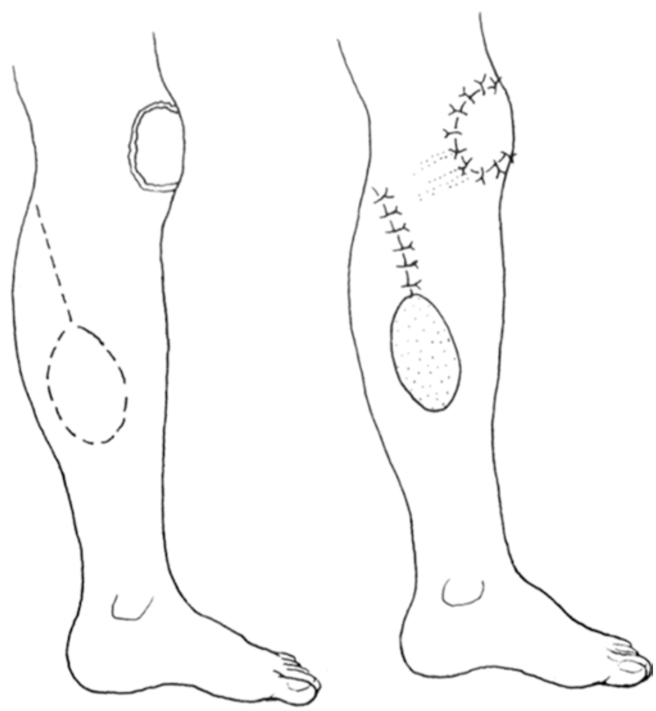
There are five methods to take a pedicled flap from the donor site to the recipient site, including rotation, advancement, interpolation, crossover, and turnover.



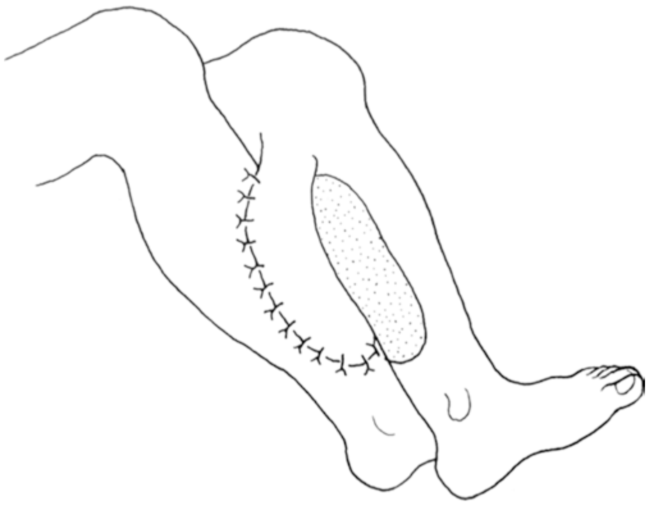
Flap rotation



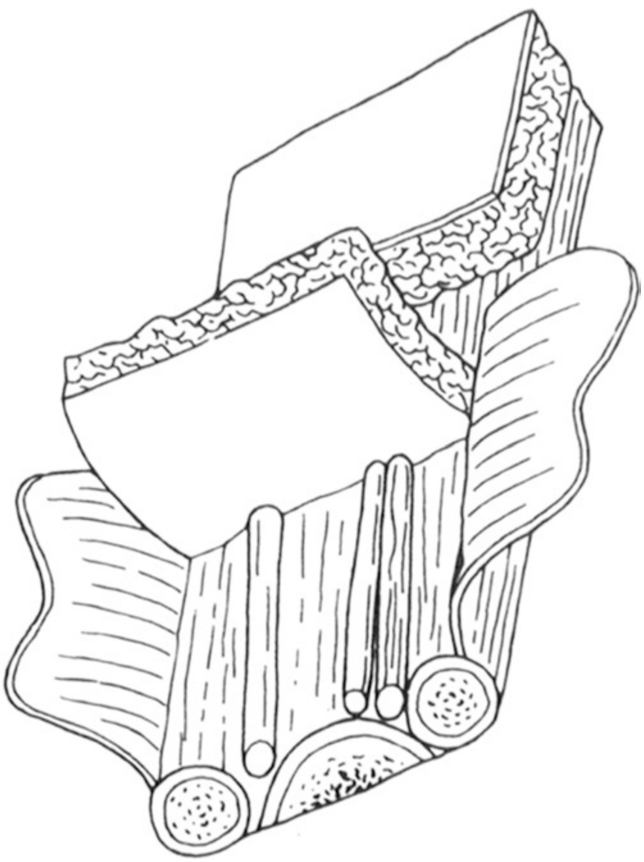
Flap advancement



Flap interpolation



Flap crossover



Fascial flap turnover

8.6 Flap Physiology

Because the viability of a flap depends on its intrinsic vascularity, fully understanding and being able to optimize the vascular physiology of a flap can make the difference between success and failure.

One of the primary normal functions of skin is the thermoregulation, which is accomplished through the regulation of skin blood flow. Heat is dissipated by increasing skin blood flow and is conserved by decreasing skin blood flow. The normal blood flow to skin is approximately 20 mL per 100 g of tissue, while its survival threshold is much less, only 2 mL per 100 g of tissue.

8.6.1 Regulation of Skin Circulation

The vascular supply of a flap includes both macrocirculation and microcirculation components. Both of these are subject to intrinsic and extrinsic factors that can dramatically influence perfusion and hence viability. The major arterial inflow and venous outflow of a flap constitute the foundation from which the microcirculatory beds then provide nutrition and oxygen and carry away carbon dioxide and waste products, thus forming the basis of cellular metabolism throughout the flap. It is at the microcirculatory level where metabolic exchange and the control of perfusion occur, the arterioles, capillaries, venules, and arterio-venous shunts.

The primary regulation of blood flow to skin is at the arteriolar level. The sympathetic tone regulates flow through the precapillary sphincters, arterioles, and arteriovenous anastomoses. When the precapillary sphincters constrict in response to either local or systemic sympathetic tone, blood flow is forced to bypass the capillary bed through arteriovenous anastomoses. In addition, a number of other factors come into play in regulating flap blood flow. These include the systemic central blood pressure and cellular factors within the microcirculation. The endothelium plays a critical role in the regulation of blood flow both through the direct release of vasoactive substances and through its effect on the circulating white blood cells and platelets.

Regulation of cutaneous blood flow occurs at two levels, systemic and local. Systemic control is exerted through neural and humoral regulations, while the neural regulation is predominant. Neural regulation is exerted primarily through sympathetic fibers and α-adrenergic receptors that induce vasoconstriction; β-adrenergic receptors, on the other hand, induce vasodilation. The serotonergic receptors located at arteriovenous shunts, also induce vasoconstriction. They work to regulate the vascular smooth muscle tone at the level of the arterioles and arteriovenous shunts.

Humoral regulation occurs through the action of systemic vasoactive substances on their specific receptors, such as that of epinephrine and norepinephrine on α-adrenergic receptors. Other systemic vasoconstrictors include serotonin, thromboxane A, and prostaglandin F. Counteracting vasodilators include prostaglandin E, prostaglandin I (prostacyclin), histamine, bradykinin.

Local control of blood flow or autoregulation, is through metabolic factors to affect skin blood flow at the local level, include hypercapnia, hypoxia, and acidosis, all of which cause vasodilation.

Physical factors such as local temperature affect the regulation of blood flow. Hyperthermia can increase local blood flow by acting directly on vascular smooth muscle relax, but local high temperature also increases the demand of blood supply as it increases flap metabolic rate.

Rheologic factors also have an effect on flow. Profound anemia can improve rheologic properties and increase flap blood flow; in some studies, it has been shown to improve distal flap survival.

8.6.2 Changes After Flap Elevation

The action of elevating a flap produces profound changes and disrupts the carefully balanced equilibrium that regulates blood flow to tissue. The hemodynamic, anatomic, and metabolic changes that follow flap elevation ultimately determine the outcome. Hemodynamic changes plays the leading role.

Although flow at the base of a pedicle flap is preserved after elevation, flow at the tip of the flap often drops to less than 20% of normal, usually within the first 6 to 12 h. Flow gradually returns to approximately 75% of normal within 1 to 2 weeks and to 100% by 3 to 4 weeks. At the same time that flow is gradually returning to the ischemic portion of the flap by longitudinal flow from the pedicle, additional flow is also returning by inosculation and neovascularization from the bed, which is a significant factor in very thin flap survival.

8.6.3 Flap Failure and Therapeutic Intervention

What causes the distal or peripheral portion to fail in some flaps, whereas in others the entire flap survives perfectly? The answer is multi-factorial, including flap composition (skin or muscle), flap design (too large over its intrinsic angiosome), systemic factors affecting the microcirculation (e.g., hypotension, sepsis, smoking, vasoconstrictors), or physical compression of the flap (e.g., from improper inset, kinking, hematoma).

Pathologically, ischemia-reperfusion injury can cause circulatory crisis, either spasm or thrombosis, or in arterial or in venous. Vascular smooth muscle cell hypersensitivity corresponds to vascular spasm, while endothelium injury corresponds to vascular thrombosis.

By far, the most important factors in optimizing flap viability are proper flap selection and design, meticulous debridement and preparation of the bed, careful flap elevation and inset, and close postoperative clinical monitoring. No drug, device, monitor, or maneuver can overcome poor planning or poor technical execution. Selecting and designing a reliable axial flap with robust, large-vessel arterial and venous flow to the majority of the flap and ensuring the patency of this large-vessel flow through careful dissection and inset will go a long way toward ensuring reconstructive success. The final stages of flap inset and dressing application, as well as postoperative patient positioning, are particularly important to prevention of compromised perfusion. Sometimes, a single poorly placed suture or piece of tape or gauze can lead to tightness or kinking, resulting in the loss of just that portion of the flap required to cover the critical portion of the defect.

A series of pharmacologic agents have been reported to improve perfusion and flap survival. These include vasodilators, steroid, heparin, aspirin, dextran, and others. Many of these have significant efficacy in experimental studies but have not yet shown predictable clinical efficacy; therefore, few are in widespread clinical use. It is hoped, however, that some of the promising therapies currently under investigation will someday provide important adjuncts to flap surgery.

8.7 Fasciocutaneous Flap and Its Variations

Fasciocutaneous flap concept was introduced by Ponten in 1981 from the viewpoint of flap constitute, as it included the deep fascia in flap structure. Fasciocutaneous flap also included the abundant suprafascial vascular plexus, so a random-pattern flap can survive to a length-to-breath ratio of 3:1 to 5:1 [1, 2].

8.7.1 Chain-Linked Vascular Plexus

Fasciocutaneous flap refers to a type of local pedicle flap that contains deep fascia structure and its vascular network plays an important role in flap survival. The fasciocutaneous flaps generally contain a multi-layered arterial network, from shallow to deep: skin papillary layer, subpapillary layer, deep dermis, superficial fascia, deep fascia upper and lower layers, and fascial septum vascular network. A dense directional plexus is formed in the body of the limb. Among the multi-layered vascular networks in which the body is organized, the deep fascia vascular network, the subdermal vascular network, and the vascular network around the cutaneous nerve are the most densely, and they are the basis of many long surgical flaps to survive. In the body, the adjacent muscle space, the ascending branch and descending branch of the arteries that go through the intermuscular space are interconnected on the deep fascia surface to form an interlinked and longitudinal chain vascular anastomosis. Some studies have shown that these longitudinal chain-linked longitudinal vascular plexus is mainly composed of arterioles, venules and thoroughfare or preferential channel histologically, and its vascular resistance is low. According to the hemodynamic Poiseuille law, the same blood flow pressure can infuse more blood flow under low-resistance conditions (blood flow Q = pressure P/resistance R); and before reaching a new hemodynamic equilibrium, the same pressure of blood along this low-resistance chain vascular plexus can run a long distance. Therefore, clinically, when designing the fasciocutaneous flap, the directionality of the vascular plexus must be considered to determine the long axis of the flap [15, 16].

8.7.2 Flap Variation in Constitutes

In theory, integument tissues consist of many components, including adipocutaneous, subcutaneous, fasciocutaneous, fascial or adipofascial. Especially, if the flap assembly comprises a subcutaneous adipose tissue layer, it may or may not be accompanied by superficial sensory nerves and/or large cutaneous veins, which is called neurocutaneous flap and venocutaneous flap. The most common used flaps clinically are fasciocutaneous flaps, adipofascial flaps, and subcutaneous flaps.

8.7.3 Indications for Fasciocutaneous Flaps

When choosing a technique for reconstructive purpose, surgeons always look for a simple and safe procedure with minimal morbidity at the donor site. From an identical donor site, both fasciocutaneous or myocutaneous flap can be harvested. How to choose in clinical practice? Generally speaking, fasciocutaneous flap is thinner than myocutaneous flap, which is more suitable for superficial wounds [17, 18]. Myocutaneous flap is usually bulky and high metabolic, which is more suitable for deep wound, complicated wound, and osteomyelitis wound (Fig. 8.13).

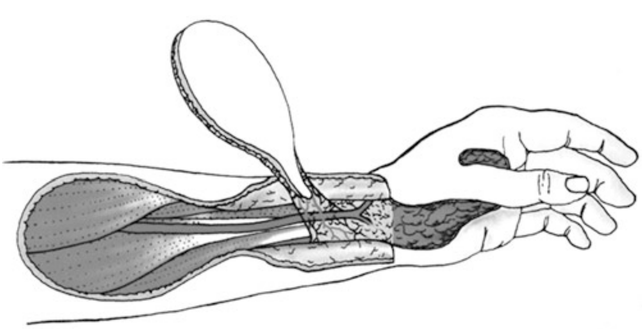


Fig. 8.13 Distally based neurofasciocutaneous flap from the radial forearm

8.7.4 Adipofascial Flap

Adipofascial flap refers to the composition of the tissue flap which is in addition to the deep fascia, it also includes more and thicker subcutaneous loose adipose tissue. The deep and superficial planes of the anatomy are the deep subfascial space and the superficial layer of subcutaneous loose tissue respectively.

Subcutaneous loose tissue is the main residence of the blood vessels. Considering the blood supply of the tissue flap and the survival of the skin flap after the donor site is removed, it is most reasonable to use the adipofascial flap on the deep and shallow anatomical plane of the tissue flap. It not only contains the rich vascular network of the body tissue in the tissue flap to the maximum extent, but also considers the survival of the donor skin, retains the integrity of the subdermal vascular network, and takes the advantages of fascial flap and subcutaneous tissue flap. (1) The deep fascia is an obvious anatomical landmark. The deep layer of the tissue flap is dissected in the loose tissue space under the deep fascia. It is not only easy to operate, but the layers are easy to grasp, and the bleeding is less. So the deep fascial space is called the "surgical plane." (2) When dissecting, the loose tissue under the deep fascia is taken. After the tissue flap is reversed and displaced, the deep fascia vascular network is a good recipient of free skin graft, and the survival of the skin is guaranteed. (3) The dermis layer is also an obvious tissue-level mark. It is close to the dermis when dissected. It is carried out in the shallow layer of the loose tissue under the skin. Only a small amount of fat particles are retained on the separated skin flap. The layers are easy to grasp. The tissue is not too deep to damage the subcutaneous tissue vascular network of the tissue flap, and at the same time it is not too shallow to damage the subdermal vascular network of the donor skin flap (Table 8.3).

Table 8.3 Comparison between fasciocutaneous and adipofascial flaps

	Fasciocutaneous	Adipofascial
Donor site		
Small or narrow flap	√	
Large or wide flap		√
Sensation preservation		√
Recipient site		
Pressure bearing	√	
Vital structure exposure		√ (Turnover)
Tenolysis or tenorrhaphy		√ (Turnover)
Neurolysis or neurorrhaphy		√ (Turnover)
Sensation reconstruction	√	

8.7.5 Neurofasciocutaneous Flap

The concept of neurocutaneous flap was introduced in the hand by Bertelli in 1991, and in the lower leg by Masquelet in 1992. In 1996, Chang pointed out that the neurocutaneous flap in essence is a specific kind of fasciocutaneous flap, and named them fasciocutaneous neurovascular flap, or neurofasciocutaneous flap [16].

Neurofasciocutaneous flap is perfused by perforators from the deep artery that enter the flap at its base and the interlinking anastomoses of the severed perforators that aligned into longitudinal pattern on the deep fascia as well as around the cutaneous superficial sensory nerve. It is no need to verify the existence of perforators at the attachment base, because chain-linked suprafascial and paraneural vascular plexuses are perfused so well that they are sufficient to support a flap with greater length to width ratio, even 5:1. The neurofasciocutaneous pedicle should be at least 3–5 cm in width to contain the chain-linked longitudinal vascular plexuses.

Table 8.4 Muscle vascular types and examples

Types	Vascular pedicle pattern	Muscle examples
Type 1	One vascular pedicle	Abductor digiti minimi (hand), Gastrocnemius (medial and lateral heads), Tensor fascia lata, Vastus lateralis femur
Type 2	Dominant pedicle and minor pedicle	Abductor digiti minimi (foot), Abductor hallucis, Brachioradialis, Coracobrachialis, Flexor carpi ulnaris, Flexor digitorum brevis, Gracilis, Hamstring (biceps femoris), Peroneus brevis, Peroneus longus, Platysma, Rectus femoris, Soleus, Sternocleidomastoid, Trapezius, Triceps, Vastus medialis
Type 3	Two dominant pedicles	Gluteus maximus, Pectoralis minor, Rectus abdominis, Serratus anterior, Temporalis
Type 4	Segmental vascular pedicles	Extensor hallucis longus, External oblique, Flexor digitorum longus, Flexor hallucis longus, Sartorius, Tibialis anterior
Type 5	One dominant pedicle and secondary segmental pedicles	Latissimus dorsi, Pectoralis major

8.8 Musculocutaneous Flaps and Muscle Flaps

Musculocutaneous flap or myocutaneous flap, is a kind of flap that its survival depends on the underlying muscle from the tiny musculocutaneous perforators. Musculocutaneous flap is a compound flap containing the muscle and the overlying tissues, including deep fascia, adipose, and skin. Currently, these musculocutaneous perforators can also survive an axial skin flap, which is called musculocutaneous perforator flap.

Muscle flap harvests the muscle merely without the overlying cutaneous components.

8.8.1 Vascular Classification of Muscles

The type of muscle vasculature determines the fate after its transplantation. Mathes and Nahai in 1981 classified muscle vascularization into five patterns. The classification was based on following anatomic relationships between the muscle and its vascular pedicle, (1) the regional source of the pedicle entering the muscle, (2) the number and size of the pedicle; (3) the location of the pedicle with respect to the muscle's origin and insertion; and (4) the angiographic patterns of the intramuscular vessels (Table 8.4).

This classification system enables the surgeon to categorize the various muscle and musculocutaneous flaps into distinctly different, clinically applicable groups based on the vascular anatomy (Fig. 8.14).

8.8.2 Indications for Muscle and Musculocutaneous Flaps

The specific characteristics of muscle and musculocutaneous flaps are, (1) muscle provides bulk for deep, dead space, extensive defects and protective padding for exposed vital structures, (2) muscle has abundant blood supply and high metabolic rate to resist to bacterial inoculation and anti-infection, (3) muscle has dynamic contraction if the motor innervations is restored as functional muscle transplantation.

Many muscle flaps may be designed for both wound coverage and dynamic functional transfer. For dynamic function to be preserved, the motor nerve must be preserved along with dominant vascular supply, the muscle must be reattached to a new bone or tendon across a joint, and the muscle must exert a direct force on its new point of attachment. Muscles that suitable to provide both coverage and function, include the latissimus, gluteus maximus (partial), gracilis, gastrocnemius, and serratus muscles. Restoration of the original muscle length-to-width ratio and repair of the motor nerve to a suitable receptor motor nerve at the recipient site are essential for restoration.

8.8.3 Clinical Principles of Muscle and Musculocutaneous Flaps

General guidelines for muscle and musculocutaneous flaps transportation are as follows.

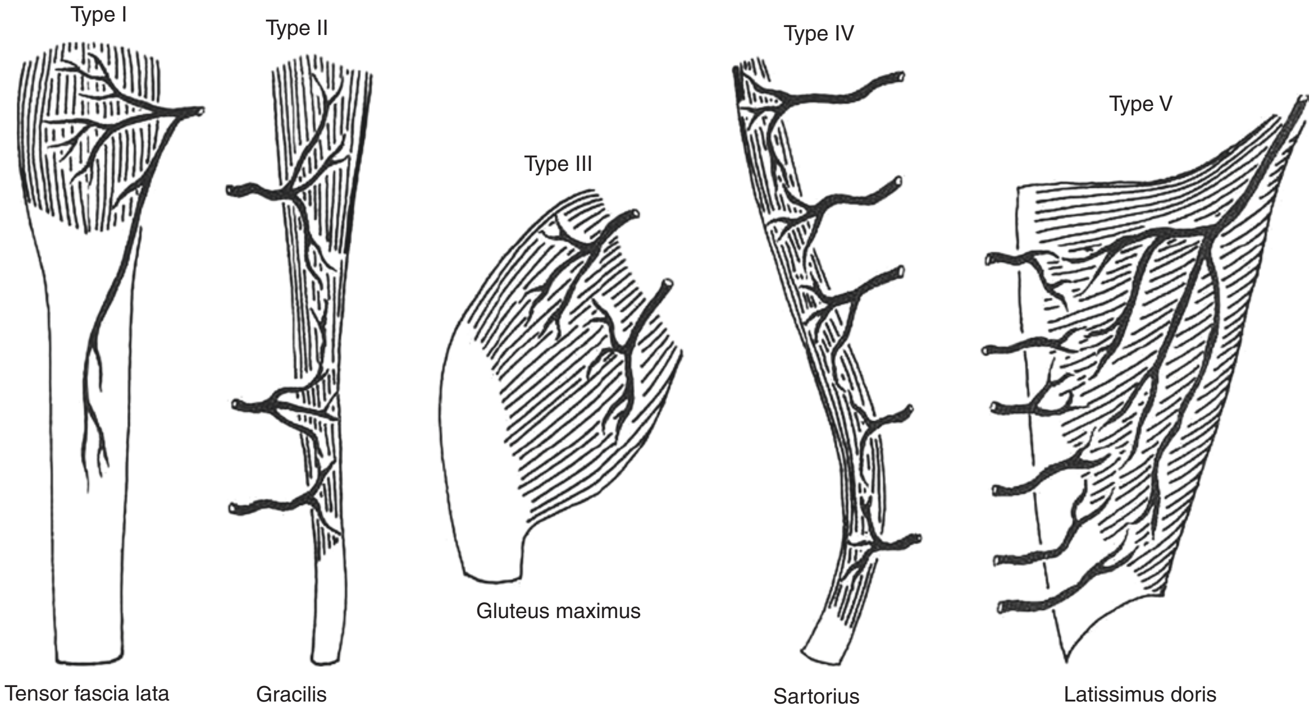


Fig. 8.14 Mathes-Nahai classification of muscle and musculocutaneous flaps according the patterns of vascular anatomy

1. Ideally, the muscle should be adjacent to the defect.
2. The muscle should be of sufficient size and bulk to cover the defect. One must also take into consideration that a significant amount of atrophy occurs if the origin, insertion, or motor nerve of the muscle is disrupted.
3. The muscle should be expendable. There are often synergistic muscles that can compensate for the loss of the selected muscle so that the donor site is not impaired. However, if no synergistic muscle groups are available, either techniques to preserve donor muscle function (e.g. muscle splitting) should be employed or a different muscle chosen.
4. The status of the vascular pedicle that will sustain the proposed flap must be known preoperatively. Selective arteriography may be considered if there is a history of previous surgery in proximity to the vascular pedicle of the proposed muscle flap or if muscle paralysis is noted on physical examination.
5. The cutaneous territory of the proposed flap must be of sufficient size and of acceptable texture. The harvested skin should be an acceptable match to the recipient site (e.g., not hair bearing).
6. If restoration of sensation or motor function is necessary, a select number of muscle, musculocutaneous, and fasciocutaneous flaps are available. Common examples of muscles that provide sensation or restore motor function are the gracilis, serratus, rectus abdominis, and latissimus dorsi.
7. Osteomusculocutaneous flaps are available for defects in need of vascularized bone in addition to soft tissue. Examples include iliac osteomusculocutaneous flap based on the ascending and transverse branches of the lateral circumflex femoral system, latissimus dorsi-scapular osteomusculocutaneous flap.

8.8.4 Muscle and Musculocutaneous Flaps in Lower Leg Reconstruction

Reconstruction of the lower extremity remains particularly challenging. Defects including exposed joints and prostheses, infected bone, and fractures are common. Furthermore, the availability of adequate soft tissue for coverage is limited, particularly in the lower third of the leg.

As the function of human lower limb is mainly weight bearing with standing and walking, muscles of the lower limb play their role mostly of stability rather than dexterity. These muscles are strong and often have synergistic muscles. So muscle flap are used frequently in the lower limb.

Two local sources of muscle or musculocutaneous flaps are available for reconstruction of the leg, one is the gastrocnemius, the other is the soleus.

The gastrocnemius is a type I muscle consisting of a medial and a lateral head. Each head has a wide arc of rotation based on its single vascular pedicle (medial or lateral sural vessels). The gastrocnemius muscle or musculocutaneous flap is the flap of choice for coverage of the knee and for coverage of exposed bone or orthopedic hardware involving the upper two thirds of the leg. Defects of the middle third of the leg can also be reconstructed with the gastrocnemius muscle.

The soleus muscle flap is used for reconstruction of defects involving the middle third of the leg. The soleus muscle is the prime ankle plantar flexor, and it serves to stabilize the ankle in ambulation by opposing dorsiflexion. Because of compensatory mechanisms, the use of the soleus muscle as a flap does not impair function at the donor site. Function-preserving technique, such as muscle splitting, is recommended if the soleus is used in a patient who does not have a functional medial and lateral gastrocnemius muscle. in the lower third of the leg, the soleus muscle can be used as a proximally or distally based flap. In this region, however, the soleus muscle flap is generally used for smaller defects. Larger defects require microvascular tissue transplantation.

8.9 Perforator Flaps

Perforator flap refers to the island flap that only supplies blood through the small perforating skin blood vessels (the diameter of vessels penetrating the deep fascia is still ≥0.5 mm), which belongs to the category of axial blood vessels (Fig. 8.15).

8.9.1 Perforating Blood Vessels of the Skin

From an anatomical point of view, the blood supply of human skin comes from the deep source artery. The source artery nourishes the skin, subcutaneous tissue, and deep fascia through three pathways, including direct skin arteries, perforating arteries, and nutrient vessels accompanying superficial cutaneous nerves. The perforating artery refers to the artery that enters the skin through the deep fascia. The perforating artery can be divided into two types according to its origin, including musculocutaneous perforator and septocutaneous perforator. The musculocutaneous perforator passes through the deep muscles and then passes through the deep fascia to the skin (indirect perforator), which is present in the flat and wide muscles, such as the torso and the proximal limbs of the limbs. After deep fascia, a long vascular pedicle can be obtained by tracking the anatomy deep into the muscle. The septocutaneous perforator passes through the intermuscular space and passes through the deep fascia to the skin (direct perforator). The septocutaneous perforator is often present in the muscle compartment of the limbs, and the muscles of the limbs are generally slender. After the separation of the muscles, the perforating vessels can be seen from the deep main artery.

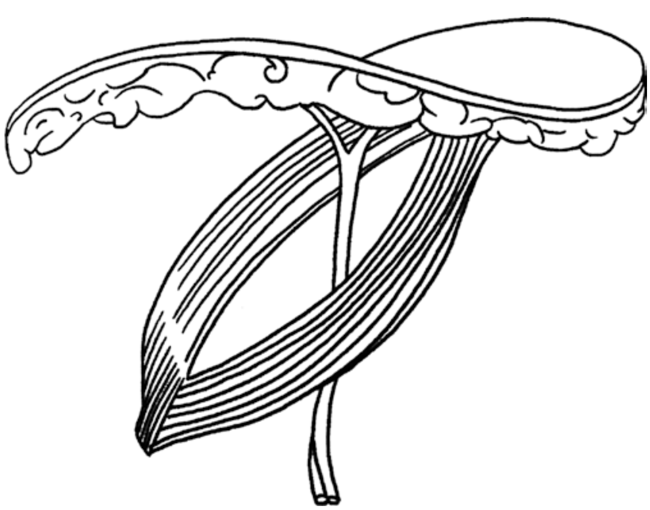


Fig. 8.15 Schematic diagram of perforator flaps

8.9.2 Classification of Perforator Flaps

Corresponding to vascular anatomy, there are two types of perforator flaps: (1) Septocutaneous perforator flap. (2) Musculocutaneous perforator flap [6].

8.9.2.1 Musculocutaneous Perforator Flap

In 1989, Koshima and Soeda first reported the free flap supplied by the musculocutaneous perforator and holded that the deep fascia vascular network did not work on the blood supply. In 1994, Allen and Treece further developed this technique, removing the perforator flap of the same perforating vascular pedicle for breast reconstruction, which is called the deep inferior epigastric artery perforator flap (DIEAP). It has been the basic surgical method of breast reconstruction.

8.9.2.2 Septocutaneous Perforator Flap

There are a lot of similarities between septocutaneous perforator flap and fascial flap, both of which have deep fascial blood networks. The caliber of septocutaneous perforator is about 1 mm. Distally-based flap with the septocutaneous perforator as the pedicle artery can be performed local transferring, which is valuable for repairing the defect of hand and foot.

8.9.3 Donor Site of Perforator Flap

Being a donor site for perforating free flap should have four conditions: (1) Preoperatively predicting a constant supply of blood vessels in the donor site; (2) There is at least one large perforating vessel, and the diameter of the artery after passing through the deep fascia is still sufficient for microsurgical anastomosis (≥0.5 mm); (3) Deep dissection can obtain sufficient vascular pedicle length; (4) There is no excessive tension after the skin of the donor area is directly suture closed.

The distribution of cutaneous perforator vessels has the following rules: (1) the blood supply to the torso is mainly from the musculocutaneous perforator, which is related to the number of flattened muscles in the torso; (2) The blood supply of the limb skin mainly comes from the perforator vessels in the intermuscular septum, which form a multi-layer vascular network in the skin, mainly distributed on the surface of the deep fascia; (3) The distribution of the perforator flap follows the typical "pressure equilibrium" rule [19], that is, the normal blood supply in a particular area is basically stable. Supplementary vessels are compensatory for each other in terms of caliber and spacing: if the caliber of one vessel is small, the adjacent another vessel is large, and the spacing is shortened accordingly; (4) The number of perforator branches per unit area is inversely proportional to the degree of skin movement, that is, the number of perforator branches is less in the parts with large skin mobility, while the number of perforator branches is more in the parts with close contact between skin and deep tissue (such as palm); (5) The distance (length) of the perforating branch and the size of the perforating diameter in the skin are proportional to the skin mobility and the supply area of the perforating branch. For example, the skin in the inferior abdominal inguinal region and the inner side of the arm is slack, and has a longer distance for the perforating vessels.

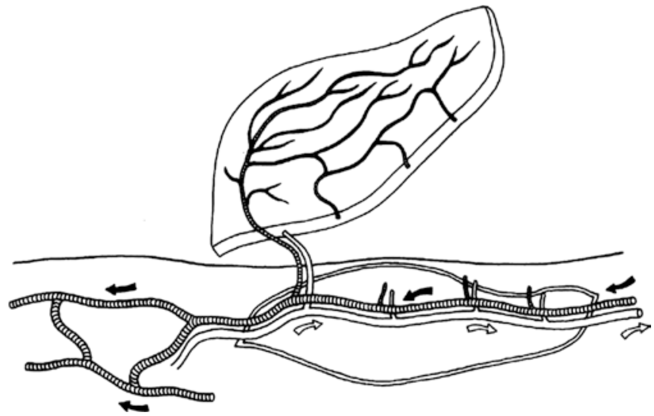


Fig. 8.16 Schematic diagram of the distal pedicle flap

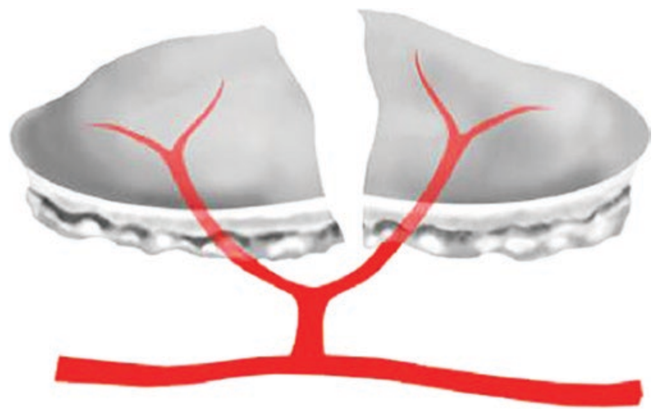


Fig. 8.17 The bilobal perforator flap

8.9.4 Clinical Application of Perforator Flap

The clinical application of perforator flaps can be divided into pedicle transfer and free transplantation.

8.9.4.1 Pedicle Transfer

The perforator flap with pedicle transfer also belongs to the septocutaneous perforator flap. The main donor area is in the limb, and it has many clinical applications. The distal pedicle flap, whose blood is supplied by the furthest lateral septal perforator from the main artery of the extremities (about 5 cm on the wrist and ankle). It includes the fasciocutaneous flap and the cutaneous nerve superficial venous vascular fascial flap, and is widely used in the reconstruction of limb trauma defect (Fig. 8.16).

8.9.4.2 Free Transplantation

Perforator flaps of free transplantation are mostly musculocutaneous perforator flaps, and the main donor area is in the trunk. The diameter of the perforating vessel is generally about 1 mm, and the vascular anastomosis has high safety. The proximal intermuscular perforator vascular flap (for example, the lateral muscle septum perforator flap of upper arm) or the deep peroneal artery perforator vascular flap has been applied clinically.

8.9.5 Multi-paddle Perforator Flap

A set of perforator flaps comprising a plurality of independent flaps (skins) of the same species but collectively originating from a larger superior maternal vascular pedicle are cut in the same vascular region (donor region). So if only one set of vascular pedicles are anastomosed (i.e., the maternal blood vessels), more than two flaps can be transplanted, including the bilobal perforator flap (Fig. 8.17) and the trilobal perforator flap.

The perforator lobulated flap is mainly used for the followings: (1) a special type of defect, such as the palmar and back of the hand and foot, or the pierced or penetrated defects of the inside and outside of coelomic cavity; (2) there are multiple independent but adjacent wounds in the receiving area; (3) The wound area of recipient site is huge, and as well to pursuit that the donor area can be directly stitched.

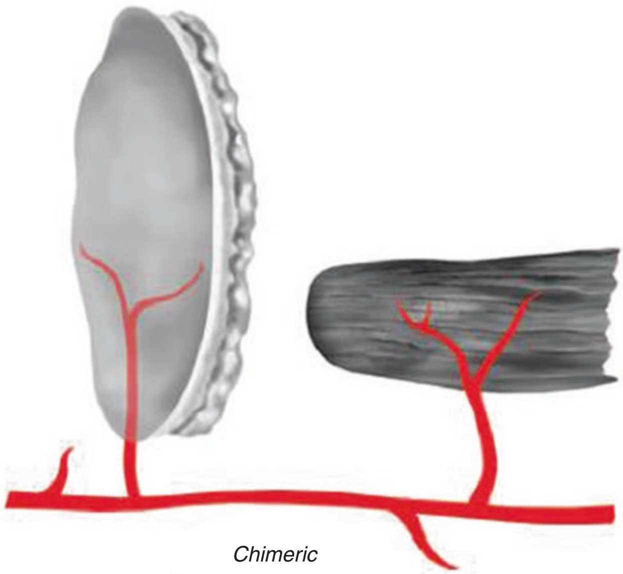


Fig. 8.18 Chimeric perforator flap

Fig. 8.19 Conjoint perforator flap

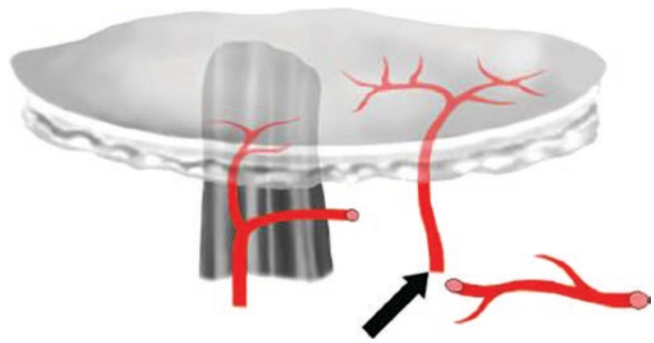


Fig. 8.20 Supercharge

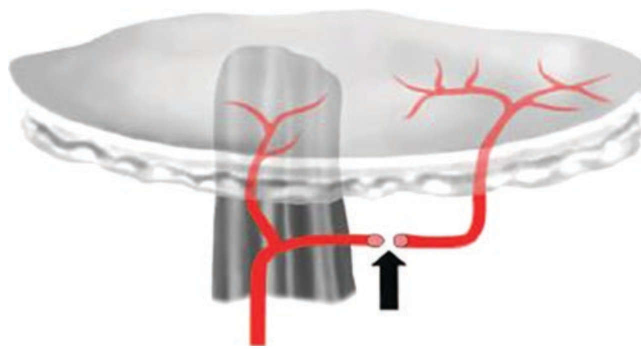


Fig. 8.21 Turbocharge

8.9.6 Chimeric Perforator Flap

Chimeric perforator flap, one kind of compound flap, is a group of perforator flaps separated from the same vascular body area (donor area) (Fig. 8.18), which containing a number of different types of independent tissue flaps (such as muscles, skin, bones, etc.) but originating from a larger parent vessel pedicle. More than two tissue flaps can be transplanted by anastomosing just one set of vascular pedicle (i.e. maternal blood vessels). The chimeric perforator flap can repair multiple tissue defects (skin, bone, muscle, etc.) in the recipient area at the same time.

8.9.7 Conjoint Perforator Flap

When the area of the flap exceeds the blood supply capacity of any vascular pedicle, the blood circulation must be reconstructed on the opposite side (Fig. 8.19) because of the continuity of the tissue structure of the transferred flap.

In clinic, all conjoint perforator flaps are mega flap. They usually reserve the vascular pedicle of one side and cut off the opposite side to obtain a huge rotating arc. But in order to ensure the survival of the flap, the distal flap needs to be anastomosed to reconstruct microvascular augmentation. If the distal perforator vessel is anastomosed with the recipient vessel outside the flap, it is called supercharge (Fig. 8.20), including arteriovenous, single artery, and single venous anastomosis, the latter is also called super drainage; if it is anastomosed with another branch of the proximal vascular pedicle of the flap, it is called turbocharge (Fig. 8.21). The conjoined perforator flap is mainly used to repair the wound with large area.

8.9.8 Flow-Through Perforator Flap

The superior parent blood vessel (source blood vessel) of perforator was used to repair the wound, to reconstruct the main blood vessel in the recipient area, or to provide the vascular anastomosis site for other tissue flaps. Also known as sequential flap or chain-link flap. The front flap is the recipient area of the posterior flap and bridged its blood supply. Therefore, it is also called bridge flap. The feature is that the vascular pedicle is longer and thicker, and can be anastomosed at both ends. Series flaps consist of forward series (referring to the normal flow of arterial blood flow in the flap as a vascular bridge), reverse series (the reverse flow of arterial blood flow in the flap as a vascular bridge) and bridge cross-series (as a vascular bridge flap, crossing across both limbs), which have been widely applied by Chinese scholars, such as Yu Zhongjia and Pei Guoxian have reported before.

8.9.9 The Merits and Drawbacks of Perforator Flap

The merits of perforator flap are: (1) no muscle cutting, no effect on motor function; (2) sometimes deep fascia is not cut; (3) less damage to the supply area and no damage to the shape of the supply area; (4) the design is flexible and can contain subcutaneous adipose tissue according to the needs of the recipient region; (5) patients recover quickly after surgery and their hospital stay is shortened.

The drawbacks of perforator flap are: (1) it is time-consuming to trace the anatomical vascular pedicle; (2) higher requirements for the microsurgical techniques of the operators; (3) there are variations in the site and caliber of perforator vessels; (4) small blood vessels are more likely to be pulled or twisted, and vasospasm is more likely to occur.

8.9.10 Nomenclature of Perforator Flap

In the early stage of the development of perforator flap, the name was confused. Many authors put forward their own methods. Most of them prefixed the name of perforator flap with qualified nouns, such as donor site, trunk artery, deep muscle, et al., that is, "anatomical site + perforator flap", "deep trunk artery + perforator flap", "deep muscle + perforator flap" and so on.

In September 2001, an international expert on perforator flaps held a symposium in Gent, Belgium, and put forward the principles of naming: (1) origin vessel + perforator flaps, such as inferior epigastric artery perforator flaps, thoracodorsal artery perforator flaps, superior gluteal artery perforator flaps, etc. (2) If multiple perforator flaps can be harvested from the source vessels, they are named by the methods of "anatomical site + perforator flap" and "deep muscles + perforator flap". For example, the lateral circumflex femoral artery can support multiple perforator flaps. The names of these flaps are "fascia lata perforator flap" and "anterolateral femoral perforator flap".

Clinical nomenclature: The clinical application of perforator flap is mainly in two forms: free graft and based flap. Zhang Shimin proposed a Chinese nomenclature, indicating the form of application and the site of repair, such as (1) ALT perforator free flap for hand reconstruction and (2) medial gastrocnemius perforator-based flap for tibial coverage.

8.9.11 Controversy Over the Concept of Perforator Flap

Regarding the exact concept of perforating flaps, scholars at home and abroad still have different opinions on the exact concept of perforator flap, and there are confusions and crossover with many flap names.

In 2013, experts of perforator flaps in China discussed and proposed a broad definition of perforator flaps: perforator flaps are island-shaped axial flaps fed by a single skin perforating vessel (Table 8.5).

This definition takes into account (1) vascular anatomy (perforator vessels), (2) surgical techniques (separation into small perforator vessel pedicles into island) and (3) surgical principles (axial flaps); Regardless of (1) the origin of perforator (muscle, intercompartmental septum), (2) the structure of the flap (fasciocutaneous flap, adipofascial flap, subdermal vascular plexus flap. Neurocutaneous flap is a special example of fasciocutaneous flap) and (3) the size of the vascular caliber. According to this concept, all perforator flaps

Table 8.5 Types of perforator flap

Basic types	Single perforator vascular bundle island-shaped axial flap	Perforator flap (subcutaneous flap, the most primitive definition) Perforator fasciocutaneous flap (fasciocutaneous flap) Perforator ultra-thin flap (subdermal vascular plexus flap) Perforator nerve fasciocutaneous flap (neurocutaneous flap)
Pedicle extension	Single perforating blood bundle + fascial pedicle	Perforator fasciocutaneous flap Perforator cutaneous nerve fasciocutaneous flap
Combined flap	Deep source artery + vascular tree branch	Perforator federated flap (conjoined flap) Perforator chimeric flap (lobulated flap) Perforator combined flap (anastomotic vessel)

are island-shaped flaps with axial blood supply. Therefore, if the perforator flaps are to be cut, it is necessary to have a thorough understanding of their blood vessels and anatomy. If the blood vessels of the flaps are not deeply understood, the flap can only be cut according to the theory of random blood supply or chain blood supply in clinic, and do not dare to deeply dissect the small perforator vessels. For example, the traditional fasciocutaneous flap (fascial pedicle) and neurocutaneous flap (subcutaneous pedicle of neurocutaneous fascia) do not belong to the perforator flap. However, if the pedicle blood supply of the flap is well understood, the surgeon can continue to deeply separate the perforator vessel and cut the island-shaped flap with the small perforator vessel bundle as the pedicle, and then it will evolve into perforator flap [20].

8.10 The Influencing Factors on Flap Survival and Complication Prevention

Post-op flap activity was depends mainly on the physiological functions of microcirculation. Arterial blood should perfuse into every part of flap, similarly, the venous blood from flap issue should return to the venous and can re-enter the circulation. Successful reconstruction of microcirculation leads to flap survival with good quality.

8.10.1 Postoperative Complications

Any adverse process of flap surgery, all needs to be carefully identified and analyzed. It may be only a postoperative unpleasant phenomenon, but also could be a real postoperative complication. In order to avoid misjudgment, it is necessary to set several explicit criteria of postoperative complications.

8.10.1.1 Major Complications

Major complications refer to any unexpected adverse circumstance that needs surgical intervention, whether the flap survived completely or not. The surgeon has no foresight to such intervention. The major complications include: (1) total and complete necrosis of skin flap; (2) partial necrosis; (3) any other cause leads to failure of wound coverage, such as ischemia causing wound dehiscence, infection, empyema under the flap needs to set off and re-debridement. The donor site management is accompanied with flap transfer, so any adverse situation in donor site that need surgical intervention is also regarded as major complication. In short, the adverse situation of flap transplantation in donor or recipient site, that need additional surgical intervention are major complications.

8.10.1.2 Minor Complications

Minor complications refer to postoperative adverse circumstance that cause delayed healing, without any kind of operation in a surgical intervention. Minor complications including (1) epidermis fall off, (2) a small split wound, (3) serum aggregation under the flap (seroma), (4) mild infection and (or) obvious inflammation fester.

8.10.2 The Influencing Factors for Flap Survival

The main factors influencing the flap survival quality, in addition to the efficiency of the blood circulation, include reasonable flap design, noninvasive operative technique, etc.

8.10.2.1 Blood Circulation

The most common reason for clinical flap failure is the venous problem. As far as the failure was concerned, problem in circulation was more often by over-perfusion than arterial insufficiency. The impact of venous return is more important than arterial perfusion in most cases. Congestion and swelling in flap may cause a lot of thrombosis, interfere tissue nutrition and eventually lead to tissue necrosis. Even if the flap survival, it may also become poor quality with fibrosis, stiff and pigmentation.

8.10.2.2 Flap Design

In the clinic, raising a flap completely reasonable, surgeon must follow the four principles, i.e. "point, line, area, and arc". "Point" indicates the position where the nutrient vessel entering into the flap. "Line" indicates the direction the nutrient vessel run in the flap. "Area" indicates the maximum survival dimension that the vessel can provide. "Arc" indicates the range that the flap is rotated with the pedicle length as radius.

The in-proper flap design will cause the necrosis. In practice, the axial point and flap axis are easy to drawn, with vascular anatomic knowledge. But the "area" is not easy to clear. Over-sized flap with insufficient blood supply will cause trouble. As a rule, a flap that slightly lager (plus 2 cm of length and width) than the recipient wound is reasonable, however a thick flap requires lager surplus, maybe 4–5 cm. In practice, it can be evaluated that if the flap can be sutured to cover the wound by 3-0 silk string, its dimension is good as there is tension-free suture. This allows arterial blood to reach the tip of the flap. If the flap cannot be sutured by 3-0 silk, which means flap dimension is not large enough, surgeon shouldn't suture such a flap by stronger string, because forced suture lead to over-pressure, blisters or partial necrosis in tip. Over-pressure suture also results in stiff, pigmentation, wide scar formation.

8.10.2.3 The Operative Factors

Whether free or pedicled, flaps should be handled softly. Surgeons should following the non-traumatic principle of plastic surgery. Subcutaneous tissue and skin should be sutured accurately with 3-0 or thinner silk, which can reduce the scar reaction. The wound should be debrided adequately, and drained effectively. The postoperative hematoma has a negative effect on flap quality. Postoperative wound infection affects the flap survival seriously. For free flap, surgeon should focus on the prevention of vascular crisis. If a flap experienced a vascular crisis, it means a significant quality reduction of survival.

8.10.3 Prevention of Complications

For avoiding complications after surgery, surgeons should take care in following aspects: recipient area preparation, flap design, flap elevation, flap transfer, post-operative observation.

1. Surgeon must be familiar with the applied anatomy for the flap, especially neurovascular pedicle position and running direction, and possible anatomical variations, so as not to make vascular damage when raising the flap.
2. The skin and muscle used as a donor tissue should have normal physiological situation. Any tissue that has undergone previous operation, suffered a trauma, or received radiation therapy should be carefully selected, because the blood vessel can be affected by different degree of damage.
3. The recipient area should be estimated correctly. The actual wound area will expand after surgical debridement, as controrary, the flap will shrink after harvest from the donor site. So the flap dimension in designing should be 20% larger than the wound area. If the muscle was taken with flap, larger flap area was required. For a wound that cannot be covered by a single flap, several flaps combined together was a better solution.
4. A reasonable local flap design means the pivot and flap range should be marked before surgery. The distance between pivot point and flap tip should longer than the distance between pivot and wound tip, such design provide a coverage without tension.
5. When a musculocutaneous flap was elevated, the most important thing is the protection of musculocutaneous perforator vessel, which is the only vascular source of flap. Any pressure or shear force on the perforator should be avoid. For the blood circulation between skin and muscle, suture anchoring is required to avoid tissue separation. If separation occurred, operation should be postponed until circulation between skin and muscle recreate after 3 weeks.
6. If the skin area is larger than the underlining muscle, the flap should include complete deep fascia, because of the deep fascia has extensive vascular network, which is important for distal flap survival.
7. Postoperative hematoma is likely to occur when using tourniquet control, due to incomplete hemostasis after operation. Surgeons should staunch bleeding carefully, and set a drainage under the flap. However, pressure bandage to stop bleeding was dangerous to flap circulation.
8. Thorough debridement is essential for success. Poor blood supply and inelastic scar tissue in the recipient should be removed completely. The suture silk on the scar after surgery may lead to a split when tissue swelling.
9. The vascular pedicle must be carefully handled. The operation technique should be gentle, the tunnel should be wide and spacious and keep away from bone prominence; The vascular pedicle must run in smooth, without acute angle.
10. The tiny vascular anastomosis is the key for free transplant. 9-0 or 11-0 sutures should be applied under microscope. A vascular bridge is better than a tension anastomosis.
11. The muscle trim should be fixed on receiving site to avoid the dead space by gravity or contraction.
12. After the surgery, the flap color, temperature, swelling and capillary reflux test must be observed carefully. Once a vascular crisis happens, find the reason and manage immediately.
13. The oral cavity is a pollution environment, the flap transplant to the oral cavity should be sutured with thick sutures to avoid split.
14. Supplemented techniques such as vasoactive drugs, growth factor, hyperbaric oxygen can help the flap survival.

8.11 Functional Evaluation After Flap Transplantation

Skin or integument covers the whole human body, it is the largest organ with area of 1500–1700 cm^2. It accounts for human weight nearly 16%. Skin contact with the outside world as a barrier, its functions include protection, aesthetics, regulating body temperature, spreading the pressure and absorbing vibration and feeling, it also take features of metabolism and synthesis.

The clinical flap surgery is considered for a variety of purposes. Wound repair, functional reconstruction and improving appearance are the main objectives. The effect of flap transplantation can be judged by several criteria, such as flap survival rate, quality of flap, whether the purpose of surgery achieved or not, specific function (feeling, movement), the patients subjective attitudes, effect on quality of day life, and so on.

8.11.1 Flap Survival Rate and Quality

Currently, the survival rate of flap after transplantation is very high, if the surgeon mastered the mature and reliable technology. 100% survival rate is the endless pursuit for a surgeon. Survival rate of free flap, mainly related with vascular anastomosis quality, has now reached more than 98%. Pedicle flap has a higher survival rate. The cases that fail was mostly attributed to unpredicted vascular variations, especially venous variation.

Factors that applied to evaluate flap survival quality include: the texture, elasticity, color, softness, thickness, hair, beauty, matching with the surrounding skin, and other elements.

8.11.2 Flap Functional Evaluation

After survived on the recipient area, flap will gradually adapt to the environment. The flap that transferred to the plantar region will evolve thick keratinizing layer. It also will occur gradually in touch with the deep structure to get stability, and reduce the sliding when people walking. However, some special feature of the flap will retain, such as the flap that harvested from abdomen and transferred to the hand region, will become fat following abdominal obesity. Such features may associate with genetic characteristics or receptor of fat cells on specific parts.

Sensory function is very important in the following parts: tongue reconstruction, reconstruction of the penis, the palm of the hand, plantar of the foot.

Sliding function is more important on multi tendon regions, like dorsum of hand and foot.

Aesthetic appearance is more important on head, face and hands.

When a muscle flap or musculocutaneous flap was used to reconstruct movement function, the recovery of muscle strength and function in daily life (like grasping) were the main indicators of functional evaluation.

8.11.3 Patient-Oriented Evaluation

In the past, traditional evaluation methods are based on the result of medical workers assessment, such as flap survival rate, strength grade, and so on. But with the modern "bio-psycho-social medical model", that these assessment methods with doctor-oriented were considered not accurately and completely reflect the degree of patient satisfaction with treatment outcomes, so evaluation of results should be more emphasis on the patient rather than the doctor's feelings. As a complete individual, the functional health effects of a patient include: mental health, social functioning, role functioning (such as worker, the role of husband and wife, parent), physical function, activities of daily living.

Currently, the evaluation methods of the functional outcome were patient-oriented, various rating scales are used. Those scales can be divided into two categories: (1) The overall function of the rating scale. The most famous one is short form-36 (medical outcome study short form 36, SF-36). (2) Evaluation for each specific anatomical site, such as "disabilities of the arm, shoulder and hand" (DASH). Those features can be deeply reflects the patient activities of daily living, recreational or professional level.

We had focused on the repair of finger pulp with various flaps, and presents a patient-oriented assessment score (see Table 8.6). After a preliminary clinical trial, we found it showed good ability to distinguish different flaps used for finger pulp reconstruction.

Such standard evaluation tables that based on patient-self feeling as a score or scale, is reliable. It can be used as a tool to compare different treatment methods.

8.12 Common Donor Site of Flaps and Musculocutaneous Flaps

1.	ALT flap
2.	Latissimus dorsi muscle flap
3.	Thoroco-umbilical flap
4.	Groin flap
5.	Sural neurovascular flap
6.	Posterior forearm interosseous artery flap

At present, more than 70 flaps have been described on the human body, include axial flap, muscle flap. If coupled with perforator flaps, the flap number is more than 100.

8.12.1 Anterolateral Thigh Flap

Anterolateral thigh flap (ALT flap) was first introduced in 1984. It is nourished by descending branch of the lateral femoral circumflex artery. In 1984, Xu described the vascular anatomy of the anterolateral thigh flap, then Luo and Song reported the surgical process and clinical study [20].

The advantage of anterolateral thigh flap include: (1) Donor site is hidden. If the flap width is less than 10 cm, it can be closed directly; (2) Anterolateral thigh flap provide a large tissue with a predictable vascular, the nourishing artery has a long route and large diameter; (3) The surgical procedure do not injury normal function; (4) It can modified to fascial flap, fasciocutaneous flap, musculocutaneous flap or perforator flap; (5) If the flap harvested with lateral femoral cutaneous nerve, it can be a sensate flap; (6) Distally pedicled flap can cover knee and proximal lower leg, with a reverse blood flow.

Table 8.6 A patient-oriented functional assessment score proposed by Dr. Chang

Name	Sex	Age	Job	
Dominant hand (Right, Left, Equal)				☐
Which side was injured? (Right, Left)				☐
Which finger? (Thumb, Index, Long, Ring, Little)				☐
What flap				☐
Surgery date				☐
Evaluating date				☐
☐				Total 100
Items	☐			Scoring
Wearability	Never ulceration			20
	Ulceration			0
Pain	No pain			20
	Pricking			0
Appearance cosmetic	Satisfactory			10
	Hide in public			0
Circulation	Normal color and temperature			10
	Slightly dim and little cold			5
	A dull color, needs protection on winter			0
Finger motion	Normal			10
	Decrease, but no influence on daily life and work			5
	Apparent decline, negative on daily life and work			0
Feeling	Normal sensation			10
	Numb			5
	No sensation			0
Finger usage	☐	3 (easy to do)	1 (inconvenience)	0 (cannot)
	Pick needle	☐	☐	☐
	Pick coin	☐	☐	☐
	Writing	☐	☐	☐
	Tie shoes or button	☐	☐	☐
	Twist the screw	☐	☐	☐
Career	Continuing previous work	☐	☐	5
	Have to change work	☐	☐	0
Donor site (minus score)	Satisfactory (no sequlea)	☐	☐	0
	Unsatisfactory (sequlea like pain, scar contracture)	☐	☐	−10

Anterolateral thigh flap have a wide range in clinical application, in addition to repair skin and soft tissue defect caused by trauma, infection and tumor excision, it also can be used for urethral, vagina and anus, reconstruction of the penis, vagina, eye socket and tongue, etc. The flap has become the most useful workhorse in clinical practice.

8.12.1.1 Applied Anatomy

The upper part of anterolateral thigh skin is nourished by superficial iliac circumflex artery, and ascending branch and transverse branch of lateral femoral circumflex artery; The lower part is nourished by descending branch of lateral circumflex femoral artery and lateral superior genicular artery. These vessels have rich anastomosis (Fig. 8.22).

The lateral femoral circumflex artery (LFCA) runs down from the deep femoral artery or femoral artery, underthrough the branch of lateral femoral nerve, then walking outward laterally in the gap behind the sartorius and rectus femoris. It then divides into the ascending, transverse and descending branches. The descending branch which is longer and the caliber is wider. It runs between the rectus muscle and vastus intermedius. In the middle point of a line between the anterior superior iliac spine and patella lateral edge, the descending vessel divides into medial and lateral collateral braches, between the vastus lateralis muscle and strands of rectus muscle. The medial branch runs between vastus lateralis and rectus femoris, gives off branches to nourish the vastus intermedius muscle, the rectus femoris and lower part of vastus medialis muscle. The terminal branch takes part in the arterial network of knee joint. The medial branch and lateral superior genicular artery composes an important part of collateral circulation between femoral artery and popliteal artery.

The lateral branch of LFCA runs down laterally along vastus lateralis, gives off 2.5 (1–8) musculo-cutaneous arteries with 0.6 mm (0.4–1.1 mm) diameter. These branches

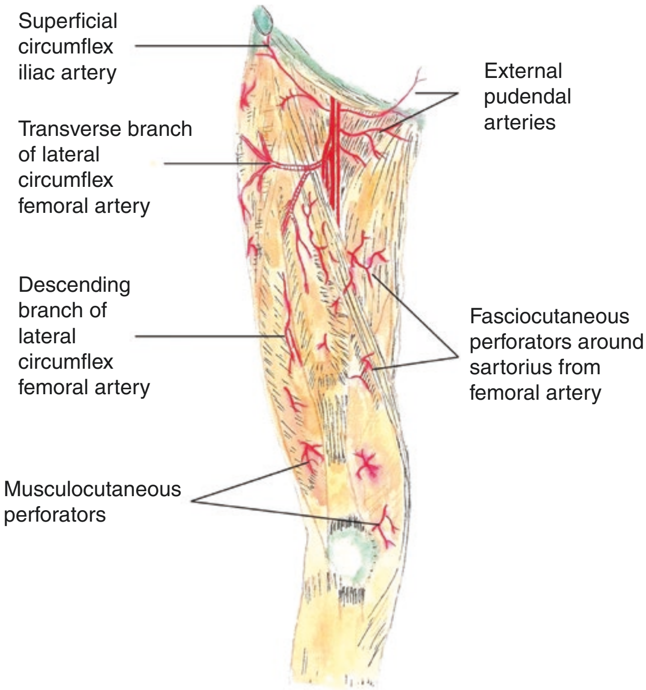


Fig. 8.22 Distribution and anastomosis of lateral femoral circumflex artery descending branch

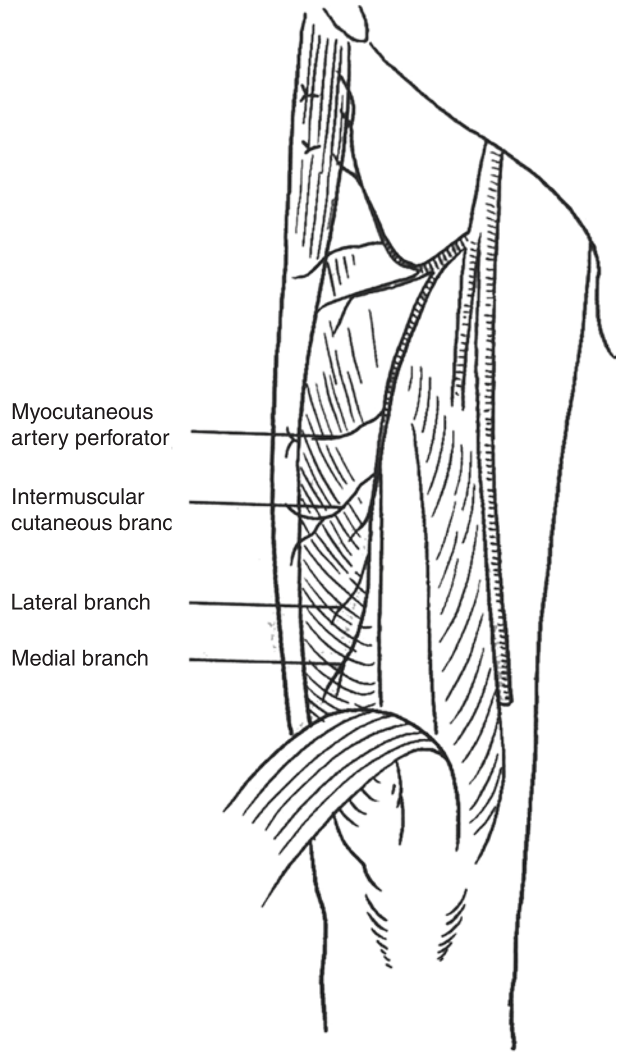


Fig. 8.23 Distribution and branches of descending branch of lateralfemoral circumflex artery

supply vastus lateralis and lateral thigh skin. They also have connections with fasciocutaneous branches of lateral superior genicular artery (Fig. 8.23). The first musculo-cutaneous branch is the main supply artery for the ALT flap, it penetrates through an fascia oval located in a circle area with 3 cm diameter. The circle center is mid-point between anterior superior iliac spine and patella superior-lateral edge (Fig. 8.24). The descending branch has an 8–12 cm long pedicle, but only 2–3 cm could be used for surgery because most part was covered by rectus femoris. The lateral superior genicular artery is giving off from lateral aspect of popliteal artery, in 2.5–3.0 cm above lateral condyle of femur, with the artery diameter 1.8–2.2 mm. Then the artery runs to anterior aspect of knee, though lateral femoral intermuscular septum. It divides muscular branches into vastus lateralis, biceps femoris, and articular branches into the knee. Those branches are 0.8–1.5 mm in diameter. There are rich anastomoses network between descending branch of lateral femoral circumflex artery and joint or muscle branch of the upper lateral popliteal artery. The anastomosis branches is located 2.5 cm above patella, 1.5 cm lateral to the iliac patellar line, 0.6–1.5 mm in diameter (Fig. 8.25). Supplied by such anastomosis, the descending branch can be used as a distally base to harvest a flap from the proximal thigh, to form a reverse flap.

8.12.1.2 Flap Design

The flap axis is centered over a line (a–b) running from the iliac spine lateral edge (a) to patella superior lateral edge (b). The lateral femoral cutaneous nerve and its anterior branch also run on this line. The first musculo-cutaneous branch can be found near the mid-point (o) on this axis by Doppler. Point e is Mid-point of inguinal ligament. The lower part of line o-e is the skin surface projection of the descending branch of lateral circumflex femoral artery. The point o should be designed on the upper part of flap (Fig. 8.26).

8.12.1.3 Flap Elevation

Dissection begins with a proximal anterior skin incision that marked before surgery. The space between rectus femoris and vastus lateralis is dissected under the deep fascia. The descending branch of lateral circumflex femoral artery can be found in the space. Following the descending branch, the first musculo-cutaneous (or intermuscular) perforator can be found. Muscle fibers need be carefully separated until the perforator passes though the femoral fascia. Another method is keeping some muscle cuff or fascia around the perforator when artery is elevated. Additional 1–2 perforator can be

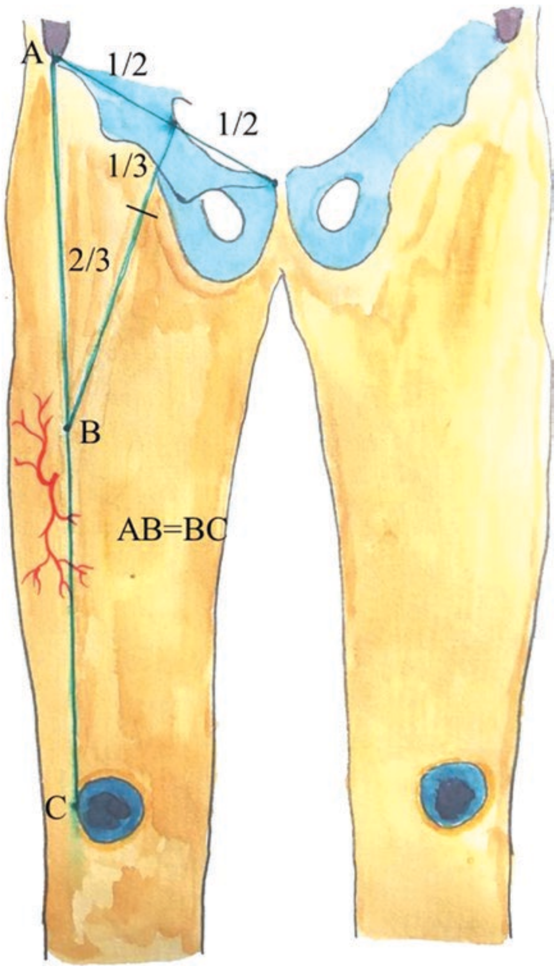


Fig. 8.24 Location of perforator on anterolateral thigh flap

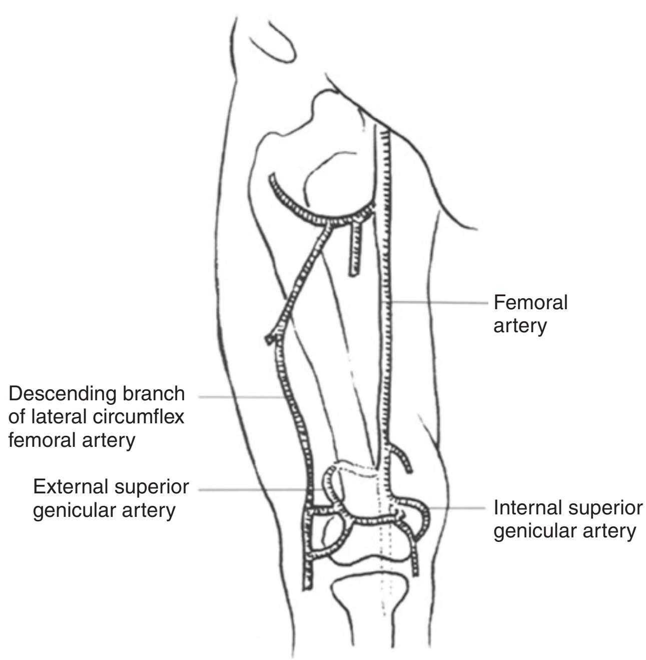


Fig. 8.25 Anastomosis between descending branch of lateral femoralcircumflex artery and lateral superior genicular artery

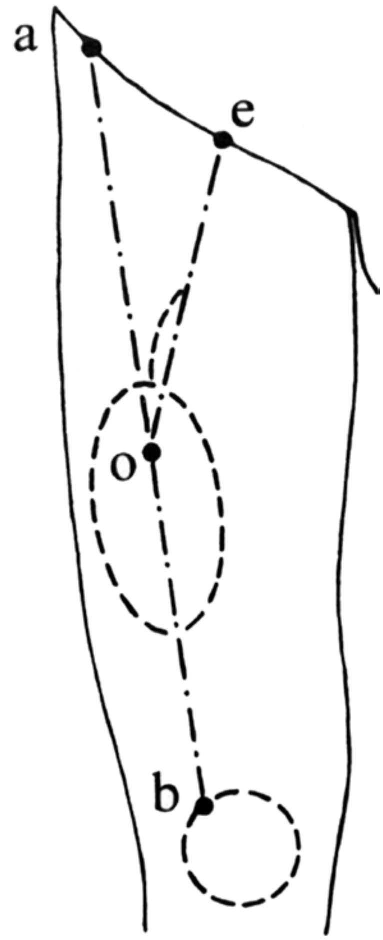


Fig. 8.26 Design of anterolateral thigh flap

kept in the flap, if a large flap is designed. When perforator artery is defined, the edge of flap is dissected. The descending branch is elevated from the spatium to the branching off point. Some branches that run into muscle need be ligatured (Fig. 8.27). Then the flap can be fully raised and transferred to the recipient site. If the vessel pedicle is not long enough, further proximal dissection of more rectus femoris can provide more 1–2 cm. When the flap width is less than 8–10 cm, donor site can be sutured directly (Fig. 8.28).

8.12.1.4 Flap Modification

Anterolateral thigh flap has a very wide range of functions, which is known as the "Universal flap". For clinical application, many modifications have been developed.

1. Super large flap: the maximum flap area is 400 cm^2. If two or more musculocutaneous perforators are preserved, the better blood supply allows large flap. Flap inferior margin can reach the superior brim of patella.
2. The distal anterolateral thigh flap is based on the anastomosis between the lateral femoral circumflex artery descending branch and lateral superior genicular artery. The pivot point should be located superior to the proximal knee articular surface within 2 cm (Fig. 8.29). Such

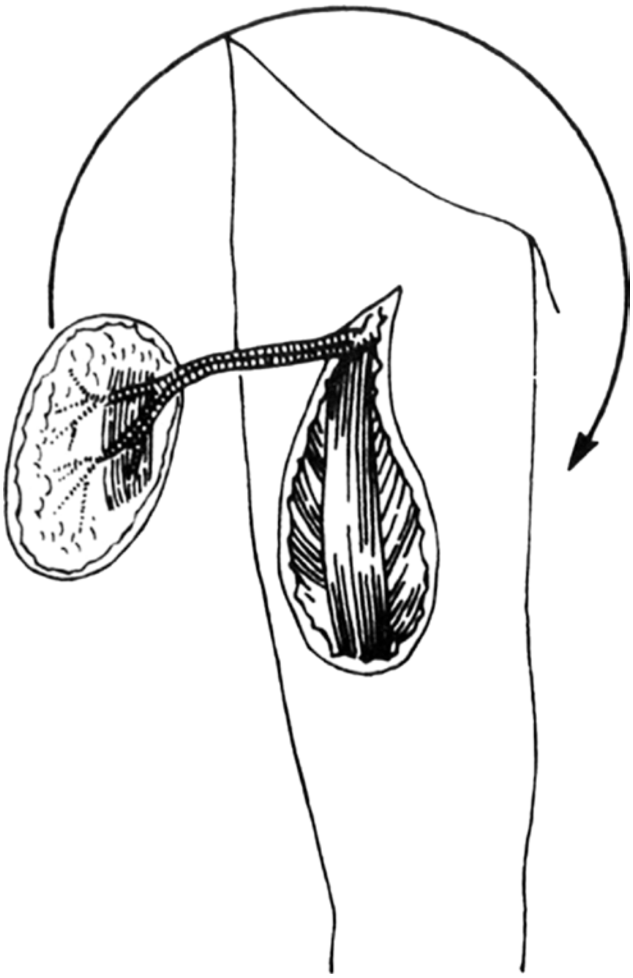


Fig. 8.27 Rotation arc

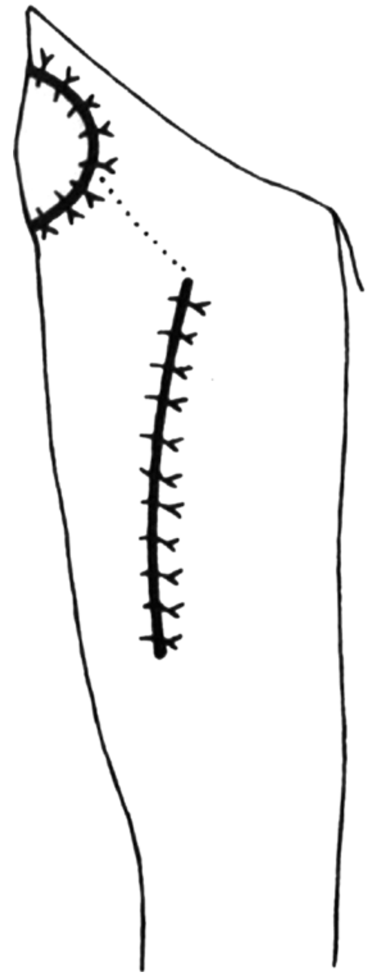


Fig. 8.28 Anterolateral thigh flap, donor site is sutured directly

design can help reconstruction of knee area and proximal lower leg wound.

3. Composite flap. The flap with tough fascia lata can be used to reconstruct galea aponurotica in head area; the iliotibial band could be used to replace the Achilles's tendon, or reconstruct flexor or extensor tendon of thumb or finger. It also can be used for reconstruction of plantar fascia.
4. Myocutaneous flap. The anterolateral thigh flap has thick subcutaneous fat, and partial vastus lateralis muscle can be carried to make the flap thickness to 1.5–2 cm. So it is very useful for large or deep defect area which need bulk tissue to fill.
5. Super thin perforator flap. The anterolateral flap can be modified as super thin flap by removing off the subcutaneous fat. The fat and deep fascia that around perforator within 3 cm be moved and the subdermal vascular network is preserved. Such flap is suitable for reconstruction of tissue defect in neck, shoulder, palm, hand dorsum and foot dorsum. Aesthetics and function is appropriately reconstructed by this flap.
6. Sensory flap. The anterolateral thigh flap with lateral femoral cutaneous nerve is a good choice to reestablish feeling function for plantar or heel for weight-bearing. Sensation reconstruction can helps flap avoid injury caused by wearing, over cold or heat.
7. Chimeric flap or multi-paddled flap. The flap is designed as two parts, based on two perforators from descending branch of lateral circumflex femoral artery. The branch needs be dissected to the branching off point. When the two perforators and branches are taken within the flap, the penetration defect on cheek or palmar-dorsal hand can be fixed and only one group of pedicle vessel needs to be anastomosed.
8. Combined transplantation and chain-linked flap. As a long and large diameter artery, the lateral femoral circumflex artery is suitable for bridging other free tissues (such as the iliac bone flap, the fibular flap, second toe). Multiple parts from different tissues can be chained one-by-one to form a mega flap, to reconstruct a complex defect.

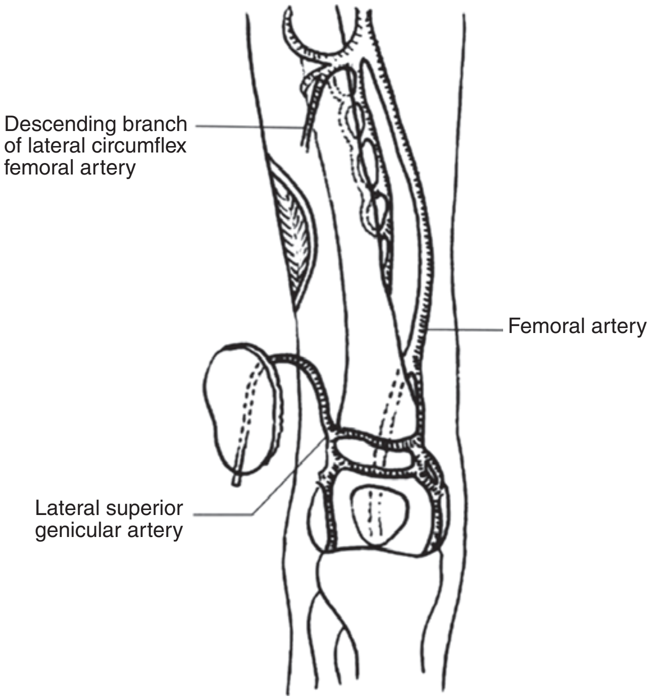


Fig. 8.29 Distally based anterolateral thigh flap

Notes

1. Muscular vastus lateralis nerve (femoral nerve branches) goes superior-laterally to the descending branch of lateral circumflex femoral artery. During the operation, it should be dissected carefully, and protected from damage. But the artery and its accompanying two veins do not have to separate.
2. Management of perforator artery. The musculocutaneous perforator and septofasciocutaneous perforator can be found in midpoint on the line between iliac and patellar rim. If the flap is small, one large perforator is used. If the flap is large, 2 or 3 perforators need be included in flap. In operation, the septal perforator is easier dealing, the fascia can be cut together; for the musculocutaneous perforator, the surround fibers should be separated or cut off. But the fibers touch to the artery is preserved to protect perforator.
3. For extending the rotation arc proximally, distal perforators can be cut off, only the first proximal perforator is retained. The flap then be rotated 180° proximally. The vascular pedicle is released, and longer rotation range can extend to proximal lower leg wound. In operation, the pedicle should be carefully dissection to avoid twisting. The flap has a good survival rate without tension.
4. The femoral lateral fascia vascular network has a rich anastomosis on the surface of iliotibial band, as a line between anterior superior iliac supine and superior lateral brim of patella. The femoral fascia and iliotibial band provide little blood to flap, but they should be cut with flap to avoid perforator separating from skin or deep tissue.
5. The superior part of flap is supplied by ascending branch of lateral femoral circumflex artery, like the tensor fascia lata myocutaneous flap. Its pivot point is 8 cm inferior to anterior superior iliac spine, the flap is useful to cover greater trochanter pressure sore. With a long tough aponeuroses, it also can be used to reconstruct defect of low abdominal wall.

8.12.2 Latissimus Dorsal Muscle Flap

In 1906, Tansini reported the experience of breast reconstruction by latissimus dorsal flap. Maxwell reported the free latissimus dorsal flap in 1978. As one of the most widely used flap in clinical activities, it has been modified to skin flap, musculo-cutaneous flap, muscle bone flap, ramified musculocutaneous flap and the series flap. The advantages include: constant vascular distribution, thoracic dorsal artery have 1.5–2.0 mm diameter for surgical anastomosis, the vascular pedicle is more than 6–8 cm, flap area is larger to 8–23 cm × 20–40 cm.

8.12.2.1 Applied Anatomy

Latissimus dorsi flap including the latissimus dorsi muscle, skin and subcutaneous tissue. Flap is based on the thoracodorsal artery and vein. The flap motor nerve is thoracodorsal nerve, which is concomitant with vascular.

1. Muscle anatomy and structure

   The latissimus dorsi is flat wide triangular muscles in back. Its upper edge is 18 cm long, trailing edge is 24 cm, front edge is 30 cm, as a similar right triangle. Latissimus dorsi originates from the lower six thoracic, all lumbar vertebral body, sacral crest, supra spinal ligament and the posterior superior iliac spine. The portion that originates from the thoracic is covered by the trapezius muscle aponeurosis. The front edge of the lower part is lock with External oblique muscle of abdomen and anterior serratus muscle. Lower edge is located on serratus anterior, inferior angle of scapula and 4 lower rib. Loose tissue is under the front upper part of this muscle, and form the axillary posterior wall. Muscle belly goes together outward and upward, around to the front of the teres major. Muscle fibers terminate into a flat tendon bundle, and inserted into the intertubercular sulcus. The function of latissimus dorsi muscle is adduction, internal rotation of the arm, participation in the spine volume stability and assisted respiration.

2. Vascular anatomy

The subscapular artery is divided into two distal branches of the scapular circumflex artery and the thoracodorsal artery about 3 cm after the start. The branches distributed in the shoulder area, the latissimus dorsi, rib and lateral chest skin. Thoracic dorsal artery is the direct continuation of scapular artery, it is 2.0 mm diameter and has two accompanying veins. Vascular bundle goes downward along the lateral border of the latissimus. Its constant branches include scapula branch, serratus anterior branch, 37.5% lateral thoracic cutaneous artery. It also gives off medial and lateral branches on 1.9 cm above the scapula inferior angle, 2.2 cm from latissimus dorsi lateral margin. Lateral branch gives off musculocutaneous perforator artery to lateral thoracic skin. (1) The scapula branch: arises at the point 4.2 (0.6–6.8) cm below thoracodorsal artery, usually 1–2 branches, 1 branch rate is 85%, 2 branches rate is 15%. Ninety percent scapular branch and Serratus anterior branch have common trunk, which has 2.0 (1.0–3.2) cm length and 2.1 (1.0–2.8) cm diameter. Scapula branch distributes in the middle-lower lateral edge of the scapula and scapula corner. (2) Serratus anterior branch. This branch originates from the thoracic dorsal artery, usually 1–2 branches. 1 branch rate is 70%, 2 branches rate is 30%. The starting point is 1.4 + 1.2 cm above the inferior angle of scapula. Branches distribute to the serratus anterior muscle and fascia, 5–7 rib periosteum. (3) Lateral thoracic cutaneous artery. It originates 2.9 cm below from thoracodorsal artery, goes along the latissimus dorsi lateral edge, distributes in the skin 2–3 cm front to axillary line, lower edge is 7–8 rib level.

The latissimus dorsi also be supported directly from the intercostals and lumbar arteries, especially the posterior branches of 9–11 intercostals arteries and subcostal artery, these branches usually in diameter on 1 mm. Using the lateral branch of posterior intercostal arteries as pivot point, the latissimus dorsi flap can turn over to cover defect on lumbosacral region (Fig. 8.30).

3. Thoracodorsal nerve

The thoracodorsal nerve originates from the posterior cord of the brachial plexus and descends on the surface of the subscapularis. It is located behind the thoracic nerve and posterior to the thoracodorsal artery. It travels with the blood vessels below the inner surface sarcolemma of the latissimus dorsi. It supplies latissimus dorsi on its deep surface. It gives off medial and lateral branches, and the lateral branches gives 2–3 branches to latissimus dorsi.

8.12.2.2 Flap Design

The latissimus dorsi front edge can be touched on axillary posterior wall, about 2 cm below. This point is the projection of cross point of thoracodorsal vessel and thoracodorsal nerve. The line between this point and superior edge of sacroiliac joint is the direction of vessel-nerve bundle. It is also the long axis of flap (Fig. 8.31). The area is up to 35 × 15 cm. If donor site wide is less than 6–8 cm, it can be sutured directly.

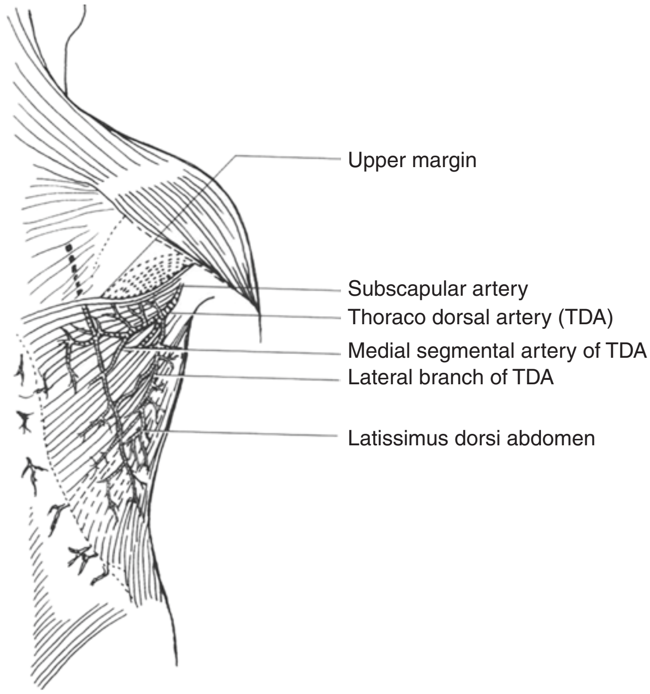


Fig. 8.30 Latissimus dorsi flap and vascular anatomy

Reverse latissimus dorsi flap: the pivot point is located on the penetrating point where the posterior intercostals artery lateral branch entry the muscle. The distal edge of flap is in the posterior axillary line, 10 cm to latissimus dorsi distal end (Fig. 8.32). Flap maximum area is up to 8 × 20 cm. In this area, 1–2 perforators of intercostal artery can be contained.

8.12.2.3 Flap Harvesting

The patient is placed in the lateral decubitus position. A 6–10 cm incision is made in the anterior border of the posterior wall of armpit and latissimus dorsi. The skin and subcutaneous tissue were cut open to the surface of the chest wall muscle to expose the latissimus dorsi front. With the index finger and middle finger, loose connective tissue that under the latissimus dorsi front edge is blunt separated. In 2–3 cm depth, the finger can touch the pulses of the thoracodorsal artery. The direction and diameter of artery can be observed clearly.

After clearing course of the thoracic dorsal artery, front edge is dissected until the latissimus dorsi surface. The latissimus dorsi trans to aponeurosis, below hypochondrium and lumbodorsal fascia area, and located with obliquus externus abdominis. The lateral branch of posterior intercostals arteries should be ligatured on the entry point to muscle.

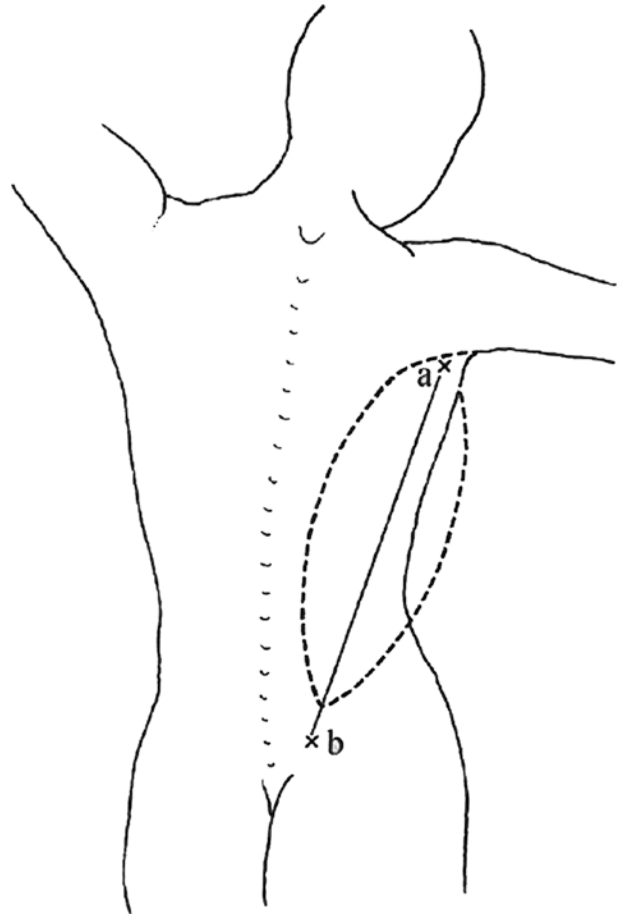


Fig. 8.31 Latissimus dorsi flap

When distal dissection is completed, vascular pedicle should be carefully dealed with. Ligation to the teres major branch and the circumflex scapular artery flap can help to obtain a longer neurovascular pedicle.

8.12.2.4 Flap Modification

Latissimus dorsi flap is widely clinical applied to perform a lot of function. It has several derived variations.

1. Antegrade flaps: such flap with thoracodorsal artery as pedicle, is used for neck, breast reconstruction, or free transplantation. For clinical application, it is useful to reconstruct elbow and digital flexion, elbow extension, shoulder abduction.
2. Reverse latissimus dorsi muscle flap: Repairing sacroiliac, or abdominal wound.
3. Combined flap with latissimus dorsi. Such flap is used to repair huge tissue defect, and just one group of vessel needs to be anastomosed. (1) latissimus dorsi—groin flap is the earliest great combined flap, Harii reported it in 1981. It based on superficial iliac circumflex artery, and thoracodorsal artery is anastomosed. (2) latissimus dorsi—rectus flap. Latissimus dorsi is suitable to combined with low abdomen flap or rectus flap. (3) scapula—latissimus dorsi—lower abdomen flap. It based on subscapular artery and superficial inferior epigastric artery. Its area is up to 80 cm × 12 cm.
4. Lobulated flap and chimeric flap. Such flap has several independent flaps based on different branches, and these

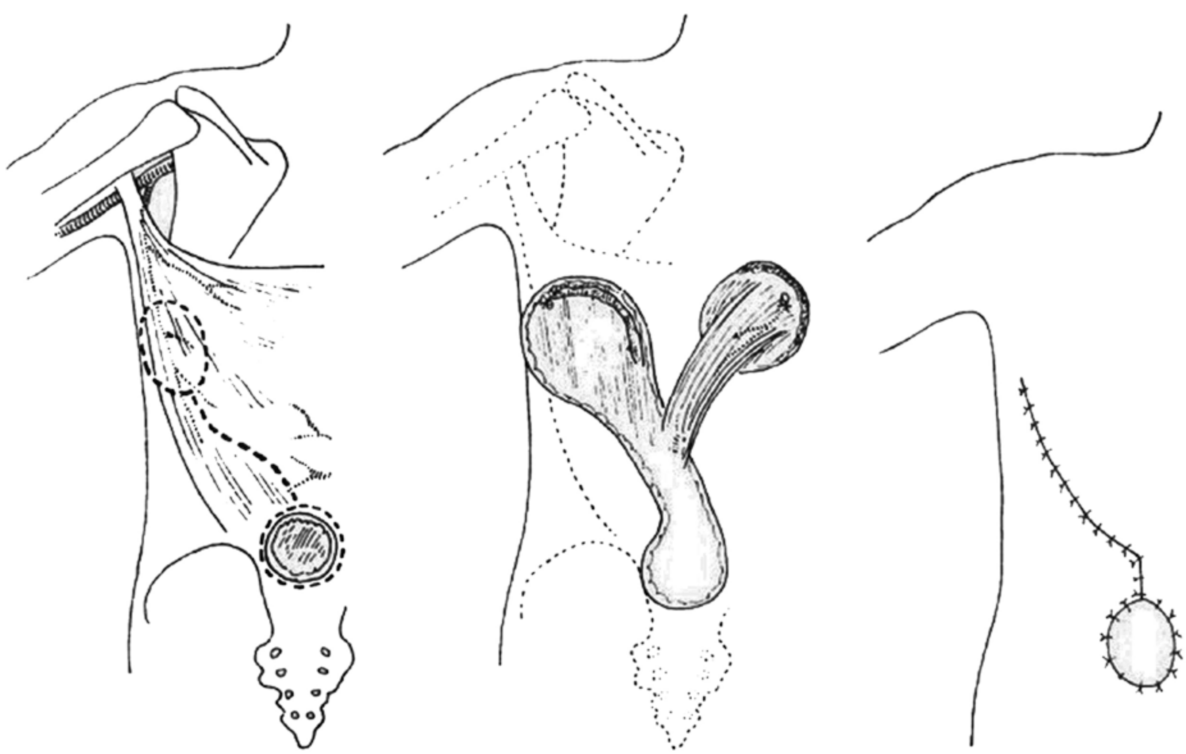


Fig. 8.32 Turn-over latissimus dorsi flap to cover sacral region

branches originate from the same source artery. Blood supply of these flaps is parallel. These flaps may have the same tissue (multiple skin flap or multiple muscle flap), may have different tissues (skin, muscle or bone). Although every individual flap (tissue) can be transplanted independently, such as scapula flap, parascapular flap, latissimus dorsi flap, serratus anterior muscle flap, scapula bone flap and rib flap, all the tissue can be transplanted in one operation based on the subscapular artery, and only this artery needs to be anastomosed. In 1982, Harii reported chimeric flap that combined latissimus dorsi flap and serratus anterior flap.

5. Series combined sequential flap. Using subscapular artery as a vessel bridge, bilateral latissimus dorsi flap can be combined sequentially. As the same method, latissimus dorsi flap can combine with free fibula bone flap, or free toes transplantation.
6. Thoracodorsal perforator flap. The perforator originates from latissimus dorsi muscle, this flap was reported by Angrigiani in 1995. The advantages include less damage of latissimus dorsi and motor function.

Notes

1. The lateral part of latissimus closed to axilla is thick, and its border is clear; the superior part is thin and unclear. So the incision starts on the lateral margin. Loose connective tissue in space between latissimus dorsi and serratus anterior is easy to separate, and associate with less bleeding.
2. When reverse latissimus dorsi flap is applied, one thick diameter artery entry the flap means good blood support to all tissue. The skin in basilar part should be cut off for better rotation, as well as muscle be preserved to protect perforator.
3. When latissimus dorsi flap is applied to reconstruct flexor function of elbow and digit, the thoracodorsal nerve must be protected. If a little rhomboid skin is left on the lower part of muscle as indicate flap, it also reduce the tension in suture and benefit muscle sliding.
4. According to the medial and lateral branches, the latissimus dorsi flap can be divided to two parts. The upper part with medial branch is used to reconstruct elbow flexion, and the lower part with lateral branch is used to digital flexion. More lumbodorsal fascia left in flap, more length help to suture tendon directly.

8.12.3 Thoraco-Umbilical Flap

In 1983, Taylor made a study for inferior epigastric vessel, then the extended inferior epigastric flap was widely applied. Fan and Zhong in China (1984) found two important cutaneous perforators in rectus. (1) Para-umbilical perforator: this perforator passes transversely on the umbilical level, flap based on this perforator is called transverse thoracoabdominal flap. (2) Thoraco-umbilical perforator: this perforator is the thickest branch and located most superior, its length is up to 19–22 cm. The artery directs to the inferior angle of scapula in 45° relative to midline. It anastomoses with lateral branch of eighth posterior intercostal artery, and distributes to superolateral abdomen and lateral thorax. Fan first reported this flap in 1987. The flap based on this perforator can be up to 40–46 cm in length.

8.12.3.1 Applied Anatomy

Most inferior epigastric artery originates from external iliac artery (92%), a few from femoral artery (8%), with 2.6 mm outer diameter. The artery passes beneath inguinal ligament, and locates behind lateral margin of rectus abdominis. Then the artery enters the rectus sheath in front of arcuate line. In the space between posterior layer of the rectus sheath and rectus abdominis, the artery goes up to umbilical region. The terminal branch anastomoses with superior epigastric artery. The inferior epigastric artery gives off muscle branch to rectus abdominis and cutaneous branches to anterior abdominal skin. The inferior epigastric artery branches form vascular network with intercostal artery and anterior cutaneous branches of lumbar arteries. The axial artery for thoraco-umbilical flap is chest navel perforator. It is the most superior and great perforator of inferior epigastric artery. The artery direct to the inferior angle of scapula, with 45° relative to midline. It anastomoses with lateral branch of eighth posterior intercostal artery (Fig. 8.33). the distance from origination point to lateral edge of rectus abdominis is 11 cm, to paraumbilical perforator is 16 cm, to thoraco-umbilical perforator is 19–22 cm. Thoraco-umbilical perforator provides a rich blood supply as it have rich anastomotic network with superior epigastric artery, intercostals arteries, and lumbar artery.

Accompanying veins of inferior epigastric artery usually are 2 (97%), a few is 1 (3%), with outer diameter 1.5–2.5 mm.

8.12.3.2 Flap Design

The axial line is determined by navel and inferior angle of scapular. The flap is located on lateral thoracic and superolateral abdominal region. Range of the flap area: upper border to posterior axillary line between 5 and 6 ribs, medial border to midline, lateral border to 14 cm to midline (Fig. 8.34). The maximum flap area is up to 46 × 12 cm.

8.12.3.3 Flap Harvest

The incision is start with thoracic part. The perforators can be found in 1–2 cm to the lateral margin of rectus abdominis.

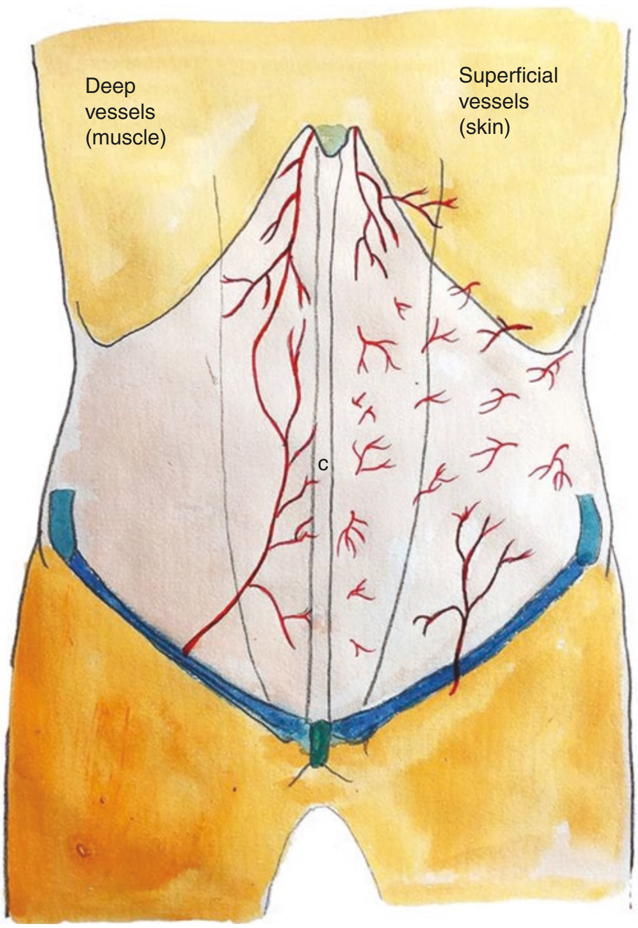


Fig. 8.33 Vascular anatomy of thoracic umbilical flap

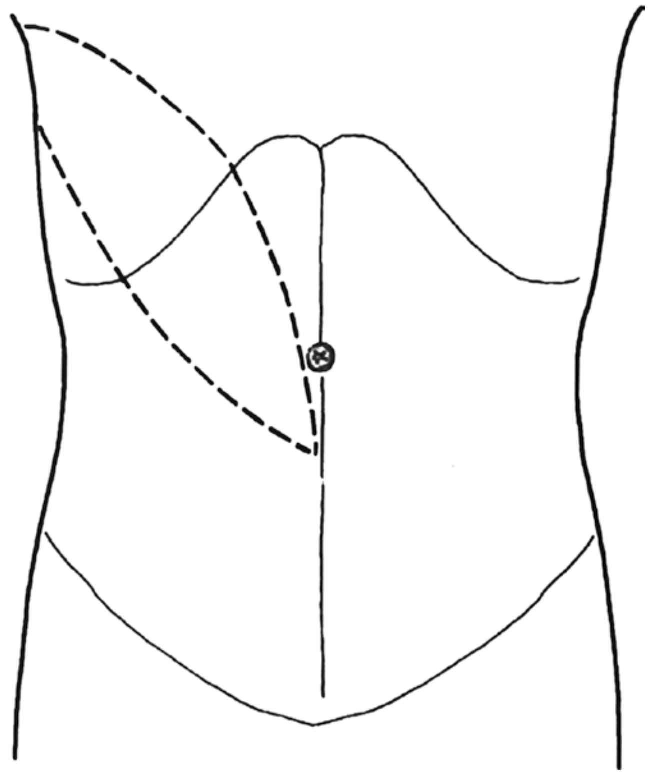


Fig. 8.34 Design of thoracic umbilical flap

Opening the front sheath along the lateral margin, pulling the rectus to inside, then the inferior epigastric artery can be found behind the muscle. When adequate artery is confirmed, dissect the artery up to its origination point on femoral artery. Dissect the route from entry point to umbilical region. Ligature the medial and upper branches, and isolate the lateral branch. Release the inferior part of flap (Fig. 8.35). If the artery is difficult to dissect in the rectus muscle, some muscle fiber should left around the artery.

The anterior rectus sheath should be sutured strictly before donor site closing.

Notes

1. The axial artery of thoraco-umbilical flap is a cutaneous branch that passes from umbilical region up to inferior angle of scapular. This branch is the largest and most superior one of inferior epigastric artery. The branch line is 45° to mid-line, and makes connections with lateral cutaneous branch of intercostal artery.
2. 1 cm muscle fiber should be left around the artery, when dissecting the rectus abdominis.
3. When the inferior epigastric artery is dissected, the obliquus internus abdominis and transversus abdominis should be pulled to lateral side, and the rectus abdominis pulled to medial.
4. After flap harvesting, anterior rectus sheath should be sutured strictly to avoid ventral hernia.

8.12.4 Groin Flap

Groin flap is harvested from ilio-inguinal region. The flap is supplied by superficial circumflex iliac artery directly, it is also one of the earliest axial flaps. In 1972, McGregor and Jackson described the anatomy of the inguinal flap which is nourished by superficial temporal artery. In 1973, Daniel and Taylor reported free flap based on SCIA. Also in 1973, Yang and Gu in China reported the free flap based on inferior epigastric artery.

The groin flap is used as a free flap, perhaps more frequently in the past than at present, because the arterial variation, thin vessel, short pedicle, and lots of fat, and many other flap was developed for reconstruction. But the advantage include hidden donor site, easy to harvest, and large flap area, so some surgeons use it as pedicled axial cross-hand flap to cover hand and forearm.

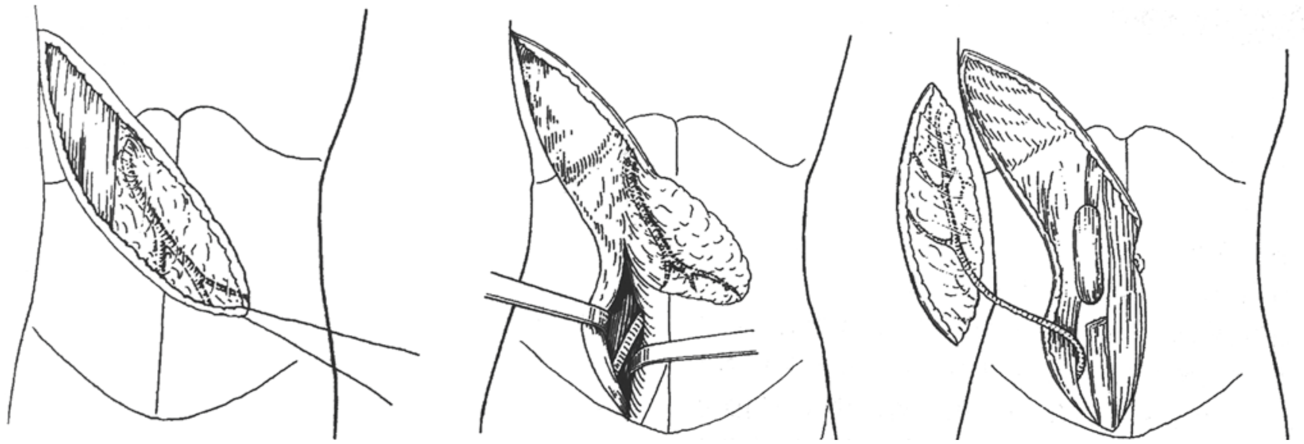


Fig. 8.35 Harvest of thoracic umbilical flap

8.12.4.1 Applied Anatomy

The superficial circumflex iliac artery originates from femoral artery, the give-off point is 2.5 cm below groin ligament. In some cases, SCIA and superficial epigastric artery have common trunk. In other cases, SCIA originates from deep femoral artery. The outer diameter in give off point is 0.5–2.9 mm (male 1.6 mm average), 0.6–2.8 mm (Female 1.7 mm average). The SCIA passes upward and laterally to anterior superior iliac spine (ASIA), then gives two branches in 3 cm far from origin point. The deep one goes under the deep fascia, distributes to upper thigh muscle, the superficial one goes superficial above the deep fascia, parallel with groin ligament and laterally. This branch is superficial, so the lateral part of the groin flap can be very thin (Fig. 8.36).

The superficial circumflex iliac vein returns into the great saphenous vein, accompanied with its artery. The outer diameter of superficial circumflex iliac vein is 1–7 mm (male, average 3.4 mm), 1–5 mm (female, average 2.6 mm).

8.12.4.2 Flap Design

Touch the maximum point of impulse (pivot point) 2.5 cm below midpoint of groin line. Then make a line between the pivot and ASIA as the flap axis. The flap length is determined by the wound length plus 2 cm, with a 5–7 cm pedicle. The flap width is wound width plus 2 cm. 2/3 part of flap should be designed above the axial line, as other 1/3 part should be below (Fig. 8.37).

8.12.4.3 Flap Harvest

The harvest is start with lateral margin to get the flap rapidly. Raising the flap on the deep fascia surface of external oblique and gluteus medius, until the lateral margin of sartorius muscle is exposed. The deep branch of superficial iliac circumflex artery should be retained in the fascia. When the perforator is revealed, follow the artery and reveal the originating point. Remove excessive fat tissue that around the pedicle to reduce the stress. The pedicle is sutured as a tube. Turn the flap to hand receiving area without tension. Double layer suture is performed on flap with wound skin and subcutaneous tissue. If the donor wound width is less than 10 cm, it can be closed directly.

If the groin flap is used to free transplant, the incision start with medial pedicle (Fig. 8.38).

Notes

1. Use the Plaster Bandage to set the upper extremity on the chest. The extremity still has a range of mobility, with the 5–7 cm long pedicle.
2. With the popular style of thin branch perforator flap, Kimura (2006) reported a new application of SICA thin flap. Using micro-dissection to remove the fat tissue in the subcutaneous loose organization, the flap can be thin in primary surgery, and more suitable for hand wound.
3. One week after surgery, the pedicle needs to be temporarily interrupted by elastic bandage, two times 1 day, until the flap have no blood change after 2 h of interruption. The surgical interruption is often in 14–21 days.

8.12.5 Sural Neurovascular Flap

This is a distal pedicle flap in the posterior lower leg. Donski reported this flap in 1983. He harvested the flap on lateral side of lower leg, based on peroneal artery septum

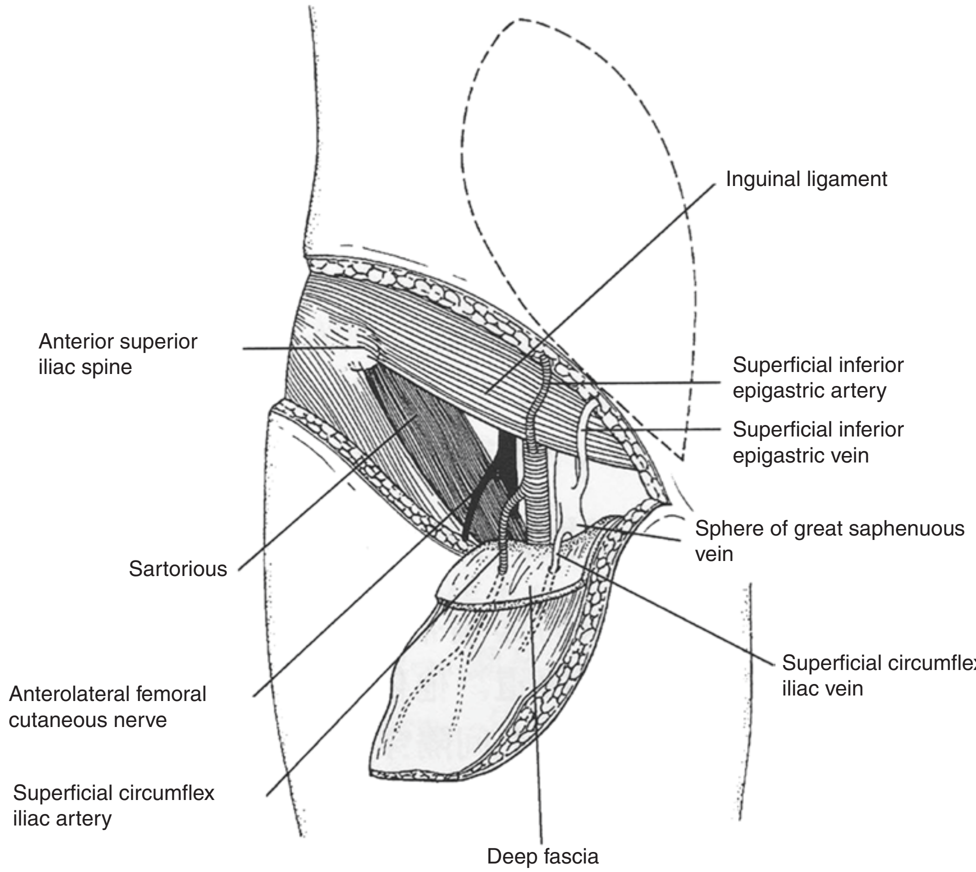


Fig. 8.36 Anatomy of vessels in groin flap

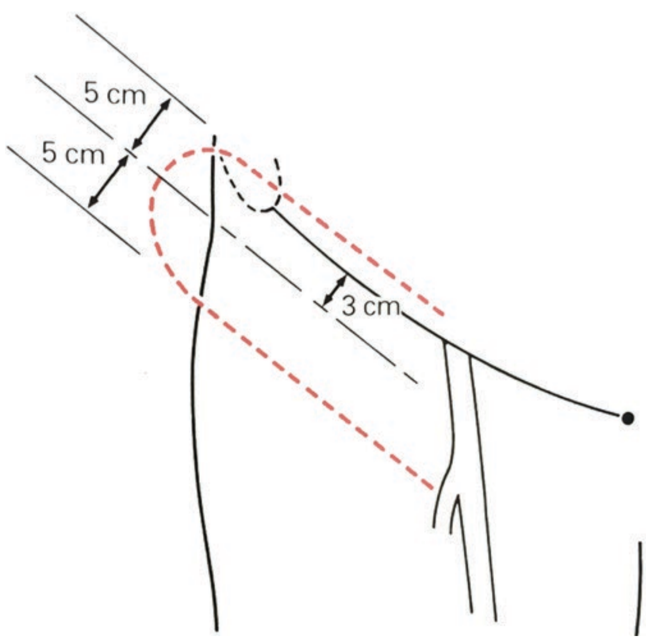


Fig. 8.37 Groin flap design

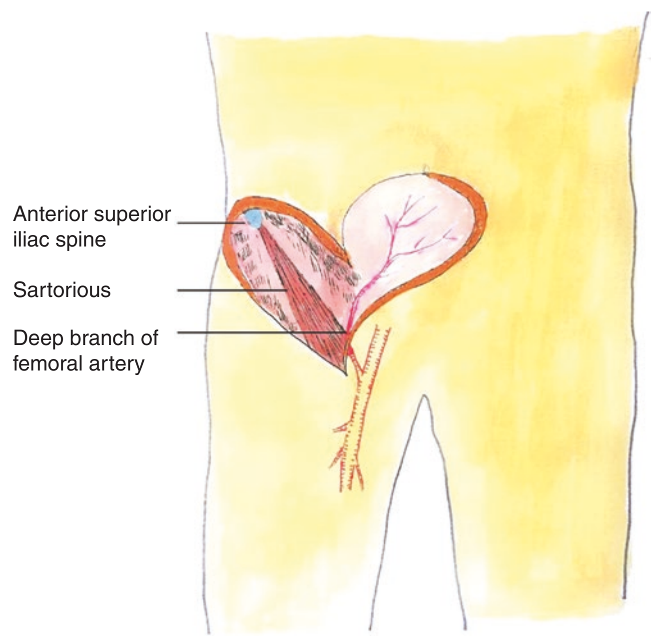


Fig. 8.38 Groin flap harvest

perforators that 4–7 cm superior on lateral malleolus. In 1992, Masquelet performed an anatomic study and found there are 3–5 branch of peroneal artery anastomosed with superficial sural artery (sural nerve vessel bundles). Based on the anatomy study, he provided a new method (neurocutaneous flap) to reconstruct the lower 1/3 part of leg, foot and ankle. Hasegawa reported the distally based superficial sural artery flap in 1994, and determined the most distal anastomosis between peroneal artery and superficial sural artery is located 5 cm above the lateral malleolus. In 1998, Nakajima's study indicated the nutrient vessels of lesser saphenous vein also provide blood supply to skin, and he proposed the concept of veno-fasciocutaneous flap. In 2000, by experimental study, Chang proposed the viewpoint that venous ingress from lesser saphenous vein to the distally based sural flap has negative effect on flap circulation, and the large superficial vein should be ligatured in the distal pedicle [21–24]. Le Fourn and Al Qattan performed a study in 2001, indicated that gastrocnemius vessels have anastomosis with sural nerve vessel bundles. Based on the study, they designed the myo-fasciocutaneous flap to treat osteomyelitis wound. In 2001, Chai changed the thick fascia pedicle to thin perforator pedicle. In 2005, based on anatomy study, Zhang proposed the flap with a lower pivot. In 2007, Chang reported the lateral retromalleolar perforator sural flap for heel coverage.

8.12.5.1 Applied Anatomy

In popliteal fossa, the medial sural cutaneous nerve originates from tibial, the lateral sural cutaneous nerve originates from common peroneal nerve. When the medial and lateral branches connect, their nutrient vessels also join together to form the superficial sural artery, which is 1.0–1.5 mm diameter. In 1/3 cases, the artery is thin and turns into longitudinal vascular plexus. Sural nerve goes down between two the heads of gastrocnemius muscle. It pierces the deep fascia in upper third of lower leg. The sural nerve nutrient vessels accompanied with lesser saphenous vein, and gives off branches to lateral 2/3 skin of lower leg. In the specimen with superficial sural artery, 65% artery can be traced to ankle, other 35% transform to longitude vascular plexus.

The proximal perforators are ligatured as distal pedicle flap is harvested. So the flap is supported only by distal perforator from peroneal artery to sural nerve vessel bundle. There are 3–5 septal perforators, the lowermost one is located on 5 cm above the lateral malleolus (Fig. 8.39).

In the lateral retromalleolar space, the terminal peroneal branch give off 2–3 cutaneous perforators, with 0.1–0.8 mm diameter. One 0.5 mm diameter perforator can be found. The vessels are distributed in accordance with the pressure equilibrium role, in diameter and interval. The diameter and distance between perforators usually compensate for each other (Fig. 8.40).

In sual flaps, there are two venous systems. One is the 1–2 veins accompanying with perforators, that feeds into the deep vein. The other is lesser saphenous vein. But some researchers consider the lesser saphenous vein cannot help venous return in distally based flaps.

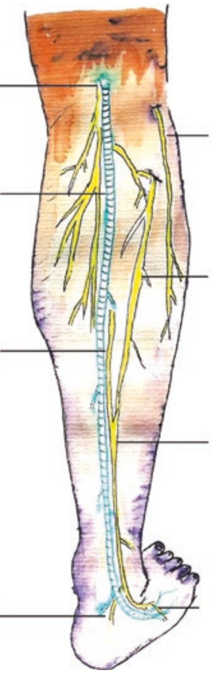


Fig. 8.39 Anastomosis between sural nutrition vascular axis and the peroneal perforators

8.12.5.2 Flap Design

According to the size, position, defect situation of the wound, this distally based flap is designed based on the 4-principles of "point, line, area, arc" (Fig. 8.41).

Point: The pivot point is the base, which is the source of blood supply to the flap. This point is generally selected as the lowest intermuscular perforator of the 5 cm radial artery above the lateral malleolus, which can be determined by ultrasound Doppler before surgery.

Line: The axis is the running line of the sural nerve. The axial line is located at the midpoint of the axillary fossa to the midpoint of the line connecting the Achilles tendon and the external malleolus. The axial line is the direction of the chain vascular anastomosis, which is the lifeline of the blood supply of the flap. Because the sural nerve has a good companion relationship with the small saphenous vein, it can be determined by the small saphenous vein under the venous tourniquet before surgery.

Area: There are two aspects of meaning. On the one hand, the cut-out area is determined by the size of the defect wound plus 2 cm as the area of the flap; on the other hand, the cut flat is in the deep fascia space, which is the "surgical flat" of the flap.

Arc: the rotation arc of the flap is the distance from the rotation axis point to the distal end of the defect pulsing 2 cm. it is drawn backwards on the axis of the axis, including the total length of the flap and pedicle.

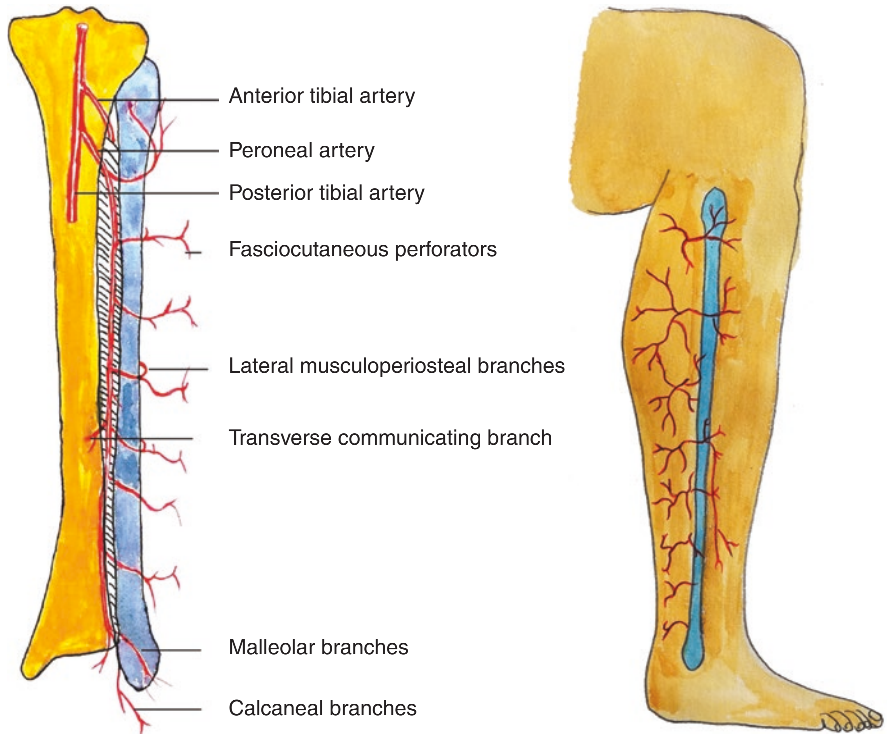


Fig. 8.40 Perforators from peroneal artery

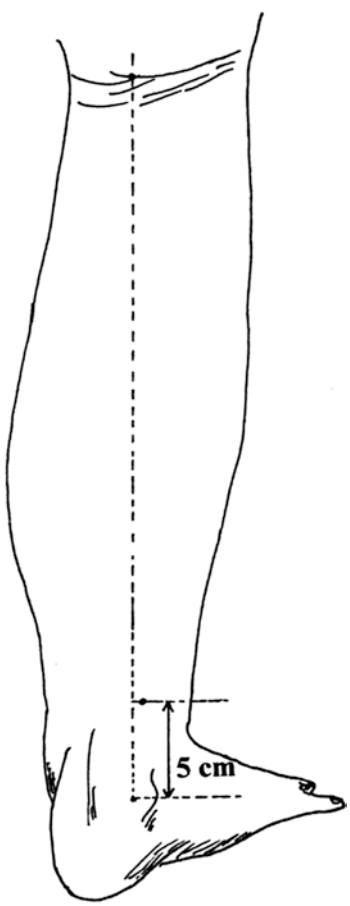


Fig. 8.41 Design of distally based sural flap

8.12.5.3 Flap Harvest

The affected limb does not drive blood, and it is operated under the control of the balloon tourniquet after raising for 3–5 min. According to the preoperative design line, the pedicle skin incision is made first, and the skin flap is opened 1.5 to 2 cm on both sides of the dermis. As a result, the width of the sural nerve fascia is not less than 3 cm. The deep fascia was cut from the side of the Achilles tendon, and it was lifted forward to observe the position of the farthest muscle of the radial artery through the branch vessel (4 to 7 cm on the lateral malleolus) and the diameter of the vessel (about 1 mm). Then adjust the flap cutting range appropriately. For the repair of the ankle, the length of the overlapping fascia pedicles is shortened by 1 cm for each 1 cm reduction of the pivot point of the flap, so the length of the incision in the donor area can be reduced by 2 cm (Fig. 8.42).

The distal incision of the flap is cut on the proximal side of the calf. Cut the skin and subcutaneous tissue to the deep subfascial space. Cut the sural nerve and small saphenous vein, included in the flap. Dissecting from the proximal to the distal pedicle in the deep fascial space, this is the "surgical flat" of lifting the flap, only need to electrocoagulate some perforating vessels. We need to pay attention to the fixation of the skin and the deep fascia at any time to prevent the skin and deep fascia from detaching. Special care should be taken when operating to the pedicle to identify the most distal perforating vessel from the iliac artery at the posterior lateral muscle to prevent injury. In general, the flap can be picked up in about 30 min. At this point we need to relax the

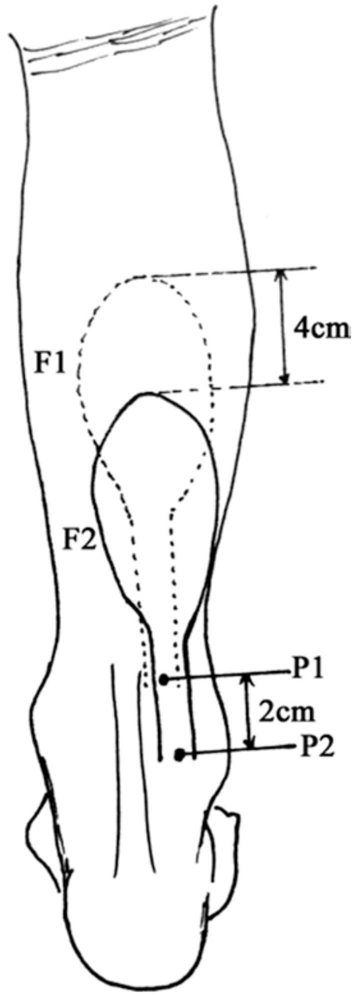


Fig. 8.42 The lower pivot means lesser donor site morbidity with lower incision. P1-F1 superior perforator and flap, P2-F2 inferior perforator and flap

tourniquet and observe the blood circulation. Under normal circumstances, there will be bright red exudation at the end of the endothelium. We need to pay attention to the tension of the small saphenous vein. If the blood flow back from the distal foot vein causes the saphenous vein to swell, we need to carefully pick out and ligature it 1 cm distal to the axis of rotation, thus blocking venous blood reflux. If there is damage to the small saphenous vein branch in the distal ankle wound, and there is no venous engorgement in the small saphenous vein, then we do not need to do ligation. Try to transfer the flap. If there is tension, the fascia tissue of the pedicle can be microscopically separated to cut off the tight fiber band. After we trim the wound in the receiving area, we transfer the flap to the receiving area without tension. If the width of the flap does not exceed 5 cm or does not exceed 1/5 of the patient's calf circumference, the donor area can be directly sutured. If the flap is difficult to suture, skin transplantation should be operated in the middle part after the suture is stitched at both ends.

Table 8.7 Variants of sural flaps

Pedicle	Sural nerve-lesser saphenous vein adipofascial pedicle (thick) Sural nerve adipofascial pedicle (without lesser saphenous vein) Lesser saphenous vein adipofascial pedicle (without sural nerve) Most distal septum-perforator pedicle (thin) Retromalleolus perforator pedicle
Pivot	Superior 5 cm (4–7 cm) to lateral malleolus. Distal septum-perforator Superior 2 cm (0–3 cm) to lateral malleolus. Retromalleolus perforator
Flap	Sural nerve fascial flap Turnover-sural nerve adipofascial flap sural nerve musculocutaneous flap, muscle flap sural nerve osteocutaneous flap, bone flap, periosteum flap Transplant sural nerve with fascial to tibial nerve Transplant lesser saphenous vein with fascial blood to tibial artery

8.12.5.4 Flap Modification

With more understanding of the flap, the researchers designed some modifications [25–30] (Fig. 8.43).

Notes

- The distally based sural nerve-lesser saphenous vein fasciocutaneous flap is very useful to reconstruct the foot and ankle. The advantages include: (1) the flap is transplanted with pedicle, that is easy to performed. (2) It cost only 30-45 min to harvest the flap. (3) One-stage procedure only involving the injured leg. (4) No sacrifice of main artery. (5) It is a local flap, the donor site has the similar texture with receiving site. (6) There are cutaneous nerve in the flap, in some cases, the nerve can be anastomosed in receiving site to restore sensation. (7) The blood flow is more normal than the reverse island flap. (8) The extremity is free, that is benefit for early movement and rehabilitation. (9) The surgery needs no microsurgery anastomosis. (10) The flap is especially pertinent for distal part of extremity.

8.12.6 Posterior Forearm Interosseous Artery Flap

The reverse posterior interosseous artery flap based on posterior interosseous artery, which is reported by Lu and Penteado in 1986. The Posterior forearm interosseous flap is a common method to reconstruct hand defect.

8.12.6.1 Applied Anatomy

Posterior interosseous artery is given off by common interosseous artery. In the upper third of forearm, the artery passes through the space between interosseous membrane superior trim and chorda oblique, to the posterior area. Then

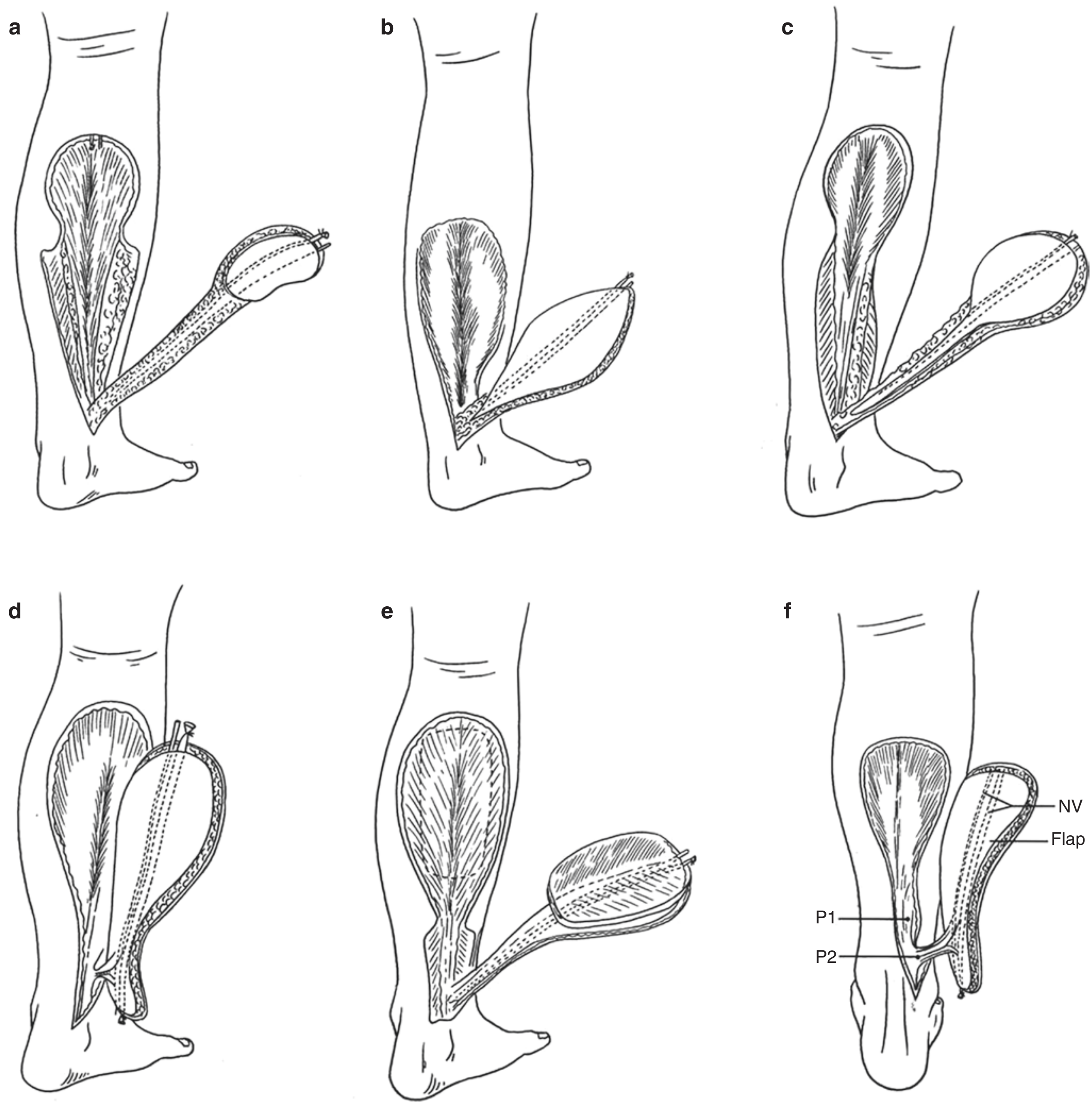


Fig. 8.43 Modification. (**a**) Sural nerve fascia pedicle island flap; (**b**) teardrop fascial flap; (**c**) racket shape cutaneousfascial flap; (**d**) island cutaneousfascial perforator flap; (**e**) island musculocutaneous fascial flap; (**f**) lower pivot with retromalleolus perforator

the artery passes the space between supinator and abductor pollicis longus. It gives off two branches, ascending branch and descending branch. The ascending branch goes to the elbow, the descending branch goes in the space between extensor digiti minimi and extensor carpi ulnaris. The descending branch reaches a length of 14 cm, with 1.5 cm diameter in origin. The terminal branch is located on 2.5 cm superior to styloid process of ulna, and has anastomosis with dorsal branch of volar interosseous artery. The Posterior interosseous artery gives off 5–13 cutaneous perforator, and form a vascular network, which reach a width of 6 cm (Fig. 8.44).

8.12.6.2 Flap Design

When the elbow flexes 90° and the wrist rotates in the neutral position, the line connecting the lateral epicondyle of the humerus to the lateral edge of the ulna is the axis of the artery and the axis of the flap. The rotation axis of the flap was 2.5 cm above the ulnar styloid, which could be confirmed by ultrasound Doppler. According to the location and

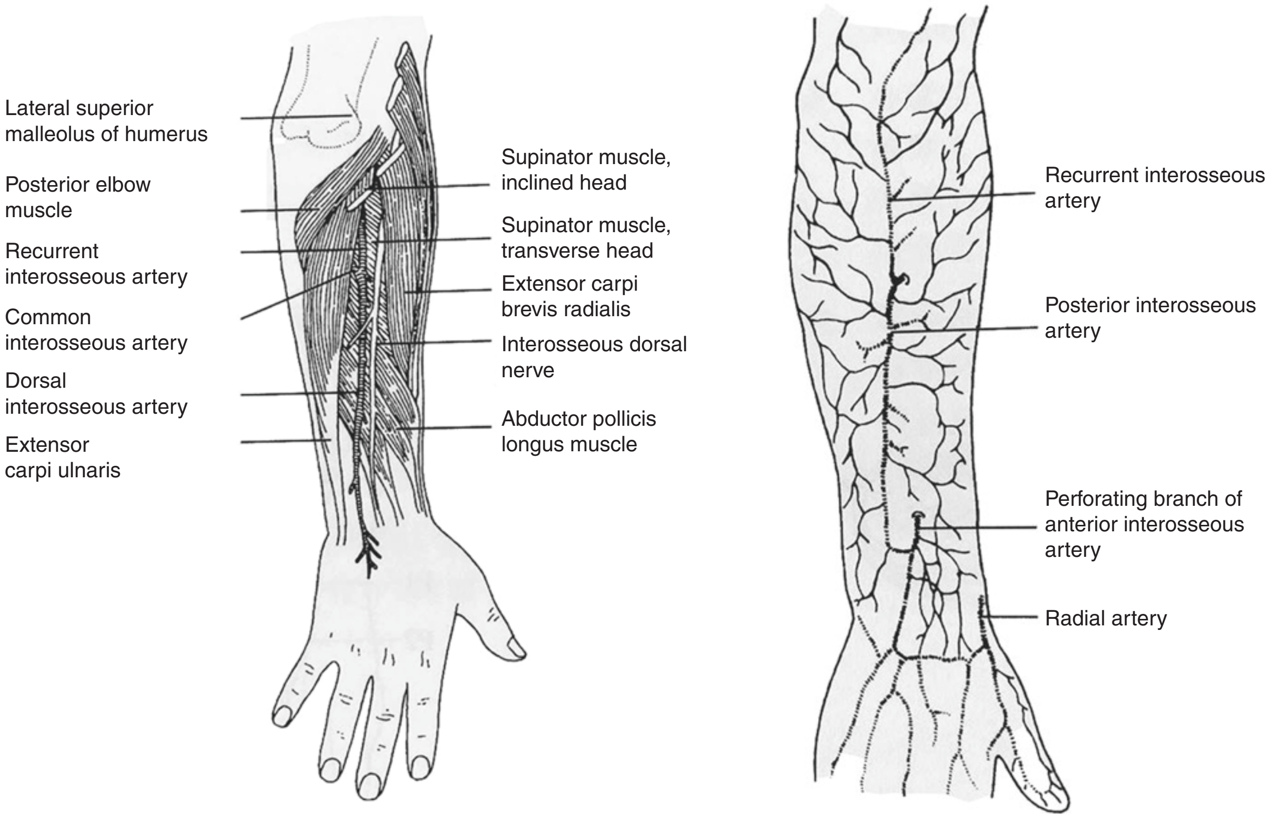


Fig. 8.44 Anatomy of posterior interosseous artery. (**a**) Perforators from Posterior interosseous artery, (**b**) PIA and AIA Anastomosis

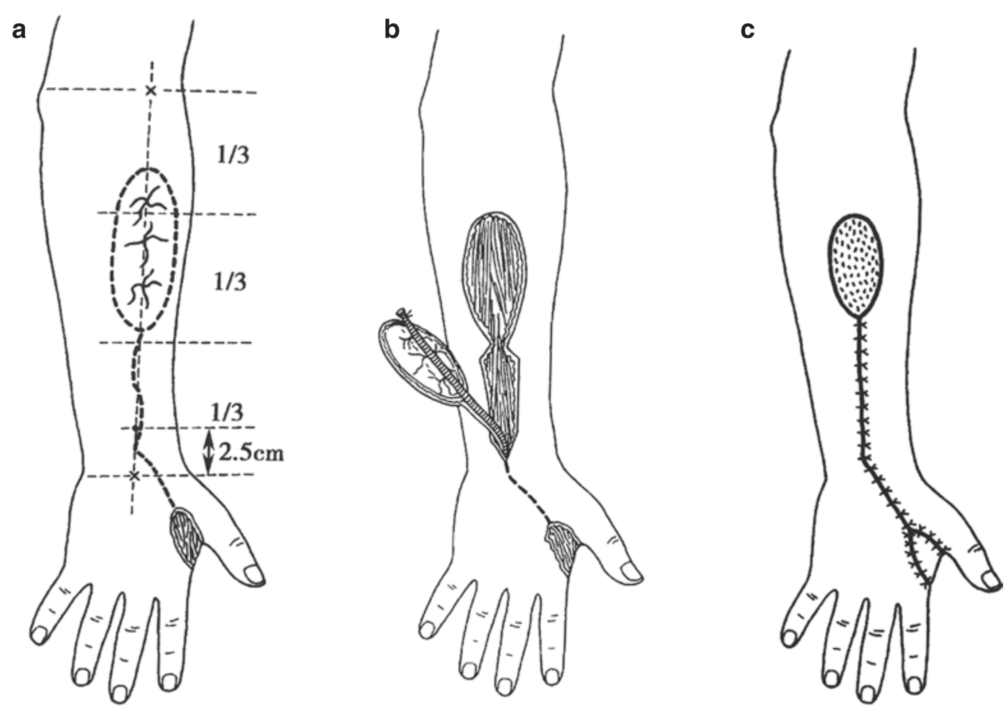


Fig. 8.45 Reverse posterior interosseous artery flap. (**a**) Design, (**b**) harvest, (**c**) transplant

size of the defect, the flap is designed in the middle third of the forearm. Generally, there is a large cutaneous branch around 10 cm on the wrist, which should be designed in the middle of the flap. If the distal vascular pedicle is too short, the flap can be extended to the proximal side, up to 4 cm below the elbow.

8.12.6.3 Flap Harvest

The operation is controlled by tourniquet without exsanguinations. Fist, the vascular pedicle is determined. The skin incision is start with pivot point. The artery can be observed under the sub fascia space. Trace the artery until the distal anastomosis point, usually 2.5 cm above ulnar head, is exposed. Then 1.5 cm width fascia pedicle and the septum is preserved to avoid vascular injury. After all the flap and pedicle is dissected, tourniquet is released to make sure the flap has a good blood supply. Then transfer the flap to the recipient site. The donor site can be cover by skin graft or sutured directly (Fig. 8.45).

Notes

1. The interosseous dorsal nerve should be protected carefully. This nerve is a motor nerve, disrupts to extensor muscle. If artery or branches cross over the nerve, the artery should be ligatured
2. The pivot point is the anastomoses arc that located 2.5 cm proximal to ulnar styloid process. So the pedicle shouldn't crossover the point.
3. If the sensory reconstruction in considered, the posterior antebrachial cutaneous nerve should be taken in the flap.

References

1. Cormack GG, Lamberty BGH. The arterial anatomy of skin flaps. 2nd ed. Edinburgh: Churchill Livingstone; 1994.
2. Hallock GG, editor. Fasciocutaneous flaps. Boston: Blackwell Scientific Publications; 1992.
3. Mathes SJ, Hentz VR, editors. Plastic surgery. 2nd ed. Philadelphia: Saunders; 2006.
4. Strauch B, Vasconez LO, Hall-Findlay EJ, Lee BT, editors. Grabb's encyclopedia of flaps. 3rd ed. Boston: LWW; 2009.
5. Taylor GI, Pan WR, Dodwell P. The angiosome concept and tissue transfer. St. Louis: Quality Medical Publishing; 2014.
6. Blondeel PN, Morris SF, Hallock GG, Neligan PC. Perforator flaps: anatomy, technique, and clinical applications. 2nd ed. St. Louis: Quality Medical Publishing; 2013.
7. Zenn MR, Jones G. Reconstructive surgery: anatomy, technique, and clinical applications. St. Louis: Quality Medical Publishing; 2012.
8. Pu LLQ, Levine JP, Wei FC. Reconstructive surgery of the lower extremity. St. Louis: Quality Medical Publishing; 2013.
9. Blondeel PN, Van Landuyt KH, Monstrey SJ, et al. The "Gent" consensus on perforator flap terminology: preliminary definitions. Plast Reconstr Surg. 2003;112:1378–83.
10. Hallock GG. The complete nomenclature for combined perforator flaps. Plast Reconstr Surg. 2011;127(4):1720–9.
11. Pignatti M, Ogawa R, Hallock GG, et al. The "Tokyo" consensus on propeller flaps. Plast Reconstr Surg. 2010;127(2):716–22.
12. Sinna R, Boloorchi A, Mahajan AL, et al. What should define a "perforator flap"? Plast Reconstr Surg. 2010;126:2258–63.
13. Lineaweaver W. Microsurgery and the reconstructive ladder. Microsurgery. 2005;25:185–6.
14. Hou CL, Chang SM, Lin J, Song DJ. Surgical atlas of perforator flaps: a microsurgical dissection technique. New York: Springer; 2015.
15. Chang SM, Zhang LS. Link pattern adipofascial flap. Br J Plast Surg. 1994;47(2):142–3.
16. Chang SM. The pedicle of neurocutaneous island flaps. Plast Reconstr Surg. 1996;98(2):374–6.
17. Chang SM. The distally based radial forearm fascia flap. Plast Reconstr Surg. 1990;85(1):150–1.
18. Chang SM, Hou CL, Zhang F, et al. Distally based radial forearm flap with preservation of the radial artery: anatomic, experimental and clinical studies. Microsurgery. 2003;23(4):328–37.
19. Zhang YQ, Wang X, Chang SM. Perforasome. Plast Reconstr Surg. 2011;127(2):1015–7.
20. Chang SM, Hou CL, Xu DC. An overview of skin flap surgery in the mainland China: 20 years achievements (1981-2000). J Reconstr Microsurg. 2009;25(6):361–8.
21. Chang SM, Chen ZW. Can superficial veins reverse flow through valves in distally based fasciocutaneous flaps? Plast Reconstr Surg. 1991;87(5):995–6.
22. Chang SM, Gu YD, Li JF. Comparison of different management of large superficial veins in distally based fasciocutaneous flaps with a veno-neuro-adipofascial pedicle: an experimental study in the rabbit model. Microsurgery. 2003;23(6):555–60.
23. Chang SM, Gu YD, Li JF. Comparison of venous drainage in reverse-flow island flaps: an experimental study of the rabbit saphenous fasciocutaneous flap. Ann Plast Surg. 2003;51(2): 177–81.
24. Chang SM, Gu YD, Li JF. The role of large superficial vein in survival of proximal-based versus distal-based sural veno-neuro-fasciocutaneous flaps in a rabbit model. Plast Reconstr Surg. 2005;115(1):213–8.
25. Chang SM, Zhang F, Yu GR, Hou CL, Gu YD. Modified distally based peroneal artery perforator flap for reconstruction of foot and ankle. Microsurgery. 2004;24(6):430–6.
26. Chang SM, Zhang F, Xu DC, et al. Lateral retromalleolar perforator-based flap: anatomic study and preliminary clinical report for heel coverage. Plast Reconstr Surg. 2007;120(3):697–704.
27. Chang SM, Zhang K, Li HF, et al. Distally based sural fasciomyocutaneous flap: anatomic study and modified technique for complicated wounds of the lower third leg and weight bearing heel. Microsurgery. 2009;29(3):205–13.
28. Chang SM, Tao YL, Zhang YQ. The distally perforator pedicled propeller flap. Plast Reconstr Surg. 2011;128(5):575e–7e.
29. Chang SM, Wang X, Huang YG, Zhu XZ, Tao YL, Zhang YQ. Distally based perforator propeller sural flap for foot and ankle reconstruction: a modified flap dissection technique. Ann Plast Surg. 2014;72(3):340–5.
30. Chang SM, Li XH, Gu YD. Distally based perforator sural flaps for foot and ankle reconstruction. World J Orthop. 2015;6(3): 322–30.

9 Compound Tissue Transfer

Yimin Chai

9.1 Overview

As neurovascular repair techniques have been continuously improved along with the development of microsurgery, reconstructive surgery, and plastic surgery, attempts to salvage compromised extremities have been made more frequently. Compound flaps, based on specific donor sites, have proved to be an ideal option for loss of composite tissues like skin, bone, joint, muscle and tendon. Although the compound flaps are frequently used in recent decades, their categorization remains controversial. Nakajima divides the flaps into five types according to their blood supply. Muscle flaps, a type according to Nakajima's classification, are further divided into five subtypes by Nahai and Mathes. Some authors still think that the classification based on the blood supply may fail to give sufficient descriptions of the flaps and a second feature should be taken into account in classification to provide more accurate descriptions in academic communication. As a result, the most accepted nomenclature of compound flaps refers to their blood supply and ingredients. For example, the compound flap of serratus and rib pedicled on the subscapular artery, and the fibular compound flap pedicled on the peroneal artery. Recently, the ever-growing wealth of literature has demonstrated us the ongoing innovation and refinement of the planning and application of compound flaps. The purpose of this chapter is to introduce the classification, clinical application, and anatomical basis of some common compound flaps.

Y. Chai (✉)
Department of Orthopaedics, The Sixth People's Hospital, Shanghai Jiao Tong University, Shanghai, China
e-mail: ymchai@sjtu.edu.cn

9.2 Classification

A compound flap is a unit which combines a variety of tissues with a common source of blood supply. Compound flaps can be divided into two types based on their major source(s) of artery/arteries: (1) solitary vascularization; (2) combinations of vascularization.

9.2.1 Compound Flap with Solitary Vascularization

9.2.1.1 Simple Composite Flap

By definition, simple composite flaps belong to the simplest type of compound flaps. They are actually an entire tissue supplied by a major artery. The branches of the major artery nourish each part of the tissue and communicating branches can be explored from one part to another. Thus, the viability of a composite flap depends on its integrity.

A myocutaneous flap is one typical type of composite flaps. The majority of simple composite flaps are monoflaps, but the distal portion of tissue components can be separated to facilitate insetting the recipient sites in some cases of composite flaps. Clinically, simple composite flaps are indicated for reconstruction of lesser loss of composite tissues, especially for resurfacing a local defect.

9.2.2 Compound Flap with Combined Vascularization

Besides simple composite flaps, the rest of compound flaps have multiple blood supplies and can be further divided into siamese flaps and chimeric flaps. This classification is based on the structure and relationship of the interconnected blood supply.

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_9

9.2.2.1 Siamese Flap

A siamese flap is a series of independent tissue components linked by connecting vessels and the area of each tissue component exceeds the supplemental area of each vascular pedicle. In order to compensate for the distal blood supply, reconstruction of distal circulation is required for the viability of entire flap. Harri et al., among the first generation who gave definition of compound flaps, introduced their design of compound flaps where the thoracodorsal artery of the latissimus dorsi flap is anastomosed with the superficial iliac circumflex artery of the groin flap. This bilobed flap, using vessel anastomosis for cascade connection, can be elevated based on either proximal or distal vessel pedicle depending on the location of defects. Once a siamese flap is elevated from the original site to cover the defects, establishment of distal blood supply is demanded due to the insufficient perfusion supplied by either of the vessel pedicles at the donor site. As a result, after Harri ligated and cut the thoracodorsal artery to elevate the siamese flap based on the superficial iliac circumflex artery, the end of thoracodorsal artery was anastomosed to the recipient vessel. Belousov et al. defined these flaps, which have an extensive area, as mega flaps requiring more than two vessel pedicles for blood supply. Nassif et al. later proposed that the tissue components of a siamese flap may not be linked together. He also shared his experience in harvesting the muscle component of latissimus dorsi flap and the fascia component of parascapular flap to connect each other through perforators. Both components survived uneventfully. According to the literature, the latest common viewpoint believes that components of a siamese flap can be connected either directly or by perforators.

9.2.2.2 Chimeric Flap

Chimeric flaps are constituted by different tissue components, each of which has its independent blood supply and all the vessels of which originate from the same maternal artery. Given the aforementioned anatomical basis, the entire chimeric flap can be supplied by one vessel pedicle after elevation. All the substructures are connected with each other in parallel. Thus, survival of different tissue components of a flap is independent. In a chimeric flap, composite tissues are of different types (such as skin combined with bone or muscle components). In a polyfoliate flap, composite tissues are of the same type. The subscapular artery chimeric flap is typical. Although each tissue component can serve as an independent grafting in a chimeric flap, such as scapular flap, latissimus dorsi flap, serratus flap, and rib flap, reconstruction of composite defects is demanded in some cases and anastomosis of one maternal vessel can fulfill the blood perfusion of the entire chimeric flap, thus allowing the synchronous transfer of all the tissue components.

As we mentioned above, the blood supply of a composite flap can be obtained by a perforator vessel and its branches. The composite flap can be called as 'perforator-based chimeric flap' in case that each branch of the perforator vessel can nourish its tissue component independently. Another special type of chimeric flap can be obtained through microsurgical technique, in which different vessels of tissue flaps from different donor sites are anastomosed. As a result, all the tissue flaps from different donor sites can be simultaneously transferred and survived based on only one pedicle vessel anastomosis to the recipient vessel.

9.3 Indications for Compound Flap

The indications for compound flaps pedicled on the subscapular vessels are: (1) composite defects involving skin, muscle and bone; (2) demand of myocutaneous flaps either at the same level or at different levels; (3) massive muscle defects with relatively less bone defects. The indications for compound flaps pedicled on the lateral circumflex femoral artery include: (1) composite defects of skin, muscle and bone; (2) massive skin defects with relatively less muscle defects (harvesting the anterior segment of the iliac bone when needed). The indications for compound flaps pedicled on the peroneal artery include: (1) composite defects of skin, muscle and bone; (2) reconstruction of long bone defects and massive defects of skin and soft tissue.

9.4 Clinical Principles for Compound Flap

An important factor to consider in the decision for primary closure is the window from the injury to definite reconstructive surgery. In general, the likelihood of infection rises with the length of time when the wound is left without debridement. The more heavily contaminated a wound is, the more important a shorter time to debridement becomes. Theoretically, all composite defects resulting from trauma, tumor, or chronic infection, can be reconstructed by compound flaps. Compound flaps containing muscle components are indicated for infectious wounds. Other factors before definitive reconstructive surgery include:

9.4.1 The Area of Compound Flap

Stable coverage of wound is one of the most important factors deciding survival of the flap, for the reason that the dead cavity due to insufficient area of the flap and postoperative contracture may result in formation of hematoma beneath the flap and secondary infection may develop if hematoma left untreated. In general, preoperative planning of compound flap plays a vital role in the entire procedure of reconstructive surgery.

9.4.2 The Donor Site Morbidity

The functional and sensational impairment of the donor sites after a compound flap is harvested also should be taken into consideration during planning, especially for the compound flaps based on the subscapular vessels, because ROM (range of motion) of the shoulder may be decreased due to the scar contracture left by the incision adjacent to the axilla fossa.

9.4.3 Backup Option for Compound Flap

When planning a compound flap, more than one backup method should be considered in decision. A proper backup option should be executed unhesitatingly as long as the initial plan fails to proceed owing to various unpredicted situations including vascular variation and accidental injury to the vessel.

9.5 Key Points for Compound Flap

9.5.1 Compound Flap Based on the Subscapular Vessel

The surgical key points for compound flaps based on the subscapular vessel are: (1) The courses of branches of subscapular vessels should be followed in design. (2) The thoracodorsal nerve should be dissected and protected when the compound flap is harvested and the long thoracic nerve should be explored and protected when the compound flap of serratus and rib was elevated. (3) Attention should be paid to the trunk artery when the pedicle vessel is dissected; it is necessary to ligate irrelevant perforators which affect flap transfer and have no connection with the compound flap, like the lingual posterior humeral circumflex artery and the lingual lateral thoracic artery. (4) After tendon harvesting or incision at the donor site tenodesis is indispensable to reduce the donor site morbidity. (5) Great attention should be paid to the pedicle skin during harvesting the compound flap based on the subscapular vessel which carries a massive area of skin paddle. Z-plasty may provide a good alternative option for treatment of pedicle skin to prevent postoperative scar contracture resulting from the surgical incision adjacent to the axilla fossa.

9.5.2 Compound Flap Based on the Subscapular Vessel

The surgical key points for compound flaps based on the lateral circumflex femoral artery are: (1) Separation of branches of the femoral nerve should be careful because they and the lateral femoral circumflex artery together with its branches may adhere to the surrounding connective tissue. (2) Preoperative radiological examination of the lateral femoral circumflex artery and its branches is necessary to get acquainted with the types of the branches so that design of the compound flap can be based on the courses of the branches. (3) The direction of the pedicle vessel is opposite to the direction of the nerve innervating the tensor fasciae latae. The dominant nerve of the tensor fasciae latae originates from the superior gluteal nerve and then descends between the gluteus medius and the gluteus minimus. It continues gradually towards the posterior border of the tensor fasciae latae and can be explored in the area where the ascending branch pierces the muscle. The function of the tensor fasciae latae can be regained by linking the dominant nerve to the recipient nerve. (4) The lateral femoral cutaneous nerve is located approximately 1 cm from the line between the anterior superior spine and the lateral border of the patella. Innervation can be achieved through anastomosis of the lateral femoral cutaneous nerve when an anterolateral thigh flap or a tensor fasciae myocutaneous flap is harvested. (5) Efforts should be made to reduce the donor site morbidity after the compound flap is harvested.

9.5.3 Compound Flap Based on the Peroneal Artery

The key points to harvesting the peroneal artery compound flap are: (1) In design the skin paddle should be at the posterior-lateral aspect of the lower extremity while the designed fibular graft should be at the middle third of the fibular. The distal 6-cm fibula should be preserved for stability of the ankle joint while the proximal 3–4 cm fibula should be preserved to prevent injury to the nervus peroneus communis. (2) The procedure starts from the skin paddle elevation by incision at the anterior border to locate the perforators within the posterior crural septum. When the posterior crural septum is reached, the septocutaneous perforators attached to the skin paddle can be identified. (3) The lateral sural nerve, accompanied by the lateral superficial sural artery, runs through the line between the midpoint of popliteal fossa and the midpoint of the lateral malleolus and the lateral border of achilles tendon. Innervation of the compound flap can be gained through neuroplasty of the lateral sural nerve. (4) When the fibular flap is planned at the proximal third of the lower extremity, the dominant perforators are intramuscular perforates which require intramuscular dissection. Muscle cuff of the soleus and flexor hallucis longus is used for protection of the perforators. When the fibular flap is planned at the distal third of the lower extremity, the procedure of intramuscular dissection can be spared since the dominant perforators are septocutaneous perforators. (5) Efforts should be made to reduce the donor site morbidity after the compound flap is harvested.

9.6 Common Compound Flaps

Dozens of donor sites have been reported for harvesting compound flaps. The following three are frequently used which are characterized by a massive area of skin paddle and a single pedicle vessel with various type of branches to nourish different tissue components.

9.6.1 Compound Flap Pedicled on the Subscapular Artery

9.6.1.1 Distribution of the Subscapular Artery

The subscapular artery gives out the circumflex subscapular artery and the thoracodorsal artery, distributing to the scapulas, latissimus dorsi, serratus, and lateral aspect of thorax. The subscapular artery can be classified as follows: (1) Direct type (52.5%): The subscapular artery gives out the circumflex subscapular artery and the thoracodorsal artery directly. (2) Co-trunk type (40%): The subscapular artery gives out the circumflex subscapular artery, thoracodorsal artery, posterior humeral circumflex artery and lateral thoracic artery. (3) Separate type (7.5%): The axillary artery gives out the circumflex subscapular artery and the thoracodorsal artery.

The subscapular artery gives out the circumflex subscapular artery approximately 1.5–2.5 cm below its beginning segment, and then divides into the superficial branch and the deep branch after going through the trilateral foramens. The superficial branch of the circumflex artery is a musculocutaneous artery, which divides into ascending branch, transverse branch, and descending branch, distributing to the fascia and skin below the area of mesoscapula. The deep branch of the circumflex artery runs along the lateral border of the scapular, dividing into anastomotic branch, infraspinous fossa branch, and branch of inferior angle of scapula. These branches spread over the area of infraspinous fossa, and the posterior-lateral and anterior-lateral aspects of the lateral border of the scapula. The thoracodorsal artery usually continues from the subscapular artery, and then descends passing the teres major deep to the lateral border of latissimus dorsi. The constant branches of the thoracodorsal artery include the scapula branch and the serratus branch. The pectoral cutaneous branch is given out with a probability of 37.5% from the thoracodorsal artery. The thoracodorsal artery divides into the lateral and medial branches at 1.9 cm above the superior angle of the scapula, approximately 2.2 cm to the lateral border of latissimus dorsi, distributing to the latissimus dorsi. The lateral branch also gives out a musculo-cutaneous artery to the lateral area of thorax.

9.6.1.2 Design of Compound Flap Pedicled on the Subscapular Artery

Design of the subscapular artery compound flap should be based on the types of the subscapular artery branches. The following are the common compositions of the compound flap: (1) the latissmus dorsi flap combined with scapular (bone) flap; (2) the latissmus dorsi flap combined with lateral pectoral flap; (3) scapular (bone) flap combined with lateral pectoral flap; (4) combination of the latissmus dorsi flap, the lateral pectoral flap and the scapular (bone) flap; (5) scapular flap combined with serratus anterior costa flap. In addition, when the subscapular artery cannot be used as the pedicle in design of compound flaps the thoracodorsal artery can be used instead, because about 3.0–16.7% of the scapular circumflex artery and the thoracodorsal artery originate from the axillary artery respectively. The compound flaps pedicled on the thoracodorsal artery include: (1) latissimus dorsi flap combined with lateral pectoral flap; (2) latissimus dorsi flap combined with serratus anterior costa flap; (3) latissimus dorsi scapular flap combined with lateral pectoral flap. So far, the compound flaps pedicled on the subscapular artery in various combinations provide the most extensive area of skin paddle. They can be designed as a myocutaneous flap and a bone flap depending on the site of defect. Innervation of the transferred flap can be achieved through anastomosis of the thoracodorsal nerve to the cutaneous nerve from the recipient site.

9.6.2 Compound Flap Pedicled on the Lateral Femoral Circumflex Artery

9.6.2.1 Distribution of the Lateral Femoral Circumflex Artery

The lateral femoral circumflex artery mostly originates from the deep femoral artery, sharing the same trunk artery with the medial femoral circumflex artery in some cases. Both of the lateral and medial femoral circumflex arteries originate from the femoral artery. The branches of the lateral femoral circumflex artery are grouped as: (1) Type I (79%): The lateral femoral circumflex artery gives out descending branch, transverse branch, and ascending branch. (2) Type II (19.5%): Descending branch, transverse branch, and ascending branch originate from two trunk arteries which are sent by the deep femoral artery or the femoral artery. (3) Type III (1.5%): The deep femoral artery or the femoral artery gives out descending branch, transverse branch, and ascending branch respectively. Of the aforementioned three types, the ascending branch originates mostly from the lateral femoral circumflex artery, and occasionally from the femoral artery. It runs upwards between the rectus femoris and the iliopsoas, and continues deep to the tensor fasciae latae with a mean length of 8.7 cm, giving out a musclo-branch to the vastus intermedius and the rectus femoris at the begging segment. The ascending branch gives out five branches when it runs through the tensor fasciae latae, continues between the tensor fasciae latae and the rectus femoris, and distributes to the anterior-lateral area of the ilium and the beginning area of the tensor fasciae latae. The occurrence rate of the descending branch of the lateral femoral circumflex artery is 97.5%. It originates mostly from the lateral femoral circumflex artery, and in some cases from the femoral artery. It descends between the rectus femoris and the vastus intermedius, and divides into the lateral branch and the medial branch above the midpoint of the anterior superior spine and the patella. The medial branch gives out branches to the rectus femoris, the vastus intermedius, and the lateral portion of the medial vastus muscle, ending up near the knee joint and then joining the vascular network around the knee. The lateral branch runs to the lateral aspect between the rectus femoris and the lateral vastus muscle, and gives out branches along its course to nourish the lateral vastus muscle and the skin of the anterior-lateral thigh. There are various types of the transverse branches at the beginning segment from the lateral femoral circumflex artery. 20% of them originate from the lateral femoral circumflex artery, and 75% share the same trunk artery with the ascending branch. The transverse branch runs laterally deep to the rectus femoris to the inferior of the tensor fasciae latae. The main trunk of the transverse branch continues superficially to the superior of the greater trochanter from the lateral vastus muscle after giving out a muscle branch to the lateral vastus muscle and 2–4 anterior branches and lateral branches to the greater trochanter, thus forming the vascular network connecting the anterior-lateral aspect of greater trochanter and the proximal portion of the femur.

9.6.2.2 Design of Compound Flap Pedicled on the Lateral Femoral Circumflex Artery

Design of the lateral femoral circumflex artery compound flap should be based on the types of the branches of the lateral femoral circumflex artery and the beginning locations of the ascending branches, transverse branches, and descending branches. The lateral femoral circumflex artery gives out ascending branches, transverse branches, and descending branches with an occurrence rate of 79%. The lateral femoral circumflex artery compound flap can be fashioned using the lateral femoral circumflex artery as a pedicle vessel together with its branches. The types of the flaps are as follows: (1) the anterior lateral thigh flap combined with the tensor fasciae latae, (2) the anterior lateral thigh flap combined with the greater trochanter bone flap, (3) the tensor fasciae latae flap combined with the iliac bone flap and the anterior lateral thigh flap, (4) the tensor fasciae latae flap combined with the greater trochanter bone flap and the anterior lateral thigh flap. The ascending branches, transverse branches and descending branches are given out by the deep femoral artery or the femoral artery through a form of double trunk arteries. The first three of the aforementioned compound flaps can be achieved when the compound flaps were designed based on one of the trunk arteries which give out two branches.

9.6.3 Compound Flap Pedicled on the Peroneal Artery

9.6.3.1 Distribution of the Peroneal Artery

The peroneal artery, one of the three main vessels in the distal lower extremity, originates from the posterior tibial artery and gives blood supply to the lateral aspect. It gives out 3–8 perforators through its entire course, and is mostly covered by the flexor pollicis longus muscle. Its perforators are: (1) septocutaneous perforators which perforate superficially through the posterior-lateral crural septum and are easily reached and dissected; (2) myocutaneous perforators which mostly run a long distance piercing the soleus and sent out multiple branches, leading to a surgical challenge for dissection; (3) myoseptocutaneous perforators which mostly run through a short distance of the flexor pollicis longus muscle, rarely give out septocutaneous perforators, and continue along the border of muscle and crural septem to the posterior-lateral crural septum. Since the myoseptocutaneous perforators perforate superficially to the deep fascia, they are easily dissected. The lengths of all types of perforators range from 2 to 7 cm, depending on the beginning site and courses of the perforators but not on the types of the perforators. The perforators in the proximal segment of peroneal artery are located deeply. Since they mostly run oblique to the distal part of lower extremity, the length of these perforators are relatively long when compared with the perforators in the distal third of the peroneal artery which mostly run vertically to the skin.

There are two clusters of perforators of the peroneal artery, located 5 to 10 cm and 21 to 27 cm proximal to the lateral malleolus respectively. Each of the clusters includes one third of the entire number of the perforators. Points approximately 1 cm, 5 cm, and 10 cm proximal to the lateral malleolus were marked as permanent perforators. Each perforator from the peroneal artery has 1–2 concomitant veins. The caliber of perforator vessel is usually 1 mm, and the diameter of the concomitant vein is larger than that of the perforator artery. The perforator divides into transverse branches, ascending and descending branches at the superficial layer of the deep fascia after piercing the crural septum of the muscle. The branches are connected with each other, becoming thinner at the distal segment. The branches of the distal septocutaneous perforators tend to gather around the sural nerve, and give out connection vessels to the nutrient vessels of the proximal sural nerve, thus forming the nutrient vessels of the distal sural nerve.

9.6.3.2 Design of the Compound Flap Pedicled on the Peroneal Artery

Similar to the design of the compound flap pedicled on the subscapular artery and lateral circumflex femoral artery, the design of the peroneal artery compound flap should be based on the types of the branches of the peroneal artery. Common combinations of these compound flaps are: (1) perforator-pedicled flap combined with fibular bone flap, (2) perforator-pedicled flap combined with sural fasciocutaneous flap, (3) perforator-pedicled sural neurocutaneous flap combined with fibular bone flap. Combination of the neurocutaneous flap and the perforator flap can not only increase the area of skin paddle, but also achieve reinnervation through neuroplasty.

9.7 Microsurgical Reconstruction with Compound Flaps

9.7.1 The Goals of Microsurgical Reconstruction with Compound Flaps

Reconstruction with compound flaps should achieve two main goals: (1) recovery of the normal contour of the upper and lower limbs, and (2) functional recovery of the upper and lower limbs. Because the main functions are ambulation and supporting for lower extremities, the priorities of reconstruction are the soft tissue, bone, and joint. The weight-bearing area is the most high-demanding area for reconstruction due to the specific anatomical structure. As for the upper extremities, the main function is the range of motion, and reconstruction of thumb opposition function is the most challenging.

9.7.2 Principle for Reconstruction of Composite Defects

The reconstructive scheme should begin with the tissue components, such as the skin, muscle, nerve, tendon, bone, and joint. The 'replace like with like' principle which was proposed by the pioneers of reconstructive surgery should be followed: selecting the most similar tissue for reconstruction.

9.7.3 Reconstruction of Soft Tissue in Composite Defects

Reconstruction of soft tissue involves recovery of continuity of skin, tendon, and muscle, functional reconstruction of muscle, and reconstruction of nerve and vessel. There are many modalities for reconstruction: transplantation of split-thickness skin and full-thickness skin, transfer of local flap, and transfer of free flap. Surgeons should choose the simplest and most effective option among various alternative methods for reconstruction. In some cases, since an ideal option for soft tissue reconstruction may require complicated free compound flaps, it is surgically challenging and time consuming. In this situation, surgeons should be aware that free flaps and local flaps are similar in the complication rates. Moreover, much more sophisticated reconstructive methods and innovations have been applied for reconstruction of soft tissues and their function, such as the sensate flap, and compound flaps carrying bone, skin, superficial fascia and nerve. The fillet flaps which use the mangled amputated limb for length preservation, and the flow-through flaps, have also resulted in satisfactory functional and aesthetic outcomes.

9.7.4 Reconstruction of Bone in Composite Defects

During a reconstructive procedure of composite defects, bone defects can be reconstructed by vascularized/non-vascularized bone autografts, bone transplantation (Ilizarov technqiue), allografts, and customized prostheses.

Microsurgical reconstruction of bony defects is to transfer vascularized bony flaps to the defects through vessel anastomoses. The fibular flaps are the most common donor site for bone defects, and the ilium, rib, scapula are also widely used donor sites. Many studies have proved that revascularization of bony flap may lead to better survival and healing rates than other reconstructive options. In addition, the intensity of a bony flap can be enhanced through the characteristic of self-hypertrophy. Vascularized bony flaps are indicated for most bony defects larger than 5–6 cm, especially for bony defects complicated with poor soft tissue conditions.

9.7.5 Transferring Reconstruction of Composite Defects

The common modalities of compound flaps for reconstruction of composite defects are as follows: (1) compound flaps based on the subscapular artery, (2) compound flaps based on the lateral femoral circumflex artery, and (3) compound flaps based on the peroneal artery. One-stage reconstruction of the composite defects may be achieved as microsurgery progresses rapidly and constantly. Application of compound flaps is not limited to post-traumatic injury. They can be used for chronic infections, congenital deformities, and incision of tumor. In some cases, more than 2 compound flaps, or combination of myocutaneous and bony flaps, are harvested to cover the defects, decreasing the donor site morbidity. The combination can be acquired through anastomoses of pedicle vessels of different compound flaps. The common combinations are: (1) scapular flap and groin flap, (2) groin flap and anterior lateral flap, (3) latissmus dorsi flap and groin flap, (4) scapular flap and pectoralis major muscle flap, (5) bilateral latissmus dorsi flaps, (6) latissmus dorsi flap and fibular flap, (7) latissmus dorsi flap and iliac flap, (8) bilateral fibular flaps, (9) lateral pectoralis flap and iliac flap, and (10) great toe wrapped-around flap and myocutaneous flap, or osteocutaneous flap. Design of pedicle vessels is the most vital procedure before combining compound flaps. When combining the latissmus dorsi flap and the fibular flap, the first step is to anastomose the subscapular artery to the recipient vessel, and the next is to anastomose the scapular circumflex artery, which is given out by the subscapular artery, to the peroneal artery. The last is to anastomose the concomitant veins. This makes the subscapular artery as the main pedicle vessel, the scapular circumflex artery as the nutrient vessel for the fibular flap, and the thoracodosal artery as the nutrient vessel for the latissmus dorsi flap.

Bibliography

1. Levin LS. New developments in flap techniques. J Am Acad Orthop Surg. 2006;14(10 Spec):S90–3.
2. Nakajima H, Fujino T, Adachi S. A new concept of vascular supply to the skin and classification of skin flaps according to their vascularization. Ann Plast Surg. 1986 Jan;16(1):1–19.
3. Mathes SJ, Nahai F. Classification of the vascular anatomy of muscles: experimental and clinical correlation. Plast Reconstr Surg. 1981;67(2):177–87.
4. Levin LS. The reconstructive ladder. An orthoplastic approach. Orthop Clin North Am. 1993;24:393–409.
5. Zenn MR, Levin LS. Microvascular reconstruction of the lower. Semin Surg Oncol. 2000;19:272–81.
6. Belousov AE, Gubochkin NG, Lushmanov GI. Use of the thoracodorsal flap in plastic and reconstructive surgery of the extremities. Ortop Travmatol Protez. 1987;11:11–4.
7. Nassif TM, Mayer B, Bijos PB. The parascapular cutaneous latissimus dorsi osteomycutaneous double flap. Free monobloc transfer in facial reconstruction. Chirurg. 1988;59(11):793–6.
8. Corderio PG, Neves RI, Hidalgo DA. The role of free tissue transfer following oncologic resection in the lower extremity. Ann Plast Surg. 1994;33:9–16.
9. Erdmann D, Berggquist GE, Levin LS. Ipsilateral free fibular transfer for reconstruction of a segmental femoral-shaft defect. Br J Plast Surg. 2002;55:675–7.
10. Erdmann D, Giessler GA, Bergqquist GE, et al. Free fibular transfer, analysis of 76 consecutive microsurgical procedures and review of literature. Chirurg. 2004;75:799–809.
11. Garrington NC, Smith RM, Knight SL, et al. Ilizarov bone transport over a primary tibial nail and free flaps: a new technique for treating Gustilo 3b fractures with large segmental defects. Injury. 2000;31:112–5.
12. Levin LS. The Ilizarov method and microsurgery: the best of both worlds. Am Soc Reconstr Mircrosurg Newsl. 1995;2:23–4.
13. Levin LS. Orthoplastic reconstruction of the arms and legs. In: Siemienow MZ, editor. Tissue surgery (new techniques in surgery series). New York: Springer; 2006.
14. Ward WG, Yang RS, Eckardt JJ. Endoprosthetic bone reconstruction following malignant tumor resection in skeletally immature patients. Orthop Clin North Am. 1996;27:493–502.
15. Johansen K, Daines M, Howey T, et al. Objective criteria accurately predict amputation following lower extremity trauma. J Trauma. 1990;30:568–72.
16. Erdmann D, Sundin B, Yasui K, Wong MS, Levin LS. Microsurgical free flap transfer to amputation sites: indications and results. Ann Plast Surg. 2002;48:167–72.
17. Kuntscher MV, Erdmann D, Homann HH, Steinau HU, Levin LS, Germann G. The concept of fillet flaps: classification, indications, and analysis of their clinical value. Plast Reconstr Surg. 2001;108:885–96.
18. Godina M. Early microsurgical reconstruction of complex trauma of the extremities. Plast Reconstr Surg. 1986;78:285–92.
19. Ilizarov GA, Devyatov AA, Kamerin VK. Plastic reconstruction of longitudinal bone defects by means of compression and subsequent distraction. Acta Chir Plast. 1980;22:32–41.
20. Tseng WS, Chen HC, Jung J, Tasi TR, Wei FC. "Flow-through" type free flap for revascularization and simultaneous coverage of a nearly complete amputation of the foot: case report and literature review. J Trauma. 2000;48:773–6.
21. Gregory RT, Gould RJ, Peclet M, et al. The mangled extremity syndrome (M.E.S): a severity grading system for multisystem injury of the extremity. J Trauma. 1985;25:1147–50.
22. Levin LS. Principles of definitive soft tissue coverage with flaps. J Orthop Trauma. 2008;22(10 Suppl):S161–6.
23. Heitmann C, Levin LS. The orthoplastic approach for management of the severely traumatized foot and ankle. J Trauma. 2003;54:379–90.
24. Erdmann D, Kovach SJ, Lawson RD, Levin LS. Ipsilateral reversed free fibular transfer for femoral shaft reconstruction: a modification of previously reported technique. Ann Plast Surg. 2006;56:216–9.
25. MacKenzie EJ, Jones AS, Bosse MJ, et al. Health-care costs associated with amputation or reconstruction of a limb threatening injury. J Bone Joint Surg Am. 2007;89:1685–92.
26. MacKenzie EJ, Bosse MJ, Pollak AN, et al. Long-term persistence of disability following severe lower-limb trauma. Results of a seven-year follow-up. J Bone Joint Surg Am. 2005;87:1801–9.
27. MacKenzie EJ, Bosse MF. Factors influencing outcome following limb-threatening lower limb trauma: lessons learned from the Lower Extremity Assessment Project (LEAP). J Am Acad Orthop Surg. 2006;14(10 Spec):S205–10.
28. Hollenbeck ST, Woo S, Komatsu I, Erdmann D, Zenn MR, Levin LS. Longitudinal outcomes and application of the subunit principle to 165 foot and ankle free tissue transfers. Plast Reconstr Surg. 2010;125:925–34.

Small Joint Transplantation

10

Jianli Wang

10.1 Overview

A joint, the location between two bones, can be divided into two categories: immovable and movable. Immovable joints include skull seam by bone fusion and chimeric structure between the teeth and mandible. Once this kind of joints is injured, there is no joint transplantation available because bone or substitutes can used to repair the injury. Movable joints are further divided into amphiarthrodial and active ones. The former connects two bones by a ligament, such as the distal tibiofibular joint. Generally, there is no need to perform joint transplantation for injury to amphiarthrodial joints because their range of motion is very limited.

In active joints which have a joint capsule and an articular cavity, two bones are connected by the joint capsule and ligaments. Most of the body's joints belong to this kind. Intra-articular synovial fluid has a lubricating property which is conducive to joint activities, and a nutrition function for articular cartilage which is hyaline and covers the end of bones. Some articular cavity also contains a cartilage plate or joint disc. Joint capsule consists of a synovial membrane layer and a fiber layer. The synovial membrane layer forms the sidewall of joint cavity which is rich in blood vessels and lymphatic vessels, secretes synovial fluid and absorbs. There is distribution of nerve endings on it. Damage or injury to the synovial membrane can cause joint pain, dysfunction, and even joint stiffness and deformity. Since the synovial membrane layer has a great effect on the normal joint function, active joints are also called synovial ones. The fibrous layer is often a part from the adhesion of the bone to the edge of the articular cartilage. Bone ends are contained in the joint cavity. Blood supply to a joint may come from one or several branches of arteries near the joint. There is a wealth of anastomosis between the arteries, sending small branches to supply the whole layer of joint capsule, the peripheral portion of articular cartilage and surrounding tissue of the joint.

The function and range of activities in active joints vary according to joint configurations. The passive range of motion of the shoulder joint is greater than that of intercarpal joint or metacarpophalangeal joint. When an active joint has a defect or rigidity, no matter what configuration it belongs to, joint transplantation is the most ideal therapy for restoration of physiological and biomechanical properties of the joint. It restores joint function and eliminates the pain. In pediatric patients, it does not interfere with the bone development because the joint grafts contain epiphysis and metaphysis. Therefore, at the beginning of the twentieth century, some surgeons tried to deal with joint deformities and defects with joint transplantation. Lexer (1914) performed autotransplantation or allotransplantation of a half joint or the whole joint using a fresh joint after amputation. Seventeen years later, Lexer reviewed the cases he treated, including allograft transplantations of semi knee joint, total knee joint, hip joint and knuckles, as well as autologous transplantations of knuckles. In these cases, the functional activity of transplanted joint, pain and other clinical symptoms were improved, but X-ray inspection indicated degeneration in all the joints transplanted. Since 1965 in China, Song Xianwen, Wang Chengwu, Shi Fengwen and Hu Jingmin have reported successive joint transplantations. Their reported cases and experimental study were free transplantation without vascular anastomosis. Their early postoperative outcomes were good, but later efficacy poor. Degeneration occurred in all the joints and articular cartilage was replaced by fibrous tissue. The degeneration occurred not only in the allogeneic joints, but also in the autologous ones.

J. Wang (✉)
Department of Orthopaedics, PLA 89th Hospital, Weifang, China
e-mail: 13905367003@163.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_10

The cartilage, capsule and ligaments of an allograft joint are all low antigenic tissue. Since at an early stage some cases can perform some of the functional activities after transplantation of an allogeneic joint, there may be a certain degree of efficacy. Compared with the autologous transplantation, the early healing of an allograft is slow. At a later stage, bone resorption and joint destruction appeared gradually. In order to reduce the antigenicity to improve the curative effect, surgeons have tried cryopreservation, lyophilization, ethanol or Thiomersal liquid soaking, Y-ray irradiation of the donor joint, and use of immunosuppressive agents after operation, improving the efficacy to some extent. But immune rejection occurs lastly, and the long-term survival of an allograft is still a difficult problem before the immune rejection is resolved.

10.2 Small Joint Transplantation Indications

10.2.1 Traumatic ankylosis

Open injury to an active joint can cause destruction and infection of the joint and its surrounding tissue, leading to ankylosis, deformity and loss of the function of the joint at last. Severe closed injury can also cause joint damage and rupture so that Haemarthrosis, stimulating the synovial membrane to produce serous exudation, ligaments, tendons, and other surrounding tissue also have hemorrhage and tissue interstitial fluid accumulation due to injury. These exudation and bleeding blocks contain more cellulose, which happens organization to form a scar resulting in the adhesion of the joints and tissues, resulting in joint rigidity. This ankylosis violate joint bone, ligament, tendon and other tissues. Both arthroplasty and artificial joint replacement are very difficult to obtain good curative effect. The joint transplantation of anastomosis vessels can according to the area of the lesion of diseased tissue, including the whole joint and the joint ligament. The tendon and skin flap were transplanted to restore the function of the joint.

10.2.2 Joint Defect

The joint transplantation of anastomosis vessels can be used to repair the defects caused by trauma or tumor resection. It is particularly suitable for pediatric patients for transplantation joint complex tissue graft containing the epiphysis and metaphysis, helping postoperative bone, joint development not affected.

10.2.3 Late Arthritic Deformity

Whether late stage of suppurative arthritis or non suppurative arthritis (such as rheumatoid arthritis), due to the articular cartilage and synovial membrane subjected to disrupt and formed fibrous adhesions, even formed bony ankylosis or deformity so that joint movement dysfunction, may carry on the joint transplantation of anastomosis vessels.

10.2.4 Congenital Articular Malformation

Such as congenital hand deformities and temporomandibular joint deformity. It can obtain better functional improvement after the use of the joint transplantation of anastomosis vessels,

10.3 Toe Joint Transplantation

Although the free transplantation of the plantar toe was started in the early part of this century, the experimental study and clinical application of the blood vessel of the anastomosis of the metatarsophalangeal joint were nearly 10 years. In the 1960s Buncke used vascular pedicle of metacarpophalangeal joint transplantation success and survival after replantation of severed limb bone and joint survived well, no joint degeneration, prompting scholars begin the experiments study of anastomosed vessels of the metatarsophalangeal joint transplantation. Hurwitz (1979) was reported to carry out the anastomosis of the blood vessels of the half joint and the joint of the dog with a total metatarsophalangeal joint transplantation of five and a half months after transplantation, the joint is normal. In 1980, Guo Entan was reported that two patients with vascular anastomosis of the second metatarsophalangeal joint transplantation to repair metacarpophalangeal joint successfully on the basis of anatomical study of the body. In the same year the Mathes reported one case of children vascular anastomosis of the second metatarsophalangeal joint transplantation for the repair of middle finger metacarpophalangeal joint, two and a half years' follow-up shows the epiphysis still continue to grow. Thereafter, Tsai reported two cases of metatarsophalangeal joint transplantation, Smith (1985) reported that one cases of congenital malformations of the hand were repaired by the second toe metatarsophalangeal joint transplantation of vascular anastomosis.

From the literature, the use of the toe metatarsophalangeal joint transplantation of vascular anastomosis is increasing. In various metatarsophalangeal joint, the second metatarsophalangeal joint is most commonly used. This is because of the first dorsal metatarsal artery from the articular branch blood, foot dorsal artery (or dorsal metatarsal artery) caliber relatively bulky, neurovascular pedicle longer, easy to be match successfully, convenient for taking, there is no significant obstacles for the donor foot function after operation.

10.3.1 Local Anatomy

The metatarsophalangeal joints consist of the metatarsal head and phalanx base, is a synovial joint. The part of the articular capsule of the dorsal part of joint are thin and loose, and the joint capsule of the two sides and the lateral part of the joint is more thickening because the lateral collateral ligaments and the plantar ligaments. Digital flexor tendon in the superficial of the plantar ligament. The extensor tendon is passed through the dorsal part of the plantar and toe joint. The healing of the toe short extensor tendon at the proximal margin of the joint capsule and the long extensor tendon in the dorsal part of the extensor tendon. Between two adjacent joints, a deep transverse metatarsal ligament connected, this ligament and plantar ligament healing in joint. Through the interosseous muscles in the back of the transverse metatarsal ligament, lumbricalis and foot bottom artery in the plantar surface through, so this ligament is regarded as the boundary between dorsal and plantar tissue curtain. Cut the metatarsophalangeal joint, joint capsule will be required in the near deep transverse metatarsal ligament. When the area is required to repair the tendon, the tendon is cut off after the joint capsule, and the length of the toe is long enough.

The source of the blood supply of the plantar toe joint can be divided into two systems of the plantar side and the back side. They communicate with each other, which constitute a very rich collateral circulation. In the lateral artery, posterior tibial artery plantar metatarsal base and from the dorsal artery of foot plantar deep anastomoses in, the formation of the plantar arch. By the plantar arch to the dorsal issued three branches of perforating arteries, through the 2, 3, 4 metatarsal clearance of the proximal part and the corresponding dorsal metatarsal artery anastomosis. Plantar arch also released forward 4 ramus of plantar metatarsal artery, along the metatarsal clearance go near to the metatarsal phalangeal joint. Every plantar metatarsal artery bifurcation 2 plantar digital artery and along the adjacent metatarsal tibial and fibular near the plantar surface forward to the toe end, and the contralateral homonymous artery kiss synthetic mesh. Worth noting is that the plantar metatarsal artery near the bifurcation issued a perforator to dorsal and corresponding dorsal metatarsal artery distal to communicate, and issued a number of small distribution to the metatarsal phalangeal joint capsule, so plantar metatarsal artery as metatarsophalangeal joint transplantation of vascular pedicle for the area of vascular anastomosis combined.

The other blood supply system of the plantar toe joint is derived from the dorsal artery of the foot. Dorsal artery of foot metatarsal basal levels in a branch and the outer side artery dorsalis pedis arterial arch formation, continue to forward and issued the deep plantar branch formation and lateral plantar artery plantar arterial arch anastomosis. The dorsal artery of the foot was carried by the dorsal artery of the foot of the dorsal artery of the first dorsal artery. The 2, 3, and 4 dorsal artery from the dorsal foot. Perforator and plantar arch anastomosis proximal portion of the four branches of dorsal metatarsal artery, in the vicinity of the metatarsal head each issued distal perforators and plantar metatarsal artery perforator anastomosis. When the dorsal metatarsal artery forward to the toe web proximal respective bifurcation for two dorsal artery along the adjacent metatarsal side, arrived at the toe and the contralateral homonymous artery kiss mesh synthetic vascular plexus. Plantar metatarsal artery and dorsal metatarsal artery distal perforator, and the artery itself a number ranging from small branch distribution to the metatarsal phalangeal joint, and the formation of vascular plexus around the joint.

The anatomical structure of hand palm knuckle, interphalangeal joint of hand, are similar with foot and metatarsophalangeal joint, Interphalangeal joints (Fig. 10.1), so we can take foot metatarsophalangeal joint, or interphalangeal joint transplantation for reconstruction of hand palm knuckle or interphalangeal joint.

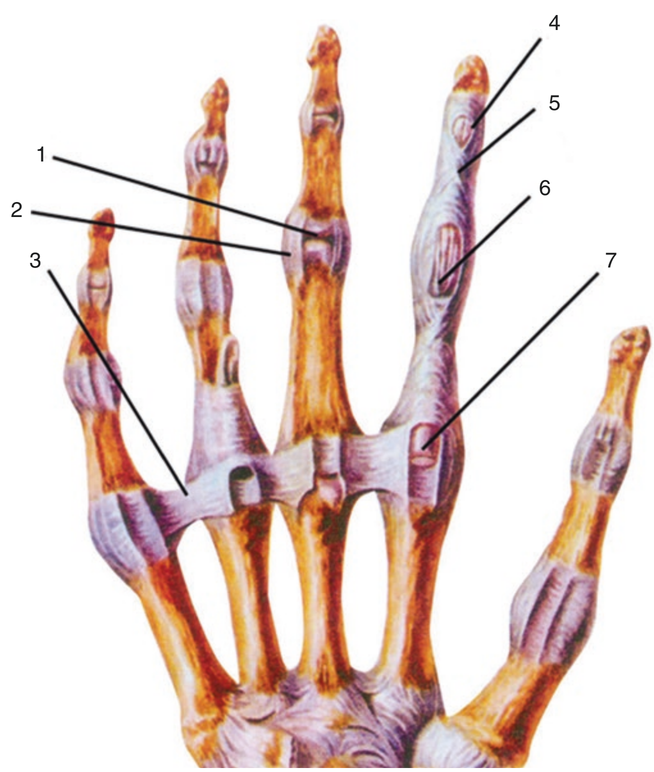


Fig. 10.1 Finger joint anatomy: *1*. Interphalangeal joint; *2*. Joint capsule; *3*. Metacarpal ligament; *4*. Refractive flexor tendon; *5*. Finger tendon fibrous sheath; *6*. Refers to the flexor tendon; *7*. Metacarpophalangeal joint

10.3.2 Surgical Method for Repairing the Metacarpophalangeal Joint

(a) **Preoperative preparation**

1. To fully understand the situation of the affected areas. In the acute phase of the infection or the rheumatoid disease, there is no such operation. In addition, the bone or joint lesion, is there any other tissue defect and the situation of the area of vascular anastomosis? Doppler flowmetry examination or angiography if necessary.
2. Is the donor area of bone and joint normal, and how the blood supply ?If foot dorsal artery pulsation cannot touch or Doppler flowmetry check results abnormal, it is not suitable for surgery.
3. The body is bad or have peripheral vascular disease, can not perform the operation. Before surgery, the patient should be examined in detail.
4. The principle of choice anesthesia is that it can prevent blood vessel spasm and safety of painless as. Epidural anesthesia is ideal. When patients can not be applied to epidural block anesthesia, then use other anesthesia methods.
5. One day before surgery, began using antibiotics.

(b) **Operation procedure**

The surgical operation includes four steps: the excision of the lesion joint, the excision of the toe joint, the joint implantation and the donor handling. Doing In two groups at the same time.

1. Removal of diseased joints In the dorsal part of the lesion hand for long arc or "S" shaped incision, dissection and examination of the flexor tendons and the case of the finger joints. Such as tendon injury, no scar adhesions incised the ulnar transverse fibers of finger extensor tendon and pull the tendon to the radial side to exposure lesion joint, since the metacarpal bones and proximal phalanx base excision lesion joint (including the joint and its subsidiary of the metacarpal bones and phalanges basilar part). At the same time we must pay attention to two points: 1. free lesion joint, cut the deep transverse metacarpal ligament near the joint capsule, avoid damage the tissues around the joints; 2. metacarpal and phalangeal resection length shall be treated by lesions, have lesions or has hardened bones completely removed, because of the blood supply is very poor, otherwise after joint transplantation, prone to nonunion. If the tendon has scar adhesive or defect, and the joint capsule and scar adhesion, then there will be a scar lesion of the tendon together with the lesions of the joint resection. For the joints and scar skin, the skin and joints are also removed, the skin of the joint and the joint of the joint is excised, and the tendon or tendon skin flap is repaired. Tendons are sticky that can cause joint functional activity.
2. Cut and take the metatarsophalangeal joint In the dorsal incision of the skin and subcutaneous tissue and exposed dorsum of foot of great saphenous vein, foot dorsal artery and the first dorsal metatarsal artery and artery with vein and deep peroneal nerve terminal branches. In the interosseous muscle anatomical separation of best under surgical microscope operation, go to recognize the dorsal metatarsal artery joint branch line and bone between muscle fibers retained in the neurovascular bundle, to prevent damage. Along the joint vessel around the joint capsule after separation to cut off the deep transverse metatarsal ligament, lateral plantar along the lateral collateral ligament stripping. If the joints are not carried by a tendon or skin flap, the right side of the tendon is separated from the tendon of the flexor tendon and the plantar ligament. On the back side, in the joint capsule and extensor tendon adhesion, cut short toe extensor tendon, the extensor hallucis longus tendon lead to plantar along the lateral collateral ligament lateral separation, and in close proximity to the joint capsule to cut the deep transverse metatarsal ligament. Then the metatarsals and phalanges metatarsal and toe direction free, off with wire saw. So far, metatarsophalangeal joint transplantation body (including joint transplantation metatarsal head, basal part of the phalanges, collateral ligaments, plantar ligament) has been completely free, only neurovascular bundle and foot connected. When the vessel is ready to be used in the anastomosis, cut off the neurovascular pedicle.

   In children, both of metatarsal bones and phalanx base portions have epiphysis, both the metaphyseal should contain in joint transplantation in vivo, bone and joint development is not affected after transplantation. Therefore, the metatarsals and phalanges should be sawed off in the joint capsule attachment from distant places. When the reception area of transplantation have a tendon defect, a joint graft is required to include extensor digitorum longus tendon or the flexor digitorum longus tendon. To isolate the joint at the shallow surface of the flexor tendon or extensor tendon, and retain the connection between the tendon and the joint capsule. Cut off the tendon according to the repair needs. The skin defect of the reception area of transplantation, and the joint transplant can be repaired with the flaps of the foot.

   The nerve distribution of the second metatarsophalangeal joint by the end of the deep peroneal nerve. In order to facilitate the joint transplantation healing and function, in the separation of foot dorsal artery and dorsal metatarsal artery, deep peroneal nerve and the continuation of support is the second metatarsal dorsal medial nerve should contain in the vascular bundle, for nerve anastomosis in transplantation.

3. Joint implant reception area The transplantation of metatarsophalangeal joint is taken from the donor site to rotate 180° so that the plantar bottom surface of the metatarsophalangeal joint is transferred to the back of the hand. Metatarsal and metacarpal is connected, phalanges and phalanx relatively, Klinefelter's needle fixation through. Under the microscope were anastomosed dorsalis pedis artery (or dorsal metatarsal artery) and radial artery, saphenous vein and cephalic vein, deep peroneal nerve terminals and the branch of the radial nerve, tendon and the skin flap, sutured closed wound.
4. Donor site treatment The defect of the graft and the left posterior of the metatarsophalangeal joint is filled with cancellous bone, and then the wound is closed.

(c) **(Two) postoperative treatment**

1. Raise the injuries hand and the foot which provide joint; room temperature maintained at 25 °C, or will place the hand injury in the oven beside the bed, the temperature in the oven to maintain in the above scope.
2. Application of drugs for prevention and treatment of blood vessel spasm (the same as general microsurgery for vascular surgery).
3. Application of antibiotics to prevent infection.
4. The removal of the Klinefelter's n needle 4–6 weeks after the operation, and the beginning of joint autonomous activities. The fixed position of the foot should remove about 6 weeks after surgery, otherwise easily lead to nonunion.

10.4 Transplantation of Interphalangeal Joint

In 1978 Watanabe, Zheng to verify the clinical application of vascular anastomosis on the transplantation of interphalangeal joint, he made a study on plantar toe joints' vascular anatomy with monkey, at the same time, the blood supply of joints between the toe was studied too. Two years later (1980), he reported that in the eight cases (included nine joints) of clinical vascular anastomosis on the transplantation of interphalangeal joint, seven of them were proximal interphalangeal joint and were successful. In 1982 Tsai used the free transplantation of interphalangeal joints from animal's forelimbs for repairing the second proximal interphalangeal joints of the hindquarters with the method of vascular anastomosis, meanwhile he did the same operation without vascular anastomosis for comparison purposes. After 4–10 months observation, all cases of the control group were failed or joint degeneration. In the experimental group, two of nine cases failed due to wound infection, the rest all successed and the joints worked normally. On this basis, he made six cases of free transplantation with nine joints of interphalangeal joint by vascular anastomosis in clinic, six cases of second and one case of third proximal interphalangeal joint were successful. In 1984 O'Brlen reported seven cases of transplantation of interphalangeal joint with vascular anastomosis. Two of them also succeeded when second proximal interphalangeal joint as donors. O'Bnen also proposed that the epiphysis at basis phalanges digitorum pedis and its caput didn't have, but the caput metatarsal bone had. As a result, the joints between the toe transplantation in children cases that contained only one epiphyseal. After the surgery, the growth of metatarsophalangeal joints would be better than that of interphalangeal joint. In 1984 Cheng-qi Wang reported the success of the interphalangeal joint's transplantation to repair the traumatic defect of thumb metacarpal joint and 2 years' follow-up studies had found that their function and appearance are better, which was reported for the first time in domestic.

10.4.1 Local Anatomy

Interphalangeal joints are basically composed of proximal caput phalanges digitorum pedis and distal basis phalanges digitorum pedis, surrounded by some sustentacular tissues like the articular capsules and the lateral collateral ligaments. Except the first toe has only one interphalangeal joints, all of the other four toes have two interphalangeal joints, distal interphalangeal joint and proximal phalangeal joints. The blood supply in interphalangeal joints is homologous with in metatarsophalangeal joints, coming from the two systems in planta and dorsum of foot. The dorsal plantar artery becomes divided into two arteriae digitales dorsales from distal toe web, following the toe side of the adjacent to the proximal interphalangeal joint of a joint branch and from plantar artery into the joint communication network, to supply the interphalangeal joints, and the toe bottom artery is from the plantar artery venae comitans. The veins except the venae comitans, the toe back venous return to the great saphenous vein. Nerve's distribution of the interphalangeal joints, the three and a half toes which inside of foot are supplied by the plantar medial nerve which come from the tibial nerve, while the fourth and fifth interphalangeal joints are supplied by nervi plantaris lateralis (Fig. 10.2).

Fig. 10.2 Interphalangeal joint anatomy: *1*: Second metatarsal dorsal artery, *2*: Toe dorsal artery, *3*: Second metatarsal dorsal artery, *4*: Deep peroneal nerve

10.4.2 The Indications

10.4.2.1 Repair the Joints of Hand

1. Trauma of interphalangeal joint or metacarpophalangeal joint cause joint stiffness and deformities, joint instability, joint pain, which seriously affects the hand function.
2. Congenital malformations, such as finger hypoplasia, defect of joint epiphysis.
3. The defect of phalangeal joint after finger or metacarpale tumor resection.
4. Patients with artificial phalangeal joint replacement failure.

10.4.2.2 Repair of Other Small Joints

Interphalangeal joint transplantation can also be used for repair of other small joints, such as repair of temporomandibular joint stiffness. Interphalangeal joint transplantation generally choose the proximal interphalangeal joint of the second toe or proximal interphalangeal joint of the third toe, use less of the first toe. When the recipient has a good skin soft tissue coverage and relatively complete system which can do flexion and extension activities, interphalangeal joint transplantation function is better. When the skin and tendon of recipient have sticky defect, should bring about the dorsal skin flap and graft to repair the tendon at the same time.

10.4.3 The Surgical Method

Preparation before surgery, anesthesia, surgical procedure and postoperative management principles are same as metatarsophalangeal joint transplantation. Now operations of cutting interphalangeal joint are summarized below.

1. Cut longitudinally dorsal skin, subcutaneous tissue, reveal the dorsalis pedis and the dorsal artery of the first metatarsal, separate dorsal metatarsal artery and its continuation (dorsal digital artery), recognize the branch towards the proximal interphalangeal joint of its second toe.
2. Reveal venae digitales pedis dorsales to protect its continuity with great saphenous vein. If dorsal metatarsal artery is very thin and non-main feeding, plantar metatarsal artery system should be used. Dissect the first plantar metatarsal artery, cut and ligature fibular plantar digital artery, dissociate tibial plantar digital artery of the second toe, as the same time dissect concomitant toe nerve. Interphalangeal joint transplantation simply cut flexion and extension tendons in terminal, dissociate joint, in the proximal and distal ends of the joint dissociate periosteum to the joint capsule, according to the missing length of the joint after resection, with a wire respectively saw off both ends of the toe joint. At this point just neurovascular pedicle connected, view the bleeding of bone marrow cavity and the joint capsule surface, judge the blood supply.
3. If the recipient is ready, you can cut off the neurovascular pedicle. The defect of donor site after excision can be left to fill the excised lesion joint. As the recipient by defect of skin and tendon, the interphalangeal joint can carry flap and flexionex, tension tendons to transplant.

10.5 Half-Joint Transplantation

When one side of the joint damage and other side intact, can use half-joint transplantation. Take appropriate side of the metatarsal half-joint or toe half-joint, and part of the joint capsule in order to facilitate suture with the recipient of joint capsule. Specific methods refer to Sects. 10.3 and 10.4 of the metatarsophalangeal joint transplantation and interphalangeal joint transplantation.

10.6 Joint Allotransplantation

Joint allotransplantation refers to transporting an allogenic joint to the joint part of a receptor to replace the function of an original function and is specifically divided into hemi-joint allotransplantation, full-joint allotransplantation, joint allotransplantation with vascular and neural anastomosis, bone, joint and tendon integrative tissue allotransplantation and the like.

Allogenic bones or joints are rich in resource and simple in incision and preservation but still under serious allograft rejection as other tissues and organs during allotransplantation. In recent 10 years, many studies on bone and joint allotransplantation have been reported, while few studies on joint allotransplantation with vascular and neural anastomosis are reported. In bone and joint transplantations including joint autotransplantation, bones or joints suffer from various degrees of degeneration, absorption and function unsatisfactory. Therefore, the joint allotransplantation may facilitate knitting of bones as well as survival and functional recovery of joints if being capable of finding ways to reduce allograft rejection and achieving joint transplantation with vascular and neural anastomosis to providing sufficient blood supply instantaneously for transplanted bones or joints.

10.6.1 Source and Preservation of Allogenic Joints

10.6.1.1 Source of Allogenic Joints

Allogenic joints are mainly derived from fresh cadavers and limbs of traumatic amputation. Cadaveric bones or joints are a rich source of clinical bone and joint allotransplantation; bones or joints from any part of limbs can be incised and stored into a bone bank in standby, before which tissue typing is not always necessary. Before allotransplantation of fresh bones or joints, blood crossmatching and lymphocyte compatibility test should be implemented on donor and receptor, wherein the donor has to be a cadaver without infectious diseases, blood diseases, malignant tumors and bone diseases, and optimally, be a healthy sudden death. It is suggested that joint incision should be completed 6–18 h after the death. During fresh joint allotransplantation with vascular anastomosis, the incision and transportation should be taken at the same time. What's more, joint incision operations should be implemented under strict aseptic conditions.

10.6.1.2 Preservation of Allogenic Joints

After the allogenic bones or joints are transported, bone knitting and joint activity have certain correlation with the preservation approaches. During gradual creeping substitution of the entire bone, it is expected to balance the absorption speed of transported bone and the regeneration speed of new bone. Among the approaches for preserving the allogenic bones or joints, the approaches of profound hypothermia and 75% alcohol achieve high effects for bone and joint transplantation.

Profound Hypothermia Preservation

Preservation includes placing incised bones or joints into sterile normal saline with antibiotics (1 g of streptomycin and one million U of penicillin per 10,000 mL) in a fridge of −40 °C or liquid nitrogen (−170 °C) for more than 6 months and rewarming at room temperature before application.

Ethanol Preservation Method

Put the bone and joint into 75%, ethanol for a few months to several years.

The bone and joint saved must be marked with donor source, type and date, etc. Normally, Immunological rejection is related to foreign proteins within the bone. After the long-term preservation of refrigeration and ethanol, which could solidify proteins and lower antigenicity. The inventory of bone and joint could not only as a simple and economical method of anti immunoreaction, but also provide transplant for joint transportation at any time. Untreated fresh allograft bone and joint have a strong immune response because of foreign proteins, which lead to the worst effect of transplantation. Other allograft joints handled by chemicals, radiation, or boil sterilization lose the biological activity and have a poor regeneration ability.

10.6.2 Indication

It is the success and the well effect of joint autograft by vascular and neural anastomosis that provide a new method with high curative effect and short treatment course for bone and joint diseases. But in some cases, The supply of autologous joints is restricted and some joints cannot be transplanted by using autologous joints, which restrict its universal use. As a result, Articular allograft transplantation with vascular anastomosis has been concerned by clinicians for a long time, but is still in the stage of experiment research, except that few scholars conducted the clinical practice, which mainly suits the cases of the benign tumors of joints with serious damage on both ends, the low-grade malignant bone tumors without transfer, the severe bone and joint injuries and defects, the failed artificial articular replacements and the reconstructions of thumb and fingers, etc. There are the most commonly applied treatments of articular allograft transportation, including the metatarsophalangeal joints, the joints of the digits, the metacarpophalangeal joints, the interphalangeal joints and the knee joints, etc. But it is forbidden using for the patients whose malignant bone tumors have had broad infiltration, whose part of skins and soft tissues of joint have been infected or formed deep blind fistula and whose systemic condition not well enough to tolerate the operation of microsurgery.

10.6.3 Operation Method

Inorder to shorten operation and reduce tissue ischemia time, we had better divide the operation into two sets at the same time. One set, when use the allogenic joints of bone bank, we should rewarm them, shave the periosteums, wash and repair the epiphyses. When apply the allogenic joints of fresh cadavers, we could lavage and dissect the entire joint and the arteries, the veins and the nerves that used to nourish the joint. Another set, we need to cut off sick bones and joints of the patient, dissociate vessels and nerves of the recipient area for the anastomosis, and make joint transplantations or graft the dissociative joints and flaps with vessels and nerves. Routinely postoperative fixation.

10.7 Recovery After Operation

Proceeding functional rehabilitation exercises especially with the guidance of doctors of the transplanted joint in time is crucial for the reconstructed fingers to recover function well. The operation is pretty successful, but it still causes traumatic responses. So if patients want to obtain an ideal effect, they should begin the functional rehabilitation exercises timely under the guidances and helps of mediciners.

10.7.1 Well-Timed Removal of Internal Fixation

Small joint transplantation generally uses the Kirschner wire of 1 mm in diameter to fixed toes or fingers in straight position to maintain the transplanted in functional position. However, there is no unified standard for the time of preferred internal fixation. The author proposes removing internal fixation as soon as possible, so that early functional exercises can be done without internal fixation. In terms of hemi-articular allograft transplantation, before patients begin to do active extension—flexion exercises gradually, internal fixation should have been keeping for 3–4 weeks. If the transplanted toes were connected with bone ends, internal fixation would be out in 4–5 weeks after surgery; By this time, there is no bony callus formation in bone union department, but the surrounding soft tissue have been healing firmly, namely, mild autonomic flexion-extension activities do not affect osseous healing. If internal fixation were removed until X ray film showed marked bony callus formation or bone union, it would be too late. Because of soft tissue healing, tendon adhesion and joint capsule contracture, functional exercise is very difficult and the effect is poor in this moment, so the operation is performed when necessary.

10.7.2 Doing Autonomic Flexion-Extension Activities Timely

After pulling out the internal fixation of smallgrafted joints, the doctor can begin to show patients how to take the initiative to flex and extend small joints. The range of motion changes from small to large step by step, which is advisable when patients feel less pain or slight pain but tolerable.

10.7.3 Passive Functional Exercise

In the 5~6 weeks of postoperation, generally that is the 1~2 weeks after active functional exercise, doctors especially rehabilitation physician assist patients with passive activities of small joints. Fixing proximal joints with one hand and holding distal joints with another hand, do flexion-extension activities slowly and gently, the range of motion varys from small to large gradually, do not act too hastily, more not move enforcedly, which is suitable when patients feel tolerable. Do passive functional exercise 1–2 times a day. Independent activities can also be used in patients after a rest of a few hours, or exercise continuously with elastic rubber supports and rubber balls. If it is combined with Chinese medicine which is for external application to active blood circulation to dissipate blood stasis, relax tendons and soften the scar tissue, promoting circulation and accelerate healing, rehabilitation effect would be better.

Provided people understood the importance of functional exercise, grasped the main point and insisted on continuous exercise with perseverance and patience step by step, day by millimeters, he would make it.

10.7.4 Other Auxiliary Therapies of Promoting the Functional Recovery

To promote reconstructed fingers to recover function as soon as possible, apart from the above rehabilitation exercise, some auxiliary therapies should be cooperated appropriately to promote the effect. They are applied for improving local blood circulation, softening the scar tissue, releasing the conglutination, improving muscle strength and so on.

Bibliography

1. Goldber VM, Heiple KG. Experimental hemijoint and whole joint transplantation.Clin Orthop Relat Res. 1983;(174):43–53.
2. Tsai TM, Ogden L, Jaeger SH. Experimental vascularized total joint autografts. J Hand Surgery. 1982;7(2):140–6.
3. Foucher G, Merle M, Maneadud M. Microsurgical free partial toe transfer in hand reconstruction: a report of 12 cases. Plast Reconstr Surg. 1980;65(5):616–27.
4. Foucher G, Leonoble E, Smith E. Free and island vascularized joint transfer for proximal interphalangeal reconstruction: a serious of 27cases. J Hand Surg. 1994;19(1):8–16.
5. Guo ET, Ji ZL, Zhao YZ. Anastomosis of the metatarsophalangeal joint of the vascular joint to repair the metacarpophalangeal joint. Chin J Surg. 1983;(11):643–5.
6. Xu CD. Reconstruction of surgical anatomy of hand function. Beijing: People's Health Publishing House; 1996. p. 189–90.
7. Ding ZH, Xie CP, Pei GX. Applied anatomy of reconstruction of finger joints in toe joint transplantation. Chin J Clin Anatomy. 1995;(4):241–3.

8. Zou SW, Gan QE, Pan WZ, et al. The clinical observation of reconstruction of another metacarpophalangeal joint. Chin J Med. 2006;(6):43–5.
9. Fu HY, Chen XW, Gao JQ. Research status of joint reconstruction of bone and joint defects in hand. Chin J Tissue Eng Res Clin Rehabil. 2008;(20):128–9.
10. Wang HW, Hou RX, Guo DQ, et al. Repair of finger complex tissue defect with second toe composite flap with proximal interphalangeal joint. Chin J Microsurg. 2009;(1):86–9.
11. Zhang XL, Wan SX, Xiao YF, et al. Microsurgical anatomy and clinical application of reconstructing metacarpophalangeal joint with free metatarsophalangeal joint. Chin J Clin Anatomy. 2009;(6):123–5.
12. Zhang JJ, Liao JW, Zhang ZW, et al. Application of second metatarsophalangeal joint transplantation in reconstruction of metacarpophalangeal joint. Chin J Hand Surg. 2007;(1):72–5.
13. Lexer E. Free transplantation. Ann Surg. 1914;60(2):166–94.
14. Hurwitz PJ. Experimental transplantation of small joints by microvascular anastomoses. Plast Reconstr Surg. 1979;64(2):221–31.
15. Smith PJ, Jones BM. Free vascularised transfer of a metatarsophalangeal joint to the hand. A technical modification. J Hand Surg Br. 1985;10(1):109–12.

11 Bone and Periosteal Flap Transplantation

Aixi Yu

Bone graft is defined as the osseous tissue with intact blood supply. In 1955, Davies et al. successfully performed hip fusion using iliac bone graft pedicled with tensor fasciae latae muscle. In 1962, Judet reported a successful transfer of femoral trochanter pedicled with quadratus femoris muscle as a treatment for femoral neck fracture. This vascularized bone tissue is capable of accelerating fracture healing, but its clinical application is limited by insufficient blood supply of its clumsy muscle pedicle and relatively small scope of local transposition. In 1973, Mccullough was the first to report his experimental success using microvascular technique to transfer a rib bone graft to the dog mandible. In 1975, Taylor firstly reported his experience with a free vascularized fibular transfer, marking the beginning of modern era of bone graft. Since then, it has been successfully employed in reconstruction of long bone, mandible and femoral head.

Bone grafting in China started from the middle 1970s in the last century, and made great progress in both basic and clinical study during the 1980s, yielding rich theoretical and clinical data. In 1980, Huang GK et al. described a vascularized iliac bone graft raised on the vascular pedicle of the deep circumflex iliac vessel. In 1983, Fan YE, Chen KG, et al. reported a vascularized iliac bone graft with superior gluteal vessel. During the same period, Zhonge SZ et al. reported a clinical case of free vascularized bone graft of the axillary border of scapula with circumflex scapular vessel. In1985, Xu DC, Chen ZG, et al. reported their anatomical study and clinical application of iliac bone graft pedicled with ascending branch of lateral circumflex femoral vessel. In 1986, Zhu SX et al. obtained encouraging results in treatment of forearm fractures and nonunion of scaphoid and long tubular bone with several kinds of periosteal flaps from a variety of donor sites. Since 1990s, bone flap graft has been improved unceasingly and it has been regarded as a common treatment in the rehabilitative and reconstructive orthopaedics.

A. Yu (✉)
Department of Orthopaedics, Central South Hospital, Wuhan University, Wuhan, Hubei, China
e-mail: yuaixi666@163.com

11.1 Classification of Bone Flaps

According to the source of blood supply, bone flaps can be divided into three categories: bone flap pedicled with muscle, bone flap pedicled with fascia and bone flap pedicled with vessel. Those pedicled with muscle are designed according to the nutrition to the bone from the nutrient vessel of the muscle at the origin and insertion of the bone; those pedicled with fascia are designed using the fascia that is attached to the bone as the nutrient vessel pedicle; those pedicled with vessel are mostly designed according to the nutrient artery of the bone or its superior one and to be transferred with its pedicle or be used as a free vascularized graft due to its large vessel diameter. Bone flaps can be also categorized according to their components: periosteal flap, bone flap, osteomusculocutaneous flap, etc. According to the source of the flap, they can be named as follows: cranial bone flap, costal bone flap, scapular bone flap, radial bone flap, iliac bone flap, femoral bone flap, fibular bone flap, tibial bone flap, etc. They can also be divided into two categories according to their donor: autogenous bone flap and allogenic bone flap.

11.2 Principles in Selection of Donor and Recipient Sites for Bone Flap and Periosteal Flap Graft

Generally, selection of a bone flap should follow the following principles. Repair a functional area with a non-functional area; repair the primary functional area with a secondary functional area; repair should be carried out first on a non-main vessel and next on the main vessel. Cortical bone is the tissue forming the outer layer of the bone, characterized by stiffness, slight flexibility and high capacity of anti-compression and anti-twist. For this reason, in repair of bone defects, long bone is preferable as the donor of bone flap when reconstruction of the supporting function of the bone is the primary concern. Spongy bone refers to the tiny lattice-shaped spicules within the interior of the bone, which has the characteristics of robust

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_11

vascularity, prompt bone union and great capacity of bone healing, represented by the iliac crest, the lateral border of scapula and scapular spine. Spongy bone can be used as the donor especially when a high standard of bone healing is required for repair of bone defects. The donor sites except for the fibula currently are considered only for vascularized bone grafts to repair a defect ranging from 2 to 7 cm. In these donor sites, scapula and radius can provide small bone blocks only, and rib is limited in application as it is too thin and slender. However, free vascularized rib transfer can still be used in one-stage repair of a defect after lesion resection in the thoracic spine. A large bone block can be harvested from the iliac, which has plenty of vessels to be vascularized. We ought to make decisions according to specific conditions of the patients. For example, anterior approach of iliac bone raised on the vascular pedicle of the deep circumflex iliac vessel and ascending branch of lateral femoral circumflex vessel is preferable for repair of a lesion of femoral head and femoral neck. The iliac bone pedicled with the third and fourth lumbar vessels is suitable for intertransverse process fusion via the posterior approach. The iliac bone pedicled with deep branch of superior gluteal vessel is a good source for onlay bone graft of the acetabulum. A free vascularized fibular graft is preferable for a long bone defect of 7 cm in length or longer. The epiphyseal plate, which is capable of dividing by mitosis, is a hyaline cartilage plate between the metaphysis and diaphysis. In an instance when a long bone defect is accompanied by a defect of epiphysis, the vascularized epiphysis transplant should be the primary choice which enables elongation of the transplant to synchronize with the recipient site, avoiding the risk of shortening deformation.

11.3 Indications

Clinical application of bone flap is usually indicated for the following: (1) Bone defects. All bony defects after trauma, inflammation, excision of tumor and congenital malformation, usually including long segmental deficiency and cavitary deficiency. For a defect greater than 6–8 cm or a quarter of the whole bony length in children, a free vascularized autogenic graft is recommended. Since vascularized bone grafts remain viable, based on their medullary and periosteal circulation, healing at the recipient site is accelerated, as quickly as the healing of a normal fracture, without undergoing "creeping substitution." For a defect of 2–6 cm, bone graft or transfer can be chosen depending on specific conditions on account of its satisfactory result which cannot be obtained by traditional bone grafting. A defect less than 2 cm should be treated as nonunion. Cavitary deficiency should be treated by bone flap graft or transfer to greatly shorten the course of healing. (2) Delayed union or nonunion of bone fracture. The transposition or free bone graft or periosteum graft with intact blood supply may help stimulate bone healing and repair the nonunion. (3) Osteonecrosis. Graft of bone flap or periosteal flap is indicated for osteonecrosis, such as osteonecrosis of the femoral head of Ficat stages II and III. After excision of necrotic segments, filling the defect with a viable bone with its vessel pedicle can support the subchondral surface and enhance the revascularization process with plenty of ossification ingredients, leading to good restoration. Bone flaps can be also used for repair of osteonecrosis of metatarsal head and humeral head.

11.4 Timing of Surgery

Generally, for patients with bone defects or nonunion, if coverage of soft tissue is adequate, bone flap graft or transfer should be performed at 6 months or later after the wound or sinus is completely healed so that the opportunity of secondary infection could be reduced. One must be cautious in feasibility assessment of microsurgical bone flap graft at the same stage with the debridement for open injury to bone and joints. As a matter of fact, such operations are contraindicated by principle. But bone graft can be applied when a wound is not severely contaminated, radical debridement is ensured and effective antibiotics are available. If microsurgical bone graft is needed immediately after the wound is completely healed after debridement of open injury to bone and joints, the principles above can be followed too. Our experience, however, suggest that it is appropriate to perform the surgery at 3–6 months after wound healing. The timing of microsurgical bone flap graft for an infectious wound is still controversial. Traditionally doctors suggest that it is reliable to perform the surgery at 6 months after wound healing. However, there are numerous reports of successful one-stage microsurgical bone flap graft in recent years, owing to several powerful measures including local application of effective antibiotics (Fig. 11.1).

Fig. 11.1 Fibular bone flap with peroneal vessel pedicle. *1*. Peroneus longus muscle. *2*. Soleus mucle. *3*. Peroneal vessel. *4*. Flexor hallucis longus. *5*. Fibular bone flap

11.5 Transplantation of Bone Flaps with Vascular Pedicle

The bone tissue pedicled with its nutrient vessel can be used as a local flap to repair nonunion, bone defects and osteonecrosis adjacent to the donor site. It can also be designed as a free vascularized bone graft with its vessel pedicle anastomosed to the vessel of the remote recipient site to repair a bone defect or osteonecrosis. Usually, blood supply of a bone flap pedicled with vessel consists of three artery systems that are both independent and related to one another. They are called nutrient artery system, epiphyseal artery system and periosteal artery system. Intramedullary arteries of nutrient arteries play a chief role in the blood supply to long tubular bones of the limb. On the contrary, the blood supply to a flat or irregular bone relies on the periosteal arteries. Compared with the muscle-pedicled and periosteum-pedicled bone flaps, the vascular-pedicled bone flaps have more abundant blood supply for transfer or transplant.

11.5.1 Scapular Bone Flap Graft

1. A scapular bone flap is designed as the bone tissue derived from the scapula with a complete circulation system supplied by muscle or vessel (Fig. 11.2).

   They can be classified according to their source of blood supply as follows: (1) Scapular spine bone flap pedicled with trapezius muscle refers to the scapular spine bone tissue raised on the fascicle group of the trapezius muscle that is attached to the scapular spine. (2) Scapular spine bone flap pedicled with deltoid muscle refers to the scapular spine bone tissue raised on the fascicle group of the deltoid muscle that is attached to the scapular spine. (3) Scapular spine bone flap pedicled with scapular spine branch of transverse cervical vessel is the scapular spine bone tissue supplied by scapular spine branch of transverse cervical artery and vein. (4) Scapular spine bone flap pedicled with infraspinous branch of suprascapular vessel is the scapular spine bone tissue supplied by the infraspinous branch of suprascapular artery and vein. (5) Scapular bone flap pedicled with deep branch of transverse cervical vessel is the medial border of scapular bone tissue supplied by deep branch of transverse cervical artery and vein. (6) Scapular bone flap pedicled with deep branch of circumflex scapular vessel pedicle is the medial border of scapular bone tissue supplied by deep branch of circumflex scapular artery and vein. (7) Scapular bone flap pedicled with scapular branch of thoracodorsal vessel is the lateral border of the scapular spine bone tissue supplied by the scapular branch of thoracodorsal artery and vein.

   They can also be classified according to their source of donor site as follows: scapular spine bone flap, lateral border (axillary border) scapular bone flap and medial border (spinal border) scapular bone flap.

   The fact that a scapular bone flap can be harvested from both spongy bone and cortical bone to support weight bearing allows it to be commonly used to repair a bony defect of medium-length. A scapular spine bone flap can also be harvested as a composite flap that contains skin and muscle pedicles for local transfer or free vascularized transplant. The lateral border of a scapular bone flap can be designed as a compound flap such as osteocutaneous flap and osteomusculocutaneous flap for local transposition or free vascularized transplant. Its disadvantages include limited bone mass, a usually shorter length compared with a fibular bone flap and a relatively smaller volume than an iliac bone flap. Currently, the scapular bone

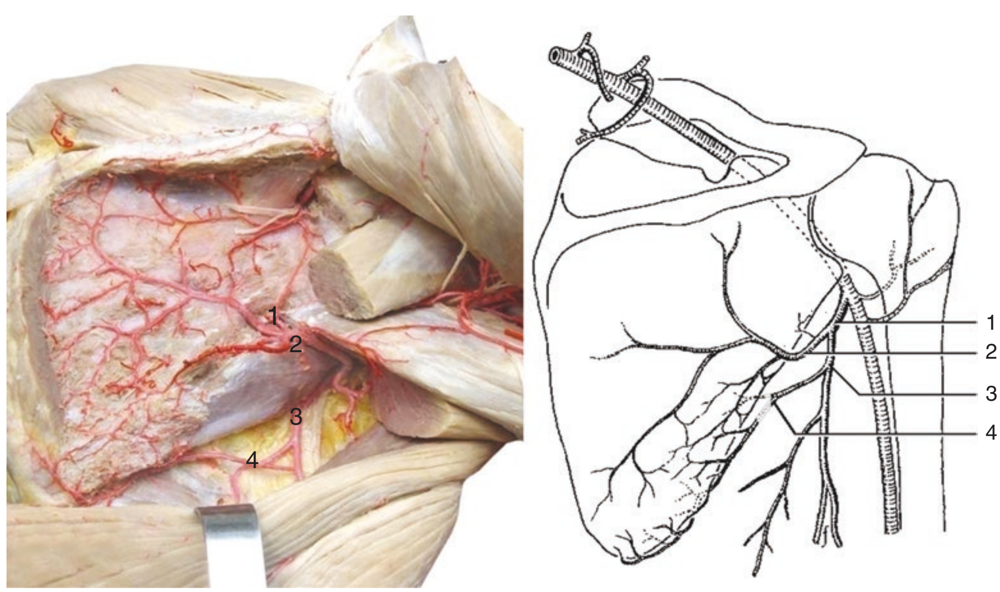


Fig. 11.2 The lateral border of the scapula vascular supply. *1*. Subscapular artery. *2*. Circumflex scapular artery. *3*. Thoracodorsal artery. *4*. The scapular branch

flap pedicled with scapular branch of thoracodorsal vessel is popular in clinical application.

2. Scapular bone flap pedicled with scapular branch of thoracodorsal vessel.

   The lateral border of scapular bone tissue with scapular branch of thoracodorsal vessel as its pedicle can be used as a free vascularized bone graft or for local transposition to repair the nonunion or bony defects of the proximal and middle humerus and shoulder arthrodesis.

   The thoracodorsal artery that directly originates from the subscapular artery courses superficially along the teres major and then runs just along the lateral border of the latissimus dorsi muscle edge and enters the muscle on its deep surface, giving off two major branches constantly: the scapular branch and serratus anterior branch. The main branch continues to run downwards, just under the deep surface of latissimus dorsi muscle, dividing into the medial branch and the lateral branch. Then it travels obliquely and medially on its internal margin right along the subscapular muscle, the lateral border of the teres major and the serratus anterior, just deep to the middle and inferior portion of the lateral margin of the scapula, giving off 4–9 osseous branches of 0.5 mm in external diameter.

11.5.2 Techniques

1. Patient Positioning and Incision

   Place the patient in the lateral decubitus position to make the donor site superior. Make a curved incision that exactly matches the surface projection of the lateral scapular margin, and extend it properly according to the requirement of operation.

2. Vessel Exposure

   Incise the skin, separate the latissimus dorsi muscle from the teres major muscle bluntly, incise downwards 3–5 cm under the point where the upper border of the latissimus dorsi muscle crosses the extended line of the scapula in the longitudinal direction, and retract the latissimus dorsi muscle laterally to expose the scapular branch of the thoracodorsal artery, which courses downwards just to the middle of the lateral margin of scapula. Clamp and divide the distal vessel and preserve the scapular branch of the thoracodorsal vessel if only a bone flap is required. According to the length of the pedicle required, dissect proximally to the axillary fossa direction, ligating and dividing the circumflex scapular branch to include the entire subscapular artery if necessary.

3. Bone Segment Harvest

   Divide the lower digitations of the serratus anterior attaching to the inferior angle of the scapula, and harvest the lateral margin of scapular segment according to the requirement of the recipient site.

4. Bone Flap Transposition or Transplant

   If shoulder arthrodesis is required, the vascular pedicle should be dissected to the subscapular artery and the bone flap should be transferred to the posterior area of the shoulder through the deep surface of teres major and teres minor muscles. Furthermore, if the bone flap needs to be transferred to the proximal and middle humerus, passing through the triangular space and the tunnel under the skin is an option. For a free vascularized bone graft, the vascular pedicle should not be divided until the recipient site is completely prepared.

   The notable features of this flap are as follows: constant anatomic location, long vascular pedicle, large vessel diameter and relatively easier accessibility. The donor site can be designed as a simple bone flap or composite flap such as osteocutaneous flap and osteomusculocutaneous flap for local transposition or free vascularized transplant. Its disadvantages include its weaker support of weight bearing than that of the fibula and limited supply of bone mass.

11.5.3 Upper Limb Bone Graft

11.5.3.1 Ulnar and Radial Bone Flaps

They are ulnar and radial bone blocks with blood supply from muscle or vessel.

Their categories based on the source of blood supply are as follow: (1) Radial and ulnar bone flaps pedicled on anterior interosseous vessels. They are the radial and ulnar bone blocks which obtain blood supply from anterior interosseous artery and vein. (2) Radial and ulnar bone flaps pedicled on posterior interosseous vessels. They are the radial and ulnar bone blocks which obtain blood supply from posterior interosseous artery and vein. (3) Radial and ulnar bone flaps pedicled on interosseous recurrent vessels. They are the radial and ulnar bone blocks which obtain blood supply from interosseous recurrent artery and vein. (4) Radial styloid bone flap pedicled on recurrent branches of radial vessels. It is the radial styloid bone block which obtains blood supply from recurrent branches of radialartery and vein. (5) Radial and ulnar bone flaps pedicled on pronator quadratus muscle. They are the radial and ulnar bone blocks which obtain blood supply from pronator quadratus muscle.

The radial and ulnar bone flaps often use non-major arteries of the forearm as their nutrient vessels. Of them, the distal end of anterior interosseous vessel and posterior interosseous vessel participate in carpal vessel network. The arteriae interossea recurrens participates in elbow vessel network. Therefore, the flaps pedicled on these aforementioned vessels can be designed as anterograde or retrograde bone (periosteum) flaps circumstantially. Radial and ulnar bone flaps can be transferred to an extensive area of bone lesion, including the lower segment of humerus, radius, ulna, carpus, and metacarpus. Additionally, as the posterior interosseous artery gives off many cutaneous branches which distribute at the back of forearm, these bone flaps can be made into osteocutaneous or periosteal-cutaneous flaps to repair composite tissue defects at the recipient site. Their demerit is limited quantity of bone mass.

11.5.3.2 Distal Ulnar Bone Flaps Pedicled on Posterior Interosseous Vessels

They are distal ulnar bone blocks nourished by posterior interoesseous vessels. There are two types of pedicle. Those pedicled on the proximal posterior interosseous vessel can be transferred to repair nonunion of upper and middle radius or ulna and defects of distal radius. Those pedicled on the posterior-anterior interosseous anastomosis or terminal branches from posterior interosseous vessel to dorsal carpal vascular network can be transferred to repair nonunion and defects of carpus and metacarpus.

Applied anatomy: The posterior interosseous artery originates from the common interosseous artery in the proximal palmaris forearm. It crosses the superior border of interosseous membrane and enters the gap between attachments of abductor pollicis longus muscle and supinator muscle to ulna. The artery accompanying the posterior interosseous nerve routes between the superficial and deep group of forearm extensor muscles. Then the trunk goes down into the deep fascia between extensor carpi ulnaris muscle and extensor digiti minimi muscle gradually. The distal part of posterior interosseous artery anastomoses with the branches of anterior interosseous artery's dorsal carpal vessels which go from laterally to medially via deep face of extensor digiti minimi muscle at averagely 2.5 cm above the ulnar styloid process. The outside diameter of posterior interosseous artery at the starting point is about 1.8 mm, whereas the outside diameter of the anastomosis between distal part of posterior interosseous artery and dorsal carpal branches of anterior interosseous artery is about 0.8 mm. Starting at 6.0 cm on the ulnar styloid, the periosteum branch that crosses the deep face of extensor carpi ulnaris distributed at the back of ulnar periosteum correspondingly. The number of periosteal branches which originate from posterior interosseous artery above the anastomosis is 2.3 on average. The outside diameter is about 0.4 mm. The anastomosis gives off 1–2 branches downwards which go distally at the posterior-lateral side of ulnar head. The branches which derive from the ulnar part of anastomosis can be seen as an extension of ulnar dorsal carpal osteocutaneous branches of anterior interosseous artery. The vessels give off branches laterally which distribute at the ulnar head. The body surface projection of posterior interosseous artery is located at middle-lower 1/3 part of the line between lateral epicondyle of humerus and radial edge of the ulnar head. The overall length is 13.6 cm on average.

Surgical Design

1. **Bone flap pedicled on anterograde-flow vessel.** (1) Position and incision: Supine position. The incision, based on the surface projection of posterior interosseous artery, starts from radial side of the ulnar head and goes upwards. The length of incision depends on the distance to the recipient site. (2) Exposure of pedicle: The deep fascia is incised at the dorsal side of extensor carpi ulnaris muscle and extensor digiti minimi muscle. After the aforementioned muscles are retracted laterally, the posterior interosseous vessel bundle can be recognized in deep fascia. In order to avoid injury to nutrient vessels, the width of deep fascia must be at least 1.0–1.5 cm when the pedicle is free. Anastomosis between posterior interosseous artery and dorsal carpal branch of anterior interosseous artery, located at about 2.5 cm above the ulnar styloid tip, is ligated far away from the ulna under the extensor digiti minimi tendon. (3) Harvest of flap: The flap locates at radial half of the ulna. The length and width are about 3.5 and 1 cm respectively. (4) Transposition of flap: Flap is transferred to bridge the nonunion or embedded into a defect of radius and ulna.
2. **Bone flap pedicled on retrograde-flow vessel.** (1) Position and incision: Supine position. Incision is longitudinal at radial side of the ulnar head. The length of incision depends on the distance to the recipient site. (2) Exposure of pedicle: Surgeons incise skin and superficial fascia and then incise the deep fascia on the dorsal side of the extensor carpi ulnaris muscle and the extensor digiti minimi muscle. After the aforementioned muscles are retracted laterally, the posterior interosseous vessel bundle can be recognized in deep fascia on the radial side of the extensor carpi ulnaris muscle. (3) Harvest of flap: The flap locates at 2.6 cm above the ulnar styloid process. The size is about 1.2 cm × 0.4 cm × 0.4 cm. (4) Transposition of flap: The posterior interosseous vessel bundle above the proximal end of the flap should be cut off and ligated. The bone flap, pedicled on anastomosis between posterior interosseous vessel and dorsal carpal branches of anterior interosseous vessel, is transferred to the recipient site of carpus and metacarpus.

Merits and demerits: The vessel which supplies blood for bone flap is a non-major artery and anastomoses with dorsal carpal branches of anterior interosseous artery distally. There can be two types, antegrade-flow or retrograde-flow flap, to repair radial, ulnar, carpal and metacarpal lesions. Since the posterior interosseous artery gives off many branches which are distributed at the back of forearm, the flap can be harvested in the form of osteocutaneous flap to repair composite tissue defects at the recipient site. The demerit of this flap is its small quantity of bone mass.

3. **Radial styloid bone flap pedicled on the recurrent branch of the radial artery** The radial styloid bone block, supplied by the recurrent branch of the radial artery, can be transferred to repair old carpal scaphoid fracture, and ischemic lunate necrosis.

   Applied anatomy: The radial artery passes under the styloid bone, goes under the surface of abductor pollicis longus tendon and extensor pollicis brevis tendon and arrives at anatomical snuffbox. The radial arterial trunk, about 1.2 ± 0.2 cm below the styloid tip, gives off a dorsal carpal branch to the ulnar side. The recurrent branch of radial artery originates from the proximal part of dorsal carpal branch or radial arterial trunk directly and then returns to the styloid tip. Seventy six percent of people possess only one branch, whereas the other 24% two branches. The average length of recurrent branch trunk of radial artery is 1.2 ± 0.3 cm. Its outside diameter at the starting point is 0.4 ± 0.2 cm. Its starting point is about 0–1.2 cm blow the styloid tip.

   Surgery design: (1) Position and incision: Supine position. According to the long axis of anatomical snuffbox, a longitudinal or "S"-shaped incision is made on the lateral wrist. (2) Pedicle exposure: The cephalic vein and superficial branch of radial nerve are exposed and pulled to one side after the skin is incised. The radial artery can be dissected between the extensor pollicis longus tendon and extensor pollicis brevis tendon at 1.2 cm from the distal radius. The styloid plane is exposed along the ulnar side of radial artery to the proximal end. Finally, the dorsal carpal branch and the recurrent branch which both originate from the radial artery are recognized. The starting point is located at the deep face of abductor pollicis longus tendon and extensor pollicis brevis tendon. (3) Flap harvest: The wrist is at the ulnar overflexion position. The surgical plane of styloid osteotomy exceeds the ulnar side of scaphoid fracture line about 0.2 cm at the carpal articular surface. The radial side of the harvest area is 0.8–1.2 cm away from the radial styloid tip. The flap needs to be properly cut into a required shape. The dorsal part of styloid flap which possesses many nutrient canals (ranging from 0.5 to 1.5 cm from the styloid tip) should be preserved. The vascular net on the surface of periosteum should be preserved carefully so that nutrient vessels are not broken. According to the required size of flap, a chip of styloid tip or dorsal styloid flap can be harvested along the distribution of nutrient vessels. (4) Flap transposition: To treat old carpal scaphoid fracture, a tunnel is drilled from the proximal scaphoid bone via the fracture line to the distal part. 2/3 or 3/4 of the tunnel is cut into a groove. Then the pedicled flap is inserted into and fixed on the groove properly. To treat ischemic lunate necrosis, the flap is transferred to the recipient site via the dorsal wrist approach.

   Merits and demerits: The anatomy of recurrent branch of radial artery is constant. Variations of pedicle are rare. The superficial vessel is easy to recognize. Treatment of old carpel scaphoid fracture with a radial styloid bone flap retains the advantage of old surgical method of simplex radial styloid resection and utilizes the excised radial styloid part in flap transfer to revascularize the ischemic carpel scaphiod bone after fracture.

4. **Iliac bone flap**

   It is taken from the iliac bone with blood circulation. Blood supply can come from a vascular pedicle or a muscle pedicle. The ilium has rich multi-derived blood supply. The start and end points of numerous vessels and muscles are available for a source of blood supply to an iliac bone graft. Since iliac bone flaps with various vascular pedicles vary in characteristics and application scopes, surgeons have plenty surgical solutions to choose from.

   According to their blood supply, iliac bone flaps can be divided into: (1) Iliac bone flap pedicled on waist rib muscle, obtaining blood supply from the waist rib muscle attached to the ilium; (2) Iliac bone flap pedicled on sartorius muscle, obtaining blood supply from the sartorius muscle attached to the ilium; (3) Iliac bone flap pedicled on tensor fascia lata muscle, obtaining blood supply from the tensor fascia lata muscle attached to the ilium; (4) Iliac bone flap pedicled on deep circumflex vessels, obtaining blood supply from the deep circumflex vein and artery; (5) Iliac bone flap pedicled on shallow circumflex vessels, obtaining blood supply from the shallow circumflex iliac vein and artery; (6) Iliac bone flap pedicled on ascending branch of the lateral femoral vessels, obtaining blood supply from the lateral femoral vein and artery; (7) Iliac bone flap pedicled on the third lumbar vessels, obtaining blood supply from the third lumbar vein and artery; (8) Iliac bone flap pedicle on the forth lumbar vessels, obtaining blood supply from the forth lumbar vein and artery; (9) Iliac bone flap vascularized by iliolumbar vessels, obtaining blood supply from the iliolumbar vein and artery; (10) Iliac bone flap pedicled on deep branch of the superior gluteal vessel, obtaining blood supply from the deep branch of the superior gluteal vein and artery; (11) Iliac bone flap pedicled on superficial branch of the superior gluteal vessel, obtaining blood supply from the deep branch of the superficial branch of the superior gluteal vein and artery; (12) Iliac bone flap pedicled on lateral sacral vessels, obtaining blood supply from the branch of the superior sacral vein and artery. According to the donor sites, iliac bone flaps can be taken from the front, middle and rear parts of the iliac crest (Fig. 11.3).

   The ilium is in a hidden part of the body with the characteristics of both cancellous bone and cortical bone. As its function is not affected after harvest and suitable for harvest at supine, lateral or prone positions, the ilium is one of the most common donor sites for bone graft. The volume of iliac bone flap is large, though its length is shorter than that of a fibula flap. It can meet the needs of most bone defects. It can be designed as an iliac periosteal flap or an iliac bone flap to meet various needs of the affected sites. Most vascularized iliac bone flaps can be transferred freely or locally.

5. **Deep circumflex iliac bone flap**

The iliac bone flap pedicled on deep circumflex vessels can treat lesions at the femoral head and neck in local transposition. A free vascularized iliac bone graft can be transferred to repair bone defects at other places.

Deep circumflex iliac artery originates from the site near the transitional place of femoral artery and external iliac artery. The branches after the start are abdominal muscle branches in groin, musculoskeletal branch within the iliac crest segment and muscle skin branch in the iliac crest segment. There are 2-abdominal muscle branches with an outer arterial diameter of 0.2–1.8 mm. At approximately 3 cm from the start of deep circumflex iliac artery, a relatively coarse abdominal muscle branch can be often seen, which travels through the transversus abdominis and between the internal oblique and transverse abdominal muscles, then anastomosis with the branch of inferior epigastric artery and lumbar artery on its way. The length of advantage muscular branches is 9.0 cm with an outer diameter of 1.4 mm at the starting point. The musculoskeletal branch is 2 cm under the iliac crest lip, traveling in the double fascia sheathes of the iliac crest and giving off 3–8 musculoskeletal branches with an outer diameter of 0.2–0.7 mm which travel through the abdominal wall and then enter the iliac crest lip, to supply blood to the iliac crest and the front surface of the skin. The musculocutaneous perforator is continuation of deep circumflex iliac artery terminal segment, which travels through the fascia and enters the edge of the iliac crest to go back into the abdominal muscle. In addition to supplying the muscles, the terminal branches cross the deep fascia to distribute the surface of the skin. (1) The piercing site of musculocutaneous perforator is an intersection point usually about 5.2 cm above the anterior superior iliac spine and 1.5 cm outside the anterior superior iliac spine. (2) The skin area supplied by musculocutaneous perforator: After piercing the deep fascia, the cutaneous artery have radial branches to anastomosis with lateral cutaneous branch of intercostal arterie, inferior epigastric perforator branch, abdominal branch and superficial circumflex iliac artery branch. The distal deep iliac artery has two accompanying veins, which are located respectively at the superior and inferior aspects of the artery and import into external iliac vein.

Surgical Design: (1) Position and incision. Supine position. In the middle of the iliac crest and the midpoint of the inguinal ligament, make an oblique incision along the iliac crest to extend downwards for 3–4 m. (2) Pedicle exposure. Find out the femoral pulse points, cut the inguinal ligament, and expose femoral vessels and the deep circumflex iliac vessels. Dissect from proximal to distal along the deep circumflex iliac artery. The musculoskeletal vessels from the iliac crest can be seen in the pedicle segment attaching to the iliac crest and supplying nutrition. Expose the iliac crest segment according to the desired length of bone. The vessels can also be separated recessively. Cut the three abdominal muscles along with the outside part of the external iliac crest in the anterior superior iliac spine, and then push the iliac fascia, about 2 cm below the lip in the iliac crest. The iliac crest segment of the deep circumflex iliac artery can be found on the surface of the iliac muscle. From that point, retrograde along the vessel, and free the pedicle to its proximal end till the desired length of the vascular pedicle. (3) Harvest of iliac bone flap. A certain volume of ilium is harvested according to the need of recipient site. (4) Bone flap transposition. The bone flap will be transferred to the recipient site after preparation. Fixation of the flap should not affect the blood supply to the flap. Generally Kirschner wires or lag screws are used.

Advantages and disadvantages: The deep circumflex iliac artery is characterized with a large diameter, long trunk, constant course and wide range of blood supply. Generally, a flap of 10.0 cm × 4.0 cm can be harvested. They can be designed as a simple bone flap, a periosteal flap or a compound osteocutaneous flap according to the needs of recipient site. They can be used for local transfer or free transplantation. Since the ilium is located a hidden part of the body, its appearance and function are not affected after harvest. The disadvantage is that it is often blocked by the iliopsoas in local transposition. Part of the iliopsoas has to be cut off when the pedicle is subjected to tension.

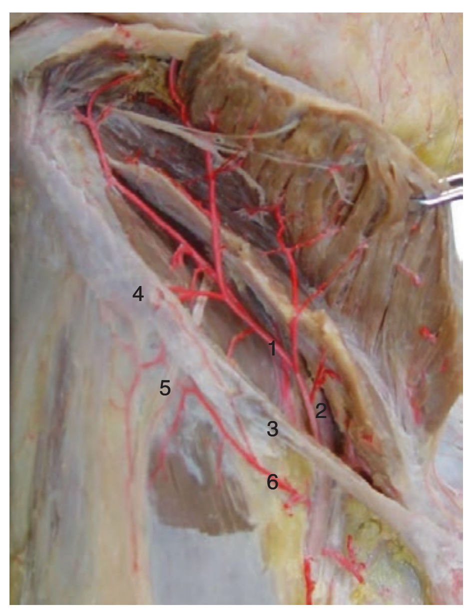


Fig. 11.3 Course, branches and distribution of the deep circumflex iliac artery. *1*. Deep circumflex iliac artery. *2*. External iliac artery. *3*. Inguinal ligament. *4*. Anterior superior iliac spine. *5*. Anterior superior iliac spine. *6*. Superficial circumflex iliac artery

11.5.4 Iliac Bone Flap Pedicled on Ascending Branch of Lateral Femoral Circumflex

The iliac bone flap pedicled on ascending branch of lateral femoral circumflex is mainly used in local transposition to repair bone lesions at the femoral head and neck, or nonunion and bone defects at the middle and upper femur. A free vascularized iliac bone graft can be transferred to repair bone defects at other places.

Applied anatomy: The ascending branch of lateral femoral artery comes from the lateral femoral circumflex artery, progresses on the femoral nerve branches and deep surface of rectus femoris, divides into the upper and lower branches about 8 cm under the anterior superior iliac spine, and goes into the deep surface of the muscle. After the upper branch goes into the muscle, it distributes mainly in the upper parts and origin of the muscles. The peripheral part of the upper branch goes into the anterior superior iliac spine to form a branch of the iliac crest. The lower branch mainly distributes in the lower anterior and posterior region. The length of ascending branch of the lateral femoral circumflex artery into the anterior muscle is about 5.2 cm, with an outer diameter of about 3.2 mm. It usually has five branches (Fig. 11.4).

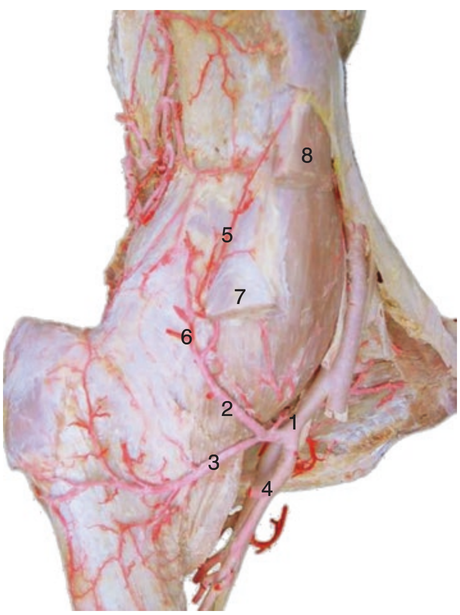


Fig. 11.4 Origin, course and distribution of the ascending branch of lateral femoral circumflex. *1*. Lateral femoral circumflex artery. *2*. The ascending branch. *3*. The transverse branch. *4*. The descending branch. *5*. The iliac crest branch. *6*. The middle gluteal muscle branch. *7*. The femoral muscle branch. *8*. The sartorius muscle

Surgical Design: (1) Position and incision: Supine position, with the recipient hip slightly elevated. Make a Smith-Peterson incision, and extend it downwards along the front of tensor fascia lata edge for about 4–6 cm. (2) Pedicle exposure: First, the lateral femoral cutaneous nerve is pulled medially for protection. Sharply separate the rectus femoris muscle and the musculus tensor fasciae latae and pull the two muscles inwards and the outwards. The ascending branch of lateral circumflex femoral artery, descending artery and its branches are visible at this point on the rectus femoris deep surface. Close to the tensor fascia lata medial surface, anatomically dissect the ascending branch root to expose the vascular pedicle. (3) Bone flap harvest: Separate the ramus upwards until the anterior superior iliac crest. Be careful to protect the iliac crest branch. If the iliac crest branch is tiny, harvest the iliac crest branch along with part of the tensor fascia lata. To ensure good blood supply to the bone flap, cut off the flap together with the attachment of the ascending branch at the iliac crest to form a vascular pedicle. According to the recipient site needs, cut a certain size of iliac bone, often including the anterior superior iliac spine. (4) Bone flap transplantation: The bone flap will be transferred to the recipient site after preparation. Fixation of the flap should not affect the blood supply to the flap. Generally Kirschner wires or lag screws are used.

Advantages and disadvantages: The pedicle of ascending branch of lateral femoral circumflex artery has advantages of large caliber, long pedicle, constant anatomical location, and dissection. It can be used for both local displacement and free transfer. It can also be used to form an iliac bone flap pedicled on ascending branch of lateral circumflex femoral artery, or a skin flap pedicled on the descending branch in chimeric transplantation to repair bone and soft tissue defects. Its disadvantage is occasional variation of the iliac crest branch, always necessitating harvest of partial tensor fascia lata.

11.5.5 Iliac Bone Flap Pedicled on Deep Superior Branch of Superior Gluteal Vessels

The iliac bone flap pedicled on the deep superior branch of superior gluteal vessels can be used in local transposition to treat femoral head or neck lesions and also for hip shelf procedure as a bone graft.

Applied anatomy: The superior gluteal artery generally comes out from superior piriform aperture, dividing into a superficial branch and a deep branch. The superficial branch comes out between the piriformis muscle and the gluteus medius muscle, with scores of small branches going into the gluteus maximus muscle and the gluteus medius muscle. The deep branch is close to the outside of iliac bone, going in the deep surface of gluteus medius muscle for 1–2 cm before dividing into two branches with deep branches distributing mainly to the gluteus minimus. The deep superior branch of superior gluteal artery curves forward in the gluteus medius muscle along the origin of deep gluteus minimus muscle on the edge. The artery terminates in the anterior superior iliac spine and anastomosis with the lower part of the deep circumflex iliac artery and the ascending branch of lateral circumflex femoral artery. The trunk is about 6.7 cm below the iliac crest point. The initial diameter is 3.1 mm, length of the trunk 9.8 cm and the end outside diameter 1.2 mm. On the course of the deep branch of superior gluteal artery, about four periosteal branches come from the main issue, distributing in the iliac wing in a fan-shape. Its accompanying veins are always more than two branches, injecting into the superior gluteal vein (Fig. 11.5).

Surgical Design: (1) Position and incision: Side-lying position, with the donor side superior. Make an incision from the 1/3 iliac crest and along the iliac crest forward to the anterior superior iliac spine, and then extend downwards to 3–4 cm. (2) Pedicle exposure: Dissect longitudinally muscle fibers of the gluteus medius muscle at the midpoint of the outer lip of the iliac crest at about 3.5 cm below. The deep superior branch of superior gluteal vessel can be found. There are many iliac periosteal branches from the deep superior branch of superior gluteal vessels, especially from the anterius segmentum and the middle part. The vascular pedicle can be dissected retrogradely. Cut the iliac flap firstly, and then expose the whole vessel pedicle. (3) Bone flap harvest: According to the need of recipient cite, cut a bone block of from the iliac crest, about 3 cm in thickness, avoiding injury to the vascular pedicle. The bone flap is often cut from the anterior part of the iliac crest. (4) Bone flap transplantation: Fix the flap without affecting its blood supply. Generally Kirschner wires or lag screws are used.

Advantages and disadvantages: The iliac bone flap pedicled on deep superior branch of superior gluteal vessel has many periosteal branches, a constant anatomical location, abundant blood supply and abundant vascular pedicle length. It is commonly used in local transposition for hip shelf procedure as a bone graft and free transplantation.

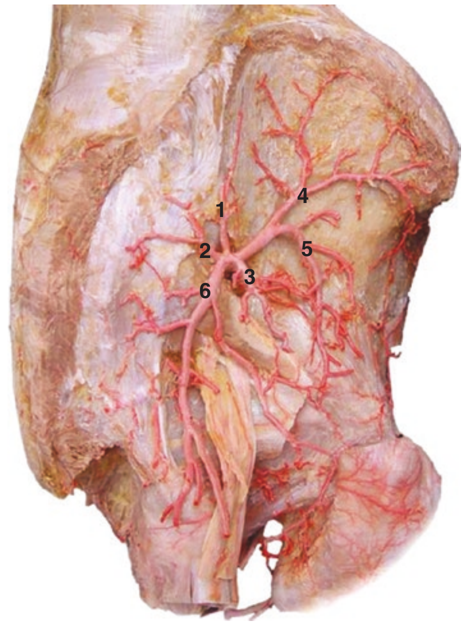


Fig. 11.5 Course, branches and distribution of the superior gluteal artery. *1*. Shallow inferior branch. *2*. Shallow middle branch. *3*. Shallow inferior branch. *4*. Deep superior branch. *5*. Deep inferior branch. *6*. Thick shallow under branch (to replace the inferior gluteal artery)

11.5.6 Femoral Bone Flaps

Femoral bone flap is harvested from the vascularized bone of femur. Its blood supply can be provided by adjacent tissues (muscle, fascia and vessel). It can be used for either local or free transfer.

According to the blood supply, femoral bone/periosteal flaps can be divided into ten different categories, including greater trochanteric bone flap pedicled with quadratus femoris muscle, greater trochanteric bone flap pedicled with deep branch of medial femoral circumflex artery, greater trochanteric bone flap pedicled with anastomosis branch of inferior gluteal artery, greater trochanteric bone flap pedicled with ascending branch of the first perforating artery, greater trochanter bone flap pedicled with transverse branch of lateral circumflex femoral artery, medial femoral condylar bone flap pedicled with the descending genicular vessels, femoral osteoperiosteal flap pedicled with deep femoral vessels, femoral osteoperiosteal flap pedicled with perforating artery of deep femoral vessels, femoral osteoperiosteal flap pedicled with lateral superiorgenicular vessel and femoral osteoperiosteal flap pedicled with the direct preiosteal branches of femoral artery. Many locations, including the greater

Fig. 11.6 Branches and distribution of the deep femoral vessel and its perforating branches. *1*. The first perforating artery. *2*. The second perforating artery. *3*. The third perforating artery. *4*. The perforator of muscular and periosteal artery

trochanter, the femoral shaft, medial and lateral femoral condyles, can be considered as the donor sites of the femoral bone/periosteal flaps (Fig. 11.6).

Because the femur is the single bone of the thigh, complications of the donor site, e.g. fractures, may occur after harvest of the femoral shaft which usually serves as a donor site of periosteal flap. Subperiosteal bone tissue can also be taken while harvesting a periosteal flap. Periosteal bone flaps can be used to repair nonunion or bone defects of a small area. The greater trochanter is a common donor site for bone flaps and periosteal flaps to repair lesions of the femoral neck and head, but generally not in free transfer. Bone flaps from the medial femoral condyle are locally transferred to repair femoral nonunion or small bone defects. The medial femoral condyle can also be a donor site for a free bone graft. Furthermore, the medial femoral condyle can be included in a vascularized bone flap of the medial femoral condyle or in a composite tissue flap with bone, tendon and skin to repair corresponding composite tissue defects.

11.5.7 Greater Trochanteric Bone Flap Pedicled with Deep Branch of Medial Femoral Circumflex Artery (MFCA)

The greater trochanteric bone flap which is nourished by the deep branch of medial femoral circumflex artery (MFCA) can be locally transferred for management of femoral neck nonunion and femoral head necrosis.

The deep branch of MFCA derives from the femoral profound artery. It perforates the gap between adductor brevis and obturator externus, and reaches behind the hip. Then it runs from the back of femoral neck base upwards and outwards. At the level of 0.6 cm below the upper border of quadratus femoris, 0.8 cm from the intertrochanteric crest, the deep branch gives off the greater trochanter branch which fans out the lateral posterior part of greater trochanter. The initial diameter of the deep branch is 1.7 mm, while the diameter of two accompanying veins is a bit larger. The anastomosis branch of inferior gluteal artery (IGA) starts from the lower border of piriformis muscle. About 78% of them travel to the femoral neck base and anastomose with the deep branch of MFCA. The distal end of the rest 22% gives off several branches, which anastomose with the deep branch. The distance from the starting point of anastomosis branch of IGA to the anastomosis site is 6.2 cm. The initial diameter is 1.5 mm. Most branches are accompanied by a single vein the diameter of which is larger than that of the artery (Fig. 11.7).

Flap design: (1) Approach and position: The patient lies in the lateral position. Posterolateral approach (Moore incision) is adopted. (2) Pedicle exposure: The iliotibial band is incised from the greater trochanter to the distal femur. Then, the gluteus maximus is separated by blunt dissection. The injured limb is internally rotated, and the partial tendon insertion of gluteus maximus at the great trochanter is cut off if necessary. Then the great trochanter branch spreads on to the posterior aspect of great trochanter in a claw-like fashion. The quadratus femoris is cut off from the origin of the great trochanter branch. Then, the deep branch of MFCA is followed

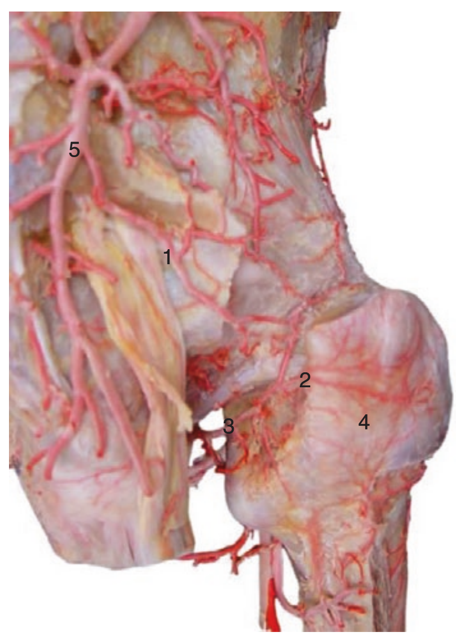


Fig. 11.7 Artery distribution of the greater trochanter (posterior view). *1*. Anastomosis branch of inferior gluteal artery. *2*. Branch of greater trochanter. *3*. Deep branch of medial femoral circumflex artery. *4*. Greater trochanter. *5*. Inferior gluteal artery

from the intertrochanteric crest to the lesser trochanter. (3) Bone flap harvest: The origin of great trochanter branch is considered as the center. Bone flap is harvested from the posteriorlateral aspect of great trochanter according to the size of recipient site. Generally the flap is about 4–5 cm in length, 2 cm in width and 1.5 cm in thickness. The periosteum can be 1–2 cm wider than bone flap. Partial soft tissue around the pedicle can be preserved. (4) Bone flap graft: After the recipient site has been well prepared, the bone flap is transferred. Usually, dead bone is debrided and bone flap is inserted in repair of femoral head necrosis. For femoral neck fracture, bone flap is commonly inserted in the bone defect at the posterior aspect before it is fixed with kirschner wires or screws.

Merits and demerits: Local transfer of the greater trochanteric bone flap pedicled with deep branch of MFCA can be performed through the posterior approach. The course of the deep branch of the MFCA is constant. The length of vascular pedicle can be up to 4 cm with rich perfusion. As only the end of MFCA is used during the operation, the basal artery ring of the femoral neck survives. The flap is especially suitable for bone graft at the femoral head and neck through posterior approach. It can also be used as a periosteal flap for treatment of femoral head necrosis and femoral neck fracture. The disadvantage is that it cannot be used by free transfer.

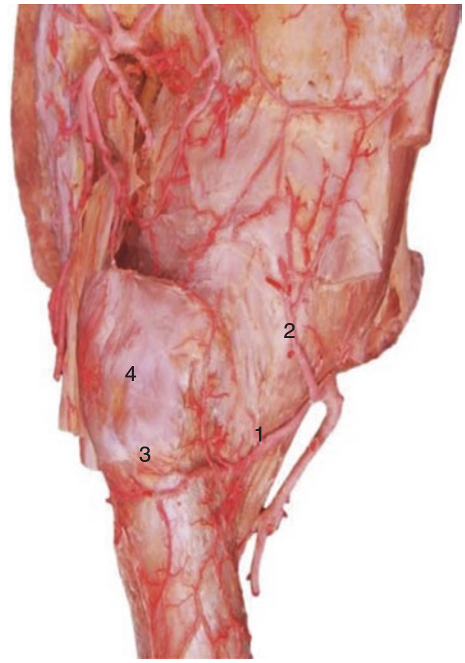


Fig. 11.8 Artery distribution of the greater trochanter (anterior view). *1*. Transverse branch of lateral femoral circumflex artery. *2*. Ascending branch of lateral femoral circumflex artery. *3*. Branch of greater trochanter. *4*. Great trochanter

11.5.8 Greater Trochanter Bone Flap Pedicled with Transverse Branch of Lateral Circumflex Femral Artery (LCFA)

The greater trochanter bone flap which is nourished by the transverse branch of lateral circumflex femoral artery (LCFA) can be locally transferred for management of femoral neck fracture/nonunion and nonunion of the upper femoral shaft.

Applied anatomy: Most lateral femoral circumflex arteries originate from the femoral profound artery which gives off the transversal branch at the level of 2.4 cm lateral to the origin. Most transversal branches derive from the ascending branch of lateral femoral circumflex artery, and the rest from the descending branch or the root of lateral femoral circumflex artery. The transversal branch runs along the deep surface of rectus femoris. Then it reaches the muscular porta of tensor fasciae latae and a branch generates to supply the vastus lateralis muscle. The vessel backbone keeps running along the deep surface of vastus lateralis muscle and reaches the inferior aspect of the greater trochanter. At the deep surface and lateral border of vastus lateralis muscle, it gives off 2–4 anterior and lateral branches and anastomose with the deep branch of MFCA. The transversal branch is accompanied by two veins, the diameter of which is a little bit larger (Fig. 11.8).

Flap design: (1) Approach and position: The anterolateral approach and the supine position are adopted. (2) Pedicle exposure: After blunt dissection from the muscular porta of tensor fasciae latae in the lateral direction, the muscle is separated and the transversal branch is exposed at 2 cm below the origin of vastus lateralis muscle. Dissociate the pedicle. (3) Bone flap harvest: According to the size of recipient site, the bone flap is designed at the anterior lateral aspect of greater trochanter. (4) Bone flap graft: After optimal treatment of the recipient site, the bone flap is transferred to the site and externally fixed.

Merits and demerits: The bone flap is nourished by the direct branch of femoral profound artery. It possesses regular vasa vasorum and abundant vascularity. Moreover, the pedicle is long enough and the bone flap can be transferred to the upper femoral shaft. The disadvantage is its limited bone mass.

11.5.9 Magnus Adductor Muscle Tendon Bone Flap Pedicled with Descending Genicular Artery

The flap consists of magnus adductor muscle tendon and bone nourished by the descending genicular artery. It can be locally transferred to repair nonunion of distal femur. The composite tissue flap can also be used as a free graft for composite defects of bone, tendon and skin. Its clinical application was first reported by Masquelet in 1985.

Applied anatomy: The descending genicular artery usually originates from the femoral artery. The starting site is located at 11.5 cm above the medial femoral condyle. The initial diameter of the artery is 2.3 mm. It perforates vastoadductory lamina and runs between the medial vastus muscle and gracilis. Then, it runs along the deep aspect of sartorius accompanied by the saphenous nerve. The artery finally gives rise to muscular branch of medial vastus muscle, joint branch and saphenous branch at the level of 10.4 cm above the lower border of medial femoral condyle. The external diameter of joint branch is approximately 1.8 cm. The main trunk runs between the posteromedial aspect of medial vastus muscle and vastoadductory lamina. The trunk then gives rise to muscular branch of medial vastus muscle, branch of magnus adductor muscle tendon and cutaneous perforator. At the level of 5.9 cm above the lower border of medial femoral condyle, the main trunk also gives rise to periosteal branch, the external diameter of which is constantly 1.3 cm. The terminal branch transits to the infrapatellar branch. The joint artery is accompanied by two veins, the external diameter of which is the same or a little bit larger than that of artery (Fig. 11.9).

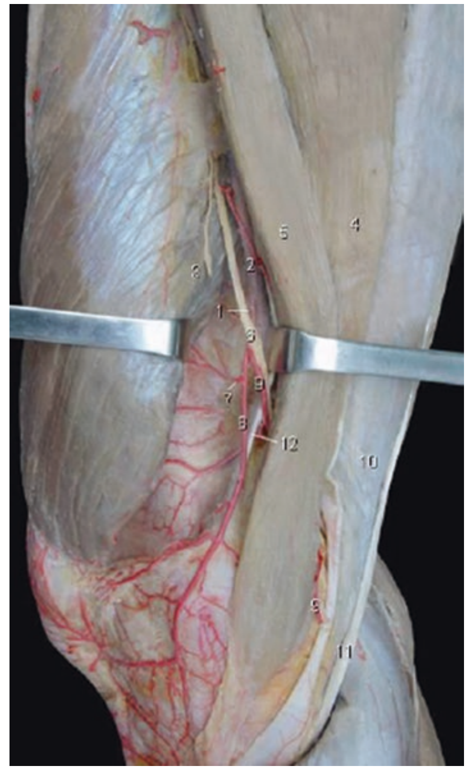


Fig. 11.9 The origin, branches and distribution of the descending genicular artery. *1*. Descending genicular artery. *2*. Femoral artery. *3*. Medial vastus muscle. *4*. Gracilis muscle. *5*. Sartorius. *6*. Saphenous nerve. *7*. Branch of medial vastus muscle. *8*. Branch of the joint. *9*. Saphenous artery. *10*. Semimembranosus. *11*. Semitendinosus. *12*. Adductor magnus

The periosteal branch runs along the anterior aspect of medial femoral condyle for 4.8 cm. During its course, it gives rise to several branches, which anastomose with the direct periosteal branch of femur, medial superior genicular artery branch and infrapatellar branch of descending genicular artery. It forms a vascular network that wraps the medial femoral condyle. The upper and lower borders of the network are 7–8 and 1 cm above the lower border of medial femoral condyle, respectively. The anterior and interior borders are inner 4/5 of anterior femur and the inner surface of great adductor tubercle and femur. The area of periosteum is approximately 7 cm × 5 cm.

Flap design: (1) Approach and position: The patient lies in supine position and the injured limb tends to turn outward. Medial approach of thigh is adopted, which originates from 3 to 5 cm above the adductor tubercle to the lower border of medial femoral condyle. (2) Pedicle exposure: Anatomic peeling is performed between the medial vastus muscle and sartorius muscle. The lower medial muscular border of medial vastus muscle and sartorius muscle are separated bluntly. Pull the medial vastus muscle, and then the beginning part of the descending genicular artery and the vascular network to the periosteum are clung to the surface of medial femoral condyle. The great adductor tendon is traced by periosteum branch and cut. The descending genicular artery issued by the anterior aspect of femoral artery is identified 7 cm away from the upper border of adductor tubercle carefully. Protect adjacent saphenous nerve. (3) Bone flap harvest: Suitable bone flap is harvested by a regressive method according to the recipient site. (4) Bone flap graft: After optimal treatment of the recipient site, the bone flap is transferred to the site.

Merits and demerits: Great adductor muscle tendon bone flap, great adductor muscle tendon osteocutanous flap and great adductor muscle tendon composite tissue flap can be harvested as needed. Different flaps own identical vessels and the operation is convenient. The vascular pedicle is long and the diameter of artery is large. It can be used for various recipient sites. It can be used for either local transfer or free graft. However, if both joint branch and saphenous branch start directly from the artery, both groups of vessels should be anastomosed when a free osteocutanous flap of great adductor muscle tendon is used. During the process of flap harvest, the knee joint may be injured.

11.5.10 Fibular Flaps

The fibula is a long tubular bone with high density and rigidity. Since its upper and middle parts are used for muscle attachment and barely bear any weight, the available part of fibula is very long, as long as 26 cm in an adult. Moreover, the fibula has independent blood supply. As its vascular system is constant with little variation and large diameters, it is suitable for microsurgery. Fibular flap graft with vascular anastomosis was first performed by Taylor et al. in 1975 to reconstruct two cases of large tibial defect. One case succeeded with blood reperfusion inside which was confirmed by arteriography, but the other case failed. In 1977, Taylor introduced this surgery in details. Meanwhile, another patient with distal femur defect was treated by grafting a free fibular flap into a defect between the femur and tibia. In 1979, a Chinese surgeon Zhongwei Chen successfully applied this surgery to cure a patient with congenital pseudarthrosis of the tibia. Since then this surgery has provided a new solution for repair of defects of long tube bone. Free fibular flaps with vascular anastomosis, both bone ones and composite osteocutaneous ones, are now widely used in clinic.

11.5.10.1 Applied Anatomy

The fibula is not a main load-bearing bone though it does bear some load. The fibular head does not take part in the knee joint, but it shares an articular surface with the lateral condyle of the tibia. An adult fibula is about 34 cm long. The upper side, quadrilateral in shape, is where the muscles attach. The lower side is trilateral in shape, taking part in the ankle joint. About 20 cm of the fibula can be harvested as the donor for segmental long bone defects in both the upper and lower extremities.

The blood supply to the fibula is peroneal artery which initiates from the posterior tibial artery in 90% of cases, from the anterior tibial artery in 1% and from the popliteal artery in 1%. Specifically, 8% of human beings have only peroneal artery but no posterior tibial artery. The external diameter of peroneal artery is 3.7 mm (from 1.5 to 6.0 mm) on average. There are two accompanying veins with a diameter of 4.5 mm (from 1.7 to 6.7 mm).

The peroneal artery arises from the tibioperoneal trunk and is closely positioned to the fibula (about 1 cm). It goes across the posterior tibia muscle from the upper behind side, then goes along the fibula through posterior tibial muscle and long flexor muscle of feet, finally it ends at the external ankle and takes part in the ankle arterial network. There are five types of branches of peroneal artery: (1) Fibular nutrient artery. It is the first branch which starts at 14.2 cm (from 10.3 to 23.4 cm) below the fibular head. The diameter of fibular nutrient artery is 1.2 mm (from 0.4 to 2.2 mm) and the average length is 1.8 cm from the start point to the fibula nutrient artery. It divides into deep branch and descending branch after entering the fibula bone marrow cavity. More smaller branches derive from these two branches to nourish the bone. (2) Arcuate artery. There are 9 (from 4 to 5) arcuate arteries on average. Arcuate arteries start from the peroneal artery. The diameter at the start point is 1.4 mm (from 0.4 to 1.8 mm). Some are close to the periosteal surface, and others run through a short course of muscle first before they reach the fibular surface and become periosteal branches which surround the fibula from outward to forward and outward. There are rich anastomoses between each of these arcuate arteries and they form a network to nourish various muscles, bones and periosteum. (3) Muscular branches: Muscular branches can be sent out from the arcuate artery. They also can be sent to gastrocnemius muscle, soleus, hallucis longus, flexor digitorum longus and posterior tibial bone muscle directly from the peroneal artery. The amount and the diameter of the muscular branches vary. Sixteen branches can be found in hallucis longus and eight in posterior tibial bone muscle. The muscular branches send out periosteal branches to participate in the composition of periosteal vascular network. (4) Cutaneous branches and musculocutaneous branches: An average of 4–8 of these branches is sent to nourish lateral leg skin through calf muscle gap. Among them, three are relatively thick and constant (1.6 mm in diameter) underneath the fibular head. The peroneal artery can provide blood supply to lateral leg skin flap up to 30 × 15 cm. 5. Ankle anastomosis: I: Perforating branches: They start 6–7 cm away from the upper lateral malleolus, go inward through the flexor and meet with the branches of posterior tibial artery and the lateral branches of dorsalis pedis artery. There are also some (up to 8) smaller branches that reach to the front of the lower leg through interosseous membrane. II: Traffic branches: They start 6–7 cm away from the upper lateral malleolus, go inward through the flexor and meet with the branches of posterior tibial artery. The above mentioned perforating branches, traffic branches and final branches of the peroneal artery form the transportation blood network in the ankle which can be used in clinic in vascularized fibular flaps and reverse lateral leg island flaps (Fig. 11.10).

11.5.10.2 Surgical Design

1. Position and incision: Lateral position or prone position is optional. Henry surgical approach is used under epidural anesthesia. The incision begins from the fibular head, goes along 5–6 cm from the upper bear side of biceps tendon. Cut down along the lateral fibula to a needed length. The lower part of the incision curves slightly backward and outward. Normally, this incision is located between the fibula and soleus muscle gap above which is the peroneal nerve.
2. Pedicle exposure: Cut the skin and fascia of crus, separate the peroneal nerve at the lower edge of the biceps tendon and then free and protect the nerve from proximal to distal to the entrance of the peroneus longus muscle. Then, separate peroneus longus and brevis soleus muscle with blunt dissection from inferior to superior, and pull back the soleus muscle. The peroneal artery and vein can be seen going from the upper back edge of the hallux longus to the deeper part of the muscle at the beginning part.
3. Flap harvest: Separate the peroneus musculus longus and brevis that attach to the outside of the fibula with a scalpel. The proximal and distal ends of the fibula are marked and the axis of the bone is drawn taking the fibular nutrient

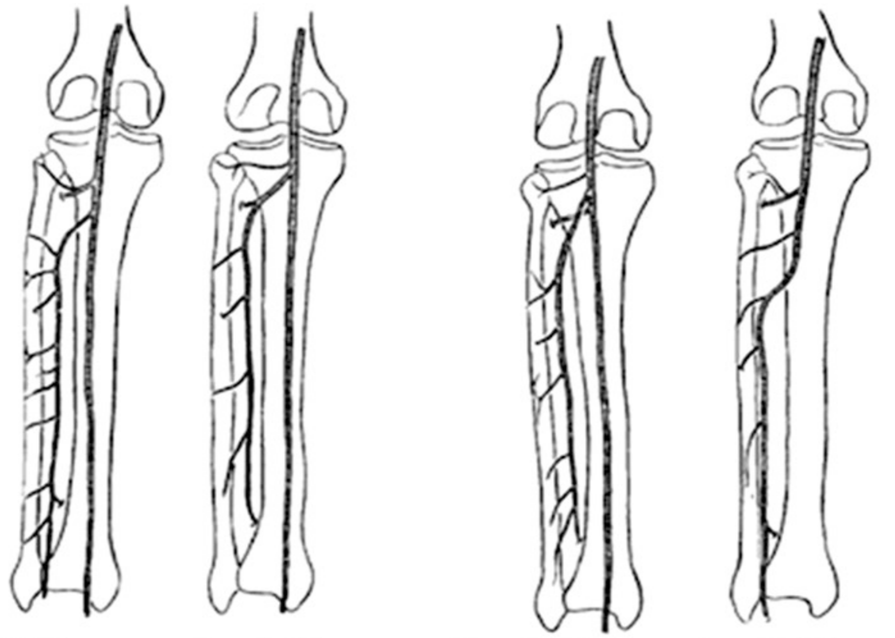


Fig. 11.10 Types of origin of the fibular artery

artery as the center. Then the osteotomy is conducted with a wire saw to harvest a needed length of fibula. If the head of the fibula is included in the osteotomy, separate the fibular head from the tibia but partially retain the soft tissue around the head so that reconstruction can be much easier when suturing the fibula flap to the receiving area. At this time, the fibula can be driven and rotated to expose the surrounding tissues. Rotate the fibula backwards along its long axis, separate the extensor and interosseous membrane in front of the fibula. It is suggested that only a thin layer of muscle can be retained (a thickness of about 2–3 mm) when cutting off the front outer side of the fibula. Rotate the fibular segment forward to clearly reveal the rear side of the tissue, cut part of the hallux longus and tibialis posterior muscle along the peroneal artery and vein, so that 0.5–1.0 cm thick muscle sleeves are reserved to contain peroneal artery and vein at the rear fibula. Cut off the distal peroneal vascular bundle firstly, and then free the upper peroneal vascular bundle after the fibula segment has been fully freed to a needed length. Thus the flap is completely harvested for further use.

4. Fibular flap graft: When the recipient site is ready, cut off the bridging segment of the fibula, fit the fibular flap into the recipient site, and suture the peroneal artery and vein to corresponding vascular vessels.

11.5.11 Related Questions

1. Surgical approach. Normally, there are two ways to harvest a vascularized fibular flap, namely, posterolateral approach and anterolateral approach. Surgeons can choose either of them according to the conditions of recipient site area and their own habits. The posterolateral approach is more often adopted for several reasons. Firstly, this approach can reveal the peroneal artery and vein and their beginning parts entering the hallux longus after separating the fibula muscles and soleus. This may avoid damaging the integrity of the blood supply to the fibula in the process of dissection. Furthermore, the posterolateral approach can be used in more surgical positions, such as supine, prone and lateral position.
2. Osteotomy level. In some surgery (using a fibular flap to repair defects at the proximal humerus or distal radius), the fibular head is usually included in the fibular flap to rebuild the function of shoulder and wrist. It is controversial whether the nutritious artery should be harvested along with the fibular head in such cases. Currently common opinion thinks that it is not necessary to reserve nutritious artery when harvesting the fibular flap which includes the fibula head and that it is best to keep both two arcuate arteries. The osteotomy level should be 12–14 cm underneath the fibular head. In some cases when the recipient site is so large that the above-mentioned method cannot repair the defect, the osteotomy level should still be 12–14 cm underneath the fibular head but more than two arcuate arteries should be harvested with the fibular flap. A fibular flap with knee lateral vascular pedicle can also be considered. The knee lateral vascular pedicle can satisfy fibular flap graft with fibular head included within 10 cm.
3. Application of the fibula folding method. After the vascularized fibula flap is harvested, cut the bone into two pieces

and then fold them up without damaging the periosteum. This method can be used in free vascularized graft or local transfer with vascular pedicle. Much stronger rigidity can be obtained due to the folded dual parallel segments. Therefore, this method can be applied to repair femoral or tibial defects.

4. Fibular flap graft with epiphysis. In 1985, Shengxiu Zhu reported successful treatment in children with long bone defects of upper extremity using fibular flap graft with epiphysis. The defects were healed successfully. After surgery, the epiphysis developed well and grew normally. Therefore, transplantation of vascularized fibular flap with epiphysis is helpful in treatment of long bone defects in children. The key to this surgery is to ensure adequate blood supply and try best to shorten the operation time.
5. A vascularized fibular flap can be used together with a hallucis longus flap to repair complex defects of bone and muscle. It can also be included in a composite tissue flap with peroneal muscle and skin. The size of the flap can be as large as 6 × 10 cm.
6. The distal 1/4 section of the fibula must be preserved, otherwise the stability of the ankle joint will be severely reduced. The inferior tibiofibular joint fusion can be performed if too much of the fibula is harvested, particularly for children.

11.5.12 Calcaneus Bone Flaps

Calcaneus bone flaps are harvested from the calcaneus bone with blood supply coming from either a vascular pedicle or a muscle pedicle. In 1992, Fahui Zhang first reported a calcaneus bone flap with lateral vascular pedicle.

Calcaneus bone flaps can be divided in to five types based on the blood supply (Fig. 11.11). (1) Extensor digitorum brevis calcaneus bone flap with blood supply from the extensor digitorum brevis muscle that attaches to the calcaneus bone. (2) Lateral ankle vascular pedicle calcaneus bone flap is an anterolateral calcaneus bone block with blood supply from the anterolateral malleolar vascular pedicle. (3) Lateral vascular pedicle calcaneus bone flap with blood supply coming from the lateral vascular pedicle. (4) Lateral tarsal vascular pedicle calcaneus bone flap with blood supply coming from the anterolateral tarsal vascular pedicle. (5) Peroneal vascular perforator and descending artery pedicle calcaneus bone flap with blood supply coming from the peroneal vascular perforator and descending artery pedicle.

Calcaneal bone flaps are often harvested from lateral calcaneal bone where the blood vascular anatomy is constant and superficial. The vascular pedicle is long enough to reach the neighboring tibiotalar joint, subtalar joint, and talonavicular joint. They can be used to repair talus fracture, talus ischemic necrosis or subtalar joint fusion. Their disadvantage is a limited bone mass.

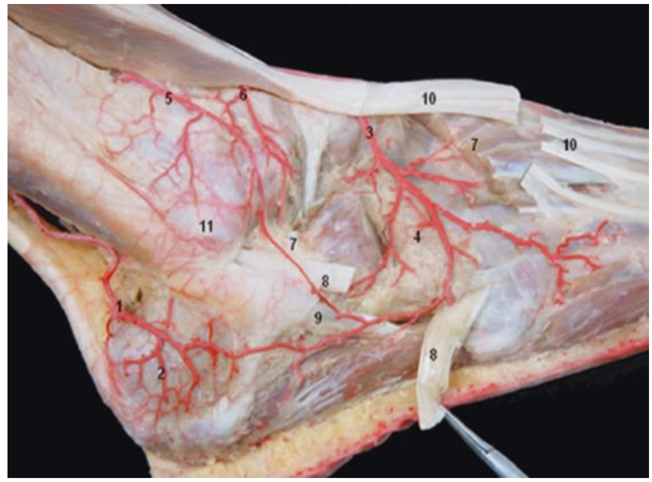


Fig. 11.11 Anatomy of the calcaneus. *1*. Lateral calcaneal artery. *2*. Calcaneal periosteal branch. *3*. Lateral tarsal artery. *4*. Cuboid bone. *5*. Descending branch of peroneal perforating artery. *6*. Anterolateral ankle artery. *7*. Extensor digitorum brevis. *8*. Peroneus brevis tendon. *9*. Peroneus longus tendon. *10*. Extensor digitorum longus. *11*. Lateral malleolus

11.5.13 Lateral Tarsal Vascular Pedicle Calcaneus Bone Flap

This is an anterolateral calcaneus bone block with blood supply coming from the anterolateral malleolar vascular pedicle. It is used locally to repair talar nonunion, ischemic necrosis of the talus and joint infusion of talus and calcaneus. Its applied anatomy was first reported by Fahui Zhang in 1992.

Applied anatomy: The lateral tarsal artery starts from 14.1 mm above the articulation talonavicularis level, issued by the lateral dorsal artery. It goes along the lateral oblique scaphoid, and deep through the extensor digitorum brevis surface close to the cuboid bone, and then reaches the bottom of the fifth metatarsal. The lateral tarsal artery issues 5–12 small arterial branches which distribute on the dorsal bone surface and penetrate the bone when crossing through the cuboid bone surface. Its outer diameter is 0.3–1.0 mm. Its branches not only nourish adjacent muscles, tarsal bones and calcaneus along the way, but also connect with lateral artery, peroneal artery perforator, anterolateral artery and arcuate artery. Besides, they also participate in the anterior dorsal arterial network. The lateral tarsal artery is the largest branch of the dorsalis pedis artery. Its outer diameter at the beginning part is about 1.9 mm. Its roots reach within the dorsal surface and the medial surface. Its stem length is about 27.1 mm. On average, it has two accompanying veins which are approximately 1.9 and 1.8 mm respectively in diameter.

Surgical Design: (1) Position and incision: Supine position and anterolateral calcaneus approach. (2) Vascular pedicle exposure: Cut the skin and superficial and deep fascia, find and protect the vascular bundle on the surface of the extensor digitorum brevis in front of peroneus brevis tendon. Pull inward the extensor tendon, lift and pull outward the peroneal muscle retractor, cut extensor digitorum brevis at the starting point and turn it over to the distal side. The vascular pedicle and blood vessels can thus be separated at the back of cuboid bone and the anterolateral calcaneus. (3) Bone flap harvest: The bone flap is located at the outside of the calcaneus. Its size is about 1.5 cm × 1.0 cm × 0.5 cm. Harvest the bone block with a chisel. (4) Bone flap graft: Dig a slot on the outside of talar neck and then embed the bone flap with vascular pedicle into the slot.

Advantages and disadvantages: The location of lateral tarsal artery is constant and superficial. Its vascular pedicle is long enough to reach the neighboring tibiotalar joint, subtalar joint, and talonavicular joint. A bone and muscle composite flap can be formed by the cuboid bone and its attached extensor digitorum brevis to repair bone and soft tissue defects at the distal and adjacent areas of distal tibia. Its disadvantage is limited bone mass.

11.5.14 Cuboid Bone Flaps

They are cuboid lamellae with blood circulation, often pedicled with lateral tarsal artery. They can be shifted locally to repair the talus neck fracture or ischemic necrosis. Fahui Zhang made an anatomical investigation in 1991 and Zhenguang Chen firstly reported the clinical application of this bone flap in 1992.

11.5.14.1 Applied Anatomy

Lateral tarsal artery is the largest branch of dorsalis pedis artery, issued from the lateral dorsalis pedis artery, about 1.4 cm above the talonavicular joint. The outside diameter of its initial part is about 1.9 mm. Its root is located between the back side and medial edge of cuboid. Its trunk is about 2.7 cm long, accompanied by two veins, the outer diameter of which is about 1.9 and 1.8 mm respectively. Lateral tarsal artery initially passes obliquely through the lateral side of scaphoid, then crosses under the extensor digitorum brevis and closely near the back side of cuboid, and arrives at the bottom of fifth metatarsal bone. About 5–12 branches, with outside diameters ranging from 0.3 to 1.0 mm, which are issued from lateral tarsal artery, spread over the dorsal surface of cuboid, and then penetrate into the bone. In addition to nourishing the adjacent muscle, tarsus and calcaneus, the branches of lateral tarsal artery also anastomose with lateral calcaneal artery, the perforating branch of peroneal artery, lateral anterior malleolar artery and arcuate artery, participating in the anterior dorsalis pedis artery network.

11.5.14.2 Operation Design

1. Position and Incision

   Place the patient in a supine position with an incision which is long enough to expose the diseased area, cuboid bone, and dorsails pedis artery.

2. Vessel pedicle exposure

   Make an incision on the skin. Pull away the extensor digitorum longus muscle. Search for the beginning of lateral tarsal artery along the lateral dorsails pedis artery at the talonavicular articulation. Cut the extensor digitorum brevis in front of the calcaneus and then turn it over to the distal. The branches of lateral tarsal artery, which distribute over the surface of cuboid bone, are thus exposed. A retrograde method can also be used to expose the vessel pedicle.

3. Bone flap preparation

   Cut the cuboid bone flap according to the recipient site after examining the border of cuboid bone. Lift the bone flap, dissect the vessel pedicle from distal to proximal until its beginning, and then ligate the anastomotic branches. The largest sectile size of this bone flap is about 2.5 cm × 1.5 cm × 1.5 cm.

4. Transposition and bone-graft

   Expose the tibiotalar joint, and subtalar joint or talar body and neck. Repair the articular facet or reduce the talar body and neck, and then make a groove to insert the cuboid bone flap. If this flap is used in supramalleolar transposition, cut and ligate the distal dorsails pedis vessels after the beginning of lateral tarsal artery. Isolate the proximal vessels and turn over the flap pedicled with anterior tibial vessels. The bone flap can be transported to the lower part of tibia to repair bone nonunion or defects.

11.5.14.3 Advantages and Disadvantages

The anatomical location of lateral tarsal artery is superficial and invariable. This pedicle can be transported to the tibiotalar joint, subtalar joint, talus and talonavicular articulation. The composite flap constituted with cuboid and the extensor digitorum brevis located on the bone surface can be used to repair the bone and soft tissue defects of distal tibia. Limited bone mass is the defect of this bone flap.

11.5.15 Foot Navicular Bone Flaps

They are lamellae taken from foot navicular bone, pedicled with blood circulation vessels. Fahui Zhang et al. firstly reported this bone flap in 1997.

According to the source of blood supply, they can be divided into three kinds. (1) Foot navicular bone flap pedicled with medial anterior malleolus vessel. (2) Foot navicular bone flap pedicled with medial tarsal vessel. (3) Foot navicular bone flap pedicled with the top branch of medial plantar artery (Fig. 11.12).

11.5.15.1 Advantages and Disadvantages

The anatomical location of the vessels in a foot navicular bone flap is superficial and invariable. The operation is simple. This bone flap can be transported to repair the talus neck fracture or ischemic necrosis. Limited bone mass is the defect of this bone flap.

11.5.15.2 Cuneiform Bone Flaps

They are lamellae taken from cuneiform bone, pedicled with blood circulation vessels. Fahui Zhang et al. made an ana-

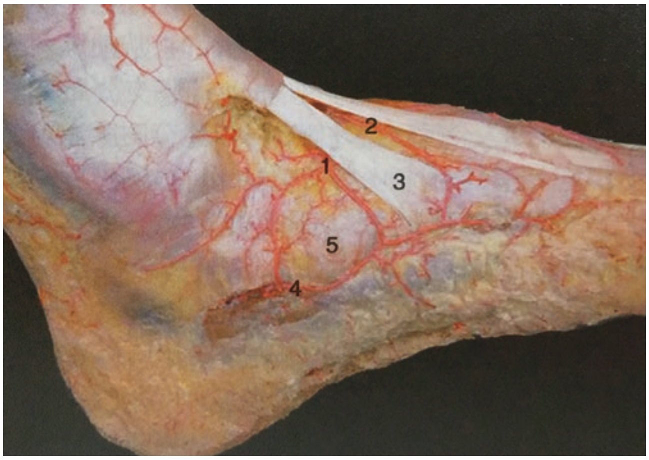


Fig. 11.12 *1.* Anterior medial malleolar artery. *2.* Medial tarsal artery. *3.* Tibial anterior tendon. *4.* Superficial branch of medial plantar artery. *5.* Tuberosity of scaphoid

tomical investigation of the medial cuneiform bone flap in 1992.

According to the source of blood supply, they can be divided into two kinds. (1) Cuneiform bone flap pedicled with medial anterior malleolus vessel. (2) Cuneiform bone flap pedicled with medial tarsal vessel.

Cuneiform bone flaps are taken from the medial cuneiform bone. The anatomical location of blood supply is reliable and invariable. This bone flap can be transported to repair talus neck fracture or ischemic necrosis. Limited bone mass is the defect of this bone flap.

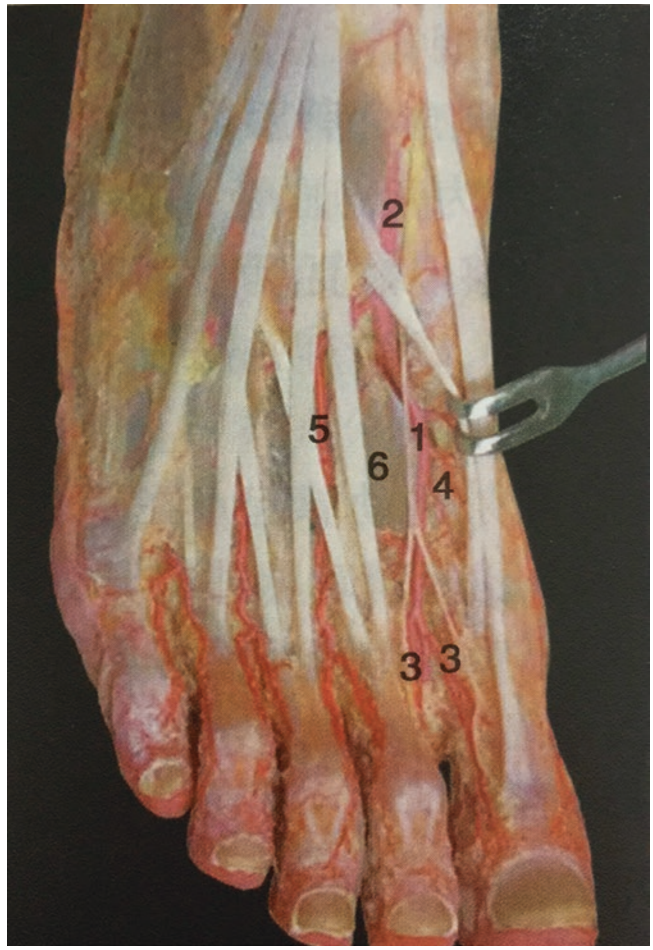


Fig. 11.13 *1.* The first dorsal metatarsal artery. *2.* Dorsal pedal artery. *3.* Dorsal phalangeal artery. *4.* Periosteal branch. *5.* Second dorsal metatarsal artery. *6.* Dorsal interosseous muscle

11.5.16 Metatarsal Bone Flaps

They are metatarsal bone blocks with blood circulation, often pedicled with dorsal metatarsal artery. They can be divided into three kinds: (1) First metatarsal bone flap pedicled with first dorsal metatarsal artery. (2) Second metatarsal bone flap pedicled with first dorsal metatarsal artery. (3) Second metatarsal bone flap pedicled with second dorsal metatarsal artery. They can be locally transported to repair the avascular necrosis of second metatarsal head. Zhen-guang Chen et al. reported their clinical application in 1994.

11.5.16.1 Applied Anatomy

About 2.6 periosteal branches are issued from the first dorsal metatarsal artery in the first interosseous metatarsal space, distributing on the medial and lateral surface of the first and second metatarsus (Fig. 11.3). The first dorsal metatarsal artery divides into two arteriae digitales dorsales at 1.59 cm from the first toe web and sends several anastomotic branches to the first plantar metatarsal artery. The outside diameter of the first dorsal metatarsal artery is about 1.6 mm, and its distal outer diameter is 1.2 mm. The trunk is about 4.5 cm long, accompanied by one or two veins. The depth of the first dorsal metatarsal artery is irregular in the first interosseous metatarsal space. About 2.4 periosteal branches are issued from the second dorsal metatarsal artery in the second interosseous metatarsal space, distributing on the medial and lateral surface of the second and third metatarsus. The second dorsal metatarsal artery divides into two arteriae digitales dorsales at 1.6 cm from the second toe web and sends several anastomotic branches to the second plantar metatarsal artery. The outside diameter of the second dorsal metatarsal artery is about 1.6 mm, and its distal outer diameter is 1.2 mm. Its trunk is about 4.9 cm long, accompanied by one or two veins.

11.5.16.2 Operation Design

1. Position and Incision

   Place the patient in a supine position. Make one "S" type of incision from the second tarsometatarsal joint to the second metatarsophalangeal joint alongside the second metatarsus. This incision is long enough to expose the first interosseous metatarsal space and the head of second metatarsus.

2. Vessel Pedicle Exposure

   Make the incision on the skin. Pull away the anterior tibial muscle and extensor digitorum longus muscle to expose the dorsalis pedis artery and branches. Search for the first dorsal metatarsal artery. If the anatomy of the first dorsal metatarsal artery is of type I, choose it as the pedicle. If the anatomy is of type II or III, choose the second plantar metatarsal artery as the pedicle.

3. Bone flap preparation

   The sectile size of this bone flap is about 1.0 cm × 0.5 cm × 0.5 cm. The size of periosteum should be larger than the bone for easy suture.

4. Transposition and bone-graft

   Clear the cavity of the second metatarsophalangeal joint. Remove osteophyma and polish the head of metatarsus. Make a 0.5 cm-deep groove at the greater tubercle of the second metatarsus head, and then clear the lesions. The size of groove should be suitable for the bone flap.

11.5.16.3 Advantages and Disadvantages

This bone flap is mainly used to repair the ischemic necrosis of the second metatarsus head. The vascularized bone flap inserted in the groove brings blood supply and osteogenic factors to the diseased head. This bone flap can also be used to repair extramalleolus bone defects. Simple operation and limited invasion are advantages of this bone flap. Limited bone mass is the defect of this bone flap.

11.6 Transplantation of Periosteal Flaps with Vascular Pedicle

In 1978, Finley first reported an experimental study on vascularized periosteal flap transplantation, indicating that periosteum with blood supply can differentiate into bone tissue. Subsequently many domestic scholars carried out relevant basic researches and clinical trials. They thought a periosteal flap with vascular pedicle could become bone or cartilage under certain conditions.

They can be divided into three sorts according to their blood supply sources for the periosteal flap: (1) Muscle pedicle periosteal flaps: The periosteal tissue is supplied by blood circulatory system of the muscle attached to the periosteum. (2) Fascia pedicle periosteum flaps: The periosteal tissue is supplied by blood circulatory system of the fascia attached to the periosteum. (3) Vascularized periosteal flaps: The blood supply to the periosteal flap comes from the vascular pedicle.

Periosteum is a layer of connective tissue membrane, which can be divided into outer periosteum and inner periosteum. Outer periosteum can be histologically divided into two layers: the outer fibrous layer and the generating layer on the deep surface. Germinal cells are undifferentiated mesenchymal cells with differentiation potential for life. They have bidirectional differentiation ability, which means they can differentiate into bone cells or cartilage cells. Differentiation of different evolution for mesenchymal cells depends on two factors: (1) Local blood supply factors: If local blood supply is good and oxygen partial pressure is high, the mesenchymal cells differentiate into bone cells and thus the periosteum changes into bone; if local blood supply is poor and oxygen partial pressure is low or the synovial fluid environment presents, mesenchymal cells differentiate into chondrocytes and thus the periosteum changes into cartilage. (2) Local stress factors: Under conditions of high local stress, mesenchymal cells differentiate into chondrocytes, whereas they differentiate into osteoblasts. The fibrous layer, which consists of fibroblasts and collagen fibers, leads to no osteogenesis, but can prevent bone tissue from growing into soft tissue around it.

Periosteal osteogenesis is related not only to the blood supply, but also to the contact with the normal bone in the graft bed. Moreover, the contact between bone and periosteal germinal layer affect the speed and extent (degree) of periosteal osteogenesis. Functional osteogenesis in periosteal transplantation is closely related to the stress it is subjected to. The periosteum with blood supply implanted into muscles displays better osteogenesis than that implanted into fascia or subcutaneously. Direct contact with bone may lead to even better osteogenesis. The periosteum transplanted on the surface of cancellous bone displays stronger osteogenesis than that on the cortical bone surface. The speed and extent of osteogenesis of the transplanted periosteum with blood supply in a state of distraction are significantly greater than those in the collapse status. When periosteum is harvested, sharp dissection should be applied to protect the integrity of the germinal layer of the periosteum and to facilitate bone growth. However, since the outer fibrous layer and the periosteal bone are closely linked by penetrating fibers, sharp dissection of the periosteum is technically difficult. Therefore, sometimes in clinic, periosteal and bone grafts are conducted using the periosteum with a thin layer of squamous subperiosteal bone. The osteogenic effect of such periosteal bone grafts is inferior to that of a simple periosteal flap.

Harvest of donor periosteum does no damage to the original bone skeleton. After resection of massive periosteum or injury to nutrient artery, no bone necrosis will happen because the blood supply can be compensated by metaphyseal vascular system and residual periosteum. New bone may grow reactively, because the regenerative capacity of periosteum is strong and the regenerated periosteum also has osteogenesis.

Due to the limited availability of donor sites, periosteal flaps with a main vessel as the vascular pedicle used to be applied in clinic, such as the anterior tibial vascular pedicle tibial periosteal flap for the treatment of tibial nonunion and small bone defects. With the developments in microsurgery and applied anatomy, many new donor sites for periosteal flap have been available. Almost all the different parts of limbs are available donor sites for periosteal flaps. Since there is no vascular anastomosis, the surgical procedure is greatly simplified. And since a non-trunk vessel can be used as the vascular pedicle to replace a main vessel, the blood supply to a limb is much less affected. In general, a vascular pedicle that can provide blood supply to a bone flap can also provide blood supply to a periosteal flap. When the periosteal tissue with circulatory system is harvested, including muscle pedicle periosteal flap, fascial pedicle periosteal and vascular pedicle periosteal flap, some of the subperiosteal bone tissue can also harvested to form a periosteal bone flap which is mainly used to repair old fracture, osteonecrosis, nonunion or small bone defects.

11.6.1 Humeral Periosteal Flaps

They are periosteal tissue with blood circulation taken from the periosteum of the humerus. Their blood supply can come from the fascia or blood vessels. They can be used in grafting by local transfer or free transplantation.

According to the blood supply, they can be divided into the following categories (Fig. 11.14): (1) Fascia humeral periosteal flap, the humerus periosteal tissue with blood supply from the fascia attached to the humerus. (2) Humeral periosteal flap pedicled on humeral anterior circumflex, the upper humeral periosteal tissue with blood supply from the lateral descending branch of brachial anterior arteriovenous pedicle. (3) Humeral periosteal flap pedicled on humeral posterior circumflex, the upper humeral periosteal tissue with blood supply from the brachial posterior arteriovenous pedicle. (4) Humeral periosteal flap pedicled on deep brachial vessel, the humeral periosteal tissue with blood supply from the brachial deep arteriovenous pedicle. (5) Humeral periosteal flap pedicled on radial collateral vessel, the lower humeral periosteal tissue with blood supply from the radial collateral arteriovenous pedicle. (6) Humeral periosteal flap pedicled on radial recurrent vessel, the lower humeral periosteal tissue with blood supply from the radial recurrent arteriovenous pedicle. (7) Humeral periosteal flap pedicled on ulnar inferior

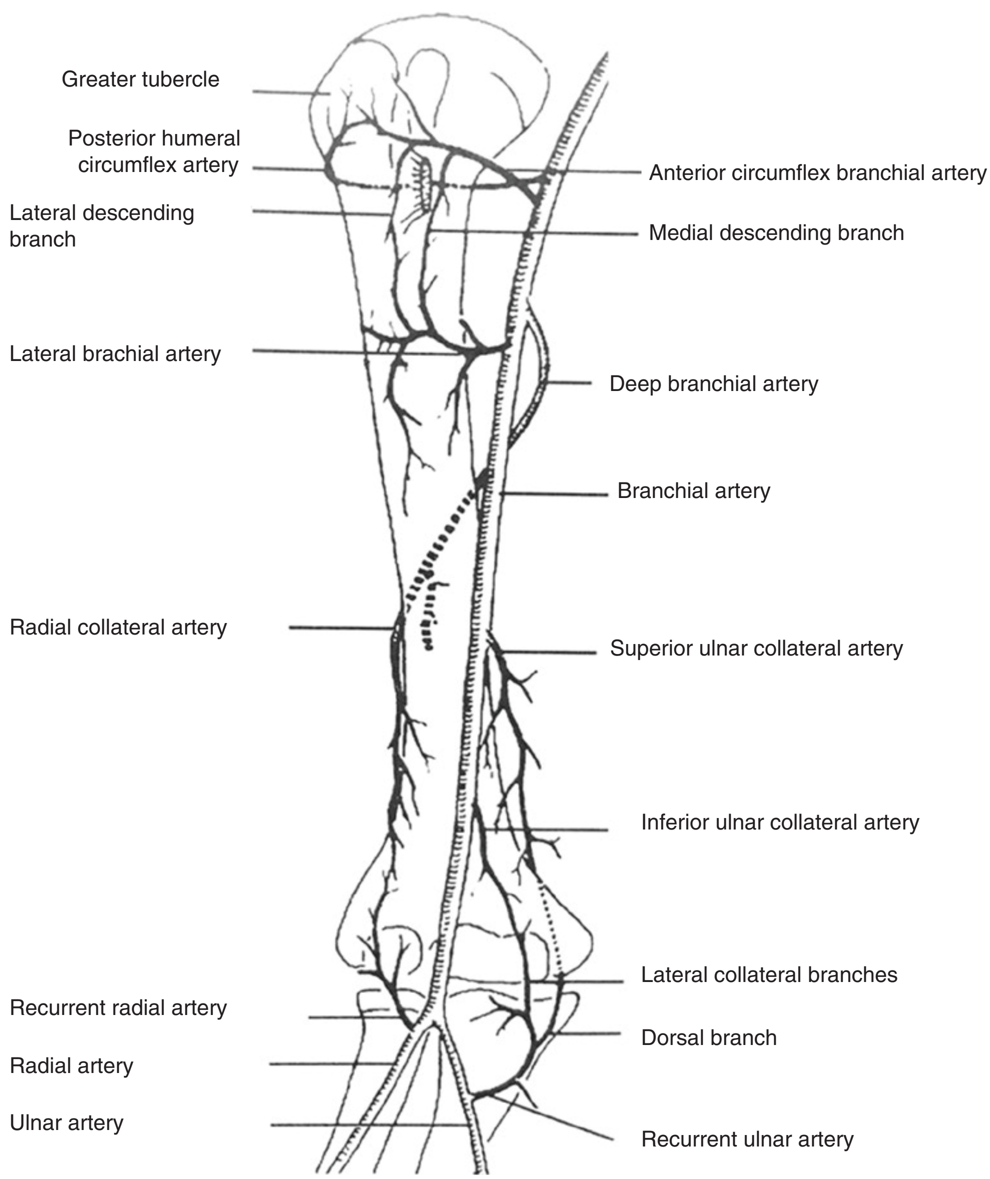


Fig. 11.14 Blood supply source of periosteal flap

collateral vessel, the periosteal tissue of inferior-medial humerus with blood supply from the ulnar inferior collateral arteriovenous pedicle. (8) Humeral periosteal flap pedicled on ulnar recurrent vessel, the periosteal tissue of inferior-medial humerus with blood supply from the ulnar recurrent arteriovenous pedicle. (9) Humeral periosteal flap pedicled on ulnar superior collateral vessel, the periosteal tissue of inferior-medial humerus with blood supply from the ulnar superior collateral arteriovenous pedicle. The upper, middle and lower segments of humerus can be used as the donor sites for humeral periosteal flaps.

As the humerus is a single tubular bone of the upper arm, fracture and other complications may happen after a bone flap is harvested from it. So it is used only as a donor site for a periosteal flap, but some of the subperiosteal bone tissue can be resected in the harvest of a periosteal flap to form a periosteal bone flap. Since the middle and the upper sections of the humerus have many muscle attachment points, the area for harvest of a periosteal flap is limited. Moreover, defects and nonunion on the upper humerus are not common. Therefore, it is not conventional to take the middle and the upper sections of the humerus as a donor site for periosteal flaps. Since defects and nonunion on the middle and lower sections of humerus are common, lower humerus, especially the lateral condyle, may be available for donor sites for periosteal flaps with a vascular pedicle. A vascularized periosteal flap or periosteal bone flap is often harvested from the distal humerus to repair nonunion or a small bone defect on the middle and lower sections of the humerus. The surgery is simple, the vascular pedicle is constant, the blood supply is reliable, providing a good bed for the radial nerves. The humeral periosteal flaps pedicled on radial collateral vessel are mostly used in clinic.

11.6.2 Humeral Periosteal Flaps Pedicled on Radial Collateral Vessel

They are the lower humeral periosteal tissue with blood supply from the radial collateral arteriovenous pedicle. They are commonly used in local transposition to repair nonunion or a small bone defect on the middle and lower segments of the humerus. They are also used for comminuted fractures of the middle humeral complicated with muscle encroachment or radial nerve injury (open reduction required). In 1995 Zhen-Guang Chen, Yu Aixi et al. conducted anatomical studies and clinical trials on them.

Applied anatomy: The radial collateral artery is the continuation of the deep branch of the brachial artery after separation from the collateral artery. The branch point is in the vicinity of the deltoid tuberosity. The distance from the epicondyle of the humerus is about 12 cm. The outer diameter at the starting point is about 1.6 mm. It declines along the radial nerve ditch, travels on the outside of the radial nerve and divides into the palm branch and the dorsal branch

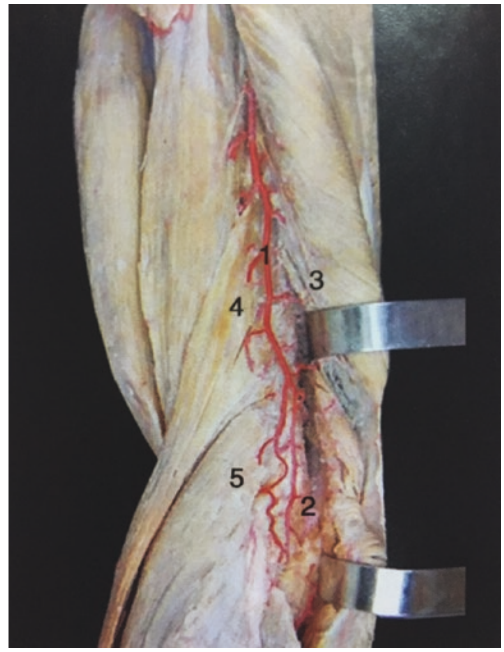


Fig. 11.15 Branch and distribution of radial collateral artery. *1*. Radial collateral artery. *2*. Musculo periosteal branches. *3*. Triceps brachii muscle. *4*. Brachioradialis. *5*. Extensor carpi radialis longus

above the starting point of brachioradialis. The distance from the branch point to the outside epicondyle is 9 cm. The trunk of radial collateral artery is about 35 mm long. The palm collateral walks through the lateral septum, accompanied by the radial nerve, and reaches the front of the elbow after crossing between brachial muscle and brachioradialis. The dorsal branch is in the back of the lateral septum, going vertically downward close to the lateral epicondyle. The outer diameter of its starting point is about 1.2 mm. The dorsal branch of radial collateral artery issues muscle periosteal branches and periosteal branches, distributing along the epicondyle crest and periosteum in adjacent areas. The range of its nutritional periosteum is: the upper boundary is 15 mm above the starting point of brachioradialis; the lower boundary is the humeral epicondyle; the front and rear boundaries exceed the midlines of the front and rear humerus (Fig. 11.15).

Surgical design: (1) Position and incision: the patient is placed in a supine position, with the elbow flexed on the chest or on the bedside surgery table. The incision starts at the insertion of deltoid muscle, and extends along the lateral septum downwards to the lateral epicondyle, and then anterior-inferiorly for 2–3 cm. The upper end of incision can be appropriately extended along the leading edge or trailing edge of the deltoid according to the lesion site and the condition of the radial nerve, etc. (2) Pedicle exposure: Cut the skin and subcutaneous deep fascia, separate the brachialis from the brachial triceps muscle and brachioradialis muscle. The dorsal branch and periosteal branch of the radial collateral artery can be seen behind the lateral brachial intermuscular septum. Usually reveal and protect the radial nerve first, and then reveal the vascular pedicle. (3) Bone (periosteal) flap harvest: Harvest the periosteal flap or together with a thin layer of bone tissue according to the needs of recipient site. The range of periosteal flap is 7–8 cm × 4–5 cm. After the periosteal (bone) flap is elevated, separate its vascular pedicle along with part of the trunk along the dorsal branch of the lateral septum, extending to the radial collateral artery. Its palm collateral is ligated. The separation can also be extended to the deep brachial artery according to surgical needs. (4) Bone (periosteal) flap transplantation: After the lesions are cleared and the internal fixation is completed, the periosteal flap is transplanted to the fracture end and then fixed to the adjacent tissue with a number of stitches. The periosteal flap should be transpositioned in the deep surface of the radial nerve, covering the fracture end with the germinal layer. The muscle surface of the periosteal flap is the bed for the reconstructed radial nerve, thus avoiding direct contact between the radial nerve and the steel plate.

Since the radial collateral vessels are not main trunks, their location is superficial and constant and they are easy to dissect and separate, they are commonly applied in clinic in recent years. In addition, since the dorsal branch of radial collateral vessel still has a cutaneous branch to supply the lateral skin under the arm, a composite tissue flap with periosteum and skin can be designed. The disadvantage is that the area of a periosteal flap is limited.

11.6.3 Tibial Periosteal Flaps

They are the periosteal tissue taken from the tibial periosteum with blood circulation from a vascular or muscle pedicle. They can be locally transferred or transplanted freely.

According to the blood supply, they can be divided into the following categories: (1) Tibial periosteal flap with saphenous vascular pedicle, the medial tibial periosteal tissue with saphenous vessels as the nutritious vascular pedicle. (2) Tibial periosteal flap with knee medial pedicle, the medial tibial periosteal tissue with knee medial vessels as the nutritious vascular pedicle. (3) Tibial periosteal flap pedicled with posterior tibial intermuscular branch, the medial tibial periosteal tissue with the posterior tibial intermuscular branch as the nutritious vascular pedicle. (4) Tibial periosteal flap pedicled with anterior tibial periosteum branch, the lateral tibial periosteum tissue with anterior tibial periosteal muscle branch as the nutritious vascular pedicle. (5) Tibial periosteal flap pedicled on anterior tibial recurrent periosteum branch, the lateral tibial periosteum tissue which uses tibial recurrent periosteal branch as the nutrient vascular pedicle. (6) Tibial periosteal flap pedicled on superficial peroneal vessels, the distal tibial periosteum tissue with superficial peroneal vessels as the nutrient vascular pedicle. (7) Tibiofibular periosteal flap pedicled on peroneal vessels, the distal periosteal tissue of the tibia and fibula with peroneal vessels as the nutritious vascular pedicle. (8) Tibial periosteal flap pedicled on soleus muscle, the tibial periosteal blocks with the soleus muscle bundle attached to the tibia as the blood circulatory system. The following donor sites are available for tibial periosteal flaps: the medial surface of the upper tibia, the medial and lateral surfaces of the tibial shaft, and the distal tibia (Fig. 11.16).

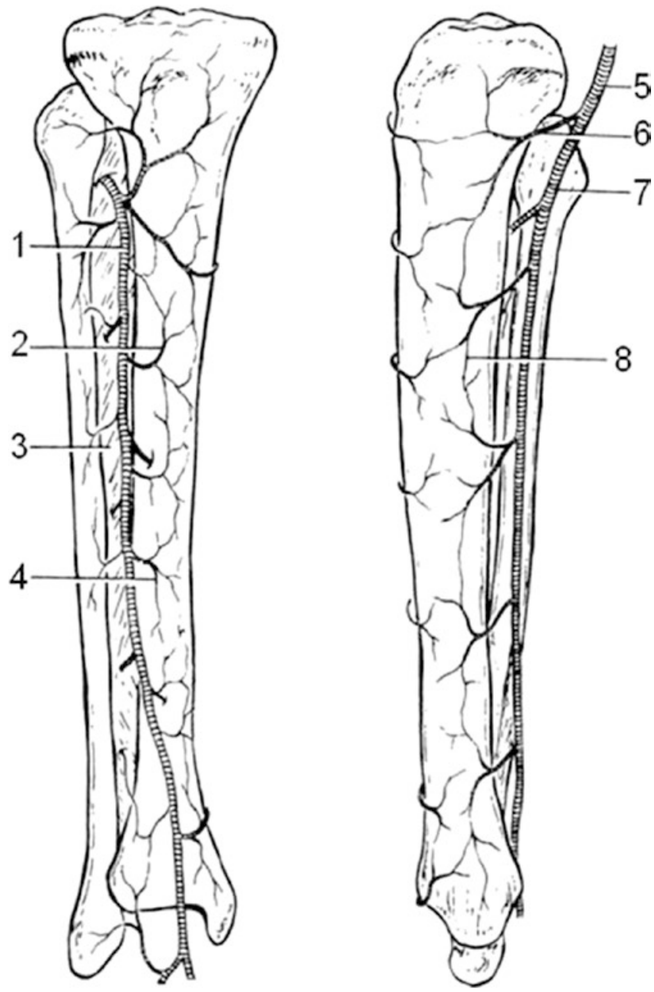


Fig. 11.16 Blood supply source of tibial periosteal flap. *1*. Arteriae tibialis anterior. *2–4*. Arteriae tibialis anterior. *5*. Posterior tibial artery. *6–8*. Branch of posterior tibial artery

Since the tibia is the main load-bearing bone of the lower limb, harvest of a bone flap from this donor site may cause bone fracture or other complications. So it is often used as the donor site for a periosteal flap, but we can also carry part of the subperiosteal bone tissue to form a periosteal bone flap while harvesting a periosteal flap. Tibial periosteal flaps are easy to harvest, and have adequate blood supply. The periosteum is thick and larger. They can be shifted locally to repair nonunion near the tibia or small bone defects, and can be transferred freely. They can also be included in a composite flap with muscle, bone and periosteum to repair nearby composite tissue defects. The tibia is not the main donor site for bone flaps.

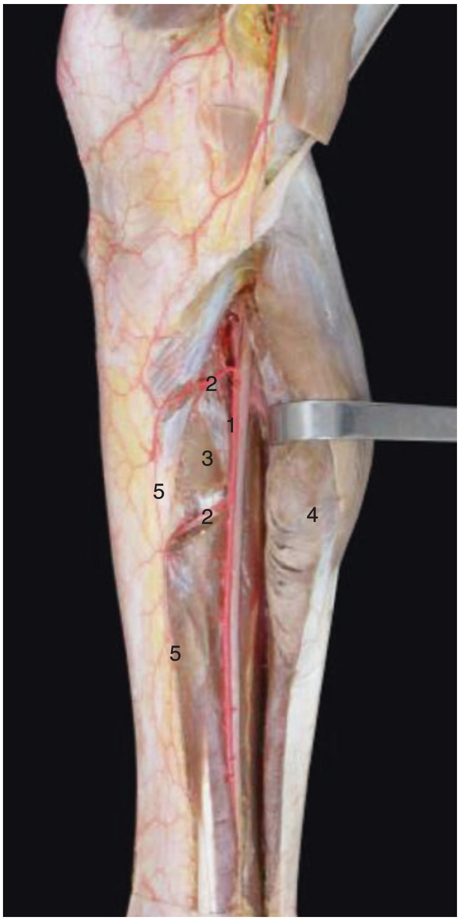


Fig. 11.17 Branches and distribution of posterior tibial intermuscular branch. *1*. Posterior tibial artery. *2*. Intermuscular branch. *3*. Flexor digitorum longus muscle. *4*. Soleus muscle. *5*. Vascular chain

11.6.4 Tibial Periosteal Flaps Pedicled with Posterior Tibial Intermuscular Branch

They are the periosteal tissue of medial tibia with posterior tibial intermuscular branch as the nutritious vascular pedicle, usually transferred locally to repair tibial nonunion.

Applied anatomy: There are 2–7 posterior tibial intermuscular branches on the medial surface of the tibia between the tibial tuberosity and the medial condyle. They are from the posterior tibial artery, go through the gap between the soleus muscle and the flexor digitorum longus, give off descending and ascending branches at the medial edge of the tibia, and issue branches distributing in the inner side of the tibial periosteal bone, forming an arterial network. After the cutaneous branch trunk goes through the deep fascia, it divides into anterior and posterior branches to nourish the medial calf skin. The cutaneous branch trunk and the issue point of direct periosteal branch are separated only by the deep fascia, almost at the same plane. The outer diameter at its starting point is 1.2 mm. There are two accompanying veins (Fig. 11.17).

Surgical Design: (1) Position and incision: Supine position, and lower limb at external rotation. A longitudinal incision is made in accordance with the lesion located at the medial tibial edge. Cut the skin and subcutaneous tissue till the superficial deep fascia. (2) Pedicle exposure: In the medial tibial edge, the cutaneous branches of tibial artery after piercing the deep fascia are visible. The direct periosteal branch and its branches from the posterior tibial intermuscular branch can be found at the issue point of the cutaneous branch through the deep fascia. (3) Periosteal flap harvest: It should be determined whether the periosteum to be harvested at the proximal or distal end of the nonunion according to the nonunion site and the location of dominant periosteal branch. A deep fascia periosteal pedicle of about 2 cm in width should be preserved to protect the periosteal branch. The available area of periosteal flap can be 6–8 cm × 3–4 cm. (4) Periosteal flap transposition: After the entire lesion is debrided and fixated, the flap is rotated to cover the lesion, and sutured with the adjacent soft tissue.

Advantages and disadvantages: The medial tibial periosteal flap pedicled with posterior tibial intermuscular branch is especially suitable for the patients who have poor soft tissue conditions at the anterolateral tibia and need surgery through medial incision and harvest of a periosteal flap.

11.6.5 Tibial Periosteal Flap Pedicled with Knee Inferior-Medial Vessels

They are the medial tibial periosteal tissue pedicled with knee inferior-medial vessels. They can be transferred locally to repair tibial nonunion.

Applied anatomy: The knee inferior-medial artery constantly starts from the popliteal artery, about 5.8 cm above the top of the tibial tuberosity. The outer diameter at the starting point is about 1.7 mm. After its trunk goes through the inside edge of the medial tibial condyle and the muscle fascia to the front side, it divides into articular and fascia periosteum branches. The articular branches anastomose with the articular branches of anterior tibial recurrent artery and the anterior saphenous artery. The fascia periosteum branches turns forward to the side of the tibia, and goes out between the medial head of the gastrocnemius and the tibia, and divides at the inside of the shin bone into a ascending branch, a descending branch and a horizontal branch (Fig. 11.18).

Surgical Design: (1) Position and incision: Supine position, and an incision via the knee inferior-medial approach, which can be extended downwards appropriately. (2) Pedicle exposure: A longitudinal incision is made to cut the skin and deep fascia. The sartorius muscle and the medial vastus muscle are dissected bluntly. Dissect the medial patellar support ligament to expose the knee inferior-medial vessels and their tibial periosteal branches. (3) Periosteal flap harvest: Expose the periosteum of the medial tibia, and elevate the periosteal flap at about 12 cm below the upper end of tibia from the distal to the proximal. A certain size of periosteal flap is harvested according to the affected area and transferred to the recipient site. (4) Flap transplantation: After the lesion area has been fully prepared, the periosteal flap is transferred and embedded into the recipient site.

Advantages and disadvantages: The surgical approach is commonly used in knee surgery, through which a periosteal flap can be harvested and the vascular pedicle can be revealed. The surgical approach which involves no major blood vessels or nerves leads to a simple operation and limited invasion. The donor site area can be properly adjusted according to the periosteal flap needed.

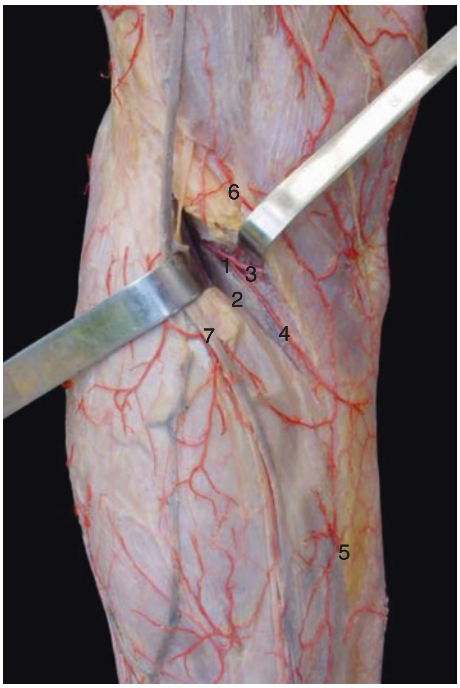


Fig. 11.18 The course, branches and distribution of the knee inferior-medial artery. *1*. Knee inferior-medial artery. *2*. Popliteal muscle. *3*. Articular branch. *4*. Osteofascial cutaneous branch. *5*. Posterior tibial intermuscular branch. *6*. Arteria saphena. *7*. Great saphenous vein

11.7 Healing Process of Vascularized Bone Grafts

Vascularized bone graft is different from traditional bone graft. Because the blood supply vessels of a vascularized bone graft are anastomosed, the bone graft transplanted still has blood supply which maintains its vitality, unlike a traditional bone graft that has become sequestrum. Therefore, there is no “creeping substitution” or “synchronous replacement” process. Because a vascularized bone graft is still alive, it is also known as a living bone graft. Its healing process is basically the same as the fracture healing process. Its bone is morphogenetically normal. As in the process of fracture healing, various osteogenetic cells appear early, and subsequently callus and new bone form between the graft and the host bone bed, finally leading to bony connection. Vascularized bone grafts heal faster and better than traditional bone grafts.

Although a vascularized bone graft has the advantage of faster bone healing, the surgery which requires vascular anastomosis is complicated, time-consuming, and technically demanding, and often needs another incision to harvest the bone flap. Therefore, many surgeons currently implement local transfer of bone grafts with vascular pedicle which keeps the advantages of living bone graft but is much simpler in surgical procedure, leading to the same bone healing process as the vascularized bone graft. The most striking feature of vascularized bone graft is that the vascularization of the graft is completed immediately after the surgery has been done, because the graft has its inherent blood supply system and thus graft is vital. A vascularized bone graft has strong healing ability, the fresh autologous bone graft results in no rejection, and new bone forms quickly to heal the lesion. Histological observation shows that the healing process and mechanism of a vascularized bone graft are consistent with repair of ordinary bipolar fracture of autologous bone. In the process of bone graft, revascularization, bone regeneration, bone union are three closely related phases. Revascularization is the initial and the most basic phase which plays a decisive role in the methods and effects of bone regeneration and bone union. The main biological evolution of bone healing includes the following five stages: (1) early stage, (2) granulation tissue formation stage, (3) callus formation stage, (4) lamellar bone callus formation stage, and (5) reconstruction and remodeling stage.

11.8 Factors Affecting Bone Graft Healing

11.8.1 Systemic Factors

1. Patient age. Various tissues grow actively in childhood and bone graft is easier to heal while in adults bone growth is relatively slow.
2. General condition of the patient. Nutritional status of the patient and presence or absence of a systemic disease will significantly affect the bone healing process.

11.8.2 Local Factors

1. Bone blood supply. In vascularized bone graft, the quality of vascular anastomosis is directly related to the flap blood supply. Since the bone graft is not directly exposed after surgery, it is difficult to determine in a short time whether the vascularization is potent or not by pathophysiological observations. Some mistakenly believe that even if the vascular anastomosis fail the vascularized bone graft can still serve as a traditional free bone graft. But Bergger thinks after failure of vascularized bone graft, ischemic necrosis of soft tissue plays a role of fence to prevent growth of new blood vessels and formation of external callus, thus preventing “creeping substitution.” Therefore, an unsuccessful vascularized bone graft is not as effective as a traditional bone graft. In transposition of a flap with vascular pedicle, if the pedicle

is subjected to tension, twisting or oppression, the blood supply of bone graft may be affected, impairing the heal process.

2. Postoperative fixation. Bone allograft fixation includes internal fixation, external fixation and extraskeletal fixation. Kirschner wires, screws or external fixators can be selected according to specific cases. The principle of fixation is that an appropriate fixation should lead to no new damage, not interfere with the blood supply of bone flap, and not affect fracture healing. Priority should be given to limited internal fixation, such as Kirschner wires, screws combined with external fixation and locking plate. Rigid fixation for 6–8 weeks postoperation is particularly important, because the healing time for living bone graft is generally 6–8 weeks. When callus grows to a certain extent, it is important to apply proper stress stimulation which is beneficial to the functional bone growth. The time for external fixation varies with specific sites of the body. For instance, in repair of long tibial defects with fibular graft, partial weight-bearing walking is indicated only under the protection of an external fixator or brace even 2–3 months after bone healing. Walking without external plaster or brace is feasible at about 2 years after surgery when the fibula grow thick enough, close to the normal size of tibia.
3. Effect of infection on bone graft. Infection is an important factor in the healing of bone graft. Although a living bone graft has rich blood supply and strong resistance to infection, severe local inflammation will affect vascular pedicle, ultimately impairing of the outcomes of living bone graft.
4. Other factors. Other factors affecting a living bone graft include blood supply to soft tissue bed, flap ischemia time, air exposure time of the flap, and physical factors like current stimulation. They all have important influence on the survival of bone flap.

11.9 Observation of Blood Supply to Bone Graft

Vascularized bone graft emphasizes high quality vascular anastomosis which is free of tension, distortion or oppression on the vascular pedicle. Intraoperative dynamic observation: marrow and muscle cuff bleeding should be observed when the bone flap is harvested and the pedicle is not cut off; bleeding and blood oozing from muscle sleeves should be observed after the bone is harvested and after bone is fixated and vessels are anastomosed at the recipient site. In cases of osteocutaneous flap with a small piece of skin, the blood supply of bone flap can be determined by observing the blood circulation of the skin flap.

Postoperatively the blood circulation of anastomotic blood vessels can be detected by high-resolution Doppler. In addition, more than 3 weeks after surgery angiography is feasible to observe anastomotic situation. In repair of bone defects at some important parts of the body, in order to accurately and directly observe graft survival, a small piece of skin carried on the flap surface can be used as "a monitoring skin island" to judge whether the bone graft survives or not.

Bibliography

1. Taylor IG, Miller GDH, Ham FJ. The free vascularized bone graft. Plast Reconstr Surg. 1975;55(5):533–44.
2. Taylor GI. Tissue defects in the limbs: replacement with free vascularized tissue transfers. Aust N Z J Surg. 1977;47(3):276–84.
3. Chen ZW. New method of treatment of congenital pseudarthrosis of the tibia—the preliminary report 12 cases of fibular graft. J Surg. 1979;17:147.
4. Chen ZG. Retrospect and prospect of bone graft. Chin J Microsurg. 2002;23:15–6.
5. Wu YM, Ding XZ. Relationship between 100 cases of peroneal artery and fibula blood supply. Anat Newspaper. 1981;12(1):20–7.
6. Chen YL, et al. Fibula blood supply (anatomical study of free vascularized fibular graft). Anat Newspaper. 198l;12:13–9.
7. Guo F. Study of fibula blood supply. Chin J Surg. 1978;16:347.
8. Tan S, Yu GR, Chen ZG, et al. Applied anatomy sural neurovascular island flap. Chin J Clin Anatomy. 2000;18(2):130.
9. Chen ZW, Ron C, Zhang GJ, et al. Treatment of tibial defect with fibula bone flap pedicled transposition. Chin J Surg. 1988;26:32.
10. Chen ZW, et al. The study and clinical application of the osteocutaneous flap of fibula. J Microsurg. 1983;11(4):11.
11. Zhang FH, Chen ZG, Xu CD, et al. Applied anatomy of transposition of calcaneus bone flap with vascular pedicle flap to treat talus fracture repair. Chin J Clin Anatomy. 1992;4:244–7.
12. Macewen WI. Intrahuman bone grafting and reimplantation of bone. Ann Surg. 1909;50(6):959–68.
13. de Boer HH. The history of bone grafts. Clin Orthop Relat Res. 1988;226:292–8.
14. Davis RF, Jones LC, Hungerford DS. The effect of sympathectomy on blood flow in bone. J Bone Joint Surg Am. 1987;69:1384.
15. Taylor GI, Muller GDH, Ham FJ. The free vascularized bone graft. A clinical extension of microvasur techniques. Plast Reconstr Surg. 1975;55:553.
16. Huang GK, Liu ZZ, Shen YL, et al. Microvascular free transfer of iliac bone based on the deep circumflex iliac vessels. J Microsurg. 1980;2:113–20.
17. Zhu SX. Modern microsurgery. Hunan: Hunan Science and Technology Press; 1994. p. 392–400.
18. Fan YE. Free vascularized iliac bone graft raised on the superior gluteal artery and vein. J Jiamusi Med Coll. 1980;1:6.
19. Chen ZG, Xu DC, Zhong SZ, et al. The iliac bone graft pedicled with ascending branch of lateral femoral circumflex vessel. Chin J Exp Surg. 1985;2:54–6.
20. Yang LM, Guo JH, Shi WY, et al. The anatomical study and clinical application of the parascapular flap. Med J Chin People's Liberation Army. 1983;8:326–8.
21. Yang LM, et al. Free vascularized scapular osteocutaneous flap grafts. Med J Chin Peoples Liberation Army. 1983;8:253.
22. Xu DC, Chen ZG, Zhong SZ, et al. Anatomic basis and clinical application of the scapular graft with the scapular branch of the thoracodorsal artery. Chin J Microsurg. 1987;10:226.
23. Xu DC, Zhong SZ. Applied anatomy of reconstruction for the proximal and middle bony defect of humerus with scapular transfer pedicled with the scapular branch of the thoracodorsal vessel (A new vessel pedicle). Chin J Reparat Reconstr Surg. 1988;2:236.
24. Chen ZG, Xu DC, Peng JQ, et al. The scapular graft and transfer pedicled with the scapular branch of the thoracodorsal vessel. Chin J Reparat Reconstr Surg. 1988;3:5–7.

25. Wu RX, Chen ZG, Peng JQ, et al. The microsurgical and anatomic study of the scapular spine graft. Chin J Exp Surg. 1990;7: 169–70.
26. Chen ZG, Peng JQ, Yu GR, et al. The scapular spine bone graft pedicled with scapular spine branch of transverse cervical vessel. Chin J Exp Surg. 1991;8:145.
27. Wang B, Chen ZG, Chen XQ, et al. Anatomic basis of the mandible reconstruction with scapular spine bone graft with scapular spine branch of transverse cervical vessel. Chin J Reparat Reconstr Surg. 1999;13:145–7.
28. Chen ZG, Yu GR, Chen LB, et al. Applied anatomy of the scapular spine bone graft pedicled with infraspinous branch of suprascapular artery. Chin J Clin Anatomy. 1993;11:297.
29. Chen ZG, Yu GR, Chen LB, et al. The scapular spine bone graft pedicled with infraspinous branch of suprascapular artery. Chin J Microsurg. 1994;17:191–2.
30. Taylor GI, et al. Superiority of the deep circumflex vessels as the supply for free groin flaps. Clinical work. Plast Reconstr Surg. 1979;64:745.
31. Chen ZW. Treatment of avascular necrosis of adult femoral head with iliac bone flap pedicled with iliac deep vascular pedicle. Chin J Microsurg. 1986;9:74.
32. Bitter K, Danai T. The iliac bone or osteocutaneous transplant pedicled to the deep circumflex iliac artery. I. Anatomical and technical considerations. J Maxillofac Surg. 1983;11(5):195–200.
33. Chang H, Nobuaki I, Minabe T, Nakajima H. Comparison of three different supercharging procedures in a rat skin flap model. Plast Reconstr Surg. 2004;113(1):277–83.
34. Xu CD, Chen ZG, Zhong SZ, et al. Applied anatomy of iliac bone grafts with anastomotic lateral femoral vessels. J Microbiol. 1985;8(2):96–8.
35. Chen ZG, Xu DC, Zhong SZ, et al. The iliac bone grafts with the lateral esophagus. Chin J Exp Surg. 1985;3:54–6.
36. Zhang FH, Zheng HP, Li FH, et al. Anatomy and application of transposition of iliac bone flap pedicled with extensor fascia and lumbar fascia. J Bone Joint Injury. 1993;8:79–81.
37. Zhao DW, Wang BJ, Wang WM, et al. Evaluation of hemodynamic changes by digital subtraction angiography after treatment of avascular osteonecrosis of femoral head with vascularized bone flaps. Zhonghua Yi Xue Za Zhi. 2006;86(7):438–41.
38. Fan YE, et al. Free iliac bone graft with buttocks on the veins. J Jiamusi Med Coll. 1980;1:6.
39. Miao H, Huang GK. Applied anatomy and free iliac bone transplantation in the treatment of hip. Anat Bull. 1982;5:304.
40. Mairesse JL, Mestdagh H, Bailleul JP, Depreux R. Contribution to the study of the vascularization of the fascia lata tensor muscle. Acta Anat (Basel). 1981;110(3):270–6.
41. Huang GK, Hu RQ, Miao H, et al. Microvascular free transfer of iliac bone based on the deep superior branches of the superior gluteal vessels. Plast Reconstr Surg. 1985;75(1):68–74.
42. Ahmadzadeh R, Bergeron L, Tang M, Morris SF. The superior and inferior gluteal artery perforator flaps. Plast Reconstr Surg. 2007;120(6):1551–6.
43. Zhang FH, Liu JN, Zhong GW, et al. Applied anatomy of transposition of femoral osteoperiosteal flap pedicled with perforating artery of deep femoral vessels. Chin J Microsurg. 1997;20(2):126–8.
44. Chen XQ, Wang ZY, Li GW, et al. Applied anatomy of femoral osteoperiosteal flap pedicled with deep femoral vessels. Chin J Clin Anatomy. 1994;12(3):171–2.
45. Doi K, Sakai K. Vascularized periosteal bone graft from the supracondylar region of the femur. Microsurgery. 1994;15(5):305–15.
46. Penteado CV, Masquelet AC, Romana MC, et al. Periosteal flaps: anatomical bases of sites of elevation. Surg Radiol Anat. 1990;12(1):3–7.
47. Hertel R, Masquelet AC. The reverse flow medial knee osteoperiosteal flap for skeletal reconstruction of the leg. Description and anatomical basis. Surg Radiol Anat. 1989;11(4):257–62.
48. Zhang FH, Zheng HP, Zhong GW. Applied anatomy of transplantation with the periosteal flap of the middle part of femur. Chin J Anat. 1994;17(5):383–4.
49. Zhong GW, Zhang FH, Zheng HP. Middle-femoral periosteal flap: anatomy and clinical application. Chin J Clin Anatomy. 1994;12(3):174–5.
50. Chen ZG, Yu GR, Zheng HP, et al. Clinical application for transposition of the pedicled anterolateral femoral periosteal flap. Chin J Microsurg. 2004;27(1):21–3.
51. Zheng H, Wang H, Zhang F, Yue S. Anatomic basis of perforator flaps of medial vastus muscle. Microsurgery. 2008;28(1):61–4.
52. Chen ZG, Yu GR, Chen LB. Transposing the great trochanter bone flap pedicled with the deep branch of the medial circumflex artery in repair of necrotic femoral head. Natl Med J China. 1994;74(9):560–1.
53. Dou ZX, Chen ZG, Chen XQ, et al. Applied anatomy of reparing neck of femur with greater trochanter flap. Chin J Clin Anatomy. 1988;6(4):208–10.
54. Chen ZG, Peng JQ, Yu GR, et al. Clinical application of vascular pedicle greater trochanter bone flap transposition. Chin J Microsurg. 1992;15(4):207–9.
55. Yamamoto Y, Ohura T, Sugihara T. An anatomic study for a vascularized bone flap of femur. Plast Reconstr Surg. 1995;95(3):520–5.
56. Zhenyu P, Aixi Y, Go-Rong Y, et al. Treatment of serious femoral neck fractures with the transposition of vascularized greater trochanter bone flap in young adults. J Reconstr Microsurg. 2011;27(5):303–8.
57. Zhao DW, Sui GZ, Du GJ, et al. Applied anatomy of the transverse branch of lateral femoral circumflex artery in the transfer of greater trochanter bone flap. Chin J Clin Anatomy. 1994;12(2):92–4.
58. Zhao DW, Du GJ, Guo L, et al. Apply of transposition of greater trochanter bone flap pedicled with branch of transverse lateral circumflex femoral vascular to repair the femoral head. J Bone Joint Inj. 1994;9(1):74–6.
59. Lin X, Tang YH, Tao SQ, et al. Anatomic study of greater trochanter flap with the transverse branch of lateral circumflex femoral artery. Chin J Clin Anatomy. 1995;13(2):94–6.
60. Zhong GW, Zheng HP, Zhang FH, et al. Anatomy and application of the greater trochanter bone flap pedicled with the transverse branch of lateral circumflex artery in the repairing of the upper and middle defects of femoral. Chin J Clin Anatomy. 1996;14(3):231–3.
61. Chen XQ, Wang ZY, Li GW, et al. Applied anatomy of the femoral osteoperiosteal flap pedicled with the descending genicular vessels. Chin J Microsurg. 1994;17(2):134–59.
62. Chen ZG, Chen XQ, Yu GR, et al. Transposition of medial femoral condylus osteoperiosteal flap pedicled with the descending genicular vessels. Chin J Microsurg. 1998;21(3):174–5.
63. Xu DC, Zhong SZ. Practical clinical applied anatomy of bone defect. 1st ed. Beijing: Chinese Medical Science and Technology Press; 2000. p. 360–4.
64. Chen LL, Lan BJ, Zheng M. Applied anatomy of leg defect repair by great adductor muscle tendon bone flap with descending genicular artery. Chin J Clin Anatomy. 2000;18(2):106–9.
65. Ye Y, Chen XQ, Li GL, et al. Applied anatomy of the medial condyle femoral and tibial periosteal flap pedicled with descending genicular vessels for repair of femur's nonunion. Chin J Anat Clin. 2001;6(2):73–5.
66. Gao JM, Xu DC, Chen ZG, et al. Applied anatomy of Achilles tendon defect repair by great adductor muscle tendon combined tissue flaps with vascular anastomosis. Chin J Clin Anat. 2000;18(2):102–4.
67. Qin DY, Zhong SZ, Li ZH. Applied anatomy of mandible reconstructed by medial condyle femoral bone flap transplantation. Chin J Clin Anatomy. 1995;13(4):245–7.
68. Huang D, Wang HW, DC X, Wang HG, Wu WZ, Zhang HR. An anatomic and clinical study of the adductor magnus tendon-descending genicular artery bone flap. Clin Anat. 2011;24(1):77–83.

69. Masquelet AC, Nordin JY, Guinot A. Vascularized transfer of the adductor magnus tendon and its osseous insertion: a preliminary report. J Reconstr Microsurg. 1985;1(3):169–76.
70. Pelzer M, Reichenberger M, Germann G. Osteo-periosteal-cutaneous flaps of the medial femoral condyle: a valuable modification for selected clinical situations. J Reconstr Microsurg. 2010;26(5):291–4.
71. Yu AX, Chen ZG, Yu GR, et al. Repair of humeral fracture and non-union with transfer of vascularized periosteal flap. Chin J Reparat Reconstr Surg. 2001;15(5):310–1.
72. Yu AX, Chen ZG, Yu GR, et al. Applied anatomy of distal humerus periosteo-cutaneous flap pedicled with collateralis radialis vessels. Chin J Exp Surg. 1995;12(6):368.
73. Chen ZGG, Yu GR, Yu AX, et al. Transposition of the distal humeral osteoperiosteal flap pedicled with the radial collateral artery. Chin J Microsurg. 1995;18(3):190.
74. Liang MY, Dai M, Li JF, et al. Clinical utilization of transposition of medial tibia periosteum flap pedicled with intramuscular branch of posterior tibial vessels. China J Orthop. 2002;15(3):142–3.
75. Liu H, Ye CY, Yu GR. Clinical application of the medial multiplex flap pedicled with the posterior tibial vessel. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi. 2001;15(3):147–9. Chinese
76. Fealy MJ, Most D, Struck S, et al. Femur lengthening with a vascularized tibia bone flap. Ann Plast Surg. 1996;37(2):140–6.
77. Zhang FH, Chen ZG, Zhen HP, et al. Applied anatomy for the transfer of medial tibial periosteal flap pedicled with the intermuscular septum nramcjes of posterior tibia vessels. Chin J Clin Anatomy. 1996;14(4):259–61.
78. Yang SH, Wang F, Sun WH, et al. Applied anatomy of knee descending artery and its clinical significance. Cina Acad J. 1984; 2(4):245.
79. Xu WH, Zhang FH, Liu JN, et al. Applied anatomy of reversed femoral osteoperiosteal flap and vascular anastomosis in upper medial leg. J Fujian Med Univ. 1997;31(4):396.
80. Chen ZG, Chen XQ, Yu AX, et al. Transposition of medial femoral condylus osteoperiosteal flap pedicled with the descending genicular vessels. China Acad J. 1998;21(3):174.

12 Microsurgical Repair of Soft-Tissue Defects of the Upper Extremity

Yongjun Rui

12.1 Principles for Microsurgical Repair of Soft-Tissue Defects of the Upper Extremity

12.1.1 Basic Principles

12.1.1.1 To Save Life

In the case of limb injuries, it is necessary to assess and treat any damage that poses a threat to life before assessing and treating the physical impairment of the limb. Most limb injuries are high-energy ones, and can be accompanied with injuries to the trunk, head or neck. The main aims of treatment should be to rescue severe damages to vital organs, detect and treat hidden damages, treat life-threatening injuries and conduct anti-shock therapy. Saving the patient's life is always the first intention, and limb salvage the second. In addition to treatment of open fractures and control of acute bleeding, the rescue procedures can be implemented before a definite diagnosis is established, followed by timely adjustments of specific treatment protocols.

12.1.1.2 To Protect the Remaining Structure

Once the patient's condition is stable, we can focus on the injured limb(s). The first emergency treatment consists of compression to halt acute bleeding. However, it must be borne in mind that the sites distal to the injury may be in an ischemic condition for a period of time. Continuous and complete blockage of the blood circulation will increase the risk of amputation. Hypothermia can be used to reduce the effects of ischemia and to preserve limb function the most effectively. Tissues without blood supply (including the fingers), mutilated tissue or other isolated tissues should be wrapped in gauze soaked with physiological saline, placed in a sealed plastic bag or container and then placed in ice until vascular repair of the tissue can be undertaken. During debridement, all complete skin bridges should be protected, because there may be some important veins within the skin bridge that enable adequate blood drainage after limb reconstruction and restoration of the blood supply. In addition, important structures such as nerves, tendons and arteries should be kept intact during debridement. Preservation of the blood supply in bone tissue is required to facilitate bone healing; preservation of bone tissue without blood supply is required to facilitate fracture reduction. Small bones that have lost their blood supply can be removed after the fracture reduction is completed, or can be saved as grafts of remnant tissue in repair.

12.1.1.3 To Preserve Function

Protection of important structures is required to preserve their function. Debridement should be carried out in association with attempts to preserve important tendons, nerves and bone tissue even in the presence of severe damage. Some important structures without blood supply can recover function if they are covered with tissues that have a sufficient blood supply. The limb must be fixed in the following protective positions postoperation to prevent contractures and promote functional recovery: slight dorsiflexion of the wrist, metacarpophalangeal joint flexion and extension of the interphalangeal joints. Edema must be controlled after operation. Targeted functional training should be started, depending on the patient's needs, to help establish a good foundation for the next functional reconstruction.

12.1.1.4 To Repair and Reconstruct the Limb

Wound closure: Wide structural wounds, such as exposed tendons, nerves, bones or ligaments/joints, should be covered by tissues with a blood supply or by flaps. Joints and tendons should be covered by tissues with a good blood supply in order to achieve good postoperative appearance and elasticity. The volar part of the hand, which bears oppression, should have a good feeling and tangential stability. Delayed wound closure should be performed once

Y. Rui (✉)
Department of Orthopaedics, Wuxi Orthopaedic Hospital, Wuxi, Jiangsu, China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_12

the wound has been stabilized. Prior to wound closure, repeated wound debridement is necessary. No significant large structure should be covered with a skin graft; smaller wounds, which are exposed to pressure and/or friction, and a large range of defects may be covered with full-thickness skin grafts.

Wound reconstruction: The reconstruction of bones, joints, nerves and tendons can be performed using transplantation or transformation, depending on the limb function.

12.1.2 Notes

1. The nature, range and severity of injury must be completely and comprehensively understood, especially, in the case of functionally important tissues.
2. To develop a forward-looking and complete reconstruction plan, frank communication with the patients and their families is required. The pros and cons of the plan should be made clear, but the final decision should rest with the patient.
3. Thorough and meticulous debridement is a prerequisite for all repair surgeries, and must follow the principles of debridement mentioned above. Meticulous attention should be paid to every step of debridement, as infection, hematoma, tissue necrosis or exudation will lead to eventual surgical failure or loss of function.
4. We should strive to achieve acute repair of the injured tissue. However, for large and complex wounds, the first step is to treat complex, life-threatening lesions; the wound can be repaired in a sub-acute manner.
5. Blood supply to the limbs and organs must be restored via vascular anastomosis as quickly as possible. However, in the case of extensive injury to the upper arm soft tissues that is associated with major vascular injury and keeps a warm ischemia time of >6 h, soft-tissue coverage should be undertaken with caution. Amputation is necessary in some situations.
6. Reliable and effective fracture fixation must be achieved.
7. The wound should be covered with soft-tissues with sufficient blood supply.
8. The repair should be followed by systematic rehabilitation.

12.1.3 Order of Tissue Repair

Contrary to debridement, tissue repair is carried out in the order from the deep to the shallow, and generally follows the order of bone and joint fixation, ligament repair, flexor tendon repair, vascular repair, nerve repair and wound closure.

12.1.4 Internal Fixation of Open Fractures with Soft-Tissue Defects

The operation should be simple. Stable fixation and anatomical reduction should be pursued. External fixation and simple internal fixation are sometimes preferred in some open fractures with soft-tissue defects. Fractures can be fixed with simple internal fixation in an effective combination with external fixation when necessary.

12.1.5 Principles of Tendon Repair

After the bone scaffold being rebuilded, the blood vessel should be repaired after tendon being repaired unless the blood supply must be restored immediately, which avoid repaired blood vessels.

If the patient's condition permits, tendon repair must always be carried out. For the flexor tendons, four or more sutures should be made through the center of the tendon before the surrounding tissues are trimmed. This technique can meet the needs of early postoperative rehabilitation. For zone II flexor tendons, both the deep and superficial flexor tendons should be repaired if possible. Repair of solely the deep flexor tendons is still in dispute. We believe that if the wound is not contaminated and the tendons have been sectioned neatly, both the superficial and deep tendons can be fixed simultaneously. Only the deep flexor tendons should be sutured when the A2 pulley to produce suture is blocked. If the soft-tissue bed is in good condition, the fracture fixation is stable and the pulley system is still intact.

The patient who suffer from tendon defect could receive emergency or subemergency tendon grafts.

If the soft-tissue condition does not allow repair, the tendons can be reconstructed with two re-flexor tendon grafts.

The repair of severe defects of the extensor tendon apparatus is often difficult, and the repair needs to be performed using a two-stage process. For zone VI extensor tendon defects, full-thickness end-to-side repair is performed; for flexor tendon defects, end-to-end transposition can often result in more satisfactory functional restoration.

In the case of severe comminuted fracture with extensor and flexor tendon defects, partial phalanx shortening or row tendon transposition can be considered. Deep flexor tendon injuries can be repaired using superficial flexor tendons. The flexor hallucis longus tendon can be used to repair the palmar metacarpal tendon or radial flexor tendons.

12.1.6 Principles of Vascular Repair

If the blood supply to the fingers is lacking, reconstruction of the blood circulation is essential. This is usually followed by complete debridement, bone scaffold set-up, tendon repair, and arterial and venous repair. However, in the case of prolonged ischemia of a large limb, the main arterial passage between the proximal and distant parts must be reestablished. The quality of vascular anastomosis must be ensured. If there is shortening of the vessel, a vascular tissue graft must be used.

The subclavian artery and axillary artery are commonly injured after blunt, crushing, squeezing or avulsion injuries. In apparent open injuries, obvious arterial damage can be easily found and properly repaired. However, in a small blunt trauma or stab wound, it is likely to overlook some major vascular injuries because the limb has some residual blood supply. In such cases, wound suturing alone can often lead to ischemia or necrosis of muscles and the distal limb. In addition, vascular injury caused by a blunt trauma is often associated with local muscle contusion and brachial plexus injury. Therefore, the wound should be fully exposed, the necrotic muscles completely removed, and exploration and repair of the nerves and blood vessels carried on. Early treatment to preserve limb function is of utmost importance. If a large limb is ischemic for more than 6 h, limb salvage must be conducted carefully, and amputation should be performed if necessary. If the radial artery and ulnar artery of the forearm are injured simultaneously, the arteries should be both repaired. If a single artery of the forearm is injured, the need for repair is controversial, but it is believed that if the vessel injury is accompanied with nerve rupture, the blood vessels and nerves should be repaired simultaneously.

12.1.7 Principles of Nerve Repair

In open hand injuries, the nerves are often the last structures to be repaired. The injured nerve(s) should be covered by a foundation bed or soft tissue that is in good condition. In contusions, the avulsed nerve endings must be trimmed to retain only the complete healthy nerve bundles which are then freed from the epineurium so that the injured nerve can be sutured without tension. If it is difficult to suture the defective nerve without tension, nerve grafts should be used to close the gap.

12.1.8 Principles of Wound Closure

1. As far as possible, **one-stage or delayed close wound should be taken.** Primary closure should not be attempted if suturing without tension is not possible.

   If wound could not be closed immediately, relaxation suture should be taken to prevent skin retraction.
2. .**The wound that perpendiculars to joint, is parallel with fingerweb and overlap tendon should receive Z-plasty to avoid suture directly**.
3. The wound should be closed according to the principles of plastic surgery. Deliberate wound edge eversion should not be made to facilitate smooth involution.
4. Before wound closure, the wound must be checked for bleeding. A tourniquet should be used to stop the bleeding. In large or deep wounds, drainage tubes should be placed.
5. If the bone, tendons, nerves or blood vessels are exposed, early coverage must be used to prevent tissue necrosis and infection.

For any soft-tissue defects, the treatment must be aimed at lasting wound closure or coverage while retaining limb function. Every effort should be made to achieve the highest success rate of wound closure. We should select the appropriate coverage method according to the site of injury and the required function. Even in patients who suffer minimal damage, unstable wound closure can lead to many complications and prevention of normal activity. For example, for a soft-tissue defect in the palmar aspect of the finger, a free skin graft can cover the wound. However, in young people who require good hand function, it is necessary to use a flap or a free flap transfer to ensure good postoperative feeling, texture and appearance. Damage to important structures such as bones, tendons, nerves, blood vessels and other exposed tissues was previously considered to be an indication for transfer of flaps. However, vacuum-assisted wound closure combined with free skin graft can preclude the need for flap repair, **Especially for the people who should receives covering wounds operation, without the need to second-stage reconstruction**. Therefore, we need not only evaluate the long-term effects, stability of and damage to the recipient wound but also consider the patient's situation and the doctor's skill proficiency in covering soft-tissue defects.

In 1993, Levin proposed the reconstructive ladder concept for soft-tissue injuries, which describes how to select different surgical protocols according to the complexity of trauma. The ladder consists of a series of conventional reconstruction methods, arranged from the simplest to the most sophisticated: primary suture, delayed closure, split-thickness skin graft, full-thickness skin graft, tissue expansion, free flap, pedicle flap and free flap. A surgeon is required to try the simplest technique first, always followed by the more sophisticated next step in the ladder only after the prior technique fails. Each step in the ladder is more difficult than the prior one. Due to the development of modern vacuum-assisted closure, some surgeons now attempt this treatment prior to delayed primary closure. Wong and Niranjan presented a reconstruction module for wound closure consisting of a combination of a variety of wound-covering techniques: partial closure, delayed closure, skin graft, tissue expansion, local flap, regional flap, free flap and development of personalized solutions in full consideration of the necessity and feasibility of the selected procedure. These techniques can be overlapped or used simultaneously. For example, local transfer and free flap can be used to repair a single wound. Considering the cosmetic outcome, age and occupation of the patient, and the fact that some local transfers may worsen wound scars, in some patients, free flaps can be used directly. Thus, the conventional reconstructive ladder concept is not strictly followed in every patient but modified to meet the specific needs of each patient.

12.1.9 Postoperative Treatment

The tourniquet should be relaxed to check the blood supply to the fingers before the wound is bandaged. The fingers must be separated by the bandage. While bandaging, we should ensure that there is no skin contact between adjacent fingers to avoid postoperative sweating erosion. Furthermore, the tips of fingers must be exposed so that the blood circulation can be monitored. Fractures, dislocations or skin grafts should be fixated with a plaster in a functional position after surgery. The injured limb should be routinely raised.

12.2 Microsurgical Repair of Soft-Tissue Defects of the Shoulder and Axilla

12.2.1 Principles of Repair

Injuries to the shoulder and axilla, the highest parts of the upper limb, are rare. However, if they are injured, the trauma is invariably severe. The most common traumatic mechanism is the upper limb is drawn into a machine, causing an avulsion-crush injury at the axilla as well as defects of skin, muscle and soft-tissue around the shoulder girdle. The injury is often accompanied by fractures of the humerus, clavicle, scapula and multiple chest ribs. The axillary brachial plexus and important blood vessels are also injured. The trauma can be severe enough to threaten life. Therefore, treatment and repair must be effective and timely.

A single soft-tissue defect at the shoulder and axilla is easy to repair. This area has considerable muscles. If the muscles have an intact blood supply, the avulsed skin can be replanted. Even if the skin cannot be replanted, free middle-thickness skin grafting can lead to quite satisfactory outcomes. If important tissues are exposed, flaps with a vascular pedicle can be used for repair. Commonly used vascular pedicle flaps are the latissimus dorsi island flap, scapular flap and ectopectoralis flap.

To repair soft-tissue defects associated with neurovascular injury at the axilla, a comprehensive evaluation of the injury conditions, the trauma mechanisms and any other complex injuries is required. Once the vital signs are stable and all sorts of combined injuries have been treated actively, the radial artery pulse should be observed. When it is difficult to judge the patency of the vessel, color Doppler examination and computed tomography angiography can be used to evaluate the extent of vascular damage. If the warm ischemia time is more than 6 h, high-level amputation of the upper limb is suggested. If the warm ischemia time is less than 6 h, repair of vessels can be conducted to salvage the limb, depending on the patient's condition. Since the patients who undergo limb salvage invariably have ischemia-reperfusion injury, the upper arm and forearm should be incised for decompression in these patients to prevent bone compartment syndrome caused by deep tissue swelling.

The wounds can be repaired in the secondary phase (10 days later). The methods used for wound repair are skin grafting and flap transfer.

12.2.2 Methods of Repair

Commonly used tissue flaps with vascular pedicles include the latissimus dorsi flap, ectopectoralis flap, scapular flap, chest wall flap and free anterolateral thigh flap. These flaps are characterized with reliable blood supply, long vascular pedicle and little anatomic variation. The main features of the latissimus dorsi flap and the ectopectoralis flap are described below.

12.2.3 Latissimus Dorsi Flap

12.2.3.1 Flap Design

Flap axis: The axis is a line connecting the anterior part of the axillary posterior wall to the midpoint of the iliac spine, marking the anterior edge of the latissimus dorsi. It is the relative body surface projection of the thoracodorsal arteries, veins, nerves and lateral branches.

Rotation point: It is located 7–10 cm from the armpit vertex in the flap axis.

Anatomical plane: The length of the flap is the longitudinal length of the axial line. The width of the flap is the distance between the two ends of the axial line.

12.2.3.2 Surgical Procedure

The skin and subcutaneous tissue under the armpit are incised along the line mentioned above to expose the anterior edge of the latissimus dorsi. Blunt dissection is performed under the latissimus dorsi muscle to reveal the harness arteries, veins and nerves. The neurovascular

Fig. 12.1 Latissimus dorsi musculocutaneous flap repairing the soft tissue defects from the upper arm to the axilla. (**a**) Left upper arm dividing, axilla soft tissue defect. (**b**) Design of latissimus dorsi island flap. (**c**) Freeing flap intraoperatively. (**d**) The flap was transferred to cover the axilla

bundle is in the deep part of the muscle. The latissimus dorsi flap is raised from the proximal part to the distal part. The long thoracic nerve, which supplies the serratus anterior muscle, is identified in the deep and anterior part of the thoracodorsal vascular pedicle and preserved. The latissimus dorsi and serratus anterior muscles are separated in the anterior side. The anterior edge of the latissimus dorsi and the rear of the iliac spine are separated distal to the flap A fan-shaped muscle sleeve is prepared from the proximal to distal direction to isolate the muscle flap. The flap is separated to reach the required length and width. The flap is raised in a retrograde fashion under the latissimus dorsi fascia to form an island myocutaneous flap carrying the latissimus dorsi, whose blood supply is from the thoracodorsal artery and its branches. A subcutaneous tunnel is made from the recipient site to the armpit. The tunnel should be made spacious to prevent pedicle compression. Alternatively, the latissimus dorsi muscle flap is transferred to the wound via an open tunnel. Then, complete hemostasis of the wound is achieved, and the flap and wound are sutured. If the width of the donor site is less than 6 cm, direct sutures are used (Fig. 12.1).

12.2.4 Ectopectoralis Flap

12.2.4.1 Flap Design

Flap axis: The projection of the pectoralis major muscle, which marks the course of the thoracoacromial artery. Line AB connects the thoracoacromial artery and the xiphoid. Point O is the intersection between a perpendicular line CD drawn from the midpoint of the clavicle and line AB. Line COB is the surface projection of the thoracoacromial artery.

Rotation point: The point is located 3–4 cm inferior to the midpoint of the clavicle.

Anatomical plane: This plane is 4 cm under the free edge of the pectoralis major muscle.

12.2.4.2 Surgical Procedure

The lower edge of the flap is inserted into the subcutaneous tissue according to the flap design. Care must be taken not to damage the pectoralis major during the incision. After the lower edge of the pectoralis major is transected, the muscle is flipped up together with the flap. The space between the pectoralis major and pectoralis minor muscles is bluntly dissected with the fingers to expose and protect the neurovascular bundle that supplies the pectoralis major. The whole thickness of the pectoralis major muscle is cut off depending on the amount of muscle tissue required. The flap is separated up to the inferior part of the clavicle and transferred before the muscle and tendon are sutured. The wound is covered and partial reconstruction of the elbow and shoulder is done. The donor-site wound can be sutured at the first stage.

12.3 Microsurgical Repair of Soft-Tissue Defects of the Elbow

12.3.1 Principles of Repair

The elbow joint is a "naked" joint, with few muscles surrounding it. There is abundant soft tissue in the anterior part of the elbow but only a layer of papery skin in the lateral and posterior parts. Thus, it is extremely easy to expose important tissues after trauma in this area. When combined with intra-articular fractures, soft-tissue defects of the elbow joint can likely lead to infection, stiffness and even dysfunction, if timely and effective treatment is not administered.

Many reconstruction options are available for repair of soft-tissue defects of the elbow joint. Treatment should be individualized according to the following factors: size of the defect, presence of intra-articular fracture(s), stability of the elbow and general condition of the patient. Considering vulnerability of the joint and requirements of hard rehabilitation of the elbow, early mobilization of the elbow must be adopted in all patients, regardless of therapeutic regimens. Most soft-tissue defects of the elbow are caused by trauma. These wounds should be recovered within 72 h. However, early soft-tissue coverage must be conducted after open reduction and internal fixation, and even artificial elbow prosthesis replacement can be used to treat soft-tissue defects combined with unstable intra-articular fractures.

12.3.2 Methods of Repair

A vascular pedicle flap from the upper limb or the chest is usually used to cover elbow wounds. These flaps are easy to harvest and have similar texture to that of the local skin at the recipient site. Commonly used flaps include lateral (or medial) upper arm island flap with vascular pedicle and island flap with a pedicle of the posterior interosseous artery or ulnar (or radial) artery. If the wound is very large, an island flap or free flap of the latissimus dorsi should be considered. In general, the lateral island flap of the upper arm is commonly used to treat soft-tissue defects of the elbow.

12.3.3 Lateral Island Flap of the Upper Arm

12.3.3.1 Flap Design

Flap axis: The axis connects the insertion point of the deltoid muscle to the lateral epicondyle of the humerus at the lateral side of the upper arm. This line is the surface projection of the lateral brachial intermuscular septum and the posterior radial collateral artery.

Rotation point: This can be any point on the flap axis.

Anatomical plane: The flap is centered on the flap axis. The upper border of the anatomical plane of the flap is the middle of the deltoid muscle, its lower border is the cubital crease, its outer border is the centerline of the posterior arm, and its inner border is the medial margin of the forearm.

12.3.3.2 Surgical Procedure

The flap is incised near the posterior edge of the skin, and dissected subcutaneously to the deep fascia. After the flap is raised forward to the lateral intermuscular septum, the radial collateral artery and lateral cutaneous nerve are identified. Next, the entire flap is isolated from the anterior and posterior sides while the radial collateral artery should be protected. If necessary, the subcutaneous cephalic vein can be included in the flap. The upper skin is incised, and the vessel pedicle is freed. Next, the flap, whose pedicle is the radial collateral artery and posterior forearm cutaneous nerve, is raised from a proximal to distal direction. If the radial collateral artery or the deep brachial artery is ligated, a reverse island flap should be made on the posterior radial collateral artery. This flap is transposed to cover the recipient site. The donor site is directly sutured when its width is less than 4 cm (Fig. 12.2).

12.3.4 Medial Island Flap of the Upper Arm

12.3.4.1 Flap Design

Flap axis: This is the surface projection of the medial bicipital groove of the upper arm.

Rotation point: This is based on the superior ulnar collateral artery and adjusted according to the specific situation.

Anatomical plane: Its upper border is the middle arm, and its lower border the humeral epicondyle. Its outer and inner borders reach up and down the midline of the arm, respectively.

12.3.4.2 Surgical Procedure

The posterior skin of the flap is incised according to the flap design, and subcutaneous dissection is continued to the

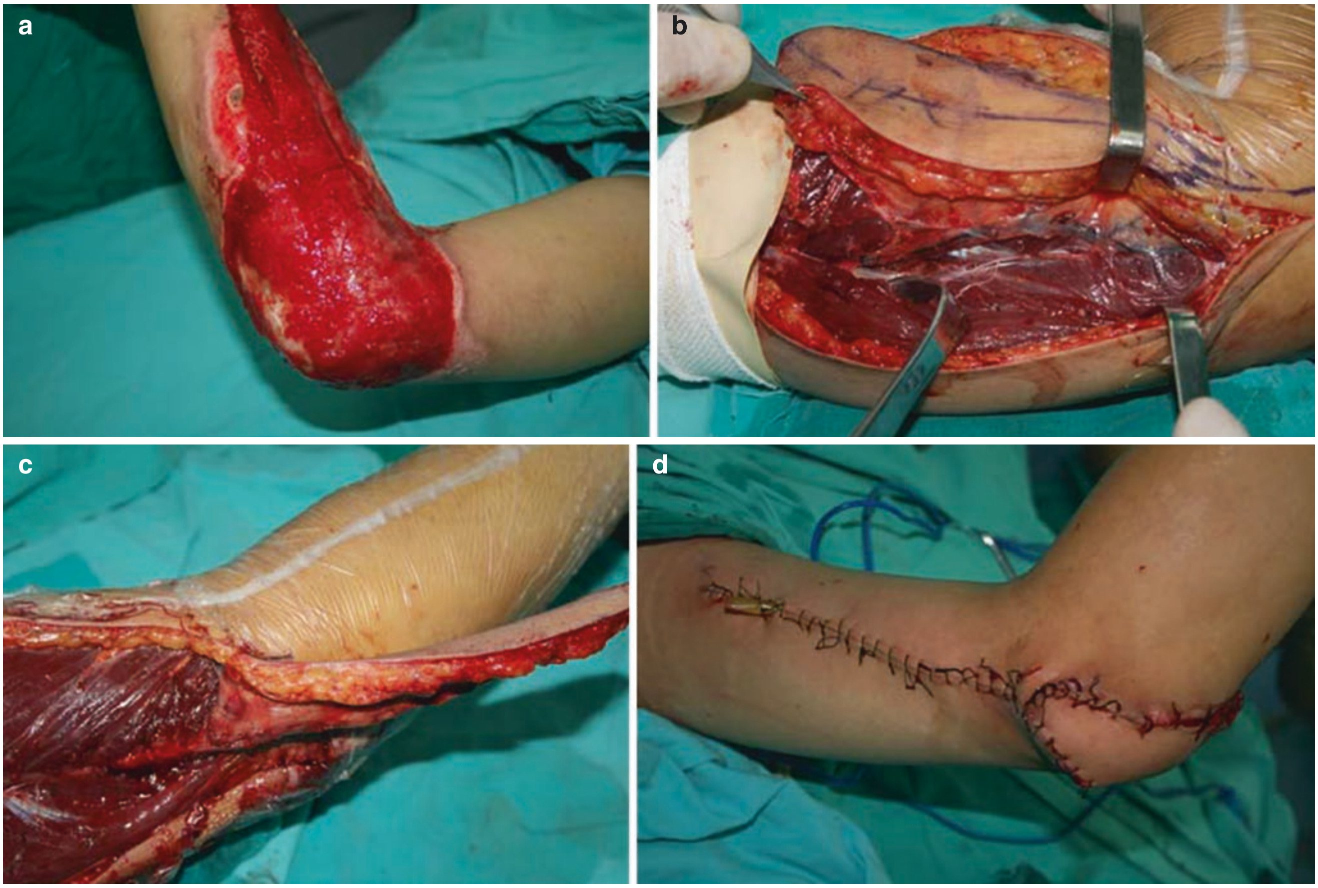


Fig. 12.2 The lateral island flap of the upper arm repairing elbow wound. (**a**) Soft tissue defect of elbow. (**b**) Exposing the radial collateral artery. (**c**) The flap dissociation was completed. (**d**) The lateral island flap of the upper arm was transferred to cover the axilla

muscle surface to separate the flap. Then, the ulnar nerve, basilic vein, *etc.* are identified beneath the spatium intermuscular between the triceps brachii and brachialis muscles. The superior ulnar collateral artery is identified beside the ulnar nerve. The cutaneous branch of the artery is retained while the others are ligated. The medial brachial intermuscular septum is reached through the incision on the leading edge of the flap. The upper and lower cutaneous branches are observed when the superior ulnar collateral artery and the ulnar recurrent artery are exposed. The entire flap with the vascular pedicle is isolated together with the superior ulnar collateral artery or ulnar recurrent artery. The flap is rotated at the rotation point determined preoperatively to cover the wound.

12.4 Microsurgical Repair of Soft-Tissue Defects of the Wrist

12.4.1 Principles of Repair

Since the soft tissues at the palm and dorsal aspects of the hands maintain continuity across the wrist, even a small defect in this area may result in limited mobility and require flap repair, especially one of the dense dorsal tissues. There are tendons that are responsible for the flexion and extension of the wrist, nerves that determine hand functions and important superficial blood vessels that supply the wrist. Consequently, even a minor damage in this region can easily lead to exposure of tendons, nerves and blood vessels. Therefore, soft-tissue defects of the wrist often require urgent repair with a graft or flap to cover the wound.

Repair of the wrist involves the dorsal and palmar aspects. Since the tough extensor retinaculum can effectively protect the extensor tendons, the need for extensor tendon sliding is much lower than that for flexor tendon repair. If the base bed is good enough, a full-thickness skin graft can be applied even in the presence of tendon exposure, leading to good results. If the retinaculum is damaged and the extensor tendon is exposed, a neighboring island flap can be applied to cover the wound. Larger flaps such as the inguinal or femoral pedicle anterolateral free flap can be utilized to cover large wounds. Because the location of the flexor tendons and neurovascular bundle is relatively superficial, adhesions of the nerves and tendons can likely occur after skin grafting. If reoperation for myotendolysis is performed, tendon exposure is inevitable, necessitating a free flap. Ulnar artery or radial artery skin flaps, bone flaps, dorsal artery flaps and superficial radial nerve fasciocutaneous flaps are commonly used. Free flaps are required for a large range of soft-tissue defects of the wrist.

Repair of soft-tissue defects of the wrist is directly related to recovery of the wrist and hand functions. One-stage repair, including debridement, hand revascularization and tissue repair of the tendons, nerves and blood vessels, is widely advocated to preserve hand functions.

12.4.2 Methods of Repair

Neighboring island flaps can be used to repair soft-tissue defects. The ulnar artery perforator flap and posterior interosseous artery perforator flap are excellent choices for wrist wound repair. Free flaps, such as the anterolateral thigh flap and dorsolateral arm flap, can also be used.

12.4.3 Island Flap of the Epithelial Branch of Ulnar Artery

12.4.3.1 Flap Design

Flap axis: The axis is the line between the pisiform bone and the epitrochlea, corresponding to the course of the epithelial branch of the ulnar artery. **According to this axis, the 5-7 cm-wide flap is designed.**

Rotation point: The point is located 4 cm proximal to the pisiform bone at the origin of the epithelial branch of the ulnar artery. It is also the pivot point for the reverse island flap.

Anatomical plane: Its distal boundary is at the pisiform, its proximal boundary the inferior margin of the epitrochlea and its lateral boundaries extend to the forearm palm and the dorsal midline. The dissection is carried out on the deep surface plane of the deep fascia.

12.4.3.2 Surgical Procedure

The flap design is subject to the size of the defect at the recipient site. Above the transverse crease of the wrist, a 5-cm-long incision is made along the radial edge of the flexor carpi ulnaris, exposing the flexor carpi ulnaris muscle. The lower part of the muscle is 4 cm proximal to the wrist. The epithelial branch of the ulnar artery can be clearly differentiated from the ulnar artery, which traverses towards the ulnar direction.

Once the epithelial branch of the ulnar artery is identified, an incision is made on the proximal part of the skin around the epithelial branch. Sharp dissection is conducted in the deep fascia from the proximal to the distal. The flap is cut along with the ulnar artery, which lies between the other branches, and freed from the wrist. Some soft tissues around the epithelial branch can be included in the flap to protect the vessels, which should be handled cautiously to preserve the connection of the branch with the ulnar vessels. The basilic vein and cutaneous nerve of the forearm, which supply the ulnar skin of the forearm, should be carefully identified during tissue dissection.

After the proximal portion of the flap of the cutaneous branch of the ulnar artery has been completely freed, an incision is made on the wrist over the cutaneous branch at the distal end of the flap, and the dissection is continued from the distal to the proximal towards the cutaneous branch of the ulnar artery. The basilic vein must be carefully dissected in freeing the distal end of the flap. Careful identification and meticulous protection is also required of the dorsal cutaneous branch of the ulnar nerve in the wrist.

After the flap has been completely freed, leaving the cutaneous branches of the ulnar artery and vein or the ulnar artery and vein, active bleeding can be seen around the edge of the flap. When the recipient site is ready, the flap can be transferred to the hand in a retrograde fashion (Fig. 12.3).

If the flap width is <3 cm, the donor site of the forearm can be directly sutured. If the flap width is >3 cm, full-thickness skin grafting, fixation and packing is required at the donor site.

12.4.4 Interosseous Dorsal Island Flap

12.4.4.1 Flap Design

Flap axis: The axis is a line connecting the 2/3rds of the lateral condyle to the lower radial margin of the ulnar head when the forearm is in pronation.

Rotation point: This is located 2.5 cm superior to the ulnar styloid.

Anatomical plane: The design is along both sides of the axis of the recipient site.

12.4.4.2 Surgical Procedure

The pedicle of the designed flap is incised around the skin and forearm. The extensor ulnaris and extensor digiti minimi are dissected to reveal the dorsal interosseous artery. A 15-cm-wide portion of the fascia is retained within the flap. The skin, subcutaneous tissue and fascia on both sides of the flap are dissected, and interrupted sutures are placed between the deep fascia and subcutaneous flap to protect the integrity of the blood supply. The artery and its accompanying vein are ligated near the perforation point of the dorsal interosseous artery flap. The flap is dissected after the artery has been

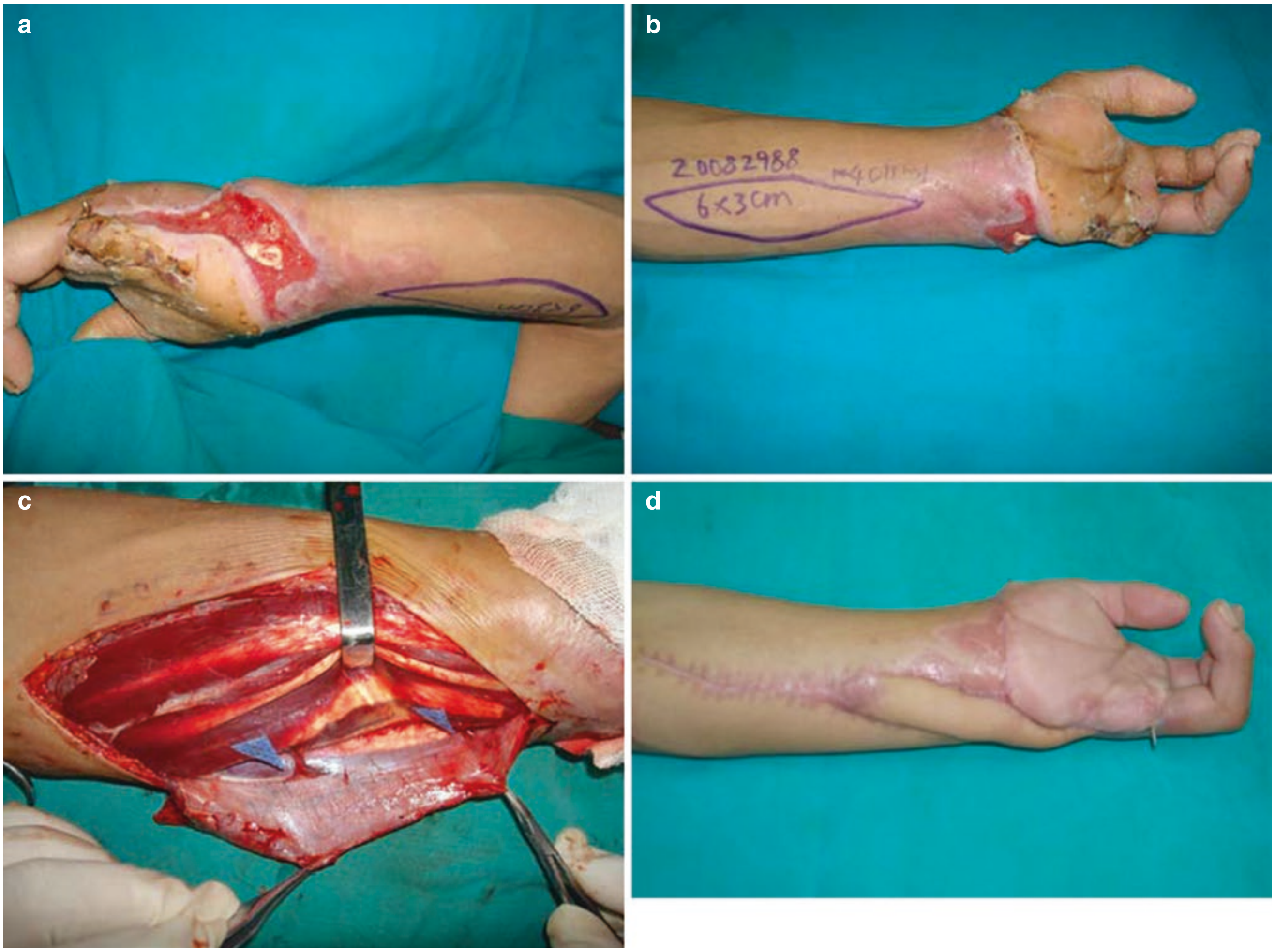


Fig. 12.3 The island flap of the epithelial branch of ulnar artery repairing soft tissue defect of wrist. (**a**) Soft tissue defect of the wrist ulnar side. (**b**) Designing the island flap of the epithelial branch of ulnar artery. (**c**) Exposing the ulnar cutaneous branch of the wrist. (**d**) Follow-up of 6 months after surgery

protected. Next, the flap is rotated through an incision in the skin of the flap or through a tunnel in the first web space to cover the defect. The donor site can be directly sutured or repaired using a skin graft, depending on the width of the incision.

12.5 Microsurgical Repair of Soft-Tissue Defects of the Hand

12.5.1 Principles of Repair

Most palmar soft-tissue defects are caused by avulsion, crushing or penetrating wounds. In the case of avulsion injuries, a retrograde distal skin pedicle can be sutured in situ if the blood supply is intact. Alternatively, vascular anastomosis can be performed when the vessels of the skin are large enough. Anterograde avulsion of the proximal skin pedicle is invariably associated with a poor blood supply. If the avulsion is superficial to the palmar aponeurosis and the wound is in a good enough condition, the defect can be repaired with a full-thickness skin graft harvested from the avulsed skin or from another donor site if the avulsed skin is too damaged. Flaps can be used to cover defects with exposed nerves and tendons, and also for wounds with segmental defects of the nerve and tendon that will be repaired later. Flaps cannot be used to restore the sliding property related to the dense dorsal tissue of the hand or non-slip property of the normal skin. In addition, they have a disadvantage of a bloated postoperative appearance. Therefore, flaps for repair of palmar defects should be thinner, denser and have a good sensation.

12.5.2 Methods of Repair

An ulnar artery perforator island flap can be used to cover small defects. Free medial plantar flaps can be used for medium-sized wounds, and anterolateral thigh flaps and lateral arm flaps are often transplanted to repair large soft-tissue defects.

12.5.3 Anterolateral Thigh Flap

12.5.3.1 Flap Design

Flap axis: This is the line connecting the anterior superior iliac spine (point M) and the superior-lateral border of the patella (point N). The midpoint of line MN is marked as point O.

Rotation point: This point is located where the cutaneous arteries of the descending branch of the lateral femoral circumflex artery perforate the deep fascia. The main perforators are detected with a handheld Doppler probe around point O. The surface projection of the trunk is along the distal 2/3 of the line connecting the midpoint of the inguinal ligament (point F) to point O.

Area: Depending on the desired size and shape, the flap is designed using the following general principles. Two-thirds of the flap is in lateral to line MN, and one-third is medial to this line. Two-thirds of the flap is below point O, and one-third is above this point.

12.5.3.2 Surgical Procedure

The proximal and lateral skin incisions are made according to the flap design. The fascia lata is included and sutured to the flap to avoid flap separation. The rest of the skin incision is made, and the flap is harvested after the flap vessels are isolated.

Dissection is performed in the intermuscular space between the rectus femoris and vastus lateralis to identify the descending and/or transverse branches of the lateral femoral circumflex artery. Along the main pedicle, one to four musculocutaneous perforators or septocutaneous vessels can be found along the medial edge of the vastus lateralis muscle (generally, one to two perforators). As for the musculocutaneous branch, the covering muscle should be gradually cut from the point where the vessel pierces the muscle and the point where it perforates the muscle membrane. Sometimes when it is difficult to identify the vessels due to the complex vasculature, including parts of the vastus lateralis muscle in the flap (muscle sleeves) will be safe. After the vessel bundle has been separated, “light transmission” (i.e., turn and lift the flap to the medial side of the thigh) will be available to recognize the vascular bundle and its branches to the skin, thereby confirming that the cutaneous branch has been included in the flap. Finally, after the medial and lower incisions are made deep to the fascia, the flap is completely islanded. Depending on the desired vascular pedicle length for the recipient site, a sufficient length of the vascular pedicle is separated in the intermuscular space between the rectus femoris and vastus intermedius. Once the recipient site is ready, the pedicle of the flap can be divided.

Debridement and hemostasis of the recipient area is followed by separation of the distal radial artery and cephalic vein. The wound is covered with the flap, and the flap is sutured to the wound. The vessels and nerves are anastomosed under a microscope with 9-0 atraumatic sutures. The radial artery is anastomosed to the descending or transverse branch of the lateral circumflex femoral artery. Both accompanying veins of the flap are anastomosed to branches of the cephalic vein, or one to the cephalic vein and the other to the accompanying vein of the radial artery. The flap nerve is anastomosed to the superficial branch of the radial nerve. After anastomosis, the flap should be monitored to confirm good blood supply. Next, the wound can be closed and dressed. A plaster must be used for immobilization.

If the width of the donor-site wound <6 cm, it can be directly sutured. If it is >6 cm, part of the wound can be sutured, and split- or full-thickness skin grafts should be used to cover the remaining part, followed by dressing with a pressure bandage (Fig. 12.4).

12.6 Microsurgical Reconstruction for First Web Space Contractures

12.6.1 Principles of Reconstruction

First web space contractures are caused by congenital and traumatic etiologies. This section mainly discusses traumatic contractures and damage to the radial aspect of the hand caused by a crushing or squeezing force. This type of damage mainly leads to injury or defect of the superficial skin and occasionally injury of the deep adductor pollicis muscle, eventually resulting in a contracture. Secondary contracture can be caused by disuse of the adductor pollicis, if regular preventive measures are not implemented after surgery. Multiple metacarpophalangeal fractures and other hand injuries can result in first web space contractures. Reconstructive surgery to correct first web space contracture must be based on the cause of contracture, severity of the injury and condition of the surrounding tissues.

First web space contractures can be divided into mild, intermediate and severe degrees according to the classification of Yu-dong Gu.

Mild contractures: This type of contracture is simply a linear superficial scar caused by a soft-tissue injury, with the deep tissue relatively intact. Various methods of skin dilation, such as local opisthenar flap rotation, dorsolateral flap of the

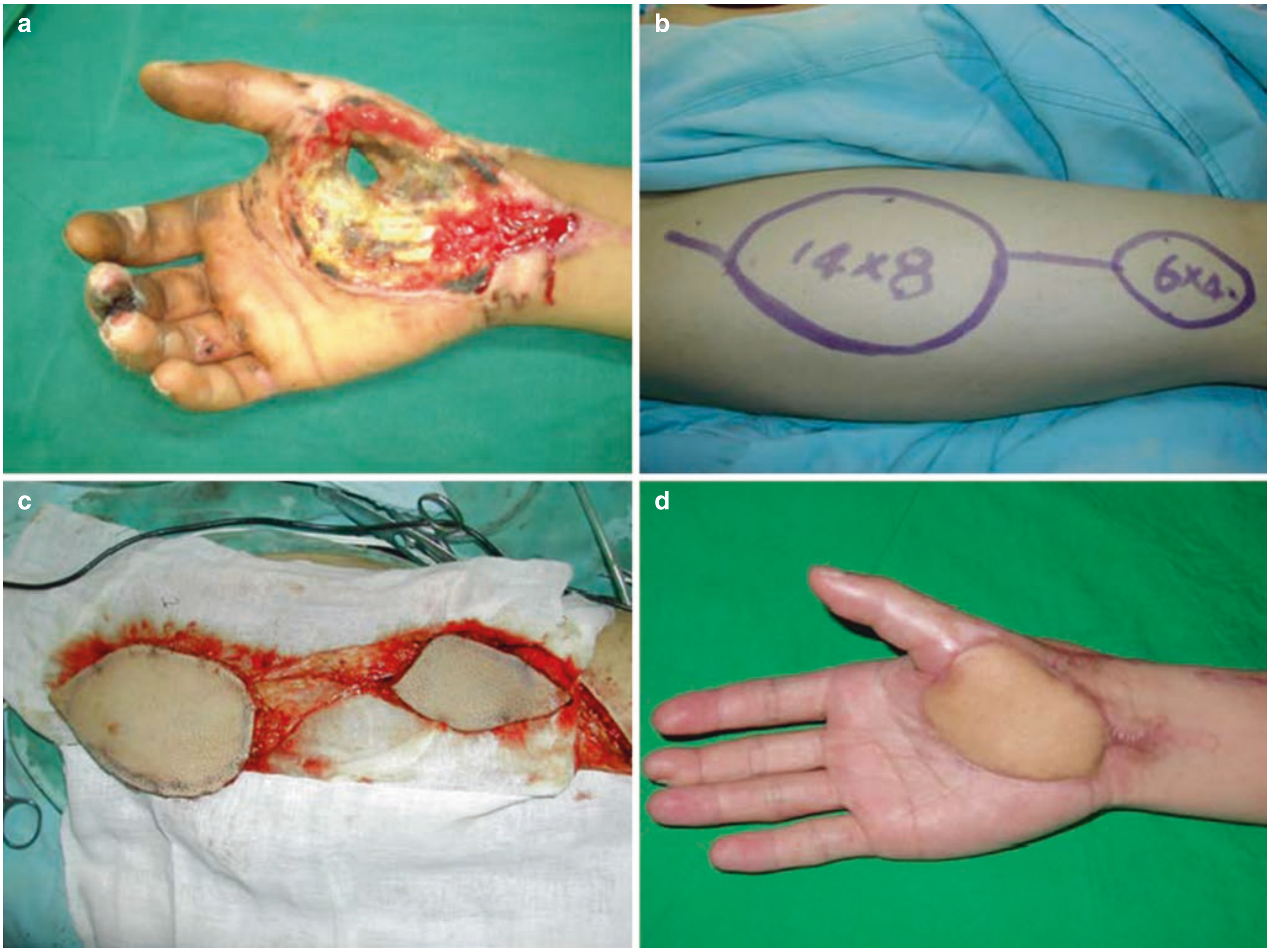


Fig. 12.4 The anterolateral thigh flap repairing soft tissue defect in palm. (**a**) Right hand penetrating injury. (**b**) Designing a "dumbbell" free anterolateral thigh flap. (**c**) The flap was harvested. (**d**) The shape of palmar after flap repairing

index finger and four or five first web plasty, are available for the treatment of this contracture. Postoperatively, the first web space is fixed with a plaster cast for 2 weeks and with a brace for 3 weeks once the sutures have been removed.

Intermediate contractures: These contractures involve not only the dermal tissue of the thumb web space but also the deep adductor muscle. Surgical release of the contracture may lead to a deep lacuna, and partial transfer can result in a hematoma or recurrence of the contracture. Therefore, a longitudinal incision should be made to examine the muscle damage. The incision should go from the dorsal parts of the first and second metacarpal bones to the palm finger joint plane of volar thumb. The level of impairment is determined on the basis of the color, tonicity and continuity of the adductor and first dorsal interosseous muscles. The vastus medialis terminal downward is available for contracture of the first dorsal interosseous. If there is a part of the stretchy muscle in the thumb web space, Z-shaped lengthening is used. Direct amputation can be used for an inelastic adductor muscle. During the separation surgery, the ulnar neurovascular bundle of the thumb and the radialis neurovascular bundle of the index finger between the first and second metacarpal bones must be protected using cross fixation with 1.2-mm Kirschner wires or external fixation. The first web space should be sufficiently large after the surgery. The wound surface of the first web space can be repaired with an interosseous dorsal island flap, radial artery perforator flap or groin skin flap. External fixation can be removed in the fourth week, followed by an orthosis used for the first web space for the next 3 months.

Severe contractures: These contractures involve a very wide area of the hand and affect the skin, soft tissue of the first web space and intrinsic muscles and may even be associated with multiple comminuted fractures of the palm. Repair of these wounds often requires multiple surgeries, resulting in extensive scar tissue formation and a poor condition of the local blood vessels and soft tissue. A longitudinal incision and release of the tissues between the first and second metacarpal bones should be conducted to open the first web space in patients with severe contractures. During the process of tissue release, the contracture scars and inelastic muscle tissues must be cut while the neurovascular bundles of the thumb and index finger should be protected. In addition, minor external fixation between the first and second metacarpal bones is used. When the thenar eminence and abductor pollicis longus muscles are damaged, radial abduction and initiative adduction of the thumb must be prevented. Restoration of the abductor function of the thumb must then be undertaken. The wound surface of the first web space can be repaired using flaps, such as an interosseous posterior artery flap, a pedicle flap or a free flap.

12.6.2 Reconstruction Procedure

Mild or intermediate contractures: Local turndown flap, four or five first web plasty, index finger dorsolateral flap or radialis rotation flap can be used for repair of congenital contractures of the first web space.

Intermediate or severe contractures: Interosseous dorsal island flap or radial artery perforator flap is used to correct post-traumatic contractures.

Severe contractures: Pedicled groin flap, free dorsalis pedis flap, anterolateral thigh flap, etc., can be used to treat this type of contractures.

12.6.3 Index Finger Dorsolateral Flap

12.6.3.1 Flap Design

Flap axis: This is the surface projection of the first dorsal metacarpal artery.

Rotation point: This point is the intersection of the extensor pollicis longus muscle tendon and the radial side of the second metacarpal.

Anatomical plane: The upper boundary of the flap is the proximal interphalangeal joint of the index finger, and its lower boundary is the dorsal carpal. Both sides reach the lateral line.

12.6.3.2 Surgical Procedure

After release of the contracture tissue, a flap is cut along the lateral ulnar margin as designed. The surgical site is incised in layers to expose the entire dorsal digital aponeurosis. Then, a flap is cut along the radial border, and the subfascial flap including the dorsal digital artery of the first dorsal metacarpal artery is dissected. When the incision reaches the proximal side, the flap is rotated to cover the wound surface if possible. Otherwise, an adequate flap is cut along the axis line and dissociated from the pedicle. The myolemma of the first dorsal interosseous may be included in the flap. The flap is rotated with an adequate isolated length to cover the wound surface. Finally, a full-thickness skin graft is harvested from the donor site for free grafting (Fig. 12.5).

Fig. 12.5 The index finger dorsolateral flap. (**a**) Designing the index finger dorsolateral flap (radialis side). (**b**) Harvesting the index finger flap, only the vascular pedicle connected. (**c**) Flap covering the thumb and releasing the wound

12.6.4 Nasopharyngeal Fossa Pedicle Island Flap

12.6.4.1 Flap Design

Axis line: This is a line connecting the processus styloideus radii to capitulum radii when the forearm is in the neutral position.

Rotation point: This is the midpoint of the nasopharyngeal fossa.

Anatomical plane: The width of the flap is equally distributed on both sides of the axis. The length of the flap is 12–15 cm, and its width is 3–5 cm.

12.6.4.2 Surgical Procedure

To release the contracture tissue, a flap must be cut from the proximal to the superficial subcutaneous fascia in accordance with the flap design. The cephalic vein and superficial radial nerve are contained within the skin flap. During flap dissection, a tunnel is opened near the superficial subcutaneous tissue. With the nasopharyngeal fossa as the midpoint, the flap is rotated to cover the first web space. Adequate drainage should be provided for the flap. Finally, a full-thickness skin graft is harvested from the donor site for free grafting (Fig. 12.6).

Fig. 12.6 The nasopharyngeal fossa pedicle island flap repairing the defect by correct first web space contracture. (**a**) The first web space severe contracture with the proximal phalanx of the thumb exposed. (**b**) Palmar contracture scar. (**c**) Widening the first web space and designing the nasopharyngeal fossa pedicle island flap. (**d**) The flap covering the first web space and the exposed bone of the thumb bone. (**e**) Six months follow-up

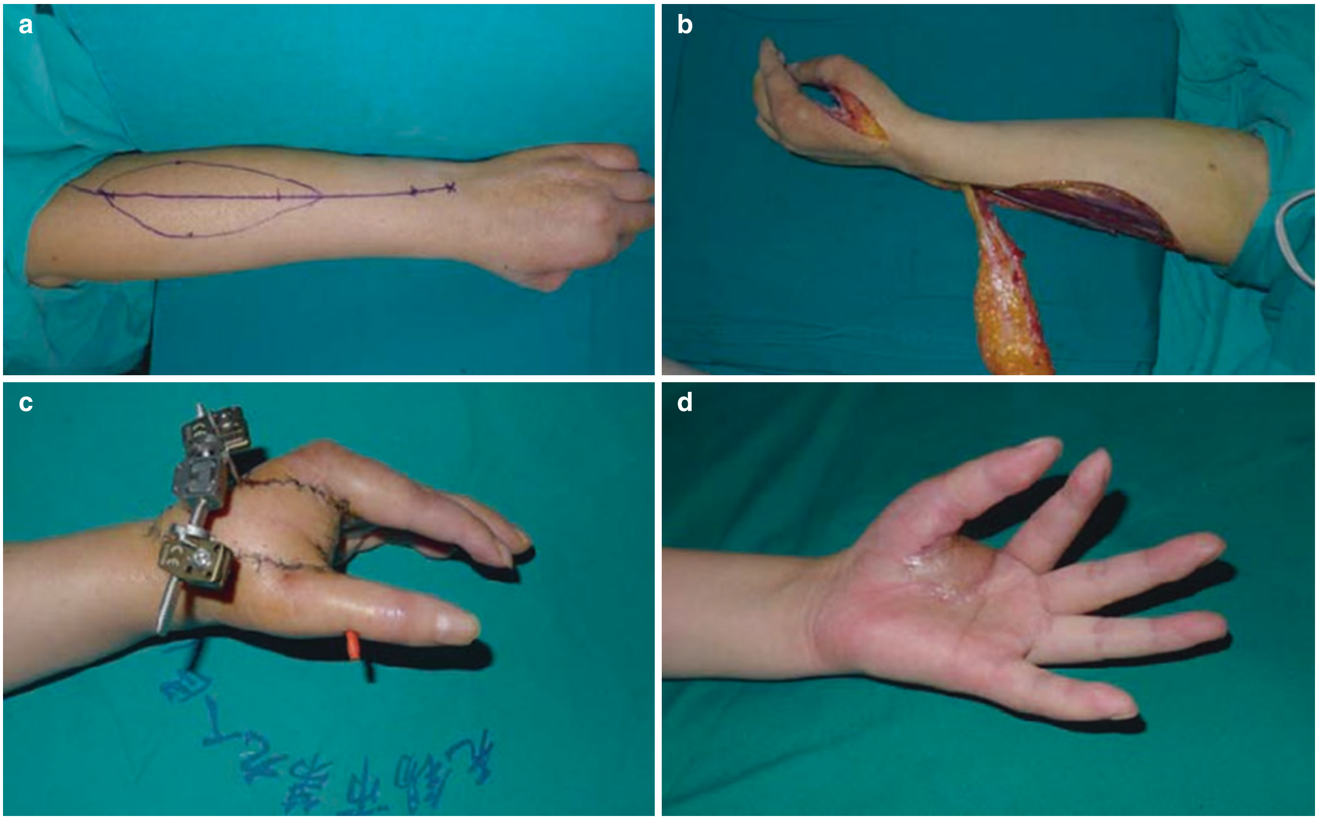


Fig. 12.7 The interosseous dorsal island flap repairing the defect by correct first web space contracture. (**a**) Designing the interosseous dorsal island flap. (**b**) Widening the first web space, the flap free completely. (**c**)The first web space was repaired by the flap with external fixed bracket maintenance the space between 1, 2 metacarpals. (**d**) Six months follow-up

12.6.5 Interosseous Dorsal Island Flap

12.6.5.1 Flap Design

Flap axis: This is a line connecting the lower 2/3 of the epicondyle of the humerus to the radial margin of the capitulum ulnae when the forearm is in pronation.

Rotation point: This point is located 2.5 cm above the styloid process of the ulna.

12.6.5.2 Surgical Procedure

The skin of the flap pedicle and the fascia of the forearm are incised, and the tissue is isolated to reveal the arteria interossea dorsalis between the extensor carpi ulnaris muscle and the extensor tendon of the little finger. A 1.5-cm-wide portion of the fascia is retained within the flap, and the skin, subcutaneous tissue and fascia on both sides of the flap are incised. Interrupted sutures are placed in the deep fascia and subcutaneous tissue to protect the integrity of the blood supply of the flap during dissection. The artery and its accompanying vein are ligated at the point where the arteria interossea dorsalis punctures the skin, in order to protect the posterior interosseous nerve. The flap is then rotated through the subcutaneous tissue or by opening a tunnel, and used to repair the wound. The donor site can be repaired directly or using skin grafting, depending on the width of the flap (Fig. 12.7).

12.6.6 Dorsalis Pedis Flap

12.6.6.1 Flap Design

Flap axis: This is a line connecting the midpoint between the medial and lateral malleolus and point B between the first and second toe web spaces.

Cutaneous branches piercing point: This is a point where the dorsalis pedis pulse is palpated.

Anatomical plane: The flap is designed according to the area and appearance of the recipient skin defect, using the dorsalis pedis as the axis. Since dorsalis pedis flaps show more shrinkage after harvest than most chest and abdomen flaps, they should be designed as 1 cm larger than the area of the recipient skin defect. The length of the flap should not exceed that of a line connecting the lower edge of the extensor retinaculum and the toe web space. The width of the flap should not exceed the inner and outer edges of the dorsalis pedis.

12.6.6.2 Surgical Procedure

The skin and subcutaneous tissue are incised from the proximal flap to the surface of the toe extensor paratenon. The great saphenous vein is isolated from the inside of the incision and transected. Its branches are ligated beyond the outer limit of the flap, taking care to keep the venous network within the dorsalis pedis flap intact. The soft tissue and skin are closed with interrupted sutures to prevent separation of the dorsalis pedis vessels and the flap when the skin flap is stripped. The tendon and lower part of the muscle belly of the extensor hallucis brevis are transected at the point where the first dorsal metatarsal artery and the deep branch of the plantar artery are located. If the first dorsal metatarsal artery is superficial, it can be retained in the flap. However, if this artery is deep, it can be divided and ligated. At the proximal end of the flap, the extensor hallucis longus tendon and extensor digitorum longus tendon cover the dorsalis pedis artery and its accompanying veins and the superficial peroneal nerve at the anterolateral aspect of the ankle. Separation of the dorsalis pedis artery and accompanying veins should be performed close to the periosteum and joint capsule. The blood supply to the flap depends on a section of the dorsalis pedis artery and its branches, which originate below the extensor band to the crotch of deep plantar branch. Therefore, if the connection of the dorsalis pedis artery and vein to the flap is kept intact, the flap will receive sufficient blood supply. The separation should be continued from the proximal to the distal direction to find the deep plantar branch of the dorsalis pedis artery in the proximal part of the first intermetatarsal space, where this branch is cut and ligated. At this point, the entire dorsal pedis flap is supplied solely by the dorsalis pedis vascular pedicle, the superficial peroneal nerve and the great saphenous vein connecting to the proximal. The tourniquet is loosened to observe whether the blood circulation of the flap is good.

The recipient site is debrided to expose its artery and vein and cutaneous nerve. If the recipient wound is in the opisthenar region, an incision is made from the wrist nasopharyngeal fossa to expose the radial artery and its accompanying veins, the cephalic vein and the superficial radial nerve. A loose subcutaneous tunnel for the opisthenar wound is prepared. Depending on the desired length of the vascular pedicle, the dorsalis pedis artery and its accompanying veins, the great saphenous vein and the superficial peroneal nerve are transected at a suitable point at the donor site. Thus, the entire dorsalis pedis flap with its neurovascular pedicle is completely separated from the surrounding tissues. The dorsalis pedis skin flap is immediately grafted to the recipient wound. The neurovascular pedicle is grafted through a subcutaneous tunnel for anastomosis with the recipient vessels and nerve. Then, 8-0 or 9-0 noninvasive sutures are used to establish an end-to-end anastomosis between the great saphenous vein of the flap and the cephalic vein of the wrist. The superficial peroneal nerve is sutured to the proximal part of the superficial radial nerve, and 9-0 noninvasive sutures are used to establish an end-to-end anastomosis between the dorsalis pedis artery and the radial artery. The tourniquet should then be loosened to observe the blood circulation of the flap. A flap with a dull red color indicates presence of a blood flow reflux. In this case, 9-0 noninvasive sutures should be used to make an end-to-end anastomosis between the accompanying veins of the radial artery and the accompanying vein of the dorsalis pedis artery. Alternatively, another vein should be identified at the edge of the flap and anastomosed with the veins at the edge of the recipient wound to improve the blood flow reflux in the flap. After the flap has recovered blood circulation, the wounds are sutured, and a rubber drainage tube is placed. A fenestrated dressing should be used to cover the flap, so that the blood circulation of the flap can be observed. The wound should also be fixed with a plaster slab (Fig. 12.8).

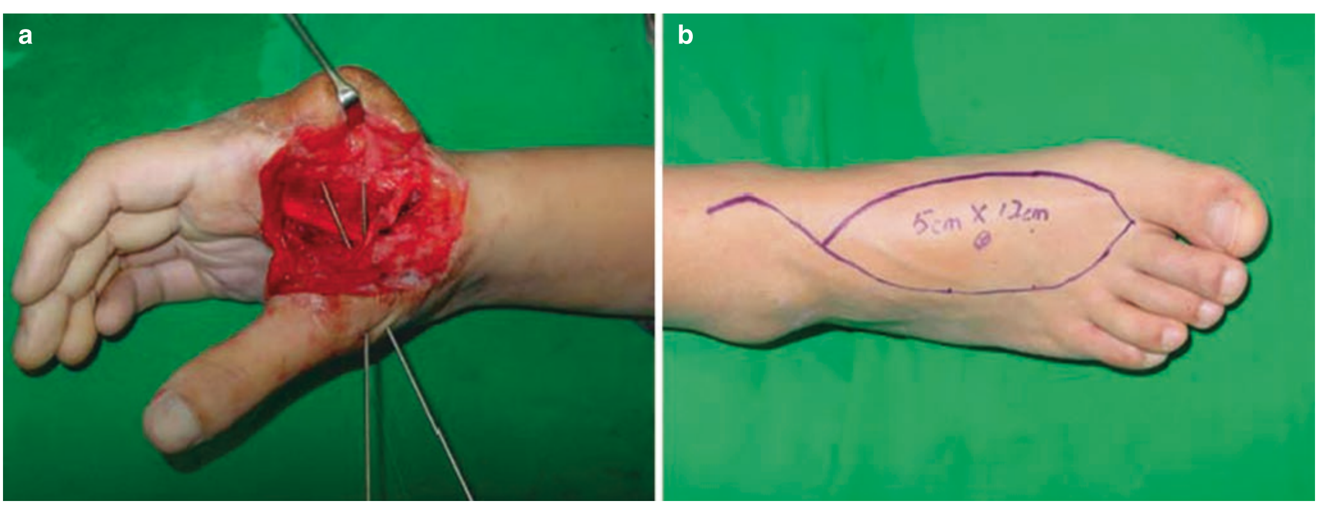


Fig. 12.8 The free dorsalis pedis flap repairing the defect by correct first web space contracture. (**a**) The soft tissue defect of first web space. (**b**) Designing the free dorsalis pedis flap. (**c**, **d**) Postoperative conditions of recipient site and donor site. (**e**, **f**) Thumb abduction and flexion function 7 months after surgery

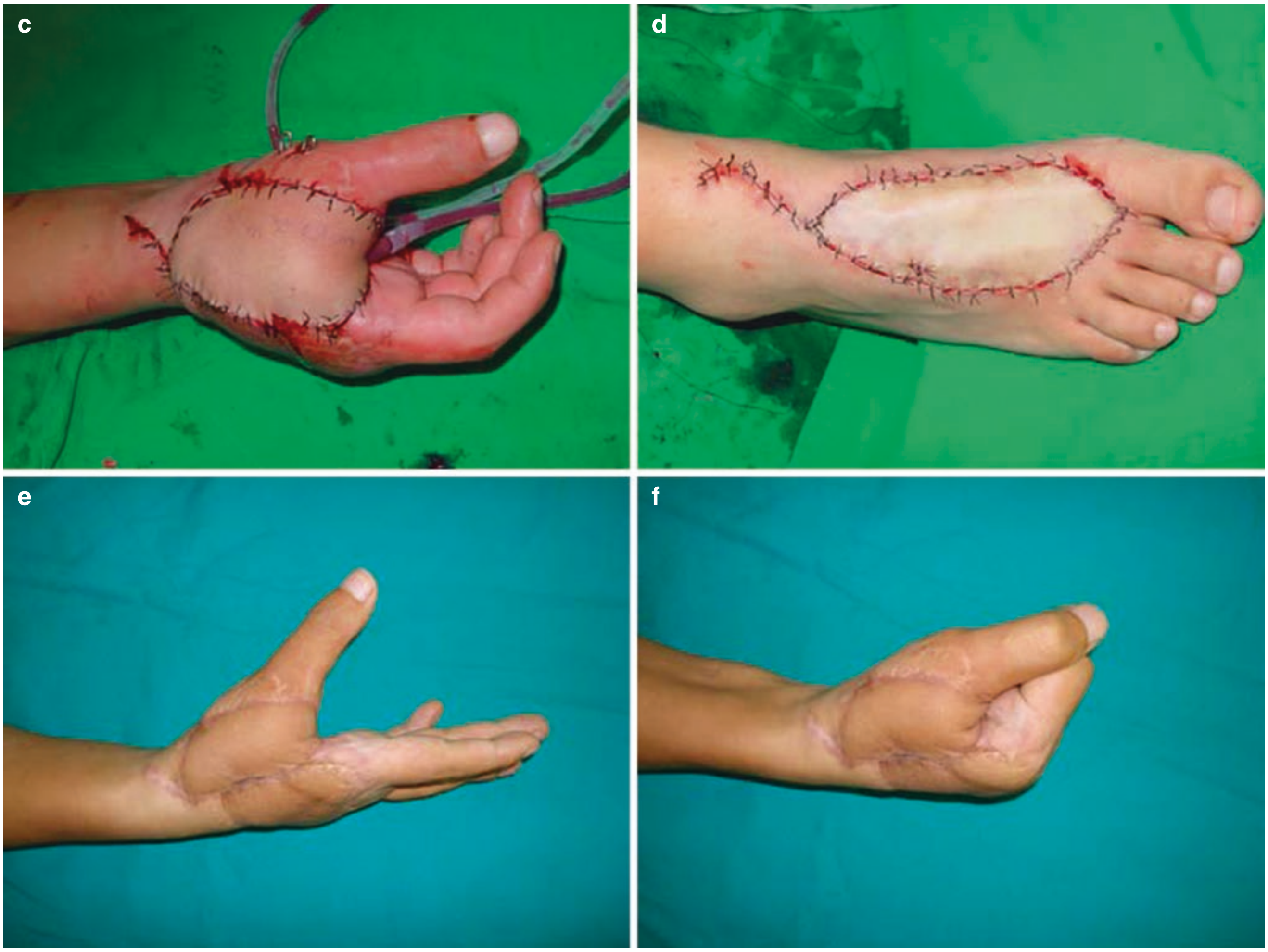


Fig. 12.8 (continued)

After harvesting the dorsal pedis flap and achieving complete hemostasis, a full-thickness skin graft should be used to repair the donor-site wound. The area should also be fixed with a short leg plaster slab.

12.6.7 Radial Artery Perforator Fascial Flap

12.6.7.1 Flap Design

Flap axis: The axis is the projection of the radial artery arranged, according to the situation, to allow a slight offset.

Rotation point: This point is located 1.5–2 cm from the processus styloideus radii.

12.6.7.2 Surgical Procedure

The flap is cut from the proximal to the superficial part of the subcutaneous and deep fascia according to the flap design. Some perivascular protective tissues are retained. The skin flap together with the subcutaneous fascia is freed from proximal to distal until 1.5–2 cm near the processus styloideus radii. The width of the separated flap pedicle is approximately 1.5 cm. During flap separation, the multi-branched radial artery perforators can be found. The proximal perforator can be ligated. The perforators near the pedicle should be retained to facilitate flap survival. The flap should be rotated in a retrograde fashion to cover the wound after flap separation has been completely achieved. Depending on the patient's requirements, this flap can be converted to a fascia flap. The flap can be prepared with or without a skin pedicle.

12.7 Microsurgical Repair of Soft-Tissue Defects of the Fingers

12.7.1 Soft-Tissue Defects of the Thumb

12.7.1.1 Principles of Repair

The movements of the thumb include radial abduction, palmar abduction and opposition to the fingers. The laxity of the first web space and the unique saddle shape of the trapeziometacarpal or the first carpometacarpal joint contribute to the mobility of the thumb. The functions of the thumb account for 40–50% of those of the hand. The primary goals of thumb reconstruction are to restore movement, sensation and appearance.

12.7.1.2 Methods of Repair

Soft-Tissue Defects of the Thumb Tip

Soft-tissue defects of any shape on the pulp or nail bed of the thumb can be covered by various flaps. Modified local advancement flaps are reliable and dependable methods to cover soft-tissue defects less than 1 cm in length. Homodigital island flaps and nail bed lengthening are preferred alternatives for covering soft-tissue defects less than 1.5 cm. Nail bed avulsion or defect may be restored using in situ nail bed sutures with or without nail bed lengthening.

Thumb Pulp Defects

The primary goal of thumb pulp defect reconstruction is to restore sensation. The Brunelli flap or first dorsal metacarpal artery island flap are reliable methods to cover thumb pulp defects. Hemipulp free flap from the great toe is a preferred choice for covering total thumb pulp defects (Fig. 12.9).

Fig. 12.9 Homodactyly ulnar anterograde island flap and nail bed enlargement surgery. (**a**) The wound of thumb fingertipe and design of the flap. (**b**) 1/3 of the nail bed defect and the enlarged design of the nail bed. (**c**) The flap was being harvested can be moved 20 mm to the distal end. (**d**) The wound covered by the flap and skin graft. (**e**) After the nail bed enlargement surgery. (**f**) Flap and nail shape after 6 months

12.7.1.3 Modified Local Advancement Flap

Preoperative Planning

A "hatchet" flap is designed on the radial side of the thumb pulp. Z-plasty is applied to the juncture between the proximal thumb pulp and the first web space.

Surgery

The dermis of the flap is cut according to the flap design. The dissection proceeds from the ulnar border of the flap. The digital proper artery and nerve of the thumb are carefully dissected. The digital proper nerve is included in the flap, and the digital proper artery is retained in place. Z-plasty is applied to the proximal flap. The sufficiently dissected flap is partly advanced to cover the soft-tissue defect of the thumb tip. When the soft-tissue defect is combined with a nail bed defect, up to 3–4 mm of the eponychium should be excised for nail bed lengthening.

12.7.1.4 Homodigital Island Flap

Preoperative Planning

A triangular flap, 1.4 cm wide and 1.5–2.0 cm long, is designed on the ulnar side of the thumb-tip defect.

Surgery

The skin over the neurovascular bundle is incised in a zigzag fashion. The proper neurovascular bundle of the thumb on the ulnar side is dissected over the aponeurosis of the flexor digital tendon in the proximal to distal direction. Approximately 4–5 mm of soft tissue around the proper digital artery must be preserved in order to include the venae comitantes in the flap and avoid venous insufficiency of the flap. After deflating the tourniquet is deflated and hemostasis achieved using bipolar coagulation, the flap is advanced in reverse to fill the pulp defect. The donor site at the base of the finger can usually be closed with a full-thickness graft from the medial border of the forearm. A shuttle-like incision, 4–5 mm high and 16 mm wide, is designed between the lunula and the interphalangeal joint, preserving the subdermal vascular network and removing the epidermis. The eponychium is excised, and the incision sutured. The nail bed is lengthened by 3–4 mm.

12.7.1.5 Hemipulp Neurosensory Free Flaps from the Great Toe

Preoperative Planning

Flap design: The hemipulp of the great toe, and if necessary, the dorsal and plantar skin are included in the flap.

Flap axis: This is the boundary between the fibular and plantar sides of the toe.

Anatomical plane: On the fibular side of the toe, a subfascial incision is made around the arteriae metatarseae plantares. On the pulp, a subfascial incision or subdermal incision is made.

Surgery

Hemipulp neurosensory free flaps from the great toe are designed according to the size and shape of the thumb tip defect. The arteriae metatarseae plantares must be connected with the flap. The skin along the boundary between the fibular side and the plantar side of the toe, and the subcutaneous veins are carefully dissected. The digital proper artery and nerve of the thumb are carefully dissected. The donor site is closed with a full-thickness graft. At the recipient site, the first dorsal plantar artery or the toe plantar artery is anastomosed with the proper digital artery, the plantar dorsal vein is anastomosed with the digital dorsal vein, and the plantar nerve is connected with the proper digital nerve (Fig. 12.10).

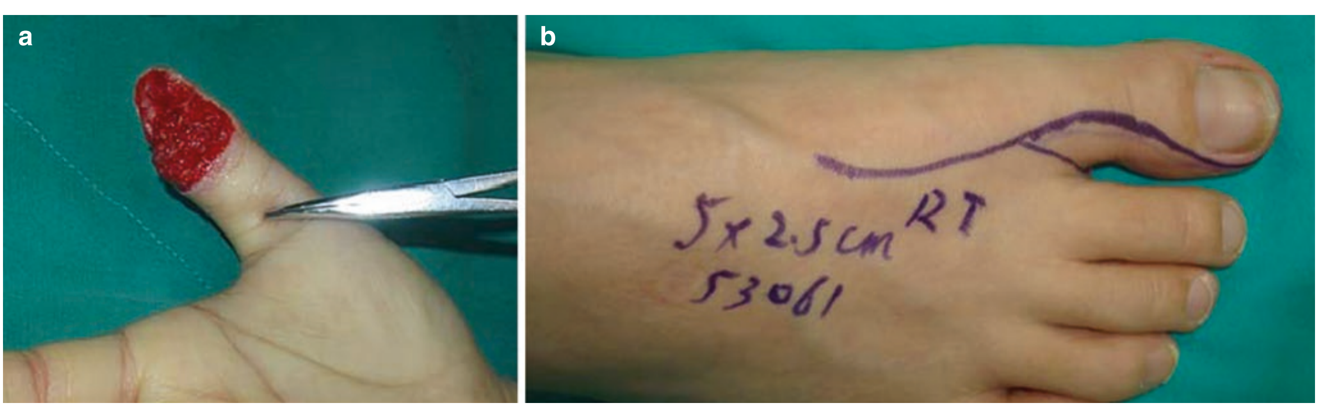


Fig. 12.10 Lateral abdominal the wraparound great toe. (**a**) Thumb pulp defect. (**b**) Designing lateral abdominal the wraparound great toe. (**c**) Freeing the flap. (**d**) Postoperative

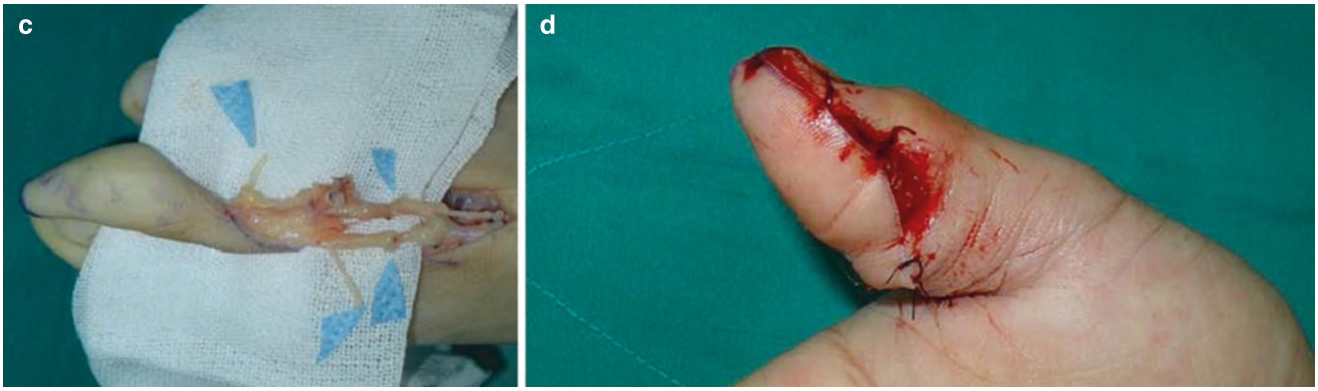


Fig. 12.10 (continued)

12.7.1.6 Island Flap on the Radial Dorsal Thumb

Preoperative Planning

Flap axis: This is the line between the nasopharyngeal fossa and the radial side of the first metacarpophalangeal joint, and can extend far to the radial side of the nail root.

Rotation point: This can be located 0.5 cm proximal to the thumb metacarpophalangeal articulation injury, and as far as the radial side of the interphalangeal joint of the thumb.

Anatomical plane: The flap is dissected over the aponeurosis of the extensor digitorum tendon.

Surgery

The flap is dissected proximally to find the superficial branch of the radial nerve, which is located on the ulnar side of the tendon of extensor pollicis brevis and is cut. Under the deep fascia, the flap is dissected first from the ulnar to the radial side of the tendon of extensor pollicis brevis. The radial cutaneous branches of the first dorsal metacarpal artery are exposed, and the branches of the cephalic vein are ligated. The flap is dissected to become the superficial branch of the radial nerve flap, with the radial cutaneous branches of the first dorsal metacarpal artery as the axis artery. The superficial branch of the radial nerve is anastomosed with the digital proper nerve using 9-0 sutures. The flap is rotated to cover the defect. The donor site is covered with a full-thickness skin graft (Fig. 12.11).

12.7.2 Degloving Injury of the Thumb

For patients over 55 years of age, a pedicle abdominal tube can be used to treat degloving injury of the thumb. Because the pedicle abdominal tube is associated with a lack of sensation, an island flap on the radial side of the ring finger can be applied to rebuild sensation in the thumb pulp. In terms of postoperative function, sensation and appearance, the great toe nail flap is a preferred choice for degloving injury of the thumb (Fig. 12.12).

12.7.3 Wounds on the Palmar Surface of the Fingers

12.7.3.1 Principles of Repair

Sensation must be rebuilt when the defects of the finger pulp are repaired. Frequently used sensory flaps include the heterodigital arterialized flap, homodigital island flap, hemipulp neurosensory free flap from the great toe and dorsal flap of the foot. The sensory nerve, which is cut and contained in the flap, must be anastomosed with the digital nerve at the recipient site.

12.7.3.2 Methods of Repair

In the case of wounds on the palmar surface of the fingers, the flexor tendon can be easily exposed because of the lesser subcutaneous fat and fascial tissues in this region. Flaps used to cover wounds on the palmar surface of the fingers must have sensation and be light. If the wound is not larger than a piece of the finger, a heterodigital arterialized flap, homodigital island flap or reverse dorsal metacarpal artery island flap can be used to cover the wound. If the wound is equal to or more than two pieces of the finger, a free flap can be considered, such as a dorsal flap of the foot and hemipulp neurosensory free flaps from the great toe. If defects are present in multiple digits, hemipulp neurosensory free flaps from the great or second toe or a lobulated flap of the dorsum pedis can be applied in a one-stage repair.

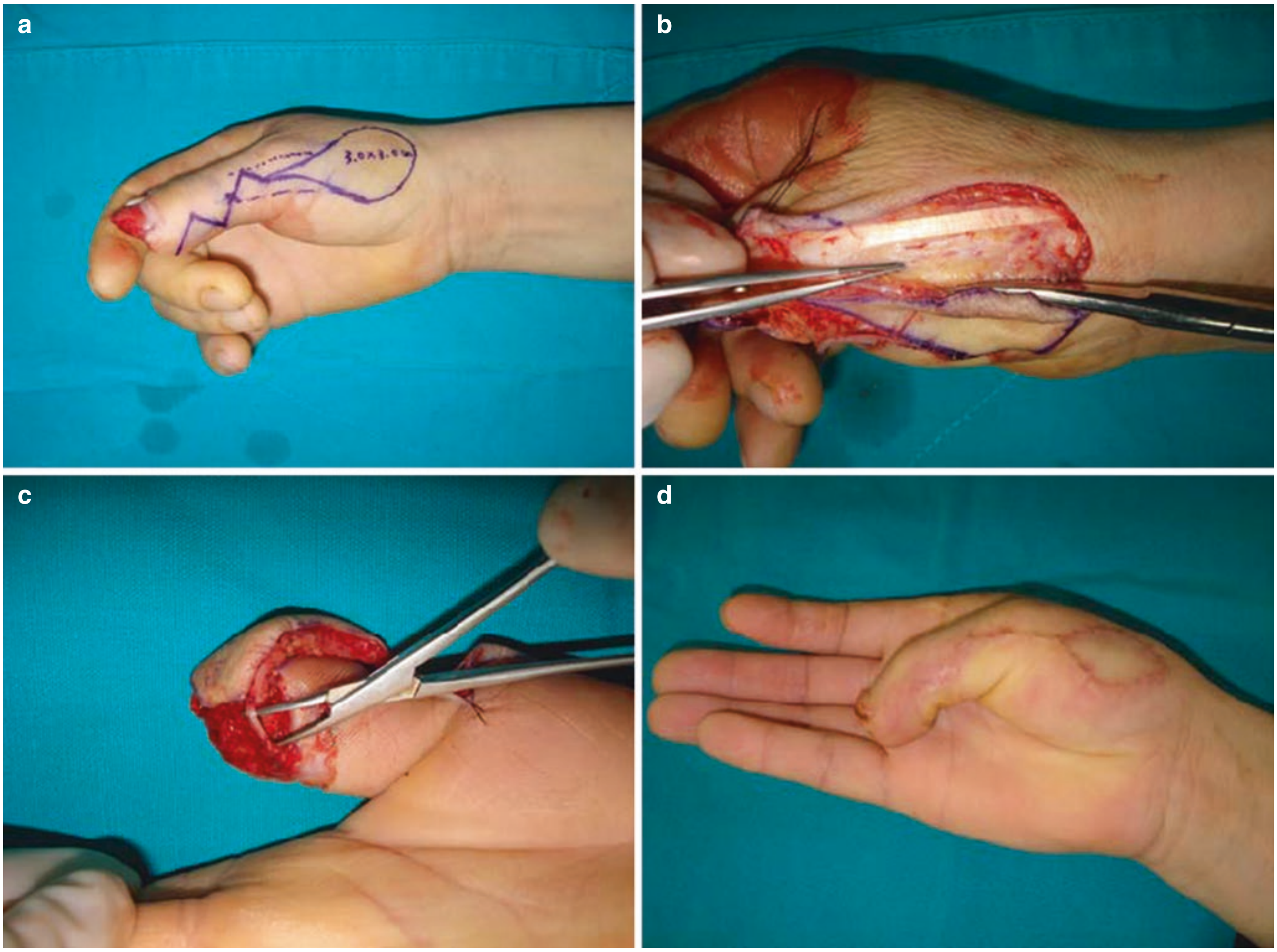


Fig. 12.11 First dorsal metacarpal flap repairing abdomen thumb defect. (**a**) Designing the first dorsal metacarpal island flap. (**b**) Exposing the first dorsal metacarpal artery. (**c**) The superficial branch of the radial nerve is anastomosed with the digital proper nerve. (**d**) Good joint function after flap repair

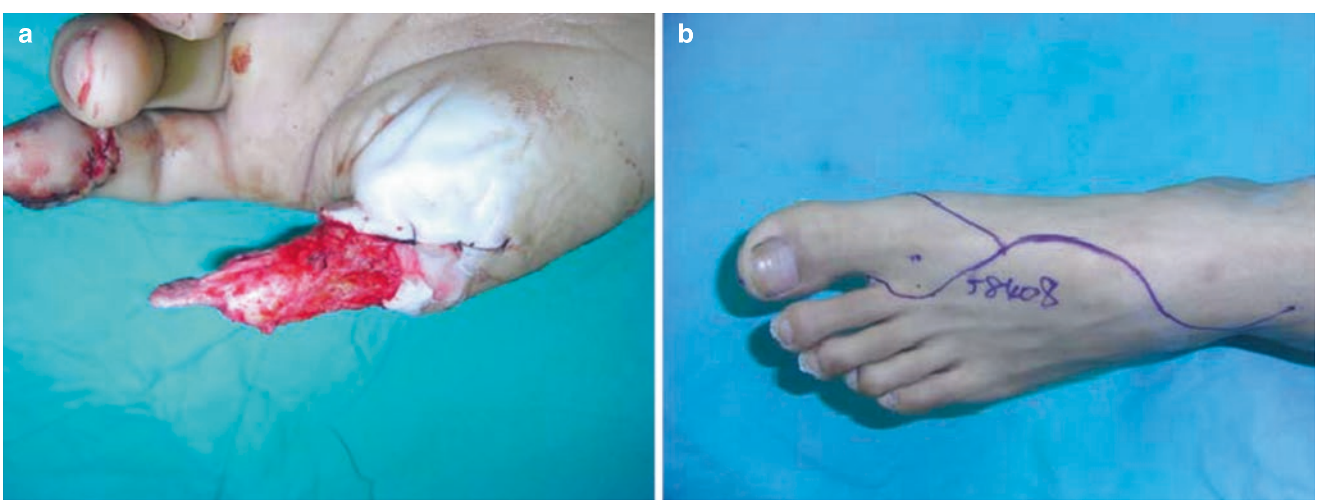


Fig. 12.12 The wraparound great toe repairing degloved injury of the thumb. (**a**) The degloved injury of the thumb. (**b**) Designing the wraparound great toe. (**c**) The appearance of the thumb after surgery. (**d**) Thumb-to-finger function

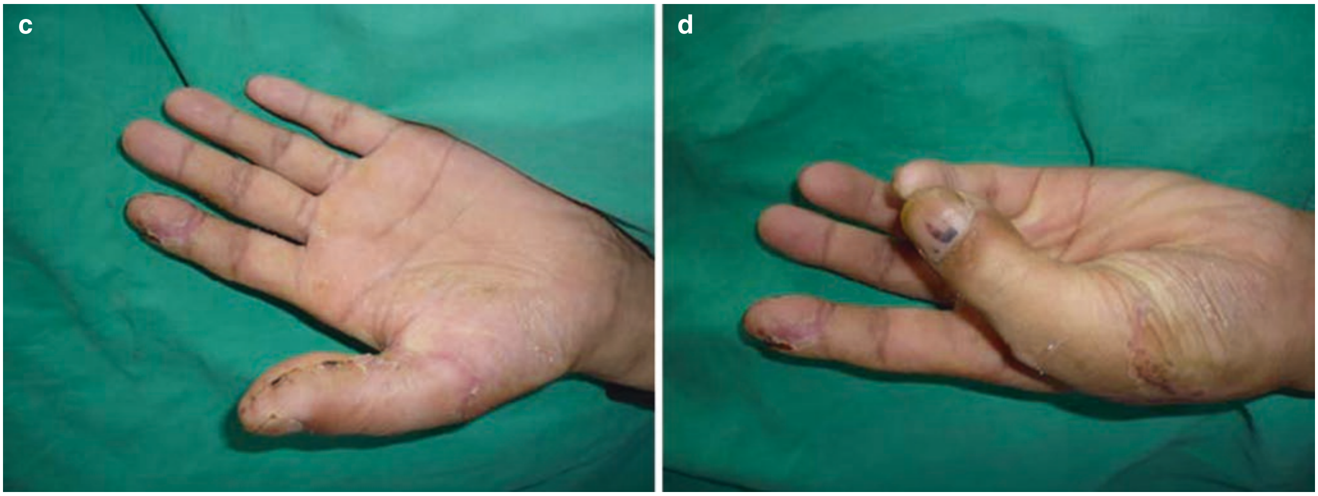


Fig. 12.12 (continued)

12.7.3.3 Reverse Dorsal Metacarpal Artery Island Flap

Preoperative Planning

Flap axis: This is a vertical line from the midpoint of the finger web edge to the dorsum of the hand.

Rotation point: This is located 1.5 cm proximal to the finger web edge, where there is an intersection between the common palmar digital arteries and their anastomotic branches.

Anatomical plane: The flap dissection plane is located between the aponeurosis of the extensor digitorum tendon and the deep fascia. The pedicle of the dorsal metacarpal artery is dissected between the deep fascia and the sarcolemma. The flap can be cut from the transverse wrist crease proximally to the finger web edge distally, with both sides of the flap being within 2.5 cm of the flap axis.

Surgery

The skin over the pedicle of the dorsal metacarpal artery is incised in a zig-zag fashion. The flap is dissected between the extensor digitorum tendons, taking care to preserve 10 mm of the soft tissue around the artery. After the anastomotic branches are found, the flap is harvested. After the flap is dissected, the subcutaneous tissue and deep fascia are closed with interrupted sutures to prevent avulsion. The dorsal branch of the digital proper nerve is anastomosed with the digital proper nerve. The extensor tendon and aponeurosis of the ring and little fingers and half of the extensor tendon and aponeurosis of the index and middle fingers can be included in the flap to rebuild the tendon. The base of the metacarpus can also be included in the flap. The dorsal carpal arch can be included in longer flaps to ensure sufficient blood supply.

After the flap is completely harvested, the tourniquet should be released, and the origin of the dorsal metacarpal artery should be clamped to observe the blood supply to the flap. The origin of the dorsal metacarpal artery is ligated if the flap is observed to have a rich blood supply. The flap is reversed through the fingerweb tunnel to cover the finger defect. The donor site is covered with a full-thickness skin graft if the width of the donor site exceeds 2 cm.

12.7.3.4 Reverse Branch of Dorsal Metacarpal Artery Island Flap

Preoperative Planning

Flap axis: This is a vertical line from the radial border of the second metacarpal head to the midpoint of the second, third and fourth finger web edges on the dorsum of the hand. **Rotation point**: This is the midpoint of the line connecting the adjacent metacarpal heads, marking the intersection between the cutaneous dorsal metacarpal artery and the dorsal metacarpal artery. This point can be located also 1.5 cm proximal to the finger web edge.

Anatomical plane: The flap dissection plane is located over the deep fascia. In the case of flaps including the extensor tendon, the flap dissection plane should be under the deep fascia and include the aponeurosis of the extensor digitorum tendon. The flap can be cut from the transverse wrist crease proximally to the finger web edge distally, with both sides of flap being within 1.5 cm of the flap axis.

Surgery

The surgical procedure is the same as that for reverse dorsal metacarpal artery island flap. However, the flap dissection plane should be much deeper (Fig. 12.13).

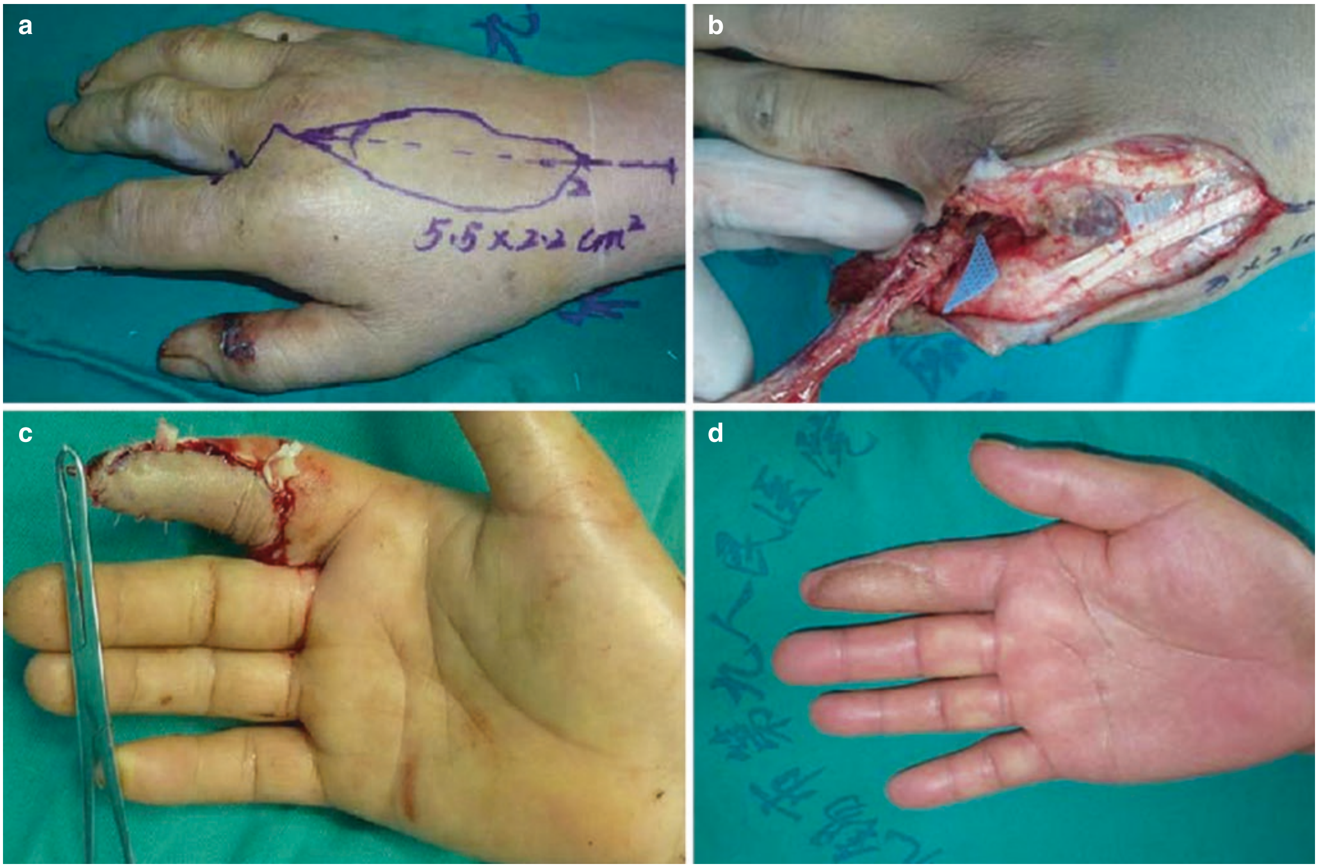


Fig. 12.13 The dorsal metacarpal artery flap repairing the soft tissue defects of fingers. (**a**) Designing the dorsal metacarpal artery flap. (**b**) Exposing perforating artery in metacarpus. (**c**) Instant appearance after flap repair. (**d**) Postoperative reexamination

12.7.3.5 Hemipulp Neurosensory Free Flaps from the Great and Second Toes

Preoperative Planning

The vascular pedicle of the flap is designed according to the shape, size and location of the defect. The length and width of the flap must be 0.5 cm greater than those of the defect.

Surgery

An arched incision is made along two sides of the flap and the back side of the toe web. The flap is dissected subcutaneously, and 10 mm of soft tissue along the incision is preserved. The toe dorsal digital veins, which have a smaller caliber and are located under the dermis, are dissected up to the toe web. The second toe dorsal digital veins of the foot, which converge into the great saphenous vein, are dissected using the same method. The first metatarsal dorsal artery (Gillbert I, II) and hemipulp flaps from the great and second toe are dissected. In the case of Gillbert III, the common plantar digital artery is dissected. Then, the toe artery and nerve are dissected. Thus, hemipulp flaps from the great and second toes pedicled with the first metatarsal dorsal artery or common plantar digital artery are completely dissected.

After isolation of the required length of the vascular pedicle, hemipulp flaps from the great and second toes can be used to cover the defect on the fingers through a subcutaneous tunnel. The first metatarsal dorsal artery or common plantar digital artery is anastomosed with the common digital palmar artery or proper palmar digital artery. The toe dorsal digital veins are anastomosed with the dorsal metacarpal veins. The toe nerve is anastomosed with the finger nerve (Fig. 12.14).

12.7.3.6 Perforator Flap of the Digital Proper Artery of the Distal Interphalangeal Joint

Preoperative Planning

In the case of perforator flaps of the digital proper artery, the perforator is localized at the intersection of the body surface projection of the digital proper artery and the distal finger crease. For retro-antegrade advancement flaps, the perforator point of the digital proper artery serves as the rotation axis on the wound side. The median line of the lateral fingers serves as the central axis. V-shaped flaps are designed to suit the wound. For reverse flaps, the perforator point of the digital

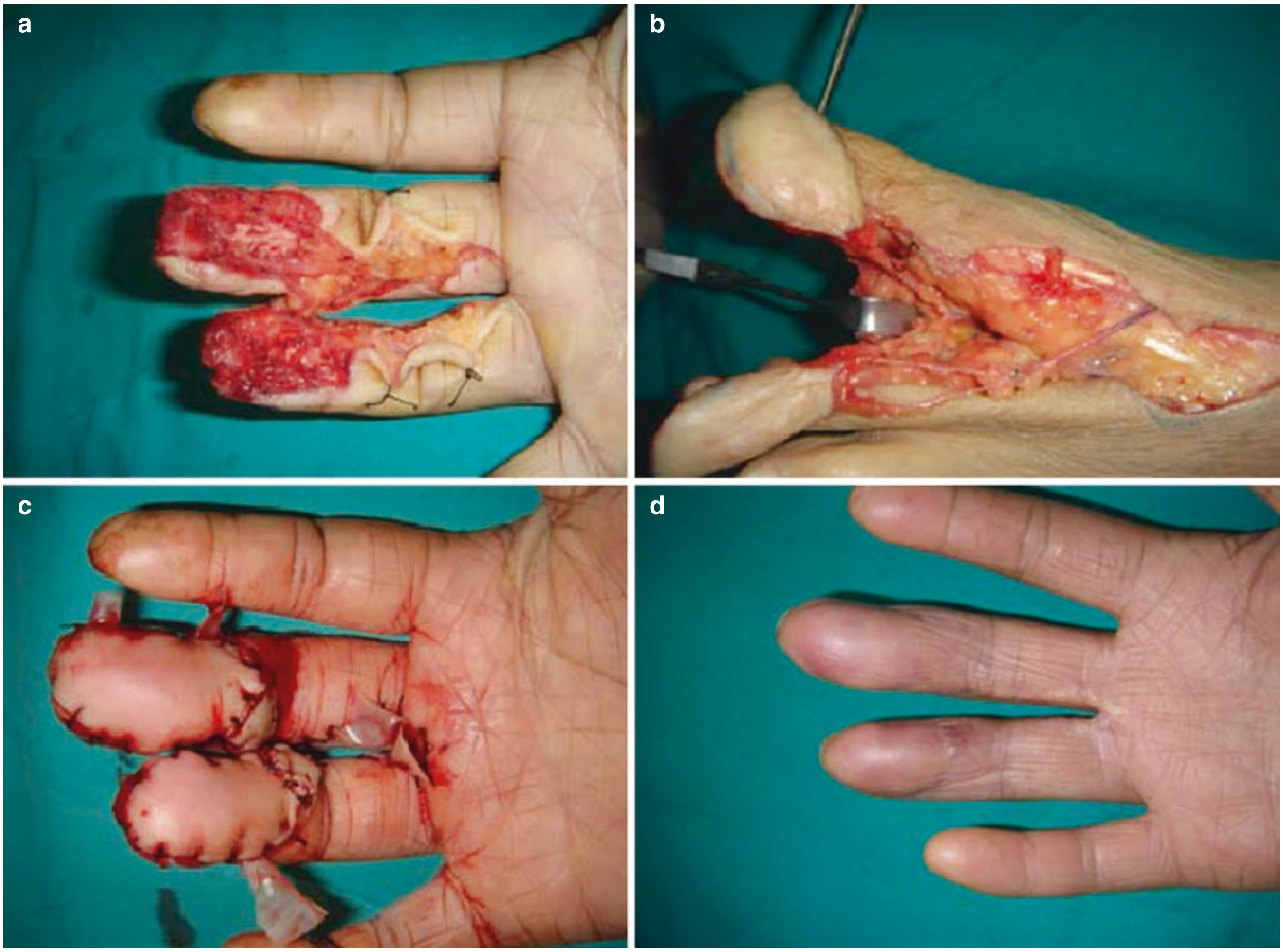


Fig. 12.14 The hemipulp neurosensory free flaps from the great and second toes repairing the defects of finger plup. (**a**) Soft tissue defects of middle and ring finger plups. (**b**) Designing the hemipulp neurosensory free flaps from the great and second toes. (**c**) Freeing the flap. (**d**) The appearance of the fingers after surgery

proper artery serves as the rotation axis on the wound side, and a line 30° to the median line of the lateral fingers serves as the central axis. The scope of flap is proximal to the proximal interphalangeal joint, with both sides to the center line on finger lateral.

Surgery

The skin over the neurovascular bundle is incised in a zig-zag fashion. The proper neurovascular bundle is dissected in the proximal to distal direction. The perforator of the digital proper artery can be found around the distal interphalangeal joint (Fig. 12.15). Retro-antegrade advancement flaps contain the digital proper nerves. Reverse flaps include the dorsal digital nerves. The flap is dissected over the aponeurosis of the extensor digitorum tendon, and 2–3 mm of soft tissue around the proper digital artery is preserved to include the venae comitantes in the flap and avoid venous insufficiency of the flap. Reverse flaps must be rotated by 150°–180° to cover the defect. The dorsal branch of the digital proper nerve is anastomosed with the digital proper nerve using 9-0 sutures. The donor site is covered with a full-thickness skin graft.

12.7.3.7 Reverse Homodigital Island Flap

Preoperative Planning

The flap is designed on the lateral proximal finger (index finger, middle finger and ring finger on the ulnar side; little finger on the radial side). The area of the flap is slightly larger than that of the wound. The skin over the neurovascular bundle is incised in a zig-zag fashion. The rotation axis is around the distal interphalangeal joint.

Surgery

The flap is dissected recessively from the distal end. The proper neurovascular bundle of the finger and the dorsal branch of the digital proper nerve are identified. The former is ligated, and the latter is cut. The skin over the

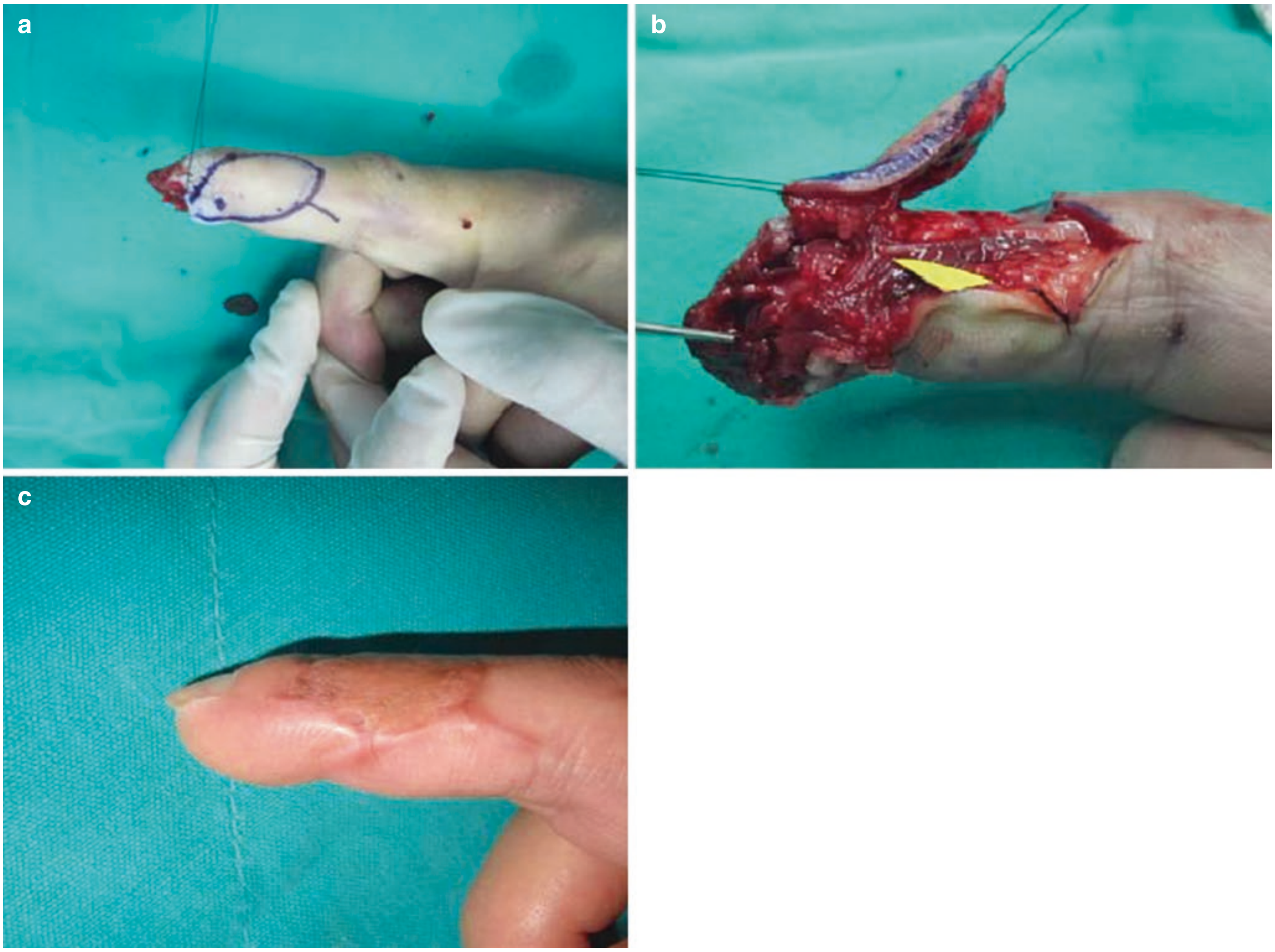


Fig. 12.15 Perforator flap of the digital proper artery of the distal interphalangeal joint (Reverse). (**a**) The design of the reverse flap. (**b**) Exposuring the perforator intraoperative. (**c**) The appearance of the finger after surgery

neurovascular bundle is incised in a zig-zag fashion. The proper neurovascular bundle of the finger is dissected over the aponeurosis of the flexor digital tendon in the proximal to distal direction, and 4–5 mm of soft tissue around the proper digital artery is preserved to include the venae comitantes and avoid venous insufficiency of the flap. The rotation axis is around the distal interphalangeal joint. The dorsal branch of the digital proper nerve is anastomosed with the digital proper nerve on the opposite side. The skin is sutured. The donor site is covered with a full-thickness skin graft. A V-shaped incision is used to reduce the risk of linear contracture (Fig. 12.16).

12.7.3.8 Lobulated Flap of the Dorsum Pedis

Preoperative Planning

To prepare a trilobed flap of the dorsum pedis, the dorsalis pedis artery should first be perceived on the dorsum pedis. Then, the flap should be designed according to the area of the wound, and should be located outside the extensor digitorum brevis, inside the tuberosity of the navicular bone and between the first and second metatarsals. In the case of bilobed flaps, one flap is located between the first and second metatarsals, and the other flap is located outside the extensor digitorum brevis or inside the tuberosity of the navicular bone. Flaps located outside the extensor digitorum brevis have longer vascular pedicles.

Surgery

A tourniquet is applied. The skin on the dorsalis pedis artery is cut, and then the extensor retinaculum is cut. The dorsalis pedis artery can be found between the extensor digitorum longus tendon and the extensor hallucis longus tendon. The dorsalis pedis artery should be followed inferiorly to locate a branch of the artery with a diameter of 0.5 mm or more. For flaps on the lateral dorsum of the foot, the artery is located under the extensor digitorum longus, and this tendon should be kept intact. For flaps between the first and second

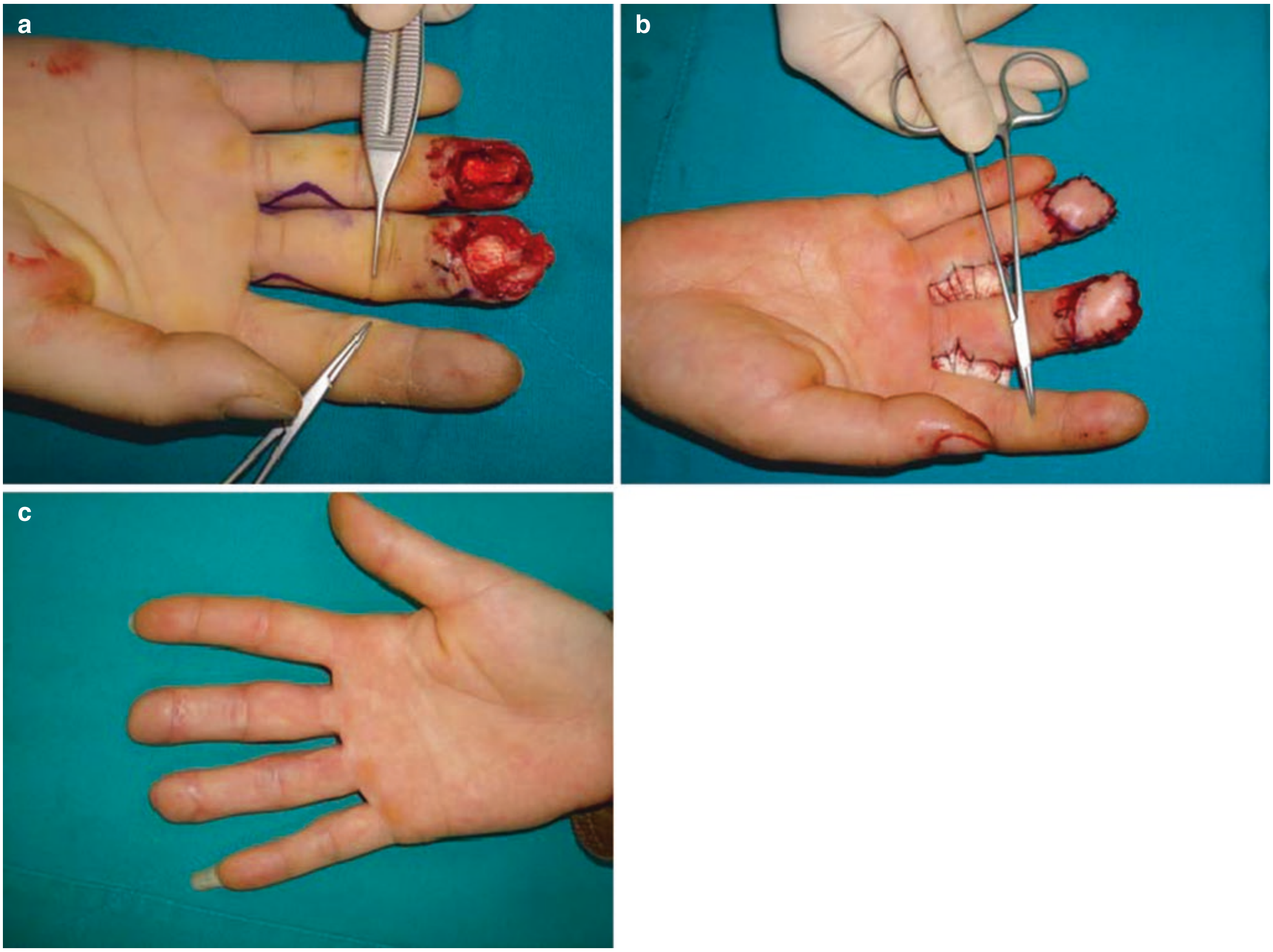


Fig. 12.16 The reverse homodigital island flap. (**a**) Soft tissue defects of middle and ring finger plups. (**b**) Immediately after surgery. (**c**) Good texture of the flap during postoperative re-examination

metatarsal, the extensor digitorum brevis should be cut. For flaps inside the tuberosity of the navicular bone, the artery is under the tendon, and the tendon must be kept intact. Dissection of the vascular pedicle must be carefully performed. The branch of the dorsalis pedis artery along with 5 mm of the surrounding fascia are preserved to ensure venous drainage, depending on the accompanying vein rather than on the great saphenous vein.

After debridement of the hand wound, the lobulated flap is matched with the hand wound. The flap and the vascular pedicle are placed on the hand wound from the vascular anastomosis surrounding the wrist. The vascular pedicle can go through a subcutaneous tunnel or be dissected in the skin by means of Z-plasty, benefiting venous drainage. The radial artery is anastomosed with the dorsalis pedis artery. The vein accompanying the dorsalis pedis artery is anastomosed with the vein along the radial artery or with the cephalic vein. The donor site is covered with a full-thickness skin graft (Fig. 12.17).

12.7.4 Wounds on the Digital Dorsum

12.7.4.1 Principles of Repair

Full-thickness or split-thickness skin grafts can be used for defects without exposed tendons or joints. Considering the skin elasticity required for finger movements, the area of the skin graft should be larger than that of the wound. Pedicle flaps (pedicle abdominal flap and cross arm flaps), island flaps (dorsal metacarpal artery island flap and homodigital island flap) or free flaps (dorsal flap of the foot and hemipulp neurosensory free flaps from the second toe) can be used to cover wounds on the digital dorsum.

12.7.4.2 Methods of Repair

Methods can be divided into two categories. In the first category, the soft-tissue defect is on the middle segment of the finger, and the nail bed is intact. Local flaps or dorsal metacarpal artery island flaps can be used to cover these defects.

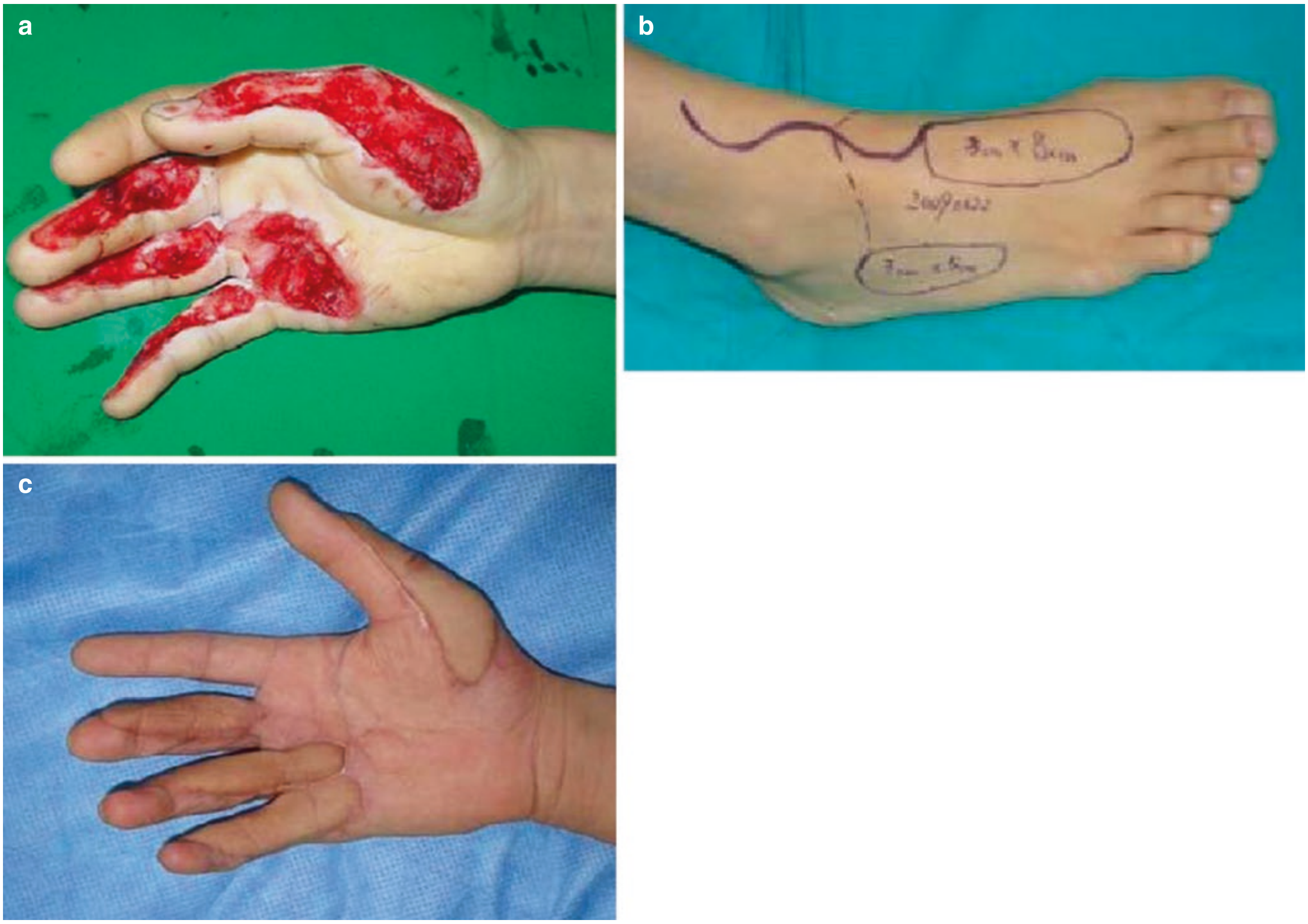


Fig. 12.17 The tri-lobulted flap of the dorsum pedis repairing palmar soft tissue defects of multiple fingers. (**a**) Soft tissue defects of thumb and palmar side of 3–5 fingers. (**b**) Designing the tri-lobulted flap of the dorsum pedis. (**c**) Follow-up

In the second category, the defect involves both the nail bed and the middle segment of the finger. Hemipulp neurosensory free flaps from the toe can be used to reconstruct the nail bed. Pedicle abdominal flaps or digital dorsal fascial vascular pedicled island flaps can be used to cover middle-segment defects.

12.7.4.3 V-Y Advancement Flap Pedicled with Dorsal Cutaneous Branches of the Digital Proper Artery

Preoperative Planning

Dorsal cutaneous branches of the digital proper artery originate from segment A (a line connecting the distal interphalangeal joint, midpoint of the middle phalanx and a point 6 mm beyond the proximal finger crease), segment B (a line connecting the midpoint of the proximal phalanx and a point 5 mm beyond the proximal finger crease) and segment C (finger web). Flaps pedicled with the dorsal cutaneous branches of the digital proper artery are designed according to the defect location. Flaps pedicled with segment A branches can be used to cover defects on the dorsal part of the distal interphalangeal joint. Flaps pedicled with segment B branches can be used to cover digital dorsal defects on the middle phalanx and the distal part of the proximal phalanx. Flaps pedicled with segment C branches can be used to cover defects on the middle and proximal parts of the proximal phalanx. V-Y advancement flaps based on the origin of the dorsal cutaneous branches are designed according to the defective area.

Surgery

The skin of the flap is cut according to the flap design. The flap dissection proceeds from the dorsal to the ventral aspect of the finger and is located above the extensor tendon aponeurosis. Dorsal cutaneous branches can be found in segments A, B or C. Dorsal cutaneous branches along with the surrounding 3–4 mm of fascia and dorsal digital nerves are preserved; the rest of the fascia can be cut. To increase the advancement distance, the neurovascular bundle consisting of the dorsal cutaneous branches and dorsal digital nerves should be dissected up to its origin. The flap can be advanced distally to cover the defect. The donor site can be sutured directly.

12.7.5 Degloving Injury of the Hand

12.7.5.1 Principles of Repair

At present, free skin grafting is not used to treat degloving injuries of the hand on account of the likelihood of contracture, insensibility and vulnerability of the graft. Flaps are the best treatment for degloving injuries of the hand.

12.7.5.2 Methods of Repair

Degloving Injury of the Distal Digit

In this type of injury, the insertions of the flexor and extensor tendons are exposed. The degloving injury to the skin, nail, nail bed and neurovascular bundle is usually combined with dislocation of the distal interphalangeal joint which in turn often leads to phalangette osteonecrosis. Finger amputation, rather than flap repair, is the optimal treatment.

Great or second toenail flaps can be considered in young patients who have a high aesthetic requirements and, or without nail.

Degloving Injury of the Distal and Middle Digits

Considering the importance of fingers, amputation should be applied for the ring and little fingers while attempts must be made to salvage the index and middle fingers whenever possible. An abdominal subdermal vascular net flap or a pedicle tube containing vessels is a possible option. Great or second toenail flaps can be considered as they are associated with good postoperative function and appearance. Double or skate flaps from the acrotarsium can be used to repair degloving injuries involving multiple fingers (Fig. 12.18).

Fig. 12.18 The wraparound great toe repairing degloved injury of the fingers. (**a**) Degloving injury of the distal and middle digits of the index finger. (**b**) Using wraparound great toe to repair. (**c**) Immediately after surgery. (**d**) Postoperative finger function

12.8 Treatment of a Degloved Hand

All hand-skin sleeve avulsions are severe traumas requiring hand surgery. In the past, amputation was recommended for this type of injuries because their treatment was difficult and outcomes were poor. It is possible to completely embed the injured hand in the abdomen for 4–8 weeks until the granulation tissue has covered the entire hand. Then, a split- or full-thickness skin graft can be used to repair the injury. However, since this method results in a prolonged treatment duration, a low skin survival rate, considerable suffering, scarring and joint stiffness, it is far from ideal. Currently, this method has been largely abandoned. Since 1997, a combination of tissue transplantations is used to treat the degloved hand. The procedures are as follows: preoperative preparation (sub-emergency) is made in 5–7 days, according to the requirements and general conditions of the patient and the wound condition as well. It involves a combination of transplantation techniques used to repair the hand. Three different approaches are available for the repair. First, free tissue surrounding the whole hand is used to surface the wound. Second, a wrapped-around flap is used to reconstruct the thumb, and two flaps are used to cover the rest of the wound and reconstruct the grasp and pinch functions. Third, the wrapped-around flap is used to reconstruct the thumb, and the second and third toes are transplanted to reconstruct the index and middle fingers to recover the grasping and pinching functions. Finally, multiple flap transplantations are performed to surface the wound.

12.9 Principles of Repair

12.9.1 Mechanism of Injury

Such injuries are typically a result of accidents involving industrial machines. If a glove or hand is caught in a machine, the human instinct is to step back, resulting in avulsion of the whole hand. Degloving injuries of the hand are divided into two types. One type involves avulsion of the skin and soft tissue only, with the shapes of the thumb and fingers still intact. Because the damage to the deep tissues is lesser and the intrinsic muscles exist in this type of injury, we can reconstruct the thumb using a wrapped-around flap, and reconstruct 2–5 fingers using two flaps. The second type of degloving injury of the hand involves skin and soft-tissue avulsion as well as crush injury by a machine. This type is more serious, as it is associated with not only skin avulsion but also multiple fractures or dislocations, tendon and nerve avulsion and severe intrinsic hand muscle injury. These injuries are difficult to repair. Usually multiple toes are transplanted to rebuild the fingers if necessary. Understanding the mechanism of the injury can help surgeons to select the best procedure.

12.9.2 Debridement

Prior to debridement, we must first determine the avulsion plane and whether the avulsion is complete or incomplete. In the case of complete avulsion, the skin potential for salvage should be evaluated. In some cases, the skin can be used to form a full-thickness skin graft for replantation. If the avulsion plane carries arteries, it can be revascularized (Fig. 12.19). It is necessary to determine whether the intrinsic muscles can be retained by observing the blood supply, color, elasticity and continuity of the muscles. Devitalized tissue must be cleared; otherwise, it will increase the chance of infection and local tissue scarring, making functional rehabilitation difficult. However, since these muscles are very important for hand function, if their vitality cannot be determined in an emergency department, the decision can be delayed after 5–7 days on the debridement of the muscles.

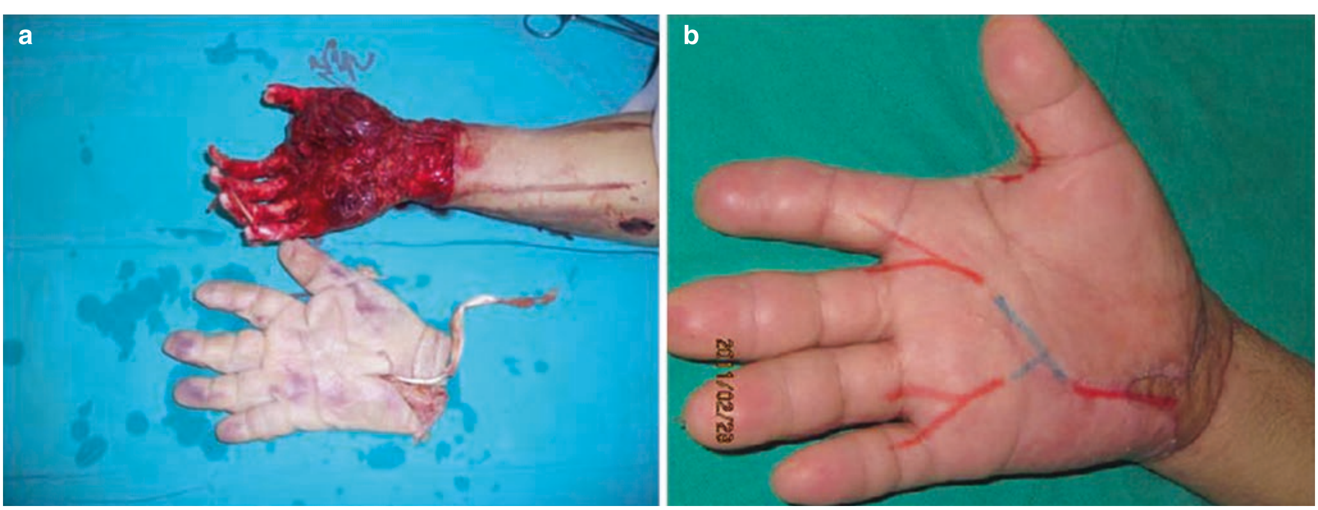


Fig. 12.19 Vascular reconstruction of total hand degloving injury. (**a**) Total hand degloving injury of right hand. (**b**) Reconstruction of arterial blood supply in the volar (red for arteries, blue for vein grafts). (**c**) Dorsal venous anastomosis

Fig. 12.19 (continued)

In addition, the tourniquet can be repeatedly released to observe the blood supply to the muscles. To reduce and fixate metacarpal and phalangeal fractures and dislocations of the wrist, carpometacarpal joint, metacarpophalangeal joints and interphalangeal joint, pinning is a wise option. The first metacarpal can be fixed to the second metacarpal in a position of palmar opposition to ensure an open and large first web space.

12.9.3 Microsurgery Protocol

12.9.3.1 Vessel Matching

According to the type of injury, the patient's age and professional requirements, a team of surgeons must undertake the repair using different methods. The goal of repair is to rebuild the whole hand function, to have a flexible thumb and the thumb on the palm of the corresponding finger function. A suitable surgical plan is formulated via consultation among surgeons, the patient and his/her family. Good communication is required to ensure full understanding and trust of the patient and his/her family. Multiple tissue grafts are required to repair whole-hand avulsion injury. The key is to rebuild blood circulation in the transplanted tissue, depending on the availability of a vascular match at the recipient site. Uninjured local arterial and venous anastomotic sites should be searched for, and the possibility to establish an independent arterial and venous anastomosis should be determined.

Multiple tissues should be prepared for transplantation. Blood vessels that appeared intact during emergency debridement need to be carefully observed once again during debridement under a microscope, because delayed vascular lesions or wound infections may sometimes be caused by secondary damage. Therefore, make vascular area as far as possible by looking at the tissue health. In each transplanted tissue graft with blood vessels, we must ensure sufficient arterial blood supply and venous drainage; vascular anastomosis series multi-parallel should be used as infrequently as possible to ensure that each graft has a separate arterial supply and venous drainage.

12.9.3.2 Finger Reconstruction

Thumb reconstruction should be performed first. In patients with thumb avulsion and distal phalanx necrosis due to lack of blood supply, the thumb can be reconstructed with a distal phalanx of the hallux nail flap, and a dorsal thumb back flap can be used to repair soft-tissue defects. If 2–5 means all phalanx complete form boxing glove-shaped fingers wrapped in two pieces of the flap. If 2–5 fingers have defects, the second toe of one or both feet can be transferred to reconstruct the middle finger or two fingers.

12.9.3.3 Flap Coverage

Full hand avulsion wounds are large. They used to be treated with a hallux nail flap, and hand wound repair used to be conducted with an abdominal pedicle. However, this technique carries a high risk of vascular crisis. Currently, free flaps are used to cover this type of wounds. An organization is difficult to cover the entire hand, palm, hand wound, commonly two anterolateral thigh flap hand, palm, back wound. The flap design should take full account of individual differences in patients. Fat women require thicker flaps than men, and can be zoomed in relatively more to ensure that the first web space is large enough to open the flap in this region to be fully adequate.

12.9.3.4 Nerve Tendon Repair

During tissue transplantation, often all the attention is focused on the reconstruction of the vasculature. However, both nerve and tendon repair are crucial to restore hand function. The local nerve is sutured with the digital nerve in the toe transplant, if the defect should be transplanted or transferred nerve repair. The nerves in the flap are sutured to the superficial radial nerve and the dorsal branch of the ulnar nerve.

12.9.3.5 Surgical Personnel Arrangement

Multiple tissue transplantations require a long operation time, usually 6–10 h. Three groups of medical staff should be engaged in the pre- and postoperative procedures, with 6–8 surgeons operating at the same time. The donor and recipient sites should be operated on at the same time to increase the likelihood of successful operation and decrease operation time. For zone 1 tissues, a hallux nail free flap is usually dissected. This should be done by the most experienced and skillful doctor. A central figure should formulate the operation procedures. The time to remove the first tissue determines the duration of surgery. Surgeons operating on the recipient site should accurately localize all recipient vessels, and be consistent in technology, and in the end to be consistent in the affected area.

12.9.3.6 Anesthesia and Postoperative Treatment

Surgery should be performed under general anesthesia which allows better control of the patient's body reactions and observation of the patient. Timely blood transfusion should be given intraoperatively to prevent low blood volume. Use of vasoconstrictor drugs should be minimized to avoid vasospasm.

After surgery, sedative analgesics and antispasmodics should be used in all patients. However, considering that multiple tissue transplants are harvested, anti-clotting drugs should generally not be used to prevent bleeding from large wounds (including the rehabilitation needs for the region to take the skin level fault for zone II) and to maintain the blood volume. The operation should be performed under warm conditions, without cold stimulation. Effective antibiotics must be administered. After 7–10 days the pain begins to substantially subside eliminate independent functional activities, For physical therapy, early elimination of swelling is required.

12.9.4 The Repair Methods

According to the debridement extent, patient's requirements and surgical design, the reconstructive surgery can be divided into three types: whole hand wrapping, thumb reconstruction, and reconstruction of grip function.

12.9.4.1 Whole Hand Wrapping

Two femoral anterolateral skin flaps are transplanted to facilitate early wound healing. In the second phase of the operation, two flaps are used to reconstruct the fingers, and the arteries in the flaps are sutured to the ulnar and radial arteries at the wrist joint. The radial artery is ligated proximal and distal to the anastomosis, and the dorsal carpal branch of the radial artery can be ligated proximal or distal to the anastomosis. The flap veins are anastomosed with the cephalic vein, basilic vein and their branches. If necessary, an end anastomosis is established between the final two vascular pedicle flaps to improve the blood supply. Index finger surgery should be delayed until the second phase of the operation because this surgery is very difficult, especially when the thumb web is not large enough, likely resulting in a poor postoperative appearance and function. This surgery is rarely used nowadays.

12.9.4.2 Thumb Reconstruction

A flap with the distal phalanx of the hallux is used for thumb repair. Two anterolateral thigh flaps are used to repair 2–5 fingers and the palmar and dorsal wound. For 2–5 refers to the residual long finger of the injured. An anastomosis is established between the radial artery (wrist or back support) and the hallux A flap of the artery (dorsal artery). The vein supplying the hallux is anastomosed to the cephalic vein or its branches. The dorsal artery is anastomosed to the deep plantar artery, and the posterior side of the anterolateral thigh flap that is descending coronary artery supplying the lateral femoral artery anastomosis (primary series), veins and your vein anastomosis. If the blood flow through the radial artery or distal dorsal carpal branches is good, this flap artery is anastomosed with this artery to form an independent blood supply system. If there are two veins, one is anastomosed to the radial vein, and the other is anastomosed to the head vein or hand vein. Because this type of thumb is an independent system, 2–5 refers to the boxer type, 4–6 months after the surgery, if the thumb can be used for 2–5 min, surgery of the fingers can be undertaken. The thumb and other fingers against finger function, currently used more often. The second anterolateral thigh flap needs the ulnar artery (Fig. 12.20).

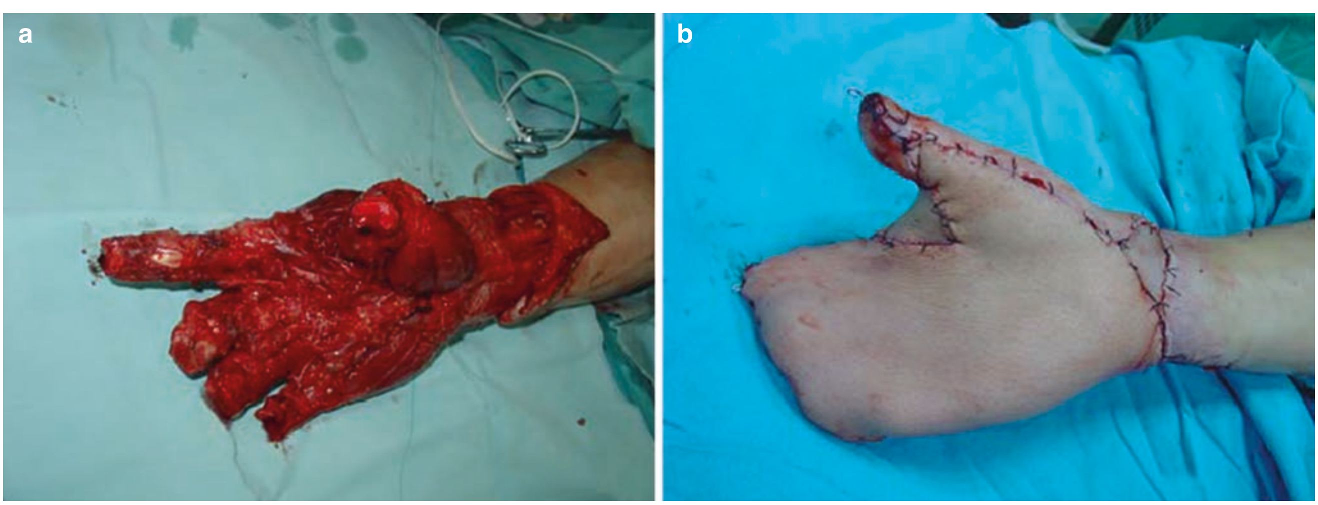


Fig. 12.20 Thumb reconstruction of total hand degloving injury. (**a**) Total hand degloving injury of right hand. (**b**) Using the flap from great toe to reconstruct thumb and using the bilateral anterolateral thigh flaps to cover the palm and back of the hand. (**c**, **d**) The functions of thumb abduction and thumb to palm

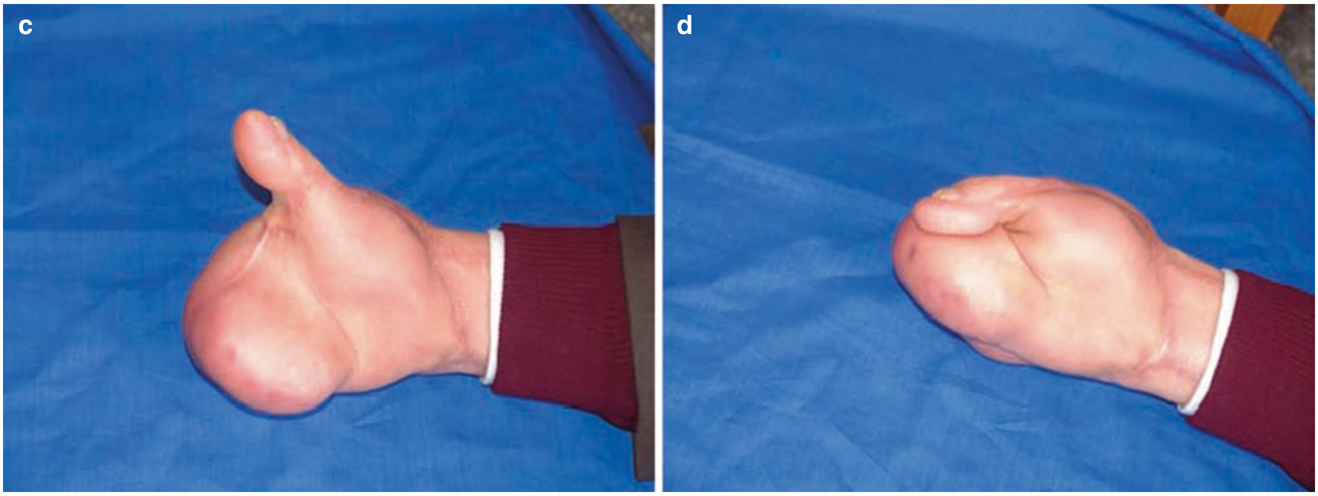


Fig. 12.20 (continued)

12.9.4.3 Reconstruction of Hand Function

If defects of 2–5 phalanges are present, or if there is incomplete hand avulsion, the thumb can be reconstructed using a hallux A flap. One or two anterolateral thigh flaps are used to cover the palm wounds, but one or both of them can simultaneously be used for the secondary reconstruction of pinching function of the reconstructed thumb. Reconstruction of the blood supply is a very complex endeavor, requiring three to five tissue transplantation surgeries. The transplantation of three dorsal distal phalanges and a hallux nail flap is used to reconstruct the thumb. A dorsal skin flap from the foot with the second toe transfer is used to reconstruct the index or middle finger. Hand wounds can be partially covered with a femoral anterolateral flap and the back of the thumb web. Vascular anastomosis is established in a manner similar to that described above (Fig. 12.21). Thus, a hallux nail flap and the second toe transfer are used to reconstruct the thumb and index finger, respectively. The dorsal artery is anastomosed to the radial artery, and the dorsal vein is anastomosed to the cephalic vein. The second toe of the other foot is transferred to reconstruct the middle finger. The feeding artery is connected to the radial artery, and the distal or hallux nail flap plantar branch is anastomosed with the dorsal artery. The dorsal vein is anastomosed to the hand vein. The feeding artery of the anterolateral thigh flap is anastomosed to the ulnar artery or the deep branch of the second toe. The flap vein is connected to the ulnar vein or its accompanying veins. The other side of the anterolateral thigh feeding and ulnar artery distal anastomosis, vein and hand vein anastomosis. After reconstruction of the thumb and fingers, finger activities such as pinching function can be restored, and sensation can be recovered (Fig. 12.22).

12.9.5 Surgical Procedures

12.9.5.1 Debridement

Tissue transplantation is performed 5–7 days after the injury. The injured hand must be thoroughly debrided, and further exploration of the palmar neurovascular bundles should be undertaken. If palmar neurovascular bundle avulsion is found, the distal and proximal phalanges of 2–5 fingers should be removed to prevent distal necrosis; the metacarpophalangeal joints and the base of the proximal phalanx should be retained. If the neurovascular bundle is intact, the distal phalanges and the distal part of the middle phalanx of 2–5 fingers should be cut; a 1.0-cm portion of the distal phalanx of the thumb should be excised. The entire length of the nerve should be identified during debridement, starting from the site of injury proximally up to a distance of 2–5 cm. The ulnar artery, radial artery and dorsal carpal branch of the radial artery and the cephalic vein, basilic vein and palmar and dorsal veins may be spared.

12.9.5.2 Bone Fixation

The knuckles and metacarpophalangeal joints should be fixed in 40°–80° of flexion because of the extensor and flexor tension imbalance, so that the phalanx stump and top flap is vertical flaps touch and affect local blood circulation that can lead to skin local flap necrosis or vascular crisis. Therefore, the front flap a tile surrounding the injured hand, the proximal interphalangeal joint should be fixed with Kirschner wires in a straight position. The metacarpophalangeal joint should be fixed in flexion, and the thumb should be fixed in a position of flexion. The Kirschner wires can be extracted after 3 weeks.

Fig. 12.21 Reconstructing the grasp functions of total hand degloving injury. (**a**) Total hand degloving injury of right hand. (**b**) The thumb was reconstructed by the wraparound great toe with distal phalangeal bone and dorsum pedis flap, the contralateral second toe was transplantated to reconstruct the middle finger, and the bilateral anterolateral thigh flaps were used to cover the palm and back of the hand. (**c**) The functions of thumb abduction

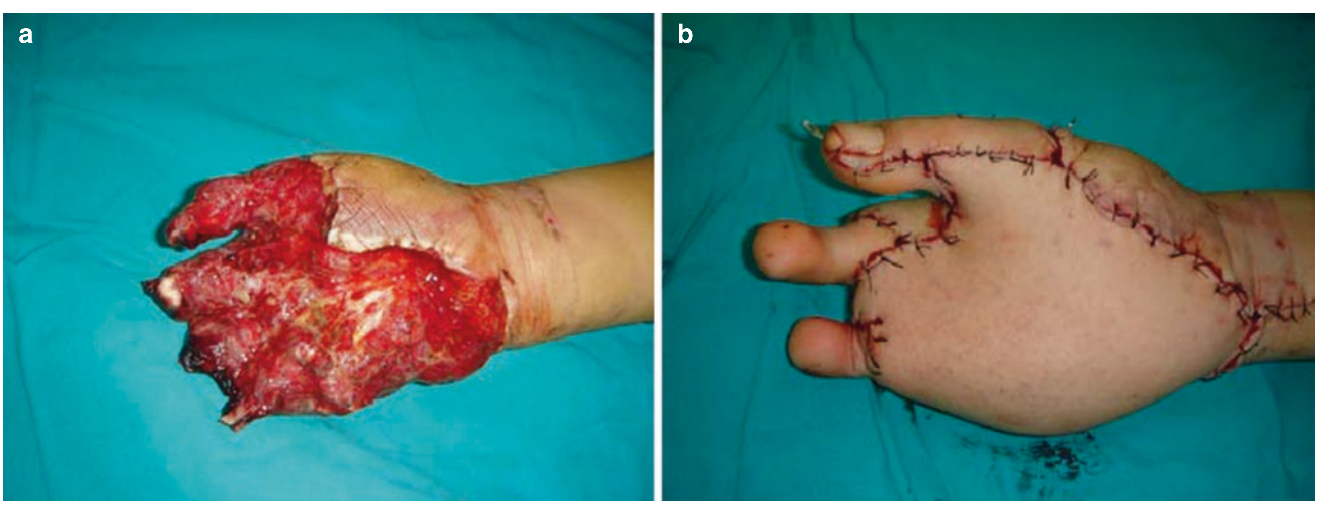


Fig. 12.22 Reconstructing the grasp functions of total hand degloving injury. (**a**) Total hand degloving injury of right hand. (**b**) Reconstruction of thumb with wraparound great toe transplantation, reconstruction of index finger with second toe transplantation and reconstruction of middle finger with contralateral second toe transplantation. (**c**) Stretch function of rebuild hand

Fig. 12.22 (continued)

12.9.5.3 Tissue Transplantation

Different repair methods can be used (such as the three ways) depending on the situation.

12.9.5.4 Treatment of Donor-Site Wounds

Foot wounds are covered with full-thickness skin grafts taken from the groin, bandaged and plaster-fixed for 4 weeks. Thigh wounds are covered with skin grafts taken from the inner thigh, and packaged bandaged. Flap donor-site wounds can also be sutured under tension and treated using vacuum-assisted closure. Skin grafting can be performed in the secondary operation. Use of vacuum-assisted closure improves survival of the skin grafts.

12.9.5.5 Postoperative Treatment

A soft and thick dressing is used to bind the wound. If there is no exudate outside the dressing, the outer dressing can be replaced after 72 h, but an analgesic should be administered before the dressing is replaced. After 3 weeks, the Kirschner wires can be removed, and functional training can begin. At 4 months to 1 year after the surgery, some patients require skin flap treatment or subcutaneous fat removal via liposuction to improve the hand shape. It is necessary to conduct adhesiolysis of the finger flexor tendons to improve hand shape.

13 Microsurgical Reconstruction of Lower Extremity Soft-Tissue Defects

Changqing Zhang, Xianyou Zheng, and Shengdi Lu

13.1 Principles for Microsurgical Reconstruction of Lower Extremity Soft-Tissue Defects

Lower extremity soft-tissue defects were clinically common, caused mainly by machine injury, burn and other diseases. Treatment of high-energy lower extremity trauma with soft-tissue defects and exposure of tendon, nerve and bone remains a formidable problem. Since the development of microsurgical techniques from 1960s, local flaps, microvascular free flaps, and arterial, nerve and bone repairs have been successfully applied experimentally and clinically, making a major breakthrough in the repair of lower extremity soft-tissue defects and reducing the risk of lower extremity dysfunction or amputation. We, the authors of this chapter, think that the followings should be the major concerns when microsurgical reconstruction of lower extremity soft-tissue defects is to be performed.

13.1.1 Preoperative Evaluation

Reconstruction of lower extremity with soft-tissue defects should be performed after evaluation of patient's condition and the cause of injury, as a lower extremity is a structural foundation of standing and walking. For patients with multiple injuries, especially those with high-energy trauma whose other body parts like craniocerebrum, chest and/or abdomen are usually injured, patient salvage takes priority over limb salvage. Therefore, reconstruction of lower extremity soft-tissue defects should be performed after excluding the abovementioned main organ injuries and stabilizing the patient. For patients with paraplegia or long-term bed rest, soft-tissue defects around the sacrococcygeal region, greater trochanter of femur or tuberosity of ischium are usually caused by pressure ulcer. Their supporting therapy to improve hypoproteinemia or anemia should be earlier than repair. In patients of diabetes mellitus who may have skin and soft-tissue defects around the distal end of the lower extremity caused by ulcers, control of the blood glucose level and other measures to improve the patient condition are of vital importance for successful reconstruction.

For the lower extremity soft-tissue defects combined with exposure of main nerves, vessels and/or tendons, primary microsurgical reconstruction is recommended under a good condition of the patient and the wound. For defects with infection but without exposure of main nerves, vessels or tendons, a secondary flap reconstruction is performed after stabilization of the patient and initial wound debridement.

It is worth noting that not all the lower extremity soft-tissue defects can be salvaged by microsurgical repair. For patients with diabetes mellitus, whose Wagner grade of foot ulcer is up to 4–5 (partial or total gangrene), amputation is indicated because microsurgical reconstruction of the defects caused by the ulcer cannot bring a good long-term outcome. Therefore, indication of the reconstruction is paramount in spite of the fact that microsurgery has advanced a lot.

Moreover, the development of negative pressure wound therapy (NPWT) makes the flap repair of soft-tissue defects easy. A topical subatmospheric pressure (50–200 mmHg below the ambient) across the wound surface is applied to create a favorable environment for healing by removing excess edema, decreasing bacterial colonization and increasing vascularity. For soft-tissue defects around the foot and ankle, limitation of local musculocutaneous flaps and fasciocutaneous flaps makes it difficult to repair the soft-tissue defects. However, NPWT technique can promote normal wound healing through rapid granulation tissue formation which can change an open wound to a controllable or even

C. Zhang (✉) · X. Zheng · S. Lu
Department of Orthopaedics, The Sixth People's Hospital, Shanghai Jiao Tong University, Shanghai, China
e-mail: zhangcq@sjtu.edu.cn

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_13

closed one. NPWT is usually applied after initial debridement and within 72 h after the injury until the wound beds are completely granulated. Many of these wounds can be closed by NPWT or a secondary skin graft. In this condition, reconstruction of the lower extremity soft-tissue defects can spare microsurgical flap repair (Fig. 13.1).

13.1.2 Rigorous Debridement

Whether primary or secondary reconstruction, debridement of the wound should be conducted clinically. Debridement applied to the wound preparation plays a vital role in the microsurgical reconstruction. The new concepts of debridement emphasize cleaning the wounds of debris and bacteria, removing foreign material, controlling infection, removing desiccated tissue and restoring a viable epithelial edge through the removal of senescent cells in the wound bed and nonmigratory cells from the wound edge (Fig. 13.2).

Debridement is one of the basic surgical skills. Scientific development leads to constant emergence of new assistant debridement techniques. Introduction of hydrodynamic surgical techniques in recent years represents a major advance in the wound debridement. Hydrodynamic debridement allows rapid and quantitative removal of necrotic tissue and bioburden with minimal bleeding and pain. It has been shown to be more effective in removing bacterial bioburden from wounds than conventional debridement.

Wounds that are less infected and involve tendons and/or nerves can be debrided in a limited way. Antibiotics can be injected locally during the operation. NPWT is applied after flap coverage. For many degloving injuries of the lower extremity, a defatted full-thickness skin graft followed by

Fig. 13.1 Negative pressure wound therapy (NPWT) is applied for the soft-tissue defects of leg

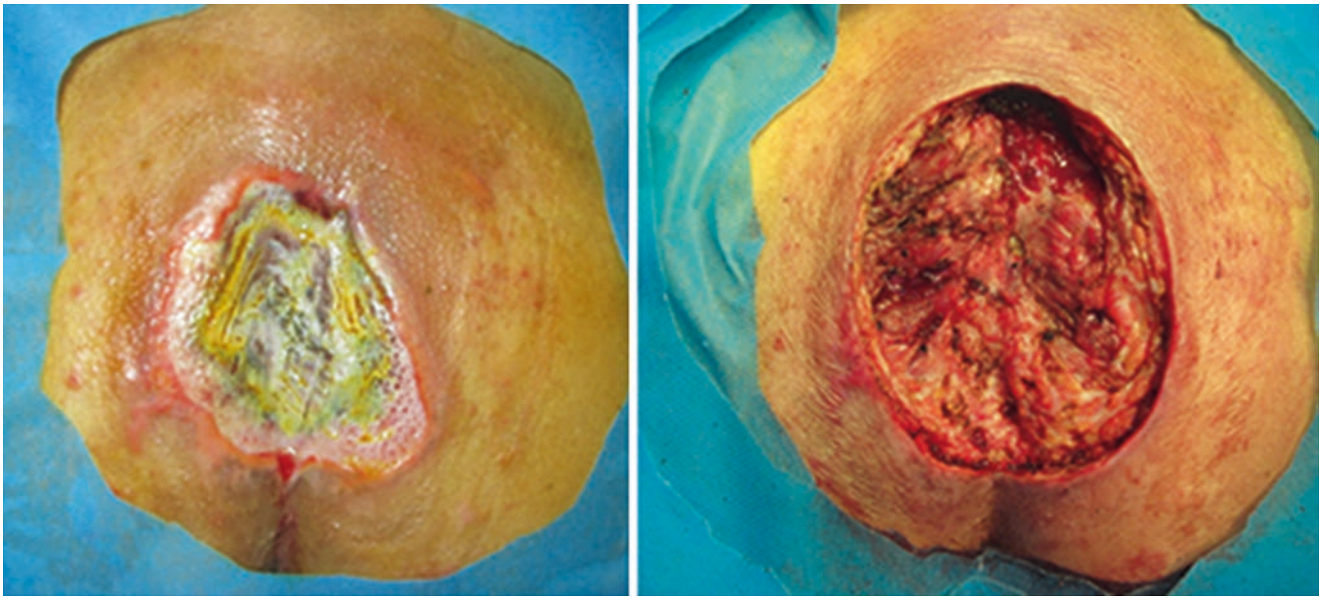


Fig. 13.2 Comparison of the soft tissue defects around the sacrococcygeal region caused by bedsore before and after debridement

conventional dressings after the initial debridement may gain success clinically.

13.1.3 Flap Selection

After stabilization of the patient and wound preparation for the lower extremity soft-tissue defects, flaps or myocutaneous flaps should be designed according to their specific locations, causes of the injury, size of the defects, blood supply, status of the donor and recipient sites and preference of the surgeons. Appropriate flaps or myocutaneous flaps are selected to gain the best surgical outcome. As to the donor site, the vessel condition around the incision area should be conducive to the vascular anastomosis of the free flaps. Besides, harvest of the flaps should not have a great impact on the function and appearance of the donor site (the principle of "balance between donor and recipient sites"). For the recipient site, anatomic location and feasibility of flap transfer should both be taken into consideration. Local pedicled flaps to repair the soft-tissue defects should not only have a similar tissue structure, but also be easy to manipulate. When the soft-tissue defects around the recipient site are small, fasciocutaneous flaps will be the choice. If deep tendons or bones are involved, myocutaneous flaps will be selected to repair the defects. For defects around the foot, sensate flaps to recover the lost sensation of the foot are crucial.

A homologous axial flap can be found for a soft-tissue defect at almost any body part. The skin width of the pedicle is not limited when this type flap is to be transferred because of the presence of vascular pedicle. This not only expands the indications of the transferred flaps for repair of the lower extremity soft-tissue defects, but also improves the repair outcomes.

Local flaps to reconstruct the lower extremity soft-tissue defects include gluteus maximums flap, musculi tensor fasciae latae flap, rectus femoris flap, gracilis flap, gastrocnemius flap, medial knee flap, sural (saphenous nerve or superficial peroneal nerve) neurovascular flap, lateral foot flap, dorsalis pedis flap and medial foot flap, etc. Both the anatomic locations of soft-tissue defects and the features of the flaps should be taken into consideration when reconstruction is to be performed.

In addition, perforator flaps representing ultramicroscopic techniques provide a new way to reconstruct the lower extremity soft-tissue defects. Perforator flaps are developed on the basis of fasciocutaneous and muscle flaps. In 1984, "anatomy of gluteal flaps based on the axis of the musculocutaneous perforator" was reported by *Shen Huailiang*, a Chinese anatomist, who proposed definitely that since the blood supply of the gluteal skin is supported by the perforators of superior gluteal artery and inferior gluteal artery, the axis of the flap could be based on these perforators. Great progress has been made in Chinese research on perforator flaps though it started late. National symposiums of perforator flaps were held for eight times from 2005 to 2013. Take the anterolateral thigh perforator flap for an example. It was developed on the basis of anterolateral thigh flap reported by *Xu Dachuan*. It is most widely used in clinical operations, including reconstruction of lower extremity soft-tissue defects, because the fat of this flap can be preserved for coverage of the deep defects, and a thin flap of vascular network under dermis can also be made by defatting. Perforator flaps are consistent with the basic principle of "like replaces like" in reconstructive microsurgery, making the flap transplantation popular.

Combined (muscle) flaps, prefabricated flaps and application of angiogenine in recent years have expanded the algorithms for reconstruction of lower extremity soft-tissue defects and improved the results.

13.1.4 Postoperative Management

Patients with lower extremity soft-tissue defects should be monitored closely after the surgery. Whether local flaps or microvascular free flaps are applied, vital signs are closely monitored to make sure blood volume is adequate. Moreover, a comfortable environment with proper temperature and humidity is necessary to prevent vasospasm owing to fluctuation of the patients' emotion or the temperature of the environment. Lamp irradiation of the local is also an effective way. Drugs that can improve microcirculation, like anticoagulation and spasmolysis, are used properly, in combination with antibiotic therapy. Flap monitoring is performed clinically, and flap color, temperature, swelling, and capillary refill are easy and effective factors. As the patients and their relatives usually suffer a lot during the procedure, especially from the mental burden, detailed explanations and psychological nursing are necessary.

Early exercise after surgery should be initiated according to the defects and specific reconstruction procedures. Active and passive motion of the knee which has a high demand of activity should be commenced early after flap reconstruction of soft-tissue defects around the knee to prevent post-traumatic knee stiffness. For patients with these defects combined with open fracture of the lower extremity, early postoperative activity on the bed can increase capillary blood flow of the flap and reduce the rates of other complications.

In short, timing of the reconstruction of the lower extremity soft-tissue defects depends on the wound condition. The indications for the reconstruction are paramount no matter how advanced microsurgical techniques have been. Initial debridement is necessary and important for a successful reconstruction. As to the flaps selection, flaps or myocutaneous flaps should be designed based on their specific locations, cause of injury, size of the defects, blood supply, status of the donor and recipient sites and the preference of the surgeons after wound preparation.

13.2 Microsurgical Repair for Soft-Tissue Defects in the Sacrococcygeal Region

Soft-tissue defects in the sacrococcygeal region are very common among the patients with sacrococcygeal tumor or long-term bedridden constraint, especially the latter. Thickness and resistance to friction of the flap are highly demanded in the repair of such soft-tissue defects. Several methods are illustrated in the following.

13.2.1 Gluteus Maximus Myocutaneous Flap (GMMF)

The gluteus is a piece of superficial and large muscle, with blood supplied by the superior and inferior gluteal artery. A variety of flaps can be designed using it to repair the soft-tissue defects in the sacrococcygeal region and greater trochanter. Postoperative adhesion can be effectively avoided because the gluteus is very thick. The gluteus maximus myocutaneous flap is often used in one-stage repair of bed sores over the places mentioned above because of its outstanding ability of anti-infection.

13.2.1.1 Anatomic Highlights

The gluteus is mainly supplied by the superior and inferior gluteal artery. The former comes out from the suprapiriformis foramen, which is located on the line between the iliac crest and ischial tuberosity and divided into a deep branch and a superficial branch. The inferior gluteal artery comes out from the infrapiriform foramen and is divided into muscular and cutaneous branches. Inferior GMMF, superior GMMF, total GMMF can be chosen to repair different injuries. The main functions of the gluteus are extension and external rotation of the thigh, and its lower part plays a more important role. The upper part of the gluteus should be used as far as possible to decrease dysfunction of the hip joint.

13.2.1.2 Surgical Techniques

Inferior GMMF

It is pedicled with the superficial branch of the superior gluteal artery and commonly used for repair of soft-tissue defects in the sacrococcygeal region because the upper part of the gluteus can be reserved. The main disadvantage is that free skin graft is necessary to cover the wound of the donor site. According to the different recipients, island flap, advancement flap and local flap might be transferred.

Local Flap Transfer

Flap Design: Pedicled with the superficial branch of the superior gluteal artery, the line between the autologous posterior superior lilac spine and the femoral greater trochanter is marked as Line AB, which is the axis of the flap. The point at its upper one-third is marked as Point Owlish, the rotation point of the flap. The medial edge of the flap is attached to the wound. The maximum distance from Point O to the edge of the wound is Line OC while that to the edge of the flap is Line OD. Line OD should be longer than Line OC. The

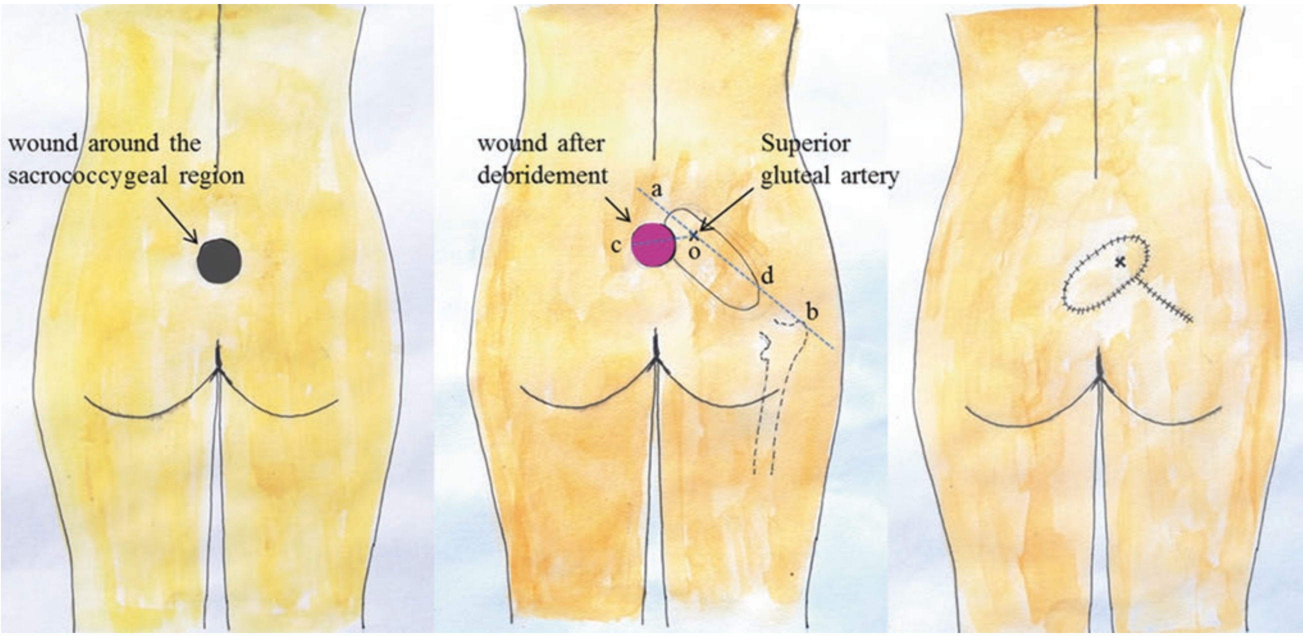


Fig. 13.3 Local transfer superior GMMF in treatment of soft-tissue defects in the sacrococcygeal region

shape of the flap is similar to that of the wound, but the area of the flap should be a bit larger to ensure that the flap can completely cover the wound after being rotated (Fig. 13.3).

Surgical Procedures: The patient is placed in a prone position. Make an incision above the flap as designed after anesthesia, disinfection and draping. Search the intramuscular septum between the gluteus maximus and the gluteus medius on Line AB and dissect it bluntly. The superficial branch of the superior gluteal artery can be seen below the gluteus maximus. Dissect the flap to the distal side and cut it near the trochanteric bursa. Make an interiorly medial incision to the flap and elevate it. Dissect the superficial branch of superior gluteal artery carefully. It is not necessary to expose the main superior gluteal artery since it may induce vascular injury. The inferior gluteal nerve can be found during the procedure. It should be reserved to ensure the function of hip joint. Finally a medial incision of the flap is made. Rotate the flap pedicled with the superior gluteal artery to cover the wound before closure. The donor site is covered by free skin graft.

V-Y Advancement Flap

The superior and inferior gluteal arteries, as the main blood supply of GMMF, both run from the lateral side to the medial into the muscle after coming out from the piriformis. Thus V-Y advancement flaps can be used to repair soft-tissue defects in the sacrococcygeal region. According to the recipient location, the superior gluteal artery and/or the interior gluteal artery can be included in the flap. Bilateral V-Y advancement flaps are suitable for a large area of soft-tissue defects.

Flap Design: The flap is triangle-shaped. The bottom line of the flap is attached to the lateral edge of the wound. The apex angle is located at the lateral side of the body, which varies from 60° to 90° (Fig. 13.4).

Surgical Procedures: The procedures are the same as the above. The flap should be advanced from the lateral to the medial after harvest. Close the wound with the shape of Y. Part of the gluteus might be dissected to achieve long-distance advancement.

The advantages of V-Y advancement flap include simple and safe procedure, extremely good survival rate, and one-stage closure of the wound. This flap is an ideal repair of the smaller soft-tissue defects in sacrococcygeal region, but it cannot be widely used in repair of larger soft-tissue defects.

Island Flap

Flap Design: The Method is similar to that of local flap transfer. The line between the autologous posterior superior lilac spine and the femoral greater trochanter is marked as Line AB, which is the axis of the flap. The point at its upper one-third is marked as Point O to be the rotation point of the flap. The medial edge of the flap is attached to the wound. Line OD should be longer than Line OC. The shape of the flap is similar to that of the wound (Fig. 13.5).

Surgical Procedures: An incision is made above the flap and the intramuscular septum between the gluteus maximus and the gluteus medius are dissected bluntly as mentioned above. The superficial branch of the superior gluteal artery can be found below the gluteus maximus. Some muscular fibers should be reserved around the vascular pedicle in order to prevent it from being compressed.

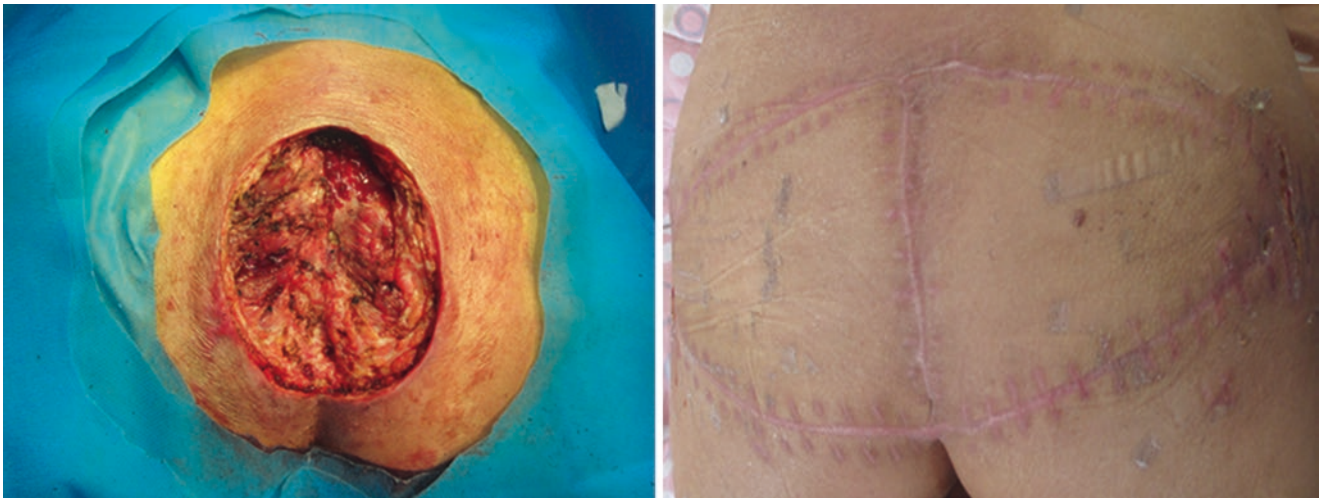


Fig. 13.4 Bilateral V-Y advancement GMMF in treatment of soft-tissue defects in the sacrococcygeal region

Fig. 13.5 Total GMMF in treatment of soft-tissue defects in the sacrococcygeal region

The island flap is rotated to cover the wound before closure. The donor site can be closed primary in most situations or with split thickness skin graft.

Total GMMF

Total GMMF is a transfer flap pedicled with inferior gluteal artery involving all parts of the gluteus, used to repair soft-tissue defects in the sacrococcygeal region.

Flap Design: From the upper side of the wound edge draw a mark line along the upper and lateral edge of the gluteus. Turn to the medial near the femoral great trochanter and finally stop between the femoral great trochanter and the ischial tuberosity.

Surgical Procedure: An incision is made above the wound edges. The intramuscular septum is dissected between the gluteus maximus and the gluteus medius. Elevate the flap and cut it near the posterior superior iliac spine and the sacrum where is attached by the gluteus. Usually the wound cannot be covered by simply rotating the flap. You must cut and ligate the shallow branch of the superior gluteal artery and rotate the flap pedicled with the inferior gluteal artery. All donor sites can be primarily closed.

13.2.2 Lumbo-Sacral Fasciocutaneous Flap

Lumbo-sacral fasciocutaneous flap is pedicled with the posterior branch of lumbar artery. It is used to repair the soft-tissue defects caused by the sacral sores by local transfer together with the skin of lumbo-sacral region, subcutaneous soft tissue and deep fascia.

13.2.2.1 Anatomic Highlights

The lumbar artery is the internal branch of abdominal aorta including four pairs totally. It crosses the posterior medial and lateral branches of the vertebral body and divided into posterior and lateral branches. As each branch of the lumbar artery has abundant anastomosis with the opposite side, the flap will survive after we cut the branches of one side.

13.2.2.2 Surgical Technique

Diamond-shaped Lumbosacral Fasciocutaneous Flap

Flap Design: The diamond-shaped flap is designed based on the size of wound after debridement. Both of the diagonal lines of the diamond are lengthened proximally, of which an angular bisector is made as one of the flap margins. The length of the flap margin is as long as that of the diamond side. The terminal point is used as the origin of the line parallel to another angular bisector of the diamond whose length is as long as the above. This line is marked as another flap margin. A Doppler probe is used to mark the point entering the skin, nearest the flap, of the posterior branches of lumbar artery (Fig. 13.6).

Surgical Procedure: The wound is debrided according to the design. The fasciocutaneous flap is dissected by the procedure mentioned above. The skin, subcutaneous tissue and deep fascia are dissected in turn. The flap is elevated under the deep fascia. The marker where the posterior branches of lumbar artery penetrate into the skin should not be dissected. The flap is locally rotated to cover and close the wound.

Transverse Lumbosacral Fasciocutaneous Flap

Flap Design: The transverse flap is designed above the wound. The lower edge of the flap is parallel to the spine and located at the side of the waist, which is close to the upper edge of the wound. For the convenience of flap transferring, there is no normal skin between the border of the wound and the edge of the flap. The closest location where the posterior branches of lumbar artery penetrate into the skin is detected and marked by color Doppler. Two piercing points should be marked at least.

Surgical Procedure: The wound is debrided. Coagulation hemostasis is performed if necessary. An incision is made at the distal edge of the flap. The skin, subcutaneous tissue and deep fascia are dissected in turn. The flap is elevated under the deep fascia. The posterior branches of lumbar artery at the opposite of the baseline is ligated and dissected. The flap freedom is continued to elevate the flap. The blood vessels marked should be protected. The flap is rotated downward to cover and close the wound.

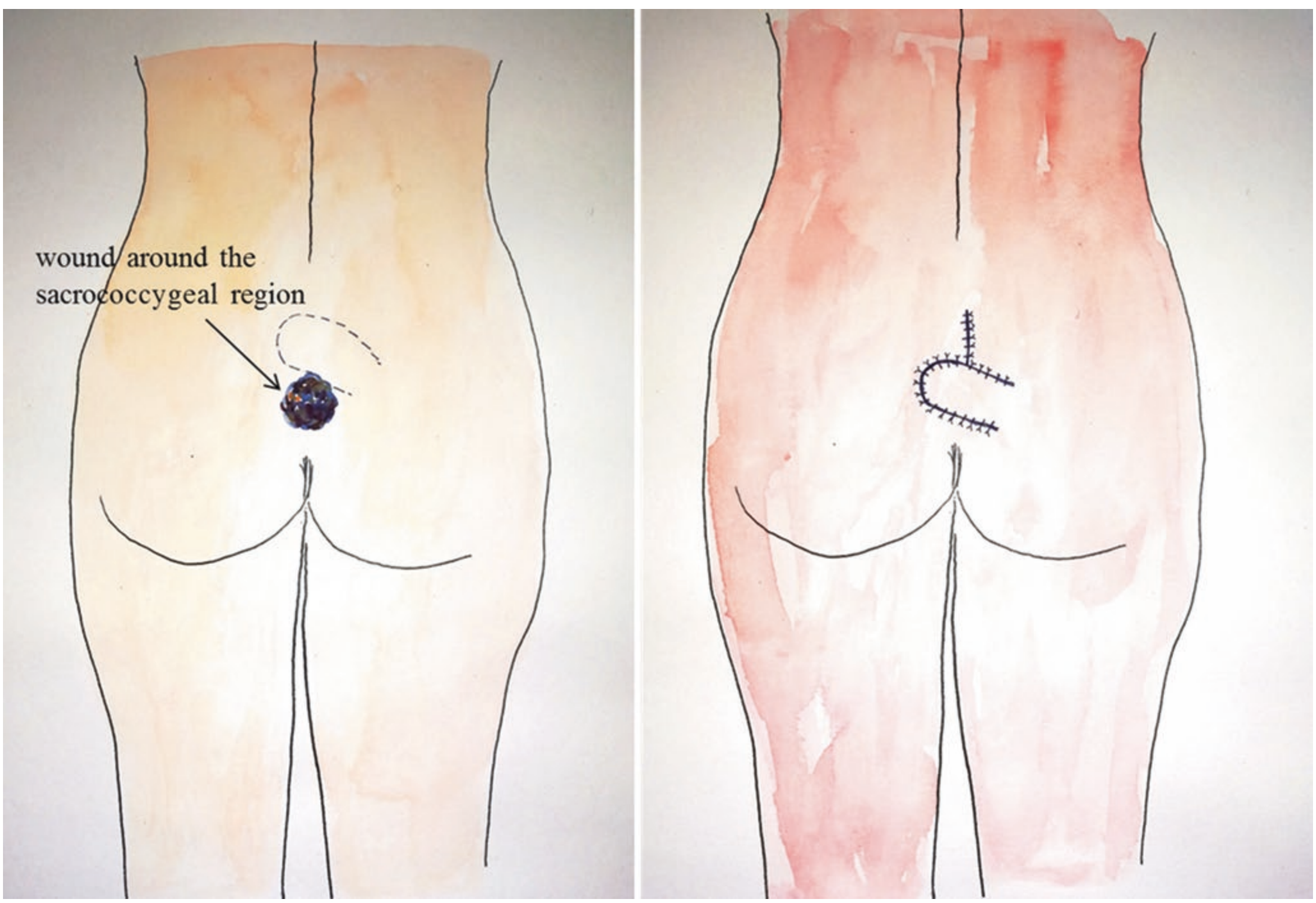


Fig. 13.6 Diamond-shaped Lumbosacral Fasciocutaneous Flap in repair of soft-tissue defects in the sacrococcygeal region

13.3 Microsurgical Repair of Soft-Tissue Defects around the Greater Trochanter

Pressure ulcer usually occurs around the great trochanter clinically. Bedsores are the main cause of soft-tissue defects. What is worse, bedsores occurring in this region often induce deep soft-tissue defects involving the bone. The patients are old, long-term bedridden, poor in constitution and vulnerable to infection. The flap to repair the wound requires abundant blood supply to ensure the survival of the flap.

13.3.1 Tensor Fascia Latae Myocutaneous Flap

Since the tensor fascia latae, adjacent to the greater trochanter, has abundant blood supply, it can be used to fill deep lacunas. It is an ideal method of repairing soft-tissue defects in this region. The size of the available muscle is large enough to be suitable for multiple needs, such as the repair for soft-tissue defects in the ischial tuberosity and the perineum.

13.3.1.1 Anatomic Highlights

Tensor fascia latae is located in the lateral femur, originating from the external lip of the spina iliaca between the anterior superior iliac spine and the iliac tubercle. The muscle belly is short and enwrapped between two fascias, which turn into an iliotibial tract at the one third position of the upper femur. Its main blood supply is from the ascending branch of the lateral circumflex femoral artery which originates from the deep femoral artery. The ascending branch goes along the rectus femoris and then into the muscle at the exterior aspect of the rectus femoris. At the same time, the artery sends out the anterior and posterior branches to feed the whole muscle and the skin in the anterolateral thigh region 5 cm above the knee. The myocutaneous flap contains two sensory nerves, the cutaneous branches of the lateral twelfth thoracic nerve and the lateral femoral cutaneous nerve. Sensation of the flap can be obtained by anastomosis of lateral femoral cutaneous nerve.

13.3.1.2 Surgical Techniques

Flap Design: The outline of the flap is designed according to the size and shape of the wound. The upper edge of the maximum range is 2 cm above the crista iliaca and the lower edge 5 cm above the knee. The flap can reach beyond the intramuscular septum of the vastus lateralis. The best size should be 110% of the wound. The position at 8 cm above the anterior superior iliac spine is taken as the pivot point, located where the ascending branch of the lateral circumflex femoral artery penetrates into the tensor fascia latae. Another triangle-shaped flap above the flap is designed to form a bilobed tensor fascia latae myocutaneous flap which enables primary suture to close the donor site.

Surgical Procedures: Firstly, the wound is thoroughly debrided to wipe out necrotic tissue in the potential lacunas. To avoid effusion under the flap, the joint synovial bursa can also be cut. As bone is often involved in bedsores near the greater trochanter, the involved bone should also be cleared up. Flaps should be dissected after thorough debridement.

Antegrade incision: An incision is made above the flap to detect the septum between the tensor fascia latae and the exterior aspect of the rectus femoris before elevation is performed bluntly. The anterior aspect of the tensor fascia latae is retracted backward, in order to detect the pedicle in the position where the ascending branch of lateral circumflex femoral artery penetrates into the tensor fascia latae around the pivot point. The pedicle should be protected. The flap is dissected toward the distal end under the fascia latae. Then the upper and lower margins of the tensor fascia latae are elevated. The flap is rotated downward to the posterior aspects, the lower part to cover the wound and the upper part to cover the defects of the donor site. All wounds are sutured primarily (Fig. 13.7).

Retrograde incision: The incision is made at the exterior and lower aspect of the myocutaneous flap before the iliotibial tract is dissected. The proximal end is dissected under the fascia latae. A medial incision is made carefully to detect the pedicle. Blunt dissection close to the pivot point should be used. The pedicle should be made sure that it has reliable blood supply, and then the flap is rotated to cover and close the wound of the greater trochanter.

13.3.2 Sartorius Myocutaneous Flaps

Since the sartorius muscle is located superficially, the flap design is relatively easy. The vascular supply with segmental distribution is adequate to make it survive easily and invulnerable to infection. Twisting of the pedicle during flap insetting is uncommon and the deep space can be covered successfully. The wound can be closed primarily at the recipient site. A sartorius flap can be divided into the upper and lower parts. The upper part can be used to repair the wound around the greater trochanter and the lower to repair the knee soft-tissue defects.

13.3.2.1 Anatomic Highlights

The sartorius muscle, the longest strap muscle (about 50 cm), originates from the anterior superior iliac spine and runs intero-inferiorly to the proximal medial tibia. The adequate vascular supply presents segmental distribution, having one perforator artery every interval of 7 cm. The branches of deep femoral artery, lateral femoral circumflex artery and

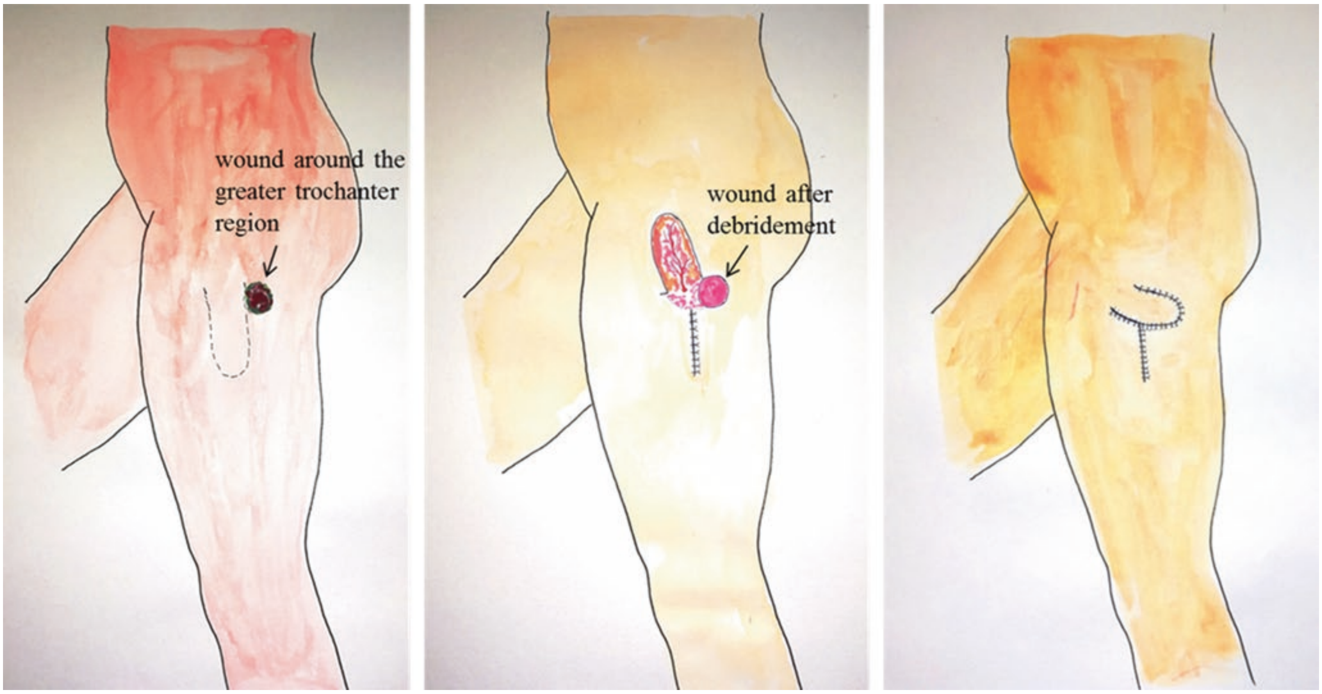


Fig. 13.7 Tensor fascia latae myocutaneous flap to repair soft-tissue defects around the greater trochanter

femoral artery are located proximally as the perforator arteries. The branch of the lateral femoral circumflex artery is usually the dominant artery, which is located 6.5 cm below the anterior superior iliac spine (8 cm below the inguinal ligament) and the axis pivot of the rotation of the flap. The lower part of the sartorius muscle is fed by the saphenous artery.

13.3.2.2 Surgical Techniques

Flap Design: The axis of the flap is drawn between the anterior superior iliac spine and adductor tubercle, and the axis pivot is located 8 cm below the inguinal ligament. The flap outline is based on the wound size and shape.

Surgical Procedure: An anterolateral incision of the flap is made to the deep fascia first. The sartorius muscle is exposed and cut at the distal margin of the flap. Dissect the sartorius muscle from distal to proximal and caution should be taken when it comes to the rotation pivot to protect the dominant artery. The other perforators can be ligated to expand the range of rotation. The posteromedial margin of the flap is cut after the flap is freed, and the skin between the donor site and the recipient site is incised. Temporary immobilization of skin, subcutaneous tissue and the muscle margin is made to avoid flap failure owing to separation. The wound is then covered and closed with the inset flap. The donor site can be closed primarily without skin grafting as there is no tension on the repair.

The sartorius muscle is small among the anterior femoral muscles and weak in strength. Although it is involved in hip flexion, abduction and external rotation, the sartorius muscle can be compensated by other synergistic muscles. Therefore, it has little effect on the hip activity after resection. The scar in the thigh is often left after the surgery. As a result, it may not be the first choice for young patients or patients who have a high demand for cosmetic appearance.

13.3.3 Vastus Lateralis Myocutaneous Flaps

The vastus lateralis muscle is located in the anterolateral thigh and has adequate vascular supply. The plump muscle can be used to cover the deep space successfully. It is supplied mainly by the lateral femoral circumflex artery. The island flap of vastus lateralis muscle can be used to repair the wound around the greater trochanter and has little effect on the lower extremity function.

13.3.3.1 Anatomic Highlights

Aponeurosis of the vastus lateralis muscle is large in size, originating from the upper of the intertrochanter, running obliquely and medially to the upper lateral part of the patella. The vastus lateralis muscle is one part of the quadriceps femoris muscle, of which the proximal two thirds is located at the superficial vastus intermedius muscle, and the distal one third is connected with the muscular fibers of vastus intermedius muscle too tightly to be dissected. The main blood supply of the vastus lateralis muscle is the lateral femoral circumflex artery, which pierces the muscle at 10 cm below the greater trochanter of femur. There are no cutaneous perforators owing to rectus femoris muscle and tensor fasciae latae. Since the perforators supplying the overlying skin of the lower part communicate a lot with the perforators of the rectus femoris muscle and tensor fasciae latae, it is possible to have the island flap in the lower part.

13.3.3.2 Surgical Techniques

Flap Design: The island flap is designed at the lower one fourth of the thigh. Its anterior margin is not to be beyond the line between the anterior superior iliac spine and the upper lateral patella, and its inferior margin is not to be located more than 4 cm of the patella. The outline is based on the wound size and shape. The incision line is marked between the donor site and the recipient site (Fig. 13.8).

Surgical Procedures: Dissection of the vastus lateralis muscle begins from the proximum to the distal end because of the adjacent relationship between the vastus lateralis muscle and the vastus intermedius muscle. An incision is made first at the proximum of the flap to expose the vastus lateralis muscle. The flap is then dissected along the designed outline after distinguishing the rectus femoris muscle and tensor fasciae latae. The iliotibial tract is cut at the proximal margin of the vastus lateralis muscle, and temporary immobilization of the skin, iliotibial tract and vastus lateralis muscle should be implemented to avoid flap failure by dissection. After dissecting vastus lateralis muscle, rectus femoris muscle and vastus intermedius muscle, the muscle belly is cut at the junction of muscle and tendon which is 5 cm above the patella. The neurovascular bundle is dissected proximally after lifting the flap. The flap is used for coverage of the donor site after rotation, following closure layer by layer. Split-thickness skin grafting is performed at the donor site owing to the skin tension.

13.3.4 Gluteofemoral Myocutaneous Flaps

Gluteofemoral flap belongs to gluteus maximus flap. It is fed by the inferior gluteal artery and its posterior femur perforator. A large size of flap can be obtained with simple management of the donor site and little effect on the gluteus maximus muscle. Not only can this flap be used to repair the soft-tissue defects around the greater trochanter, but also to repair the defects in the sacral and perineal regions.

13.3.4.1 Surgical Techniques

Flap Design: Midpoint of the line drawn between the ischial tuberosity and the greater trochanter is marked first, and the midpoint of popliteal fossa is then marked. The line drawn between the two midpoints is marked as the flap axis. The rotation pivot is located where the inferior gluteal artery pierces the muscle. Tongue-shaped flap is designed on both sides of the axis. Its distal margin is located 8 cm above the popliteal fossa.

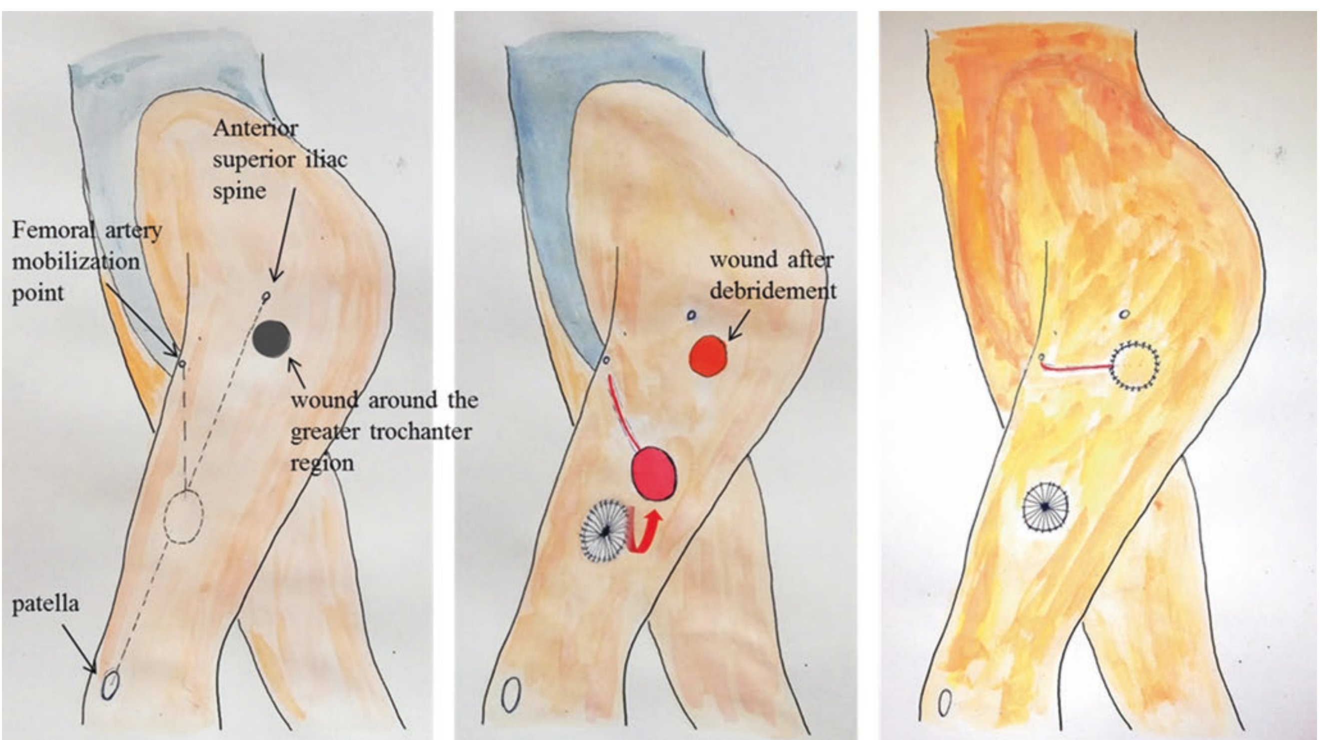


Fig. 13.8 Vastus lateralis flap is used in the microsurgical reconstruction of soft tissue defects around the greater trochanter

Surgical Procedures: An incision at the distal margin of the flap is made and the retrograde dissection to the proximum is performed in the deep fascia. Dissection to the deep layer of muscle from the inferior of gluteus maximus muscle is made to protect the posterior femoral vessels and nerves. The gluteus maximus is cut at both sides of the axis and the inferior gluteal neurovascular bundle is freed to have the island flap, which is used for coverage of the recipient site after rotation. The donor site can usually be closed primarily, and split-thickness skin grafting is performed when necessary.

The major concern when this flap is used to repair the wound around greater trochanter is that the superior gluteal nerves can be easily injured to affect the activity of the lower extremity because most of the gluteus maximus muscle will be freed to get the full rotation. As a result, this flap is more applied in the paraplegic patients.

13.4 Microsurgical Reconstruction of Ischial Tuberosity Soft-Tissue Defects

Pressure ulcer usually occurs around the ischial tuberosity, the greater trochanter of femur and the sacrococcygeal region. If the ischial tuberosity is involved in the pressure ulcer, it cannot be repaired by skin grafting or skin flap. In this condition, myocutaneous flaps should be used to repair the soft-tissue defects.

13.4.1 Gracilis Myocutaneous Flap

The gracilis muscle is located superficially in the medial thigh. Its function includes adduction of the thigh and medial rotation of the leg. Incision of the gracilis muscle flap has little effect on the above function and sensation of the flap can be even preserved. The superficial muscle can be incised easily following a primary closure of the donor site. It can be used to repair the soft-tissue defects around the ischial tuberosity and perineum, and also can be applied to reconstruct the anal sphincter. The disadvantage of this flap is that it cannot be applied to repair large soft-tissue defects because the gracilis muscle is slender and deficient in width.

13.4.1.1 Anatomic Highlights

The gracilis muscle is a flat, thin strap muscle lying immediately posterior to the sartorius muscle. Its origin includes thin and long tendinous aponeurosis on the ramus of the pubis and the ischium. This muscle goes straight down, becoming narrow. An oblateness-shaped tendon is formed at the superior margin of the patella followed by the insertion at the medial tibial tuberosity. The gracilis muscle has adequate vascular supply and its dominant is the muscular branch of deep femoral artery which originates about 9 cm below the midpoint of inguinal ligament, running obliquely and inferiorly between the adductor longus and brevis before inserting 8 cm below the pubic tubercle. There is no perforator entering at the lower one third of the gracilis muscle, and the upper one third should be incised for harvest of the flap.

13.4.1.2 Surgical Techniques

Flap Design: The flap is designed being posterior to the line drawn between the pubic tubercle and the medial knee semitendinosus with a range of 10 cm. The axis pivot is made 8 cm below the pubic tubercle, the upper one third of the gracilis muscle. The flap outline is based on the wound size and shape, and the incision is marked between the donor and the recipient sites.

Surgical Procedures

Antegrade Harvest: An incision to the deep fascia at the proximum of the flap is made first. The dissection is performed bluntly in the intermuscular septum between the adductor longus and the gracilis muscle, continuing to the distal end. It should be performed carefully in the upper one third of the gracilis muscle to explore the muscular branch of the deep femoral artery, because the vessels here are enwrapped by the adductor longus and brevis muscles. Injury to these vessels should be avoided. Temporary immobilization of the skin, subcutaneous tissues and the muscular margin is made after proper dissection. Then the dissection continues distally from the deep layer of the gracilis muscle until the full dissection of the needed flap. Ischial tuberosity wound is near the gracilis muscle and can be covered by local transfer. The flap can be transferred through the subcutaneous tunnel or the incision of the skin between the donor site and the recipient site. The branches except the dominant vascular pedicle can be ligated if rotation of the flap is limited (Fig. 13.9).

Retrograde Harvest: The lateral inferior of the flap is incised and the gracilis muscle is lifted by wet gauze to make sure whether the gracilis muscle has entered the area of designed flap or not and also to exclude the overlapped part of the gracilis muscle and the sartorius muscle. The flap is then elevated and freed from distal to proximal after confirmation. The vascular pedicle is explored at the upper one third of the gracilis muscle and protected. The flap can be temporarily immobilized. The flap is rotated and used for coverage for the wound after full dissection. The width of the local flap of gracilis muscle is narrow, and the thigh skin is relatively loose. Primary closure at the donor site can be performed either in the antegrade procedure or in the retrograde procedure. It is noteworthy that the vascular pedicle twisting should be avoided and partial muscular pedicle can be preserved to protect the vascular pedicle.

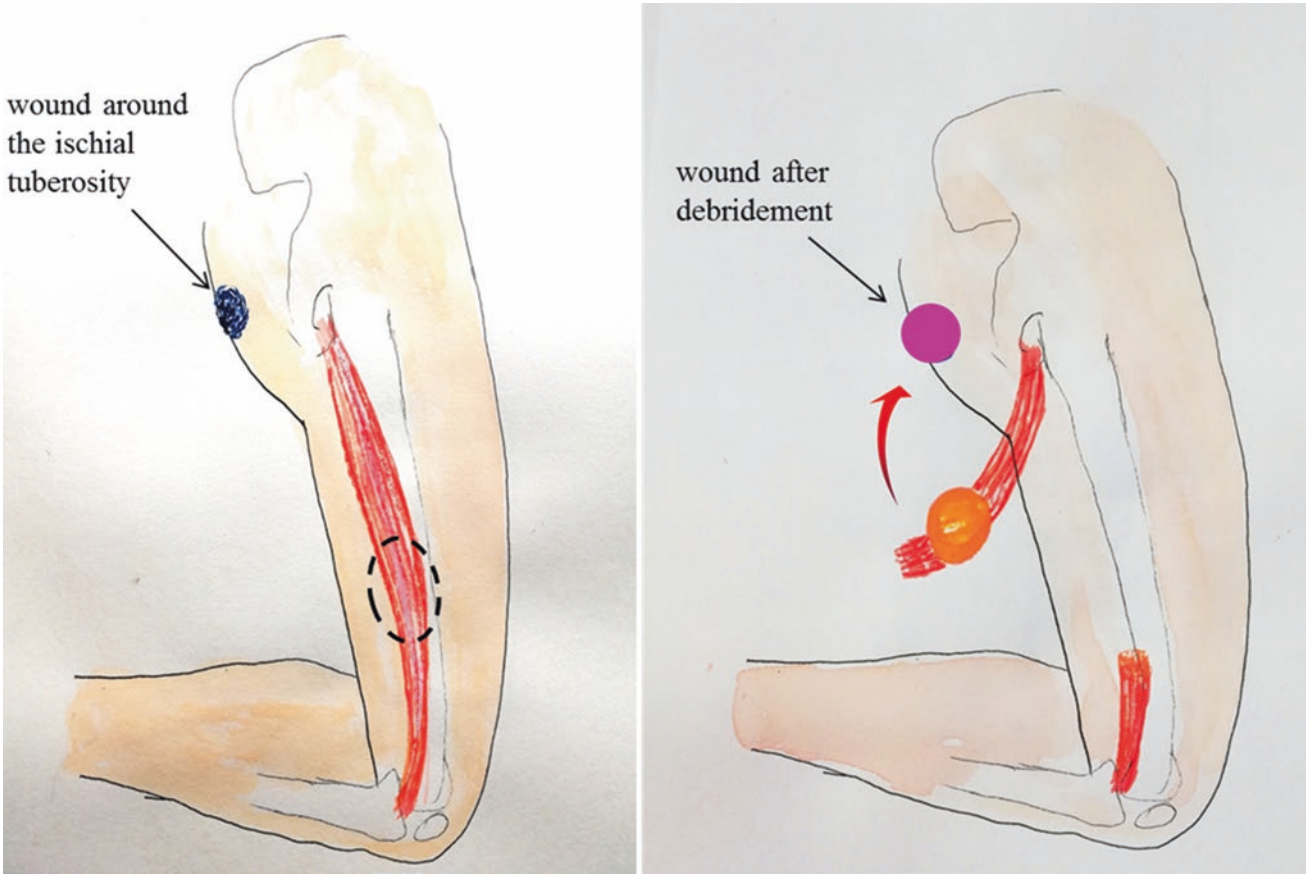


Fig. 13.9 Gracilis flap is applied to repair the wound around the ischial tuberosity

13.4.2 Posterior Thigh Myocutaneous Flap

The posterior thigh muscles, originating from the ischial tuberosity, contain biceps femoris, semitendinosus and semimembranosus muscles which have a large muscle belly and adequate vascular supply. With an advantage of anatomic location, the flaps in this area can be used to cover the wound around the ischial tuberosity through advancement procedure, leading to little effect on the hip extension and knee flexion.

13.4.2.1 Anatomic Highlights

The posterior thigh muscles contain biceps femoris, semitendinosus and semimembranosus muscle, originating from the ischial tuberosity and ending at the capitulum fibulae. Their vascular supply presents segmental distribution. They are supplied by the first perforator of deep femoral artery which runs towards the posterior thigh 8 cm below the ischial tuberosity and gives out muscular branches to the biceps femoris, semitendinosus and semimembranosus muscle. The perforator enters the muscle near its midpoint. Branches of the sciatic nerve are the innervating nerves.

13.4.2.2 Surgical Techniques

Flap Design: A reversed triangular flap is designed. Its bottom margin is located superiorly near the inferior margin of the wound. The bottom margin should be larger than the transverse diameter of the wound but not more than 20% as the ischial tuberosity skin is tight. The biceps femoris, semitendinosus and semimembranosus muscles are located from the superior side to the inferior side. If a biceps femoris flap is to be harvested, the pivot of the design line should be located at the line drawn between the ischial tuberosity and tendon of the biceps femoris. If the other two muscles are to be harvested, the pivot should be located at the line between the ischial tuberosity and the semitendinosus. (Fig. 13.10).

Surgical Procedures: A V-shaped incision to the deep fascia is made below the wound. Take the biceps femoris flap for example. The long head of the biceps femoris is found near the distal pivot of the V-shaped incision, and the two sides are freed to the proximum. Dissection from the short head of the biceps femoris and vastus lateralis is performed in the lateral side. Dissection from the semitendinosus and the semimembranosus is performed in the medial side. Dissection continues to the proximal end at the deep LAYER of the long head

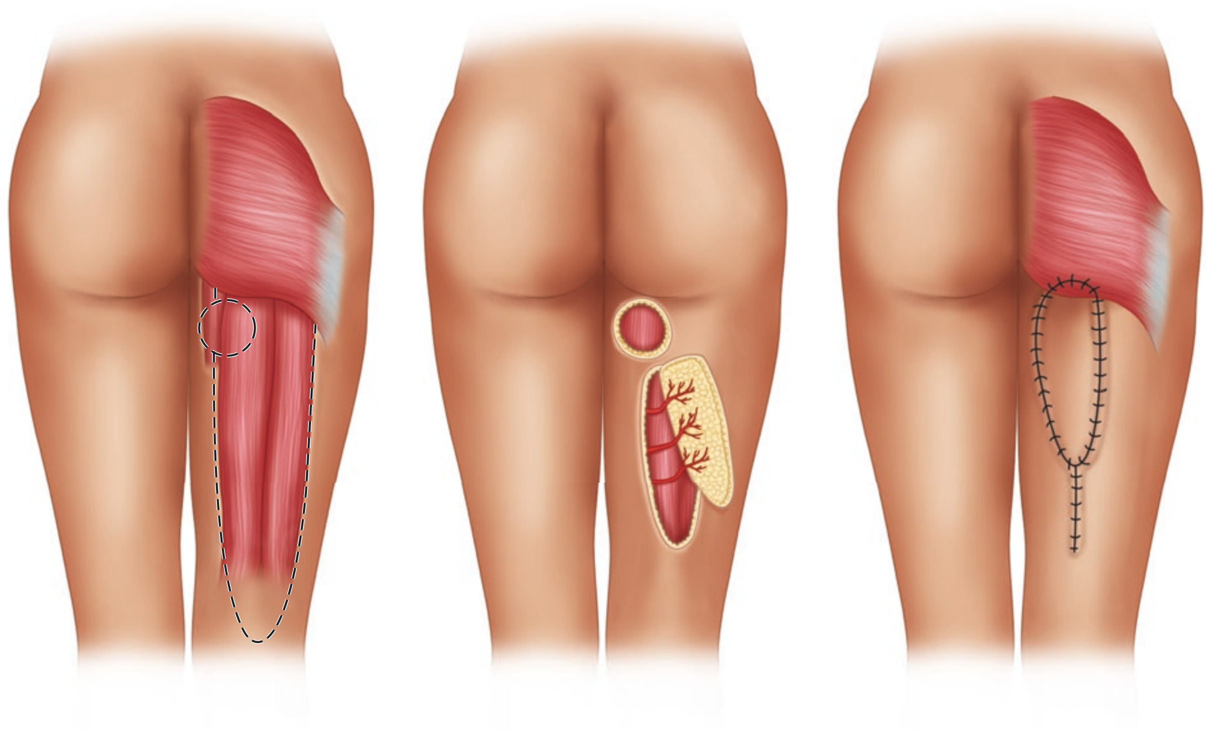


Fig. 13.10 Long head of biceps femoris muscle flap is used to repair the soft-tissue defects around the ischial tuberosity

of the biceps femoris. Vascular perforators of the biceps femoris can be found during the dissection and the dominant artery in the middle is to be preserved. The dissection goes to the bottom margin at the proximum and the muscle is cut at the insertion of muscle around the ischial tuberosity. At last, a vascular pedicled V-Y advancement flap is formed and advanced proximally to cover the wound. If the wound is too large in size or the advancement is poor in excursion, the distal end of the muscle can be cut or the distal tendon can be prolonged by Z-plasty to increase the advancement distance. The wound can be closed by Y-plasty. During the flap harvest, it should be noticed that branches of the sciatic nerve cannot be injured.

Each of the biceps femoris, semitendinosus and semimembranosus can be designed as a V-Y advancement flap. Two or three of these muscles can be united to design the flap, and the lower pivot is located between the pivots of the above two flaps. The other procedures are similar to the above.

13.4.3 Inferior Gluteus Maximus Myocutaneous Flap

The gluteus maximus, the superficial muscle of the buttock, is easy to dissect. Since its muscle belly is thick and large in size, it can be made into various myocutaneous flaps according to specific requirements. Inferior gluteus maximus flap can be used to repair soft-tissue defects around the ischial tuberosity, greater trochanter and sacrum. Application of the flap in the ischial tuberosity is the most common.

13.4.3.1 Anatomic Highlights

The gluteus maximus is supplied by the superior and inferior gluteal arteries, and the inferior gluteus maximus is fed by the latter. The inferior gluteal artery pierces the infrapiriform foramen medially at lower one third of the line drawn between the iliac crest and the ischial tuberosity, where it gives out muscular and cutaneous branches.

13.4.3.2 Surgical Techniques

V-Y Advancement Flap

Flap Design: A line is drawn between the posterior superior iliac spine and the greater trochanter. A triangular flap below the line is designed with its pivot pointing to the superomedial. The bottom margin is near the ischial tuberosity wound and longer than the width of the wound.

Surgical Procedures: An inferolateral incision is made first and the inferior gluteus maximus is dissected bluntly and elevated to expose the branch of inferior gluteal artery entering the muscle. The gluteus maximus is cut between the superior and inferior gluteal arteries. The inferior gluteus maximus is cut at the insertion to sacrum. A triangular flap pedicled with a branch of the inferior gluteal artery is formed. Then the flap is advanced inferiorly and laterally to cover the wound and sutured by Y-plasty.

Local Flap

This flap can be applied for soft-tissue defects around the ischial tuberosity, greater trochanter and sacrum.

Flap Design: A curved flap outline is drawn along the lower margin of the gluteus maximus. The length of the flap is based on the wound size. For sacral and ischial tuberosity soft-tissue defects, this curved line is located inferiorly and laterally, while medially for defects around the great trochanter.

Surgical Procedures: An incision below the designed line is made to expose the lower margin of the gluteus maximus. A blunt dissection in the deep layer of the gluteus maximus runs to the insertion at the femur where the muscle is cut. The branch of inferior gluteal artery and the vascular pedicle usually do not need to explore with intensive attention. The flap is elevated and rotated to cover the wound. The skin at the donor site can be closed primarily without tension.

Local inferior gluteus maximus flap has a limited area and poor excursion, but the surgical procedure is easy with a low morbility at the donor site. It is a good choice for reconstruction of a small size pressure ulcer around the ischial tuberosity, sacrum and greater trochanter.

Anterolateral thigh flap is applied widely and thus called "versatile flap". It is also applied in the microsurgical reconstruction of soft-tissue defects around the ischial tuberosity.

13.5 Microsurgical Reconstruction of Thigh Soft-Tissue Defects

Abundant skin, muscle and other soft tissues exist in the thigh. Skin grafting is usually performed after skin defects. The healthy part is an ideal donor site for nearby soft-tissue defects. However, for high-energy injury, burn or tumor resection involving deep tissues and vessels, reconstruction with skin graft is not suitable. Flap reconstruction is also faced with many challenges. Large soft-tissue defects in this area are formidable as few reliable flaps are available from other parts of the body for the coverage. Local transfer flaps or flaps from the abdomen become the parvus selections.

13.5.1 Anterolateral Thigh Flap

Free flaps are usually applied to reconstruct soft-tissue defects of large area around the thigh. Without the limitation of local pedicled flaps, free flaps make it possible to repair the defects, though vascular anastomosis is performed and a failure risk exists. Anterolateral thigh flap is called "versatile flap" because its donor site is insidious, it provides a large area for incision, has adequate vascular supply and leads to a high survival rate. It is widely used to reconstruct soft-tissue defects of large area all over the body, including the thigh. The design of anterolateral thigh flap is versatile according to specific wounds.

13.5.1.1 Anatomic Highlights

Anterolateral thigh flap is supplied by the descending branch of the LCFA, which does not divide and continues inferiorly along the intermuscular septum of the rectus femoris and vastus lateralis muscles, and gives off perforators longitudinally to the anterolateral thigh skin. Long length but limited width of this flap makes it difficult to satisfy large soft-tissue defects. As a result, anterolateral thigh flap itself cannot be used to reconstruct soft-tissue defects of a large area. Studies have found that constant branches are divided medially from the beginning of the trunk of the descending branch of the LCFA and travel along the intermuscular septum of the rectus femoris and sartorius muscles. Therefore, anteromedial thigh flap combined with anterolateral thigh can meet the requirements of length and width, and ensure safe vascular supply as well.

13.5.1.2 Surgical Techniques

Flap Design: Anterolateral thigh and anteromedial thigh bilobed flaps are designed based on the area and shape of the donor site. The boundary between these two flaps is the longitudinal line drawn between the anterior superior iliac spine and the midpoint of the patella. A Doppler probe is used to determine the locations of the perforators of the descending branch of the LCFA preoperatively. Perforators that supply the anterolateral thigh flap are usually located at the line drawn between the anterior superior iliac spine and the lateral border of the patella, while perforators that supply the anteromedial thigh flap are usually located at the line drawn between the anterior superior iliac spine and the medial condyle of femur.

Surgical Procedures: Incision is made on the boundary of anterolateral thigh flap and anteromedial thigh flap, and the two flaps are elevated to two sides. The descending branch of the LCFA can be detected in the intermuscular septum of the rectus femoris and vastus lateralis muscles, of which one large branch is given off and pierces the rectus femoris inferiorly, reversing to the intermuscular septum of the rectus femoris and sartorius muscles where perforators supplying the anteromedial thigh flap are divided. Perforators supplying the anterolateral thigh flap are given off from the trunk of the descending branch of the LCFA. Perforator of anterolateral thigh flap is dissected and the distal end of the perforator is ligated. Rectus femoris is pulled upward laterally to expose the nourishing vessels of anteromedial thigh flap to the start of trunk of the descending branch of the LCFA. Then the two flaps are dissected and incised along the drawn outline. Lateral femoral cutaneous nerve can be included in the anterolateral thigh flap. Anterior cutaneous branches of femoral nerve and lateral femoral veins can be included in the anteromedial thigh flap. The two nourishing vessels have one pedicle anastomosed to vessels at the recipient site. Thus the defects at the recipient site are closed by the two flaps. Wider defects at the flap donor site will require closure with a split-thickness skin graft.

Flap length can be increased when defects of a large area are reconstructed by the anterolateral thigh flap itself but the width cannot. This section discusses the anterolateral thigh and anteromedial thigh bilobed flaps pedicled with the descending branch of LCFA which are incised respectively to preserve the length and width. This type of flaps can be applied for penetrating injury because of its flexibility. The nourishing vessels of these two flaps converge under the flaps presenting like "Y". And most of the concomitant veins of the two flaps converge in the proximal. Therefore, vascular anastomosis exits in two places, which reduces the operation time and increase the survival rate of the flaps. The surgery is easy to perform since locations of the two flaps are nearby. The disadvantage of these flaps is that secondary flap defatting is usually needed owing to the thick skin of the anterolateral thigh flap.

13.5.2 Inferior Epigastric Artery Perforator Flap

Deep vessels are usually involved in thigh soft-tissue defects, including branches of the superficial femoral artery in the injury caused by radiotherapy after tumor resection. Free flaps cannot be applied in this condition owing to lack of vessels in the recipient site, and pedicled flaps in the thigh are not available. As a result, abdomen flaps are selected to repair the defects. The inferior epigastric artery perforator flaps are a choice of priority because the vascular supply or the recipient site of the superficial epigastric artery and groin flaps is injured in the situation above mentioned.

13.5.2.1 Anatomic Highlights

Most of the inferior epigastric arteries originate from the external iliac artery, and some from the femoral artery, running parallel above the rectus abdominis muscle. Two terminal branches of the inferior epigastric artery dividing at the umbilicus level communicate with the terminal branches of the superior epigastric artery which are located on the tendinous intersection above the umbilicus. Segmental arteries are given off laterally which run between the obliquus internus abdominis and transversus abdominis muscles and communicate with the intercostal arteries. The musculocutaneous perforators pierce to feed the muscle and overlying skin in the area of tendinous intersection of rectoabdominal fascia.

13.5.2.2 Surgical Techniques

Flap Design: A Doppler probe is used to mark the locations of the perforators of inferior epigastric artery preoperatively. The axis of the flap is based on the line drawn between the perforators and angulus inferior scapulae. The flap is outlined by the size and shape of the wound.

Surgical Procedures: An incision to the deep fascia caudal to the flap is made first, and a blunt dissection proceeds to the origin of the perforators around the umbilicus. Reunion is used to dissect the vessels. The inferior epigastric artery is found below the incision following the body surface projection. Then the anterior tendinous sheath of the rectus abdominis muscle is incised longitudinally. The inferior epigastric artery is freed reversely to the origin of the perforators. Partial muscle pedicle should be preserved at the exit points of the perforators in the rectus abdominis muscle. An inferior epigastric artery pedicled island flap is formed to reconstruct the thigh wound. After harvest of this flap, the anterior tendinous sheath of the rectus abdominis muscle should be repaired and skin grafting is used to repair the defect at the donor site.

Inferior epigastric artery perforator flap has the advantages of long length and wide width, large vessel caliber, long pedicle, well concealed donor site and ability to repair distant soft-tissue defects. Since the vessels of the flap are freed in the rectus abdominis muscle, this may have an effect on the fertility of women. Moreover, the anterior sheath of the rectus abdominis muscle should be repaired carefully to avoid incision hernias on the abdominal wall.

13.6 Microsurgical Reconstruction of Knee Soft-Tissue Defects

The thin skin around the knee and popliteal fossa and few soft tissues under the skin result in vulnerability of soft-tissue defects and exposure of tendons, bone and/or joint. Flap reconstruction is necessary in this situation.

13.6.1 Superomedial Knee Flap

The superomedial knee flap, also called saphenous artery flap, is located at the medial side of the knee and can be transferred locally to repair the knee soft-tissue defects. As the saphenous artery (descending branch of genicular artery) is the major nourishing vessel and its anatomic location is relatively constant, the surgery safety increases. Moreover, the saphenous nerve can be included in the superomedial knee flap to repair soft-tissue defects when sensory recovery is needed.

13.6.1.1 Anatomic Highlights

The saphenous artery flap is supplied by the saphenous artery, ranging from 10 cm above the knee to 20 cm below the knee. This flap was first reported by Acland RD and his colleagues in 1981. The saphenous artery originates usually from the descending branch of genicular artery, but a few from the femoral artery directly. The descending branch of genicular artery runs 0.5–2 cm long behind the sartorius muscle and gives out the saphenous and articular branches. The saphenous branch runs distally behind the sartorius muscle in the adductor canal accompanying the saphenous nerve and enters the subcutaneous tissues after piercing the sartorius muscle in the lower three fourths of the thigh. The distal end feeds the skin overlying the superomedial leg.

This flap has advantages of adequate vascular supply, large area of harvest and protection of the major vessels in lower extremity. The course of the saphenous artery is relatively constant, with few variations. Its long pedicle makes distant transfer and rotation easy. Its well concealed incision and its thinness satisfy the reconstruction of soft-tissue defects around the knee. Venous drainage of this flap is supported by two venae comitantes of the saphenous artery and the great saphenous vein, resulting in less swelling after surgery. Although the saphenous artery is small in diameter, its interstitial branches can increase the blood supply by retrograde flow to ensure adequate blood supply to a large area. The concomitant saphenous nerve can be anastomosed to reconstruct the sensory of the flap.

13.6.1.2 Surgical Techniques

Flap Design: The saphenous artery is marked by a Doppler probe preoperatively to be the axis of pivot. The flap axis is drawn vertically in the medial of the knee. The flap outline is designed around the axis based on the wound size and shape. Its width is no more than 6 cm bilaterally distant to the axis, and its length can be up to 10–15 cm below the knee. In order not to affect the knee function, the proximal margin of the flap should be located below the knee (Fig. 13.11).

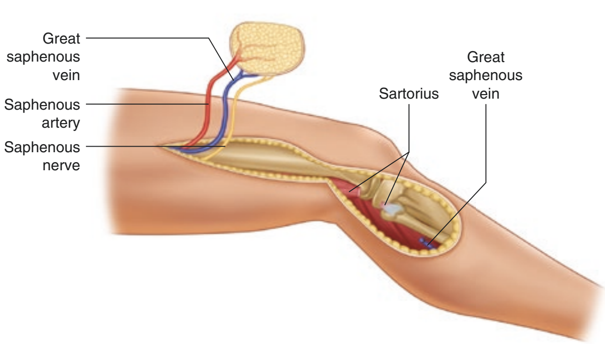


Fig. 13.11 Harvest of the superomedial knee flap

Surgical Procedures: The descending genicular artery is dissected first. A longitudinal medial thigh incision up to 10 cm is made 10 cm above the knee and the deep fascia is incised along the anterior margin of the sartorius muscle. Neurovascular bundle of the descending genicular artery can be found between the deep side of sartorius muscle and medial vastus muscle following a blunt dissection. Branches of the descending genicular artery are dissected distally along the neurovascular bundle, and its articular branch and muscular branch are ligated. The aponeurotic part of the sartorius muscle can be incised to expose the saphenous artery if needed.

The vascular pedicle may contain the anterior and posterior branches of the saphenous artery or not. The descending genicular artery can be preserved as the vascular pedicle sometimes to extend the transfer. The flap can be freed from the deep layer of the deep fascia after incision of the anterior, posterior and cadual margins of the flap following the designed flap outline, and the neurovascular bundle can be included. The vascular pedicle should be protected in this procedure and the flap can be immobilized temporarily. The flap can be rotated to cover the defects after dissection. Skin grafting is usually used for the donor site closure as the donor site is near the joint motion region and its skin is tight.

The superomedial knee flap is particularly useful for small soft-tissue defects of the extremities. The knee soft-tissue defects can be repaired through the above procedure safely and successfully. Meanwhile, this flap can be used to repair the soft-tissue defects of the opposite lower extremity by cross-leg transfer and to repair the soft-tissue defects of upper extremity or other body parts by free transplantation.

13.6.2 Superolateral Genicular Artery Flap

Superolateral genicular artery flap supplied by the superolateral genicular artery can be used to reconstruct the soft-tissue defects of extremities complicated with defects of the femur, periosteum and/or iliotibial tract.

Knee soft-tissue defects can be repaired by local transfer of this flap. Its advantages are the following. (1) Since this flap located at the triangular fovea of the inferolateral thigh has little subcutaneous fat, it is suitable for repair of thin soft tissues as secondary trimming of the bulk is unnecessary. (2) Anastomosis of lateral femoral cutaneous nerve can be performed to reconstruct the flap sensation. (3) Early postoperative exercise after the flap transplantation can avoid tendon adhesion at the recipient site which usually contains tendons. (4) The iliotibial tract in this flap can be used to repair the tendon injury, and the periosteal flap can be used to repair bone exposure, nonunion and other complex soft-tissue defects. (5) The donor site can be closed primarily, because the major vessels as well as activity of the knee are not affected. (6) The donor and the recipient sites are located at the same surgical field when this flap is used to repair the knee soft-tissue defects. Moreover, harvest of the flap at the donor site, debridement of the recipient site and vascular anastomosis are all performed under application of a tourniquet, reducing the surgical risk.

13.6.2.1 Anatomic Highlights

The superolateral genicular artery is located 3 cm proximal to the lateral epicondyle of the femur and originates from the popliteal artery (some share the same trunk with the middle genicular artery). Two concomitant veins begin with the origin of the artery (2 mm in diameter). It divides into three branches (anterior, posterior and distal) when it pierces the lateral intermuscular septum. The anterior branch runs through the lateral margin of the lateral muscle and proceeds vertically to the iliotibial tract. The perforator feeding the overlying skin is formed at the lateral epicondyle of femur. The posterior branch pierces to the skin at the proximum of lateral epicondyle of femur behind the lateral intermuscular septum. The distal branch supplies the skin overlying the distal femur through the iliotibial tract at the proximum of lateral epicondyle of femur. Since about 33.3% of the anterior and posterior branches of the superolateral genicular artery are small in diameter or absent, the uppermost lateral genicular artery can be used as a nourishing artery. The uppermost lateral genicular artery is located proximal to the lateral epicondyle of the femur and originates from the popliteal artery. Its trunk runs inferiorly and laterally, giving off the periosteal branch together with the muscular branch after piercing the lateral margin of the vastus lateralis muscle. Its innervating nerves are the terminal branches of the lateral femoral cutaneous nerve.

13.6.2.2 Surgical Techniques

Flap Design: Perforator of the superolateral genicular artery flap penetrates the deep fascia in a small triangular area surrounded by the vastus lateralis, the biceps femoris muscle, and the lateral femoral condyle. The penetrating point is located about 4 cm proximal to the lateral condyle of the femur, where an intersection is made between the horizontal line at the superior margin of the patella and central axis of the lateral thigh in extension position of lower extremity. The point is used as the rotation center, and one third of the flap is distal to the point, two thirds proximal. The anterior and posterior borders of this flap are determined by the wound size and shape. The biggest incision size of the flap can be up to 17.0 cm by 11.0 cm according to the results of ink perfusion, and the bone flap can be up to 8.2 cm by 3.4 cm. The proximal margin of the flap should be below the knee in order not to affect the knee activity.

Surgical Procedures: An incision under the deep fascia is made near the anterior margin of the flap. It is better to immobilize the deep fascia and skin first owing to the movement of the iliotibial tract and skin. The anterior branch is dissected bluntly along the surface of the vastus lateralis muscle, and the muscular branches are ligated. Superolateral genicular artery is freed medially and its periosteal branches are ligated. If the anterior and posterior branches run above the femur, the cutaneous perforators originating from the uppermost lateral genicular artery will be considered. Its origin is found upward along the cutaneous perforators by freeing the trunk of the uppermost lateral genicular artery.

The terminal branch of the lateral femoral cutaneous nerve is marked at the superficial fascia of the flap's proximum. Then the flap is incised along the proximal, distal and posterior margins. Temporary immobilization of the flap is performed to preserve the connection of cutaneous perforators with the flap. Thereafter, the whole flap is freed with only the vascular pedicle left. If bone flap is needed, it is harvested by a swing saw and a bone drill. Holes should be drilled deep to the marrow cavity along the designed outline. The anterior branch can be preserved only when distant defects are to be repaired. Distal branch or rami communicans in the knee vascular network of periosteal branch should be reserved when local flap transfer is used to repair the knee soft-tissue defects. Bone flaps can be immobilized by Kirschner wires at the recipient site. The pure skin flaps are pedicled with the superolateral genicular artery. Distal branch should be preserved when a complex flap is to be harvested to repair the tendon injury because the blood supply of the iliotibial tract comes mainly from the distal branch. The iliotibial tract is incised into 2–4 cords to repair tendon injury. The donor site usually can be closed primarily.

Since the nourishing vessels of the superolateral genicular artery flap vary a lot and their dissection is relatively complex, they are not the first choice for reconstruction of knee soft-tissue defects. But this flap can be made into a complex one carrying bone and iliotibial tract. For complex tissue defects, the complex flap can be used to repair the defects at one stage, reducing the operation time and the affliction of the patient.

13.7 Microsurgical Repair of Soft-Tissue Defects in the Leg

Soft tissue in the leg is relatively thin and the blood supply in the middle and lower parts of the leg is relatively poor. As a result, trauma is more likely to result in soft-tissue defects and bone exposure. With social and traffic development, the rate of traffic injury has risen perpendicularly. Trauma of the legs is common in a traffic accident. Therefore, repair of soft-tissue defects in the leg has become a challenge to orthopedic surgeons.

13.7.1 Gastrocnemius Myocutaneous Flap

The gastrocnemius myocutaneous flaps supplied by the sural blood vessels are often used in the repair of soft-tissue defects in the leg. They can be divided into two kinds. One is the gastrocnemius myocutaneous flap with medial head, and the other is the gastrocnemius myocutaneous flap with lateral head. The former is the most commonly used in the repair of soft-tissue defects in the leg, and the latter more advantageous in the repair of the anterior and lateral leg though its application scope is relatively narrow. As the main function of the gastrocnemius is the plantar flexion of the ankle joint, harvesting one of the two heads will not greatly influence the function of the ankle joint. The gastrocnemius can be regarded as a soft cushion because of its strong muscular fibers and also good buffer effects. Meanwhile, the gastrocnemius myocutaneous flap has adequate blood supply and its muscular tissues have a powerful ability of anti-infection and healing. The operation is simple and can be completed without special facilities, because the anatomic location of the posterior leg is constant and superficial. Moreover, because the flap has a large diameter and is easy to rotate in different directions, it can be used extensively. This section takes the medial head gastrocnemius myocutaneous flap as an example.

13.7.1.1 Anatomic Highlights

The gastrocnemius myocutaneous flaps are pedicled with sural blood vessels, including the medial head gastrocnemius myocutaneous flap and the lateral head gastrocnemius myocutaneous flap. The gastrocnemius belongs to the posterior muscles of the leg and has a relatively superficial dissection position. The medial and lateral heads originate from the back of medial femoral epicondyle and lateral femoral epicondyle respectively, descend along the middle and lower parts of the leg, turn into an aponeurosis of flat wide shape, and converge into the soleus tendon to form the Achilles tendon. The small saphenous vein and the sural nerve, regarded as anatomic landmarks, are located between the muscle belly of the medial and lateral heads. The nutrient arteries of the medial and lateral heads originate from the popliteal artery, then cross through the deep layer of the proximal muscle, and finally divide into many vessels to supply the above muscle and skin. Harvest of the head of the gastrocnemius should be performed in the septum between the gastrocnemius and the soleus. The septum should also be separated from upward to downward, because the connection between the two muscles is looser in the upper part than in the lower part. Since the small saphenous veins and the sural nerve are constantly under the deep fascia of the leg, we can regard them as the boundary of the medial and lateral heads of the gastrocnemius.

13.7.1.2 Surgical Techniques

According to location and severity of injury, different kinds of gastrocnemius myocutaneous flap can be designed to repair the soft tissue defects.

Full-pedicled Gastrocnemius Myocutaneous Flap

During harvesting the medial head of the gastrocnemius, the skin and muscle in the pedicle are not cut off and the blood vessels are not exposed. The operation is a simple and safe, suitable for repair of the wounds in the upper and middle parts of the leg. However, a small available angle in the flap rotation limits its clinical application. The following takes pretibial wounds as an example to illustrate this kind of flap.

Flap Design: The posterior midline of the leg is used as the axis of the flap. The center of rotation is located at the posterosuperior part of the leg. The front edge of the flap adjoins to the wounds. The outline of the flap is designed according to the size and shape of the wound. Making sure that the flap is 3–5 cm larger than the wound.

Surgical Procedures: The patient takes a prone position. An incision to the deep fascia is made in the popliteal space. The small saphenous vein and the sural nerve should be detected, and pulled to the other side with wet gauzes. The medial head of the gastrocnemius is bluntly dissected from the lateral head and the soleus. Then the distal and rear sides of the flap are elevated. Skin and muscle in the basilar part of the flap need not to be dissected. Then the flap is pivoted forward to cover the wounds. The wounds of the donor site are closed with split thickness skin graft.

Double-pedicled Gastrocnemius Myocutaneous Flap

The skin in the distal part of the myocutaneous flap is reserved without dissection. As a result, the flap becomes bipedicled. This kind of flap can have a longer length and adequate blood supply at the cost of the range of motion, suitable for wounds in distal parts of the leg.

Flap Design: Take the medial head gastrocnemius myocutaneous flap for repair of pretibial wounds as an example. The front edge of the flap adjoins the wound. The posterior midline of the leg is the trailing edge of the flap. The distal part descends forward to the top of the medial malleolus. About 4 cm-wide skin and subcutaneous tissue is preserved intact as the distal pedicle of the flap (Fig. 13.12).

Surgical Procedures: The proximal pedicle of the flap is dealt with in the same way as is the above pedicled gastrocnemius myocutaneous flap. The distal harvest should be in the medial of the Achilles tendon. The perforating branches from the soleus should be ligated. The flexor retinaculum and posterior tibial neurovascular bundle should be protected. The myocutaneous flap is advanced forward to cover the wound after the flap is completely elevated. If the flap's range of motion is limited, the skin of the proximal pedicle

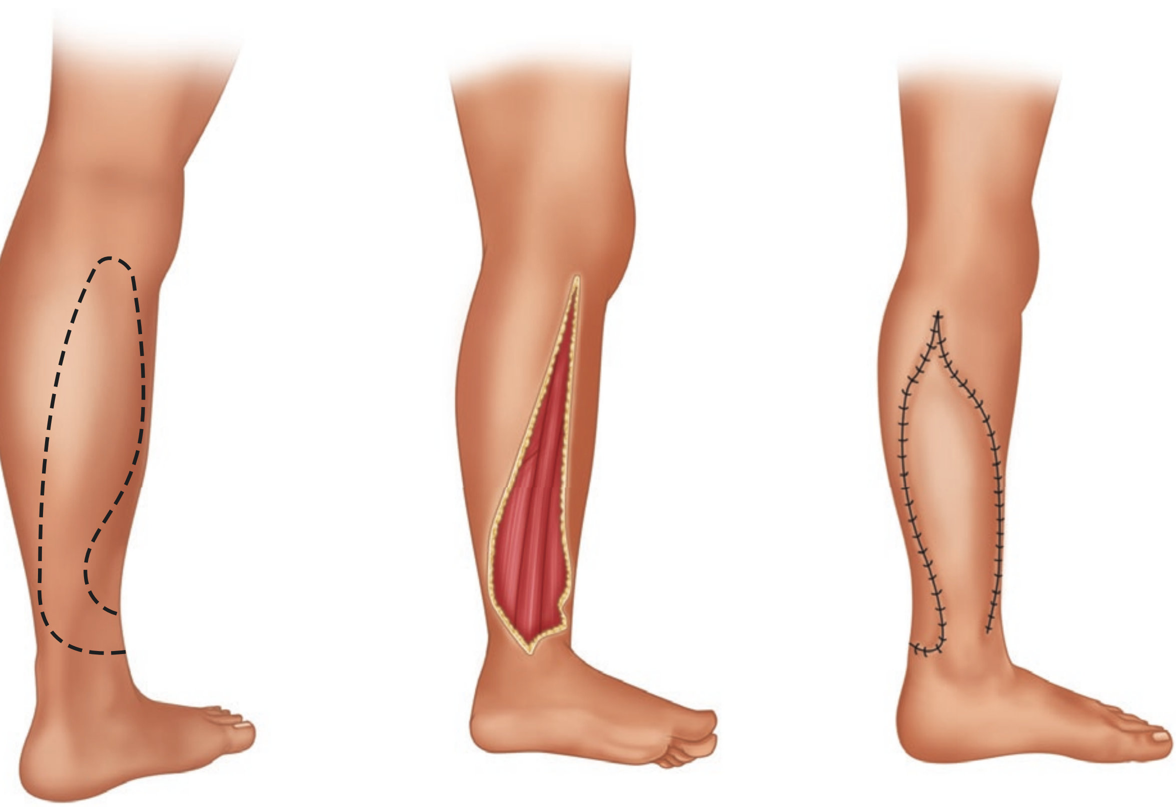


Fig. 13.12 Bi-pedicled gastrocnemius medial myocutaneous flap to repair the distal wounds of the leg. (Hou Chunlin, Gu Yudong. Flap surgery, 2006, 627)

and the insertions of the medial head of the gastrocnemius can be dissected without injuring the intact blood vessels in order to increase the excursion of the flap.

The Medial Head Gastrocnemius Myocutaneous Advanced Flap

With longitudinal advancement of the flap, the distal wound of the leg can be repaired.

Flap Design: A larger longitudinal oval flap should be designed in order to cover the wound. The rear edge of the flap is 2 cm surpassing the posterior midline; the lower edge is 3 cm above the medial malleolus, adjoining the wound.

Surgical Procedures: The procedure of harvesting the flap is the same as mentioned above. The skin, subcutaneous tissue of the proximal pedicle and the insertion of the medial head should be dissected in order to advance the flap distally to cover the wound. To avoid overstretching blood vessels, the medial head should be pulled back slightly and fixed onto the soft-tissue. The wound of the donor site is primarily sutured directly.

After such procedures, the affected knee should be immobilized in flexion for 3 weeks.

Transposition of the Medial Head Gastrocnemius Myocutaneous Flap

A cross-leg flap should be used to cover the wound when local soft-tissue defects are too severe to be repaired with free flap or local flap transfer. This type of flap is more flexible in controlling the ratio of length to width than a traditional cross-leg flap.

Flap Design: The medial head of the gastrocnemius myocutaneous flap on the uninjured side is dissected according to the above procedures. The flap should be large enough to be transferred to the injured side.

Surgical Procedures: The method of harvesting the flap is the same as mentioned above. It is difficult to close the pedicle of the flap with a tube because there is a bulk of muscle. Therefore, Professor Hou Chunlin suggests that the pedicle is spiralled into a tube which can close the pedicle and lengthen the skin tube. The pedicle will be cut off 3–4 weeks after operation. The remnant muscular flap is sutured back.

This type of flap can also be used to repair of soft-tissue defects around the knee and on the foot.

13.7.2 Posterior Tibial Artery Perforator Flap

The perforator flap, which attracts more and more attention in recent years, has an advantage over the traditional axial flap because it can avoid losing main blood vessels on the premise of adequate blood supply. The posterior tibial artery perforator belongs to intramuscular perforators. The perforator is easy to elevate without injuring muscles because it is located in the posteromedial tibia. The flap can repair adjoining wounds through local transferring.

13.7.2.1 Anatomic Highlights

The posterior tibial artery has many perforators which supply the skin. In general, perforators of the upper part of the leg are longer than those of the lower part. The second part and fifth part have six perforators separately, with an occurrence rate of 100%. These perforators have larger diameters and constant locations. On the contrary, locations of perforators in other regions are not constant. The posterior tibial artery perforators have one to two accompanying veins whose diameter is larger than that of the perforator artery. These accompanying veins, connecting the great saphenous vein inside the flap, converge into the posterior tibial vein. The perforators in the upper part of the leg accompany the great saphenous veins and the saphenous nerve.

13.7.2.2 Surgical Techniques

Flap Design: Before operation, the locations of perforators penetrating out of the deep fascia should be marked by a Doppler ultrasound blood flow detector. After marking the location of the pedicle, the outline of the flap can be designed on the basis of the size and shape of the wound.

Surgical Procedures: Firstly, an incision is made in one side of the pedicle, and then perforators are detected under the deep fascia. The suitable perforator should be protected. An incision from the skin to the deep fascia is made according to the outline of the flap in order to separate the flap from its ambient tissue. After elevation, the flap is rotated to cover the wound. The wound of the donor site is covered with split thickness skin graft (Fig. 13.13).

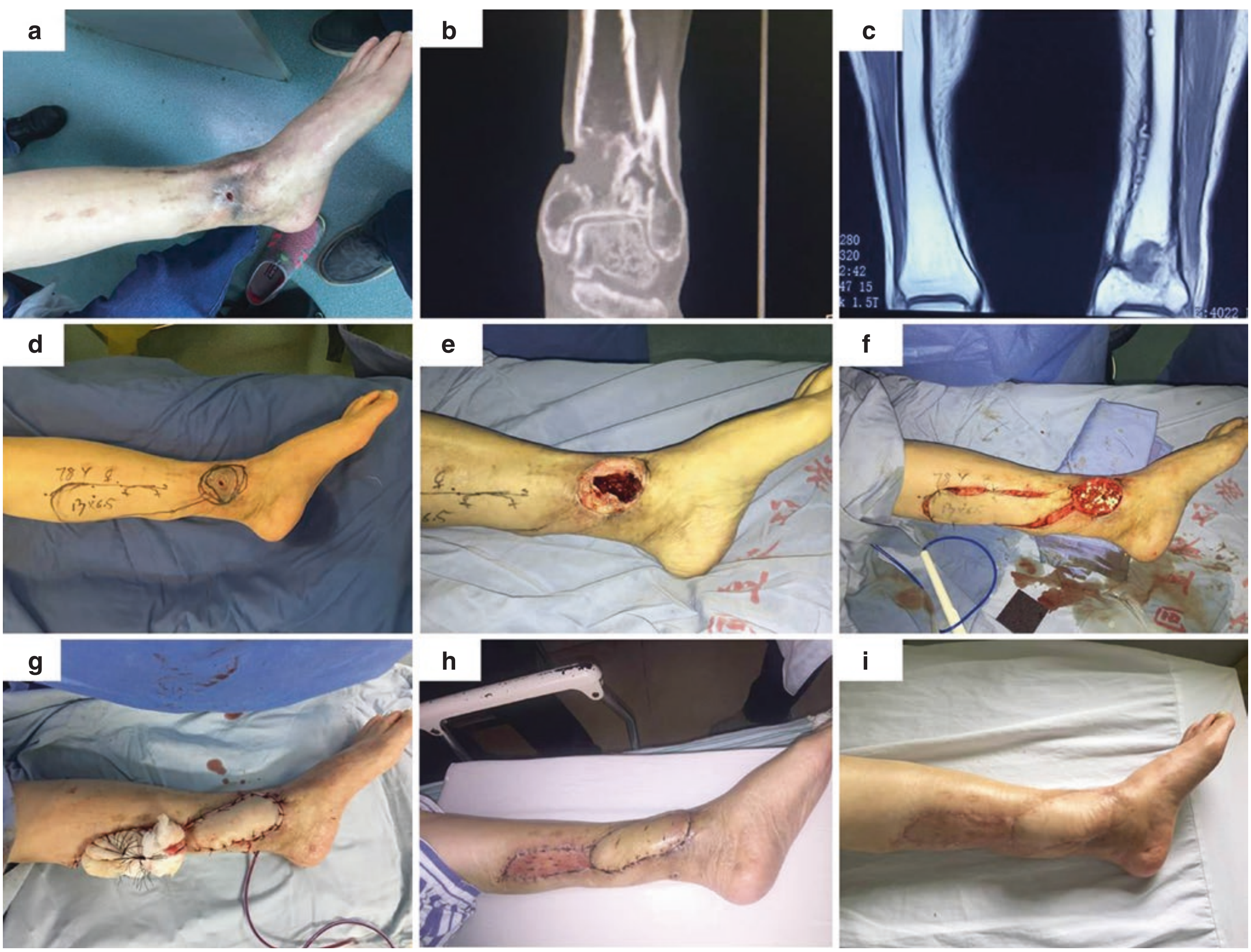


Fig. 13.13 A 78-year-old woman with traumatic osteomyelitis after internal fixation of distal tibial fracture for 5 years (**a**, gross view; **b**, x-ray; **c**, MRI) was treated with autologous iliac bone loaded with antibiotic calcium sulfate artificial bone for mixed bone grafting (**d**, flap design; **e**, debridement). The soft tissue defect was repaired by rotating the perforator flaps of posterior tibial artery (**f**). The last three pictures were taken at the end of the operation (**g**), 20 days (**h**) and 6 months (**i**) after the operation. (This case was provided by Professor Zhang Chun from Zhejiang Tongde Hospital.)

This type of flap can also be used to repair the soft-tissue defects around the knee and on the foot.

13.8 Microsurgical Treatment of Soft Tissue Defects at the Ankle Joint

There are many sorts of flap for reconstruction of soft tissue defects at the ankle. Most of the flaps do not require vessel anastomoses as needed for free tissue transfer. Local flaps harvested from the lower extremity and foot can be used.

13.8.1 Reconstruction of the Ankle Soft Tissue Using Reverse Transposition of a Lower Extremity Flap

Soft tissue defects of the ankle joint can be resurfaced by various flaps, such as lateral crural flap, medial crural flap, sural neurocutaneous flap, lateral supramalleolar flap, medial supramalleolar flap, and saphenous neurocutaneous flap. These flaps have their advantages and disadvantages. For example, the medial crural flap proves to be a good option for excellent texture, but it also has a disadvantage of sacrificing a main artery of the lower extremity. Similarly, the lateral crural flap has disadvantages of sacrifice of the peroneal artery and technical difficulty in elevation due to its deep location at the lateral aspect. With the development of perforator flaps in recent decades, the sural neurocutaenous flaps pedicled on the perforator of peroneal artery and pedicled on the posterior tibial artery perforator have been widely applied in clinic in the reconstruction of lower extremity soft tissues.

13.8.2 Reconstruction of the Ankle Soft Tissue Using Transposition of a Foot Flap

The dorsal foot flap and the medial plantar flap are indicated for reconstruction of the ankle soft tissues. The dorsal flap should be used very carefully, because free skin grafting is needed after harvest of the flap and its poor wear-resisting and pressure-resisting performance. In addition, the medial plantar flap is not suitable for massive defects at the ankle joint, because of its limited area of harvest.

13.8.3 Reconstruction of Combined Defects of Soft Tissue and Achilles Tendon

As the achilles tendon plays an important role in ambulation, weight-bearing, and plantar flexion, it should be repaired or reconstructed simultaneously in the reconstruction of soft tissues. The methods to reconstruct the achilles tendon are discussed in the next section “Microsurgical Treatment of the Achilles Tendon”.

13.9 Microsurgical Treatment of the Achilles Tendon

The achilles tendon is the thickest one in a human body. It provides not only an excellent sliding function for movement of the ankle joint, but also a powerful anti-tension force to balance our entire body when we walk and jump. The region of achilles tendon also has functional and aesthetic demands for weight-bearing and foot-wear, which requires good wear-resisting and appearance. According to our clinical experience, injured achilles tendon is often accompanied by other defects, such as composite defects of the achilles tendon, skin and soft tissue, composite defects of achilles tendon, calcaneus, skin and soft tissue. Their reconstructive procedures are still a great challenge to plastic surgeons. Since Taylor et al. introduced vascularized compound flaps for reconstruction of the composite defects of achilles tendon and soft tissues, the method of vascularized tendon tissue or vascularized compound flap has gained great popularity. With the ever growing microsurgical techniques, it has become the main method to reconstruct achilles tendon.

13.9.1 Mechanism and Healing Process of Achilles Tendon Injury

The achilles tendon, with a mean length of 15 cm, is musculotendinous tissue. Its contour becomes wider and thinner from distal to proximal, and its narrowest part is at 3–6 cm proximal to the calcaneus tuberosity. Its rupture happens usually at the joint part of musculotendinous tissue and the muscle belly, and sometimes at the distal part of calcaneus tuberosity. The following factors may influence the healing of the achilles tendon: (1) the injure to the surrounding soft tissue may impair the blood supply to the achilles tendon; (2) the rebounding force from the triceps surae on the achilles tendon may increase the tension of the suture, also impairing the blood supply to the achilles tendon and the soft tissue; (3) immobilization and infection may also result in malnutrition and delayed healing; (4) improper immobilization and early motion.

13.9.2 Classification

Based on the defective components, the injury of the achilles tendon can be divided into three types. Type A: simple defects; type B: composite defects of the achilles tendon and soft tissue; type C: composite defects of the achilles tendon, soft tissue and the calcaneus. It can also be divided into three types according to the severity of injury. Type I: the defect length is less than 3 cm; type II: the defect length ranges from 3 to 6 cm; type III: the defect length is greater than 6 cm.

13.9.3 Reconstruction of the Achilles Tendon

Reconstruction of the injured achilles tendon depends on the type of injury. For type A: Direct anastomosis can be performed for patients with injury of type I. As for injury of type II, common reconstructive options are the Bosworth's method, Lindholm's method, and Abraham's reverse 'V-Y'-plasty. All these methods extensively dissect the proximal part of the achilles tendon and stretch the remaining part by taking advantage of the elastic characteristic of the Achilles tendon. The extensive dissection may, however, impair the blood supply to the achilles tendon and increase the risk of second rupture. The force of plantar flexion may also be sacrificed. In the recent decades, many plastic surgeons tend to use vascularized adductor magnus tendon for type II injury, and they have achieved good functional results. To treat type III defects, vascularized iliotibial band is commonly used.

Type B: Local flaps or pedicled axial flaps, combined with direct anastomosis of the achilles tendon are indicated for type I defects. The choices include: lateral calcaneus flap, medial plantar flap, dorsum pedis flap, medial supramalleolus flap, lateral supramalleolus flap, and sural neurocutaneous flap. Multi-staged reconstructive procedures are usually performed for type II defects. Transplantation of vascularized musculotendinous tissue should be done after successful transfer of flap. As the techniques for one-stage reconstruction of the achilles tendon and soft tissue are constantly improving, several flaps could be considered, including local flap or sural neurocutaneous flap combined with V-Y plasty of gastrocnemius muscle, and vascularized adductor magnus myocutaneous flap. One-stage reconstruction is also valid for type III defects. The flap options include: vascularized iliotibial band fasciocutaneous flap, vascularized tensor fasciae latae myocutaneous flap, anterior rectus abdominis myocutaneous flap, and latissimus dorsi myocutaneous flap.

Type C: Treatment of patients with type C injury often requires multiple procedures and prolonged hospitalization. Most surgeons prefer multi flaps for reconstruction of composite defects, including vascularized fibular bone flap, and vascularized adductor magnus osteomyocutaneous flap. Fibular segments are used for bony reconstruction and the vascularized adductor magnus osteomyocutaneous flap can be used for composite reconstruction of the calcaneus, distal part of the achilles tendon and overlying soft tissue.

13.10 Microsurgical Treatment of the Dorsum Pedis Defects

The foot, as an important functional structure with incredibly complex mechanism, can perform functions of weight-bearing, walking and vibration absorption. Reconstruction of the foot should vary with defects at different regions, in order to fulfill different functional requirements of the non-weight-bearing region and weight-bearing region. The dorsum pedis, located at the non-weight-bearing region, has relatively thinner subcutaneous tissue and larger underlying tendons. The shearing force in a traumatic injury may easily result in degloving injury to the dorsum pedis skin and the underlying structures of vessels, nerves, and bones. To prevent necrosis of the underlying structures, fasciocutaneous flaps or myocutaneous flaps are better options to resurface the dorsum pedis. An ideal donor site for reconstruction of the dorsum pedis should be thin and pliable, and allow for tendon sliding and normal foot-wear.

13.10.1 Reconstructive Method for Dorsum Pedis Defects

The cross-leg technique used to be the only one option for reconstruction of the distal leg and foot for quite a long period of time after Hamilton first introduced it in 1854. However, its disadvantages include long period of immobilization and other complications. Recently, it has been replaced by various local flaps from the lower extremity and free flaps from other donor sites, which are supplied by perforator vessels and thus preserve the main trunk artery for the entirety and can be elevated easily. However, according to the long-term follow-up results, these aforementioned flaps are still too thick, especially its pedicle region, for the foot function of wearing shoes. This disadvantage becomes significant when forefoot defects are involved, and the scar tissue left at the donor site will also affect the aesthetic appearance. Given that the ankle and foot are often exposed, scar tissue left at these parts may be unacceptable by the people who have a high demand of their appearance. Therefore, we tend to harvest free flaps from the body trunk and proximal lower extremity to resurface foot and ankle defects, instead of choosing flaps, like the latissmus dorsi flap, the scapular flap and the anterior lateral flap, which are too gross and require multiple trimming surgeries. A combination of fasciocutaneous flap and skin graft can successfully meet the demands of thinner texture and dorsum pedis reconstruction. In reconstruction of composite defects with open fracture of the foot, myocutaneous flaps can be used with better outcomes due to its sufficient blood supply and capabilities of obliterating dead space and preventing occurrence of osteomyelitis.

13.10.2 Common Flaps for Dorsum Pedis Defects

The anterior ankle flap, pedicled on the dorsails pedis artery, is an axial pattern and can be rotated reversely from the anterior aspect of the ankle to the dorsum pedis. Its area reaches from the distal ankle to the proximal dorsum pedis, and its width can be equivalent to the distance between the lateral and the medial malleolus. The flap is basically elevated in the same manner as the dorsum pedis flap. The key points are careful dissection of the cutaneous perforator and repair of the anterior transverse ankle ligament after incision. Its indications are soft tissue defects of the dorsum pedis with intact dorsails pedis artery and its perforators. It can be rotated on a pivot point, which is the same point of the perforator of the dorsails pedis artery to cover a defect of dorsal fore foot. The donor site is usually covered with split-thickness skin graft.

The perforator-pedicled sural neurocutaneous island flap, utilizing the perforator vessel to supply the entire flap and thus preserving the main arteries of the lower extremities, is indicated for soft tissue defects of dorsal foot with injury to the dorsails pedis artery and anterior tibial artery. Since the posterior tibial artery is the only vessel to nourish the foot, it should not be harvested as a pedicle vessel of the flap. Its elevation is similar to that of the reverse sural flap. Since the so-called 'neurocutaneous island flap nourished by the sural nerve' prevents insufficient blood supply and problems of venous drainage by preserving the sural nerve and its nutrient vessels and deep fascia into the pedicle, it is reliable and effective in reconstruction of massive skin and soft tissue defects at the dorsum pedis.

Free flaps, compared to local pedicle flaps, have much more choices for donor site. Their ideal donor sites should have merits of thinner subcutaneous tissue, less functional impairment and direct closure. Anterior lateral thigh flaps and scapular flaps are commonly used in practice. Their pedicle vessels can be anastomosed to the distal end of dorsails pedis artery or the anterior tibial artery so that the veins of the flap can be connected to the great saphenous vein thorough end-to-end or side-to-end anastomoses.

Combination of the trimmed latissmus dorsi muscle flap with skin graft can also lead to good functional and aesthetic outcomes for soft tissue defects at the dorsum pedis. The latissmus dorsi muscle is supplied by the thoracodosal artery which can provide a long and large pedicle vessel for microsurgical procedure. The latissmus dorsi can be fashioned based on varies patterns of defects with ease of elevation. The concealed location of donor site can be closed directly with limited morbidities. In addition, transfer of muscle flaps has merits of both sufficient blood supply and less grossness compared to other fasciocutaneous flaps which may lead to atrophy after denervation of the muscle tissue. The contour can be improved through trimming of the muscle flap with split-thickness or full-thickness skin graft.

13.11 Microsurgical Reconstruction of the Forefoot Soft Tissue Defects

The forefoot is, as anatomically defined, the distal part of the foot from the Lisfranc-joint which is vulnerable to traumatic injury compared to midfoot and hindfoot due to its protruding location. As a result, reconstruction of the forefoot soft tissue presents a great challenge for plastic surgeons because of its requirements of long distance transfer and dissection of long pedicle vessels. Flap coverage becomes significantly valuable because shortening the Lisfranc-joint to close the defects can cause loss of forefoot function. Various flaps are reported for the reconstruction of forefoot soft tissue, such as the cross-leg flaps, pedicled local flaps, and free flaps. In clinic situations, choice of flaps should follow the reconstruction principle: the simplest technique should be explored first to avoid a secondary impact by complex surgical procedures.

13.11.1 Reconstruction of Small Forefoot Soft Tissue Defects

As for small soft tissue defects at the forefoot, medial crural flaps and free flaps harvested from a remote donor site should not be the first option because of their large area of dissection and great donor site morbidity. Similarly, the pedicled local flaps also have limitations of a small harvest area and few donor sites. According to our clinical experience, small defects of the forefoot are better covered with local flaps from other portions of the foot, based on conditions of the defect and availability of surgical resources and skills. The common methods are as follows:

1. Medial plantar flaps or lateral plantar flaps

   Medial plantar flaps and lateral plantar flaps, pedicled on the distal ends of medial plantar artery and lateral plantar artery, respectively, are reverse island flaps. As both flaps have similar indications and surgical procedures, we discuss them together.

   A subcutaneous tunnel is not suitable for transfer of the medial or lateral plantar flaps due to the tension of local skin at the area. As the space of tunnel is limited, over-stretching the pedicle vessels may impair the vessels themselves. Dissection of the tunnel in a sharp way may injure the vertical fibrous tissue of plantar foot, impairing the function of the foot.

   To facilitate rotation of the flap, the defects on the lateral aspects of the foot are repaired with a medial plantar flap while the defects on the medial aspects of the foot with a lateral plantar flap. The viability of these two flaps is based on the plantar arteria arch and the communicating branches of the medial and lateral plantar arteries which are easily injured in patients with forefoot injury. The reversed medial and lateral plantar flaps are not indicated for patients who sustain severe forefoot injury. For the sake of safety, flap vascularization should be observed before dissection of the proximal part of the medial or lateral plantar. In addition, the surrounding subcutaneous tissue of the pedicle vessel should be retained to increase the survival rate of the flap if no tension or twisting is caused to the pedicle vessel. Besides, preoperative inspection of pulse of the dorsails pedis artery can ensure the viability of the flap, because the blood supply of the flap originates from the dorsails pedis artery after flap elevation.

Sensation of the forefoot plays an important role in the mobile and supporting function. Skeletonization of the medial plantar nerve should be performed after flap elevation and anastomosis to the digital nerve, giving innervation of the plantar foot. However, the procedure of neuro-repair can be skipped if the flap diameter is less than 2 cm, as the innervation can be achieved by the infiltration from the soft tissue bed.

2. Medial hallucis flaps
   The medial hallucis flap provides an effective alternative for small forefoot defects. It is nourished by the medial hallucis artery and its concomitant veins. The texture and color of the medial hallucis flap fit the plantar skin, and the flap thickness is appropriate. Recovery of the plantar aspect can be regained by including the fibulare hallucis digit nerve into the flap. Its disadvantage is that its area and range of rotation are limited. Its design should be based on the defect pattern. Its incision can be started at the plantar web between the first and second toes, where the fibulare hallucis digit artery and nerve can be explored and skeletonized according to the length of the pedicle. The entire flaps can be elevated and transferred to the defects after successful dissection of the pedicle vessels and nerves. The donor sites can be closed either directly or through skin graft.
3. First metatarsal dorsal artery reversed flaps
   The first metatarsal dorsal artery reversed flap, pedicled on the first metatarsal dorsal artery, has less anatomical variation and reliable blood supply. Preoperative evaluation of the dorsails pedis artery can be easily made through palpation and a Doppler ultrasound. Normally, when the distal end of the dorsails pedis artery serves as the pivot point of the flap, the first metatarsal dorsal artery reversed flap can reach any region of the forefoot. As a result, the first metatarsal dorsal artery reversed flap becomes one of the most effective and reliable means for reconstruction of forefoot soft tissue. The axis of the flap is the line between the midpoint of the first and second heads of the metatarsal bone and the midpoint between the lateral and medial malleolus. Its pivot point is located at about 2 cm proximal to the first toe-web. The distance from the pivot point to the proximal edge of the wound is equivalent to the length of the pedicle. The flap pattern should be based on the size and outline of the defects. To ensure adequate tension-free coverage, a 10–15% larger pattern should be designed than what would anatomically be necessary. The procedure begins at the incision of the proximal edge of the flap to explore the dorsails pedis artery. In some cases, the flap should be redesigned to fit the location of the dorsails pedis artery. The distal edge of the flap can be incised deep to the deep fascia before sutures are made to fix the skin and subfascia tissue. Elevation of the flap should be performed below the level of deep fascia, and care should be taken to protect the arteria branches reaching to the flap. Before elevation of the flap, a vessel clamp should be applied temporarily at the dorsails pedis artery to observe the vascularization of the forefoot and toes. After cutting and ligation of the proximal end of the dorsails pedis artery, the pedicle vessels are skeletonized retrogradely to the pivot point. The first plantar perforator of the dorsails pedis artery should be ligated and cut through the dissection. The flap can be transferred to the defects through either a skin incision or a subcutaneous tunnel. A flap wider than 4 cm usually requires skin grafting, otherwise the donor site can be closed directly.

13.11.2 Reconstruction of Massive Forefoot Soft Tissue Defects

The aforementioned flaps cannot cover massive soft tissue defects of the forefoot due to their limited area. Superficial peroneal nerve neurocutaneous flaps, sural artery flaps, anterior tibial flaps, and posterior tibial flaps are useful for dorsum pedis defects, but they cannot reach the defects of forefoot plantar. Retrograde flaps pedicled on the posterior tibial arteries can cover the plantar defects of forefoot after their pivot point is shifted at the distal level, but their indications are limited and they may lead to morbidities of the donor site because they sacrifice a major artery of the lower extremity. As a result, free flaps become the first choice in most situations.

1. Posterior/anterior tibial artery flaps
   The axis of posterior tibial flaps is the line between the junction point of the fibular head and the lateral crest of tibia and the midpoint of the lateral and medial malleolus. The pivot point can be selected either as the midpoint of the first and second heads of metatarsal bones or the midpoint of the lateral and medial malleolus. The flap pattern should

be based on the size and outline of the defects. To ensure adequate tension-free coverage, a 10–15% larger pattern should be designed than what would anatomically be necessary. The procedure begins at the incision of the medial edge of the flap to the deep layer of deep fascia. Elevation of the flap should be performed at the level between the deep fascia and the gastrocnemius. Exploration of the pedicle vessels should proceed between the intermuscular space of the soleus and the flexor digitorum longus. The muscular branches of the posterior tibial artery should be ligated and cut through the course of retrograde dissection, but the cutaneous branch reaching the skin paddle should be preserved and protected. Vascularization of the foot should be observed using vessel clamps at the proximal portion of the posterior tibial artery before ligation. When viability of the forefoot is assured, the proximal posterior tibial artery can be ligated and cut, and the flap can be elevated reversely from the proximal to the distal. Transfer of the flap can be done through a skin incision from the donor site to the defect. Donor site can be closed by full-thickness skin graft.

Advantages of the artery flap include: (1) less variation of the pedicle vessels, (2) stable blood supply to the flap, (3) sufficient length of the pedicle vessels, and (4) a wide range of transfer. On the other hand, it is inevitable to sacrifice a major artery of the lower extremity when an artery flap is harvested.

2. Sural neurocutaneous flaps
   The axis of sural neurocutaneous flap lies between the midpoint of the lateral malleolus and the achilles tendon and the midpoint of the medial and lateral femoral epicondyle, and the distal perforator of the peroneal artery, 2–3 cm above the lateral malleolus, serving as the pivot point of the flap. Besides a larger pattern than the defective area, the wide pedicle should retain at least 1.5–2 cm of skin pedicle. Dissection should be performed at bilateral sides of the skin pedicle at the subcutaneous level. The proximal border of the flap is dissected for exploration of the sural nerve and the location of flap is then adjusted according to the course of the sural nerve. Advantages of the sural neurocutaneous flap are preserving the major artery for its entirety and easy harvest. Selection of the pivot point of the flap is significantly important when the flap is used to resurface the forefoot defects. The distal perforators of the peroneal artery, about 2 cm above the lateral malleolus, are a reliable pivot point for flap rotation and normally only one perforator can be found at that area. A sufficient width of skin pedicle is one of the major factors influencing the viability of a large flap.
3. Free flaps
   It is technically demanding for surgeons to use free flaps to resurface forefoot defects, but there is a variety of options. Besides, donor site morbidities of free flaps are less than those of posterior tibial artery flaps. Thus, free flaps are frequently used in clinical practice due to the omission of massive dissection of pedicle vessels. Anterior lateral thigh flaps, medial thigh flaps, and dorsum pedis flaps are alternatives. The anterior tibial artery can be used as the recipient artery for anastomosis while the great saphenous vein can be chosen as the recipient vein. Venous drainage problems should be prevented after the flap is transferred to the distal portion of the extremity. If underlying edema is accumulated, there are few effective treatments to prevent further shrinking of the flap. To avoid such a situation, a 20% larger pattern should be used for what would anatomically be necessary. On the other hand, the quality of vein anastomosis should also be ensured to increase the survival rate of the flap.

13.12 Microsurgical Reconstruction of Soft Tissue Defects of the Heel

13.12.1 Characteristics of Soft Tissue at the Heel

The soft tissue paddle under the calcaneus consists of fat cells which are surrounded by intensive linear fibrous septums. The septums, rich in collagenous fibers, form a sealed space containing fat cells. The soft tissue paddle serves as cushion in order to buffer vibration. It can eliminate the peak values produced during motion and vibration, and transform the mechanic energy to heat energy in order for absorption and storage.

13.12.2 Reconstructive Goals of the Heel

1. The graft should be endurable enough to resist pressure and shearing force, satisfying the functional demand of the heel.
2. Innervation of the skin should be reconstructed to regain sensory function; skin reconstructed can resist cold; the flap should have sufficient thickness of subcutaneous tissue to distribute pressure and absorb vibration.
3. One-stage reconstruction of skin and subcutaneous tissue is preferred in order to recover the integrity of anatomical structure of the heel, thus shortening hospital stay and promoting efficacy.
4. Blood supply is reliable to all the grafts, and a single pedicle vessel is preferred.

13.12.3 Common Reconstructive Methods for the Heel

In recent years, neurovascular repair techniques have been greatly improved. Therefore, attempts to resurface the soft tissue defects of the heel have been made more frequently. Various pedicled flaps, perforator-pedicled flaps and free flaps have been clinically applied by plastic surgeons. The most common options for heel reconstruction include pedicled local flaps and free flaps.

Pedicled local flaps include sural neurocutaneous flaps, medial plantar flaps, reverse posterior tibial artery perforator-pedicled island flaps, peroneal artery perforator-pedicled flaps and peroneal artery-pedicled osteocutaneous flaps. Advantages of these flaps are as follows: (1) innervation achieved by anastomosis, (2) reliable blood supply without sacrificing a major artery, (3) high capability of anti-infection, (4) less anatomical variation in neurovascular structure, and (5) less donor site morbidities. Their disadvantages include: (1) limited area of flap, (2) sensational impairment to the lateral aspect of the heel after sural nerve is harvested, (3) lymph edema or insufficient vascularization in some patients postoperatively, (4) locations of most donor sites at the distal lower extremities where major cutaneous branches of the posterior tibial artery gather, and (5) poor sensory recovery of reverse flaps if neural end-to-side anastomosis cannot be performed.

The free flaps include anterior lateral thigh flaps, latissimus dorsi flaps, and thoracic umbilical flaps. Most of them are indicated for massive degloving injures which cannot be covered by local tissues. Their advantages are: (1) more alternative options for donor site, (2) sufficient amount of tissue, and (3) feasibility of being fashioned according to the reconstructive demands. Muscles and subcutaneous tissues can be included into the flap to play the cushioning function of the heel. Their disadvantages include: (1) high technical demand, (2) anastomosis of the pedicle vessels and recipient vessels at the cost of sacrificing one of the major arteries of the lower extremity, partial functional recovery of which needs neural anastomosis.

13.12.4 Reconstructive Methods for Small Defects of the Heel

The ideal methods for small defects of the heel are medial and lateral plantar flaps.

The medial plantar flaps are pedicled on the medial plantar artery. Dissection of the distal posterior tibial artery and the cutaneous branch of the medial plantar nerve is required for flap elevation. If defects of the heel are small, the flap area can be adjusted accordingly. The skin between the heel wound and the planned flap should be incised to allow tension-free transfer of the flap. A subcutaneous tunnel is not suitable for transfer of the medial or lateral plantar flaps due to the tension of local skin at the area. As the space of tunnel is limited, over-stretching the pedicle vessels may impair the vessels themselves. Dissection of the tunnel in a sharp way may injure the vertical fibrous tissue of plantar foot, impairing the function of the foot.

The medial plantar is a non-weight bearing region, but it has similar vertical fibrous structures as a weight bearing region. Its durable skin can resist wearing force during motion. Its underlying plantar aponeurosis is strictly anchored to the calcaneus, thus preventing flap sliding. The medial plantar flaps are sensory, and their thickness can basically meet the reconstructive goal of the heel. Therefore, they are ideal for reconstruction of the heel soft tissue.

The lateral plantar flaps are designed in the center of plantar, pedicled on the lateral plantar artery and the cutaneous branch of lateral plantar nerve. The axis of the flap is the line between the junction of vertical line of the anterior border of the medial malleolus and the medial border of plantar and the midpoint of the fourth and fifth metatarsal head. If fashioned as an advanced flap, the medial border of the flap should be adjacent to the defect, and the width of the flap should be equal to the width of the defect. If fashioned as a rotation flap, the pivot point is located at the junction of anterior border of the medial malleolus and the medial plantar border, the distance between the pivot point and the distal border of the flap should be 2–3 cm longer than the distance between the pivot point and the distal border of the wound, ensuring a tension-free transfer of the flap. The incision should begin at the anterior-lateral border of the flap, continuing to the deeper level of the plantar aponeurosis. Care should be taken to retain as much vertical fibrous structure as possible. The digit artery of the fifth toe can be explored between the abductor digiti minimi and the flexor digitorum brevis, and the lateral plantar artery can be traced reversely from the proximal of this artery. The flap is elevated from distal to proximal, from lateral to medial, until the original part of posterior tibial artery is reached. The cutaneous branch of the lateral plantar nerve should be protected and included into the flap.

Since the underlying skin and soft tissue of the metatarsal heads and the lateral boundary of the plantar are weight-bearing regions, they should be avoided for flap harvest. The donor site can be closed directly if a small flap is harvested; otherwise a split-thickness skin graft should be applied. Existence of the posterior tibial muscle and the peroneus muscle can maintain the arch of the foot even when the plantar aponeurosis is included into the flap.

13.12.5 Reconstructive Methods for Massive Defects of the Heel

If defects of the heel are massive, especially complicated with injury to the medial malleolus and the underlying medial plantar arteries, the medial or lateral plantar flaps cannot be used for reconstruction. The free flaps, due to their technical challenge and risks of postoperative spasm or thrombosis of anastomosed vessels, are not prior choices for reconstruction. According to the literature, common methods for massive defects of the heel include reverse sural neurocutaneous flaps, lateral crural flaps, and medial crural flaps. The perforator flaps have been improved so that they can be used as neurocutaneous flaps, such as the peroneal artery perforator sural neurocutaneous flap and the posterior tibial artery perforator saphenous neurocutaneous flap. These flaps have achieved good functional and aesthetic results in clinical practice.

The posterior tibial artery perforator saphenous neurocutaneous flap is pedicled on the perforator of the posterior tibial artery, together with the saphenous nerve. A hand-held Doppler ultrasound should be used to locate the perforators 6–8 cm proximal to the medial malleolus, which serve as the pivot point after flap elevation. The anterior boundary of the flap is the medial aspect of the tibia, the posterior boundary of the flap is the midline of the gastrocnemius muscle, the proximal border of the flap is about 8–10 cm distal to the popliteal wrinkle, and the distal border is about 6–8 cm proximal to the medial malleolus. Incision should begin at the proximal border of the flap. The deep fascia, the saphenous nerve and the myolemma should also be dissected and included into the flap. Then elevation of the flap can proceed to the point where pedicle vessels perforate the deep fascia. Care should be taken to prevent injury to the perforators which access the flap. Only when vascularization of the dominant perforator is ensured after other perforators are ligated temporarily by vessel clamps can ligation and cutting of other perforators be performed. Then the flap can be rotated and inset to the defect.

The key points to harvesting the flap include: (1) A hand-held Doppler ultrasound must be used to locate the perforators preoperatively. (2) Dissection of the perforators should be performed after incision of the posterior border of the flap, and all the available perforators should be retained before the dominant perforator is selected. (3) The pattern and location of the flap should be re-adjusted according to the location of the selected perforator. (4) Vascularization of the flap should be observed according to the distal bleeding at the distal margin of the flap. (5) Design of the flap should take full consideration of its relationship to the defect.

The peroneal artery perforator sural neurocutaneous flap, pedicled on the perforator of the peroneal artery, use the line between the fibular head and the medial malleolus as the axis. A hand-held Doppler ultrasound is used to locate the distal perforator of the peroneal artery. The flap should be fashioned according to the pattern and size of the defect. Incision should begin at the posterior border of the flap, deep to the deep fascia, continuing to the posterior aspect of the fibular. Exploration of the perforators can be performed at the intramuscular space of the peroneus longus muscle and peroneus brevis muscle. After careful skeletonization of the perforator, the flap can be elevated after dissection of the anterior border of the flap to the perforator. The proximal end of the sural nerve and the lesser saphenous vein should be marked and cut, and they are used for neural anastomosis after the flap is transferred to the defect.

The key points to harvesting the flap include: (1) A hand-held Doppler ultrasound is used to find out whether there is any variation in neurovascular structure preoperatively. (2) Radical debridement, especially for infectious wounds, should be performed preoperatively. (3) Complete elimination of necrotic bone in patients with osteomyelitis is utmost important for preparation of healthy granulation for flap transfer. (4) For a rational flap size, a 10–15% larger pattern should be designed for what would anatomically be necessary. (5) The pedicle should be skeletonized for at least 3 cm to prevent kicking and twisting of the pedicle vessel after flap rotation. (6) The sural nerve should be included into the flap in order to achieve innervation of the defective area.

13.13 Microsurgical Reconstruction of Plantar Soft Tissue Defects

If the plantar artery is intact in patients with defects of the sole, the medial crural flap can be harvested for resurfacing, because innervation of the sole can be regained through neuroplasty when the cutaneous nerve is included into the flap. The muscle can also be included into the flap to provide extra thickness of the graft to meet the requirements of sole reconstruction. However, in most cases, since soft tissue defects of the sole are often complicated with injury to plantar arteries, the medial crural flap is not indicated for such cases. As a result, free flaps become suitable options for sole reconstruction, including medial crural flaps and anterior lateral thigh flaps, because they have merits of large area for harvest, and innervation result and sufficient cushioning structure. When the aforementioned flaps are not large enough for patients with soft tissue defects of the sole, the heel and the lateral aspect of the foot, the paraumbilical flaps and the latissimus dorsi flaps become ideal reconstructive means to resurface such massive defects.

Recently, prefabricated flaps, defined as a special kind of free flaps, have gained popularity in clinical practice due to their effective and reliable functional results. Their advantages include: (1) Autogenous spare parts are fully used to reduce donor site morbidity. (2) The major artery is preserved for its entirety and the skin paddle is also preserved at the donor site, leading to good aesthetic result. Their chief disadvantage is that multi-staged procedures are required to prolong hospital stay. In addition, sophisticated microsurgical techniques for vessel anastomosis are needed, posing a challenge to plastic surgeons. In some cases, degloved skin and poor soft tissue condition of the sole and wound may restrict application of such flaps.

13.14 Microsurgical Reconstruction of Total Foot Soft Tissue Defects

Soft tissue defects of the total foot usually result from degloving injury, often requiring complicated procedures to achieve a full coverage and effective functional recovery. The emergency treatment plays an important role in the whole procedures, including radical debridement and appropriate bony fixation. The weight-bearing region should be preserved as much as possible. Except for the sole skin, the degloved skin of the other portions can be thinned and replanted. Vacuum assisted closure can be applied to assist survival of replanted tissues.

The key treatment is suitable coverage of the sole, which should not only keep mobile and weight-bearing functions, but also achieve the aesthetic result for normal foot-wear. Common methods include anterior lateral thigh flaps, latissimus dorsi flaps, and sural neurocutaneous flaps. The split-thickness skin graft can be used for dorsum pedis resurfacing, to increase the postoperative bulk of the foot. In cases with exposure of the tendon and bone of the dorsum pedis, vacuum assisted closure can be used to stimulate growth of the granulation tissue.

Bibliography

1. Granick M, Boykin J, Gamelli R, Schultz G, Tenenhaus M. Toward a common language: surgical wound bed preparation and debridement. Wound Repair Regen. 2006;14(Suppl 1):S1–10.
2. Schultz GS, Sibbald RG, Falanga V, Ayello EA, Dowsett C, Harding K, et al. Wound bed preparation: a systematic approach to wound management. Wound Repair Regen. 2003;11(Suppl 1):S1–28.
3. Yan H, Liu S, Gao W, Li Z, Chen X, Wang C, et al. Management of degloving injuries of the foot with a defatted full-thickness skin graft. J Bone Joint Surg Am. 2013;95(18):1675–81.
4. Chammas MF Jr, Gurunluoglu R, Carlsen SN, Molina W Jr, Moore EE, Kim F. Surgical debridement of mineral pitch and nonviable penile tissue using water-jet power: a preliminary report. BJU Int. 2009;103(7):974–6.
5. Tenenhaus M, Bhavsar D, Rennekampff HO. Treatment of deep partial thickness and indeterminate depth facial burn wounds with water–jet debridement and a biosynthetic dressing. Injury. 2007;38(5):S38–44.
6. Shen HL. Anatomy of sciatic flaps pedicled with musculocutaneous perforator. Chin J Clin Anatomy. 1984;3:156–7.
7. Gir P, Cheng A, Oni G, Mojallal A, Saint-Cyr M. Pedicled-perforator (propeller) flaps in lower extremity defects: a systematic review. J Reconstr Microsurg. 2012;28(9):595–601.
8. Lakhiani C, Lee MR, Saint-Cyr M. Vascular anatomy of the anterolateral thigh flap: a systematic review. Plast Reconstr Surg. 2012;130(6):1254–68.
9. Devine JC, Potter LA, Magennis P, Brown JS, Vaughan ED. Flap monitoring after head and neck reconstruction: evaluating an observation protocol. J Wound Care. 2001;10(1):525–9.
10. Haskins N. Intensive nursing care of patients with a microvascular free flap after maxillofacial surgery. Intensive Crit Care Nurs. 1998;14(5):225–30.
11. Wu Liza C, Djohan Risal S, Liu Tom S. Proximal vascular pedicle preservation for sartorius muscle flap transposition. Plast Reconstr Surg. 2006;117(1):253–8.
12. Xu DC, Zhong SZ, Kong JM, et al. Applied anatomy of the anterolateral femoral flap. Plast Reconstr Surg. 1988;82:305–10.
13. Lin CH, Wei FC, Lin YT, et al. Lateral circumflex femoral artery system: warehouse for functional composite free-tissue reconstruction of the lower 1eg. J Trauma. 2006;60:1032–6.
14. Song YG, Chen GZ, Song YL. The free thigh flap: a new free flap concept based on the septocutaneous artery. Br J Plast Surg. 1984;37:149–59.
15. Kroll SS, Rosenfield L. Perforator-based flaps for low posterior midline defects. Plast Reconstr Surg. 1988;81:561–6.
16. Wei FC, Jain V, Celik N, et al. Have we found an ideal soft tissue flap? An experience with 672 anterolateral thigh flaps. Plast Reconstr Surg. 2002;109:2219–26.
17. Gedebou TM, Wei FC, Lin CH. Clinical experience of 1284 free-anterolateral thigh flaps. Handchir Mikrochir Plast Chir. 2002;34:239–44.

14 Functional Reconstruction of the Upper Extremity

Liqiang Gu and Jiantao Yang

With the development of microsurgery, microneurovascular muscle transfer and transplantation are gradually used to restore active functions of extremity damaged following traumatic muscle loss of the upper extremity or peripheral nerve injury, especially brachial plexus injury. This is microsurgical reconstruction of limb function.

Free functioning muscle transplantation (FFMT) is a procedure that involves microneurovascular transfer of a muscle to reconstruct the function of upper extremity following traumatic muscle loss and brachial plexus injury. Viability of the transferred muscle is maintained by microvascular anastomosis between the muscle's artery and vein and a suitable artery and vein in the recipient area. Reinnervation and active muscle contraction are achieved by suturing a motor nerve in the recipient area to the motor nerve of the transferred muscle. However, besides the cost of sacrificing the function of the donor muscle, two other problems also need to be considered regarding survival and reinnervation of the transferred muscle. Therefore, FFMT still has problems to be resolved, like donor site morbidity and possibility of failure. To improve the reconstructed function of the upper extremity, it is very important to conduct related clinical research to establish technical norms and standards of FFMT.

L. Gu (✉) · J. Yang
Department of Orthopedics, The First Affiliated Hospital of Zhongshan University, Guangzhou, China
e-mail: guliqiang1963@aliyun.com

14.1 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.1.1 Bipolar Transfer of Pedicled Sternocostal Part of Pectoralis Major Muscle for Elbow Flexion

1. Indications

   Severe crush injury involving the upper extremity from the arm to the elbow, or elbow flexion muscle loss (biceps, brachialis and brachioradialis) due to necrosis and infection, with nearly normal muscle strength of the sternocostal part of pectoralis major muscle (M 4–5).
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: sternocostal part of pectoralis major muscle; (2) Neurovascular pedicle: thoracoacromial artery and vein, medial pectoral nerve (branched from medial cord, C8 and T1); (3) Design of the pedicled sternocostal part of pectoralis major muscle flap: the size of the flap is approximately 12–15 cm × 3–5 cm based on the skin defect of the arm after muscle transfer.
   (b) Anesthesia and position. The procedure is performed with the patient under general anesthesia and in a supine position (Fig. 14.1a).
   (c) Harvest of the sternocostal part of pectoralis major muscle. (1) A long incision is made from the coracoid process to the insertion of the pectoralis major muscle, along its lateral aspect, continuing to the level of the axilla with the forearm held in a neutral position; (2) The entire mass of the pectoralis major muscle is then detached from its origin along the medial half of the clavicle and its sternocostal border. While the

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_14

Fig. 14.1 A patient with hemophilia and necrosis of medial flexors of the arm due to infection (**a**). Bipolar transfer of pedicled sternocostal part of pectoralis major muscle was performed to cover the wound and reconstruct elbow flexion (**b**-**e**). Survival of the muscle flap (**f**). Postoperative rehabilitation (**g**)

pectoralis major is elevated from the chest wall and the underlying pectoralis minor, meticulous care must be given to preservation of its neurovascular pedicles (Fig. 14.1b–e).

(d) Bipolar transfer of the sternocostal part of pectoralis major muscle. (1) Placement of the sternocostal part of pectoralis major muscle: a second S-shape incision is made over the antecubital fossa to expose biceps tendon with shoulder adduction and elbow extension. The origins of the sternocostal heads with attached anterior rectus abdominis sheath are rolled into a tube which is directed downwards the arm through an anterior subcutaneous tunnel, exiting through the second incision; (2) Fixation of the insertion: the humeral attachment of the muscle is directed cephalad and sutured securely to the coracoid process with suture anchors (Schottstaedt's procedure, by contrast with Carroll-Kleinman's procedure in which the attachment of the muscle is sutured to the acromion). The origins of the sternocostal heads are sutured to the biceps tendon using a Pulvertaft weave and nonabsorbable sutures with the muscle under appropriate tension and the elbow flexed to 45°; (3) The incision is closed in layers (Fig. 14.1d, e).

3. Critical points
   (a) Bipolar transfer of pedicled sternocostal part of pectoralis major muscle is more suitable for male patients than for female ones due to its adverse effect on the appearance of the breast.
   (b) Care should be taken not to stretch the neurovascular pedicle when the sternocostal part of pectoralis major muscle is harvested.
   (c) Postoperative protocol. Immediately after the surgery, the shoulder is immobilized in 60° of flexion and 30° of abduction and with the elbow in 90° of flexion. At the end of the second week, rehabilitation is started under protection, but passive or active extension of the elbow more than 60° is prohibited until the seventh postoperative week when the splint is removed (Fig. 14.1f).

14.2 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.2.1 Microneurovascular Transfer of Gracilis Muscle for Finger Flexion

1. Indications

   Severe injury of upper extremity from elbow to forearm, resulting in the defect of forearm flexors.

2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: anterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein.
   (b) Harvest of the donor muscle. Critical points: A line is drawn from the pubic tubercle along the adductor longus prominence to demarcate the anterior border of the gracilis. A flap is designed which is 6–10 cm distal to the pubic tubercle, with a size of about 5 × 15–18 cm (Fig. 14.2). We incise the anterior border of skin paddle firstly. The vascular pedicle and motor branch of the obturator nerve of the gracilis are confirmed through the intermuscular septum between the gracilis and the adductor longus, commonly located 8–12 cm inferior to the pubic tubercle (Fig. 14.3). The adductor longus is mobilized posteromedially and the pedicle is dissected from its origin of the profunda femoris vessels, with the longest possible pedicle (6–8 cm). The gracilis motor nerve should be followed as proximally as possible to the obturator foramen, with a length of 8–12 cm. Then,

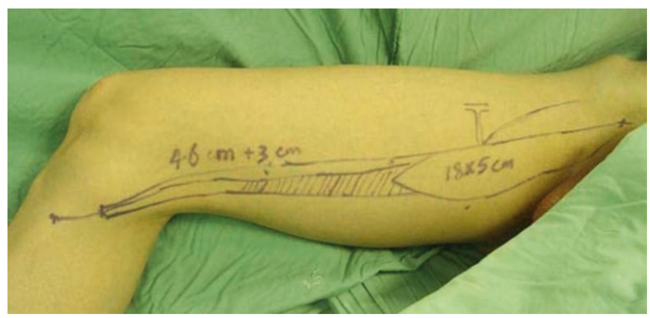


Fig. 14.2 Surgical design of gracilis muscle flap

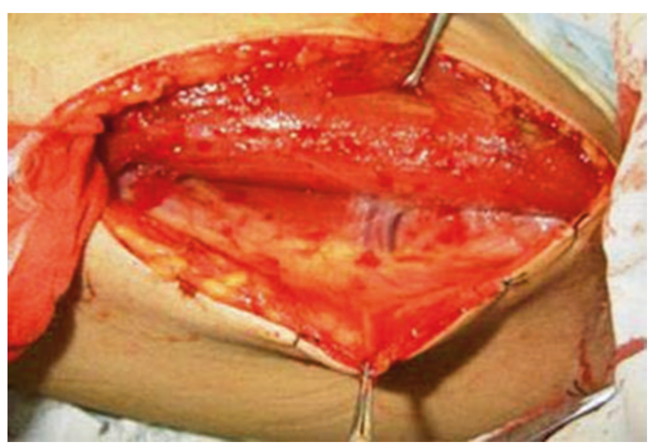


Fig. 14.3 Exposure of vascular pedicels of the gracilis muscle flap

we continue to dissect the belly and tendon of the gracilis, including the fascia around the gracilis. Finally, the vascular pedicle and nerve of the gracilis are ligated and cut respectively, and dissection of the gracilis is completed proximally up to its origin from the pubic arch (Fig. 14.4).

(c) Microneurovascular transfer of gracilis muscle for finger flexion. The gracilis muscle flap is placed above the arm, elbow and forearm, with the proximal site of muscle anchored to the medial brachial intermuscular septum. The distal tendon is then woven into the flexor digitorum profundus and flexor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to the brachial artery (end to side) and cephalic vein (or brachial vein), respectively. The gracilis motor nerve is sutured with anterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve (Fig. 14.5).

Fig. 14.4 Gracilis muscle flap

3. Critical points
   (a) The entire gracilis muscle and its tendon should be harvested to maximize the length. The pedicle is dissected from its origin in the profunda femoris vessels, with the longest possible pedicle. The gracilis motor nerve should also be followed as proximally as possible to the obturator foramen.
   (b) The nerve bundle to the gracilis should be evaluated and trimmed to confirm that there are more than two motor branches.
   (c) The gracilis motor nerve should be confirmed by electrical stimulator to identify its relationship with muscle fibers. If necessary, the muscle could be divided into two separate motor units based on the direction of the muscle fibers.
   (d) The length of the motor branch should be reduced as much as possible in conditions of suitable muscle tension to reduce the time needed for nerve regeneration.
   (e) Postoperatively the upper limb is immobilized for 4–6 weeks with the elbow in 30° of flexion, the forearm in supination and the hand in functional position.
   (f) Rehabilitative treatment plays an active role in nerve regeneration, and regular follow-up to evaluate the muscle function is also very important to obtain good functional outcomes.

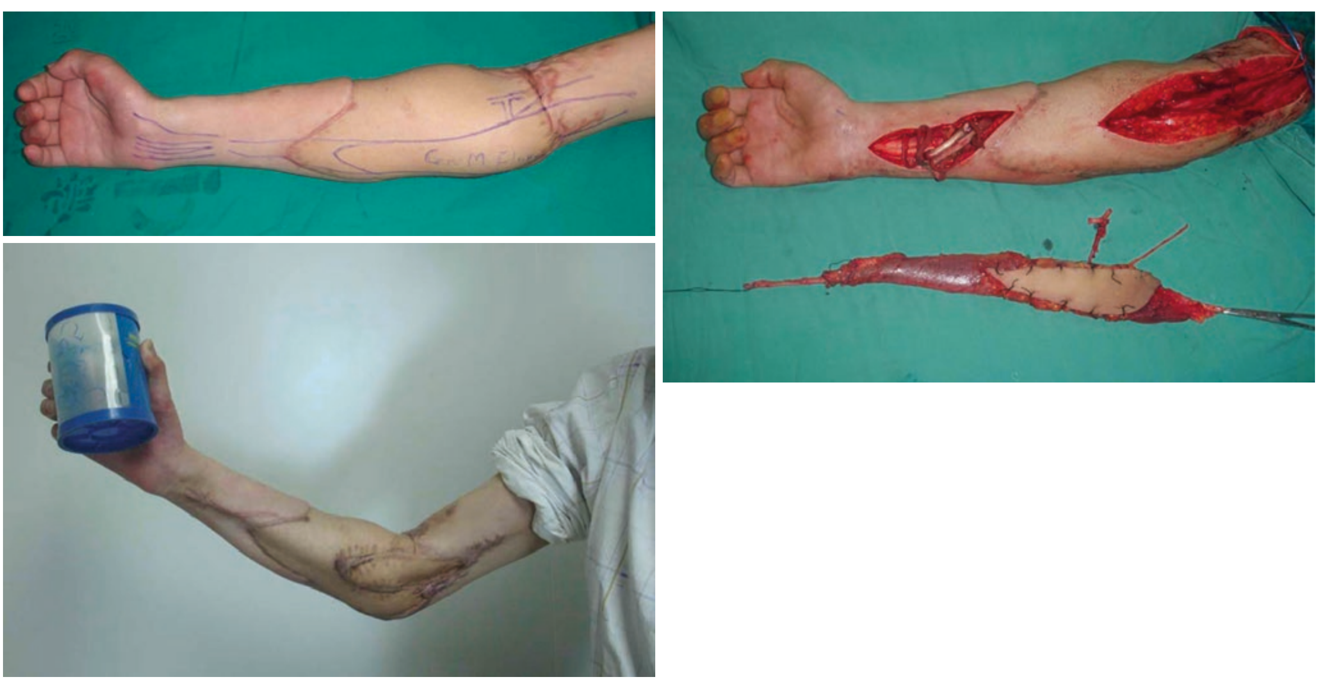


Fig. 14.5 Microneurovascular transfer of gracilis muscle for finger flexion following severe injury of upper extremity

To address the usage of brachialis muscle branch of musculocutaneous nerve (BMBMCN) as a recipient nerve, a microanatomical study of 30 limbs from 15 adult cadavers performed by Zhou and Gu [1] shows that there are three branching types observed: type I, single branch in 25 limbs (83.33%); type II, two branches in 1 limb (3.33%); and type III, multiple branches in 4 limbs (13.33%). The mean length of BMBMCN is 52.66 ± 6.45 mm, and its mean diameters 1.39 ± 0.10 mm. The average number of nerve fibers of brachialis muscle branch of musculocutaneous nerve is 2.83 ± 0.46, and that of myelinated nerve fibers 1964.71 ± 310.32.

14.3 Functional Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.3.1 Microneurovascular Transfer of Gracilis Muscle for Wrist and Finger Extension

1. Indications

   Severe injury of upper extremity from elbow to forearm, resulting in the defect of forearm extensors and partial injury to the flexors of the hand and wrist (M 0–3).
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: posterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein.
   (b) Harvest of the donor muscle, as described previously.
   (c) Microneurovascular transfer of gracilis muscle for wrist and finger extension. The gracilis muscle flap is placed at the dorsal side of the arm, elbow and forearm, with the proximal site of muscle anchored to the lateral brachial intermuscular septum. The distal tendon is then woven into the extensor digitorum communis and extensor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to brachial artery (end to side) and cephalic vein (or brachial vein), respectively. The gracilis motor nerve is sutured with posterior interosseal nerve or brachialis muscle branch of musculocutaneous nerve.
3. Critical points

   Postoperatively the upper limb is immobilized for 4–6 weeks with the elbow in 30° of flexion, the forearm in pronation, and the wrist and hand in functional position.

14.3.1.1 A Case Report

Wu Yongxian, male, 26 years old, complained of limited mobility of the left hand due to a gunshot injury for 11 months. The main problem was defective extensors of the left elbow and forearm, in addition to complete injury of left radial nerve and partial injury of the left ulna and median nerves. On June 6, 2012, a functional gracilis muscle transfer was performed to reconstruct his finger extension. The recipient vessels and nerve were brachial artery and vein and brachialis muscle branch of musculocutaneous nerve, respectively. Six months postoperatively, the transplanted gracilis could contract and functional recovery of wrist and hand extension was achieved to some extent (Fig. 14.6).

14.4 Function Reconstruction for Traumatic Muscle Loss of the Upper Extremity

14.4.1 Microneurovascular Gracilis Muscle Transfer for Elbow Flexion and Finger Extension

1. Indications

   Severe crush injury to the upper extremity involving the arm, elbow and forearm, resulting in defects of elbow flexors and forearm extensors.
2. Surgical methods
   (a) Surgical design. (1) Donor muscle: gracilis muscle. (2) Recipient nerve: trapezius muscle branch of accessory nerve or phrenic nerve. (3) Recipient vessels: brachial artery and brachial or cephalic vein, or transverse cervical artery and external jugular vein.
   (b) Harvest of the donor muscle, as described previously.
   (c) Microneurovascular transfer of gracilis muscle for elbow flexion and finger extension. The gracilis muscle flap is placed from the shoulder, arm and elbow to the dorsal side of the forearm, with the proximal site of muscle anchored to the acromion or the periosteum of the lateral clavicula. The lower part of the gracilis and the tendon are directed to the dorsal incision of the forearm through submuscular tunnel of brachioradialis and extensor carpus radialis and subcutaneous tunnel of forearm. The distal tendon is then woven into the extensor digitorum communis and extensor pollicis longus tendons with the elbow in 90° flexion, and the wrist and hand at extension position. The vascular anastomosis is performed under a microscope, with the artery and vein of the gracilis anastomosed to transverse cervical artery and external jugular vein, respectively. The gracilis motor nerve is sutured with trapezius muscle branch of accessory nerve or phrenic nerve. If only reconstruction

Fig. 14.6 Functional gracilis muscle transfer for wrist and finger extension following severe injury of the upper extremity

of elbow flexion is needed (severe crush injury to the extremity from arm to elbow, resulting in defects of elbow flexors and concomitant injury to latissimus dorsi and pectoralis major, M 0–3), the distal tendon is woven into the biceps tendon.

(d) Critical points

Postoperatively the upper limb is immobilized using plaster for 4–6 weeks with the shoulder in 60° of flexion and 30° of adduction, the elbow in 90° of flexion, and the wrist and hand in extension position.

14.4.1.1 A Case Report

A boy, 4 years old, with the main complaint was open fracture at the left upper extremity (Gustilo IIIc + IIIb) due to a car accident. Debridement, external fixation of the left extremity fracture and ALT-flap using flow-through technique were performed to repair soft tissue and vessel defects simultaneously. In the second stage, microneurovascular transplantation of gracilis muscle was performed to restore his elbow flexion and finger extension of the left extremity (Fig. 14.7).

Fig. 14.7 Functional gracilis muscle transplantation was performed to restore elbow flexion and finger extension

Fig. 14. 7 (continued)

14.5 Functional Reconstruction for Volkmann's Ischemic Contracture

Volkmann's ischemic contracture of the forearm can be one of the most devastating complications following elbow trauma and crush injury, fracture and vascular injury of the forearm. It is a dismay consequence of an acute compartment syndrome which is not diagnosed or treated timely. What's more, sustained ischemia can result in irreversible changes to the forearm flexors, leading to necrosis. Then the necrotic muscle is replaced with fibrotic tissue, clinically presenting as severe irreversible deformity and dysfunction of the limb at the late phase.

Now surgery has been the main treatment for Volkmann's ischemic contracture, including neurolysis, tendon lengthening and transfer, and osteotomy (orthopedic treatment). What's more, functional free muscle transfer with vessel and nerve anastomosis is an effective microsurgical technique to reconstruct the forearm flexors after Volkmann's ischemic contracture of the forearm. The suitable muscles for reconstruction surgery include pectoralis major, gracilis, latissimus dorsi. Currently, in most cases, functional free gracilis transfer for Volkmann's ischemic contracture is reported which has achieved substantial improvements in postoperative function of digital flexion so that the patients can complete simple activities alone.

1. Indications

   Fibrosis and functional loss of the forearm flexors resulting from injuries at the late phase.
2. Surgical techniques
   (a) Surgical design. (1) Donor muscle: the gracilis muscle. (2) Donor motor nerve: the anterior interosseous nerve or brachialis muscle branch. (3) Donor vessels: brachial artery, cephalic vein or brachial vein.
   (b) Harvest of donor muscle: as described previously.

Fig. 14.8 The finger flexion was reconstructed by functional free gracilis muscle transplantation for Volkmann's ischemic contracture of the forearm following rupture of the left brachial artery

(c) Microneurovascular transfer of gracilis muscle for finger flexion. The gracilis muscle is placed along the ventral part of the upper limb. Its proximal origin is sutured to the medial muscle interval of arm. Note that the elbow should be extended to maintain proper muscle tension. Its distal tendon is then sutured to the flexor digitorum profundus tendons and flexor pollicis longus muscle tendon in the distal forearm. The artery of the muscle is anastomosed to the brachial artery, and the vein to the cephalic vein or brachial vein. The anterior branch of obturator nerve is sutured to the anterior interosseous nerve or brachialis muscle branch.

3. Critical points

   The elbow is maintained in a position of 30° of flexion, the forearm in supination, and the wrist and hand in functional position. Plaster immobilizes the upper limb for 4–6 weeks.

14.5.1 A Case Report

Functional free gracilis transfer with vessel and nerve anastomosis was performed to reconstruct the digital flexion of a patient on 3rd, December, 2009. Fifteen months later, great improvement was achieved in postoperative digital flexion. The power of finger flexion was from M3 to M4. The patient could grasp light objects (Fig. 14.8).

14.6 Functional Reconstruction for Intrinsic Muscles Injuries

14.6.1 Microneurovascular Transplantation of Extensor Digitorum Brevis Muscle

Shengxiu Zhu et al. (1982) reported reconstruction of thumb opposition and adduction by microneurovascular transfer of the extensor brevis digitorum. A cadaveric study conducted by et al. [2]. involving 30 sides shows that the extensor brevis digitorum is a pennate muscle which has three tendons in 80% of the cases and four tendons in 20% of the cases. The mean length, width and thickness of the extensor brevis digitorum are 6.15 ± 0.40, 3.85 ± 0.04 and 0.21 ± 0.02 cm, respectively. The extensor brevis digitorum is mainly supplied by dorsalis pedis and innervated by branch of nervi peronaeus profundus which can be retrogradely dissected as long as 27.47 ± 2.56 cm. Quantitative analysis shows there are 934.500 ± 57.740 myelinated nerve fibers in the branch of nervi peronaeus profundus.

1. Design of the extensor brevis digitorum flap. Mark the course of dorsal pedal artery, and design the extensor brevis digitorum flap with a size of 6 × 2 cm (for the sake of direct suture of the wound after flap dissection).
2. Exposure of the vessels and nerves. Incision is made at the midline of the ankle anteriorly. Skin, fascia, anterior

talofibular ligament and cruciate ligament are incised. Between the musculi hippicus and the hallucis longus, the vessels and nervi peronaeus profundus are separated. A longitudinal incision, 1–2 cm away from the lateral side of dorsalis pedis, is made to open the periosteum and soft tissue around the tarsometatarsal joint. Then the dorsalis pedis under the tissue is separated. The vessel pedicle supplying the extensor brevis digitorum should be protected.

3. Harvest of the extensor brevis digitorum flap. The flap is harvested from inside to outside, and from distal to proximal along the maker. The margin between the flap and muscle membrane is sutured temporarily. The tendons of the extensor digitorum longus and extensor digitorum brevis of the Second-fourth toes are incised distally to the flap. Then the dissection is performed between the extensor brevis digitorum and the tarsometatarsal joint and the periosteum. The anastomotic vessels around the flap are ligated before the origin of extensor brevis digitorum was incised from the calcaneus anterior to the tarsal sinus. The nervi peronaeus profundus is isolated from the anterior tibial neurovascular bundles through the ankle incision, and its epineurium is incised. Then the branch to the extensor brevis digitorum is isolated, which is confirmed by electrical stimulation.
4. Transfer of the extensor brevis digitorum flap.
   (a) Skin and subcutaneous tissue are incised along the radial side of the palmar crease and thenar stripes, until proximally to the wrist crease. The dissection is performed at both sides of the flap. The scar and abnormal tissue are excised before the extensor brevis digitorum flap transplanted to the hand. To reconstruct the thumb opposition, the proximal part of the extensor brevis digitorum flap is sutured to the distal margin of the transverse carpal ligament, and the extensor brevis digitorum tendon is sutured to a previously-made bone hole which is located at the radial side of the proximal phalanx of the thumb through a subcutaneous tunnel. The tension of the transplanted muscles should be adjusted appropriately.
   (b) Management of vessels at the receipt site. Isolate the radial artery at the wrist level, and observe the blood supply after temporary occlusion of blood flow with vascular clamps. Insufficient blood supply means that this artery cannot be ligated but can only be anastomosed end to side. Then the cephalic vein and dorsal subcutaneous vein was exposed.
   (c) Vessels and nerve anastomosis. The radial artery-dorsalis pedis, cephalic vein-dorsocuboidal vein are anastomosed in an end to end fashion under a microscope. The branch of nervi peronaeus profundus is anastomosed to the recurrent branch of median nerve.
   (d) Incision closure. After thorough washing of incision and hemostasis, a full thickness skin graft harvested from the abdomen is used to close the incision. Skin and subcutaneous tissue at the donor site incision can be sutured directly. The ankle joint should be under plaster fixation in a neutral position for 3 weeks.

14.6.1.1 Transfer of Pedicled Abductor of the Fifth Finger Muscle

A female with injury to the left median nerve at the axillary region (18 months after injury) received transferring of pedicled abductor of the fifth finger muscle for functional reconstruction of thumb abduction and opposition.

Origin: transverse carpal ligament.

Insertion: the dorsal radial side of the head of the first metacarpal (Fig. 14.9).

14.7 Functional Reconstruction for Brachial Plexus Injury

Generally, nerve repair can have little effect on functional recovery for delayed brachial plexus injury. Consequently, the residual muscles of less importance can be transferred to the dysfunctional ones which are responsible for more important function. The complexity and variety of brachial plexus injury usually lead to various protocols of muscle reservation, so accurate evaluation of the strength of the residual muscle is critical in functional reconstruction. For functional deficits due to brachial plexus injury, Moberg proposes the following key points: (1) stability of the scapula; (2) rotation function of the shoulders; (3) flexion of the elbows; (4) flexion of the wrists; (5) most importantly, grasp and prehension of hands, which means opposition function of the thumb and digits.

For upper brachial plexus injury, the primary goal is to reconstruct shoulder abduction and elbow flexion. Generally, transfer of the trapezius muscle is used for reconstruction of shoulder abduction. Transfer of the sternocostal part of pectoralis major, latissimus dorsi, pectoralis minor, and triceps brachii, and Steindler's flexorplasty can be used for elbow flexion reconstruction. For lower brachial plexus injury, the primary goal is the thumb opposition and digital flexion and extension. Therefore, only forearm muscles and tendons innervated by C5, C6, and C7 are preserved. Reconstruction procedures include, (1) brachioradialis transfer for flexor pollicis longus, (2) flexor carpi ulnaris transfer for flexor digitorum profundus, (3) extensor carpi radialis longus transfer for thumb opposition, and (4) Zancolli's operation. For total brachial plexus injury of more than 2 years in which muscle atrophy has developed, sternocleidomastoid can be transferred for elbow flexion which is the most important function of the upper limb.

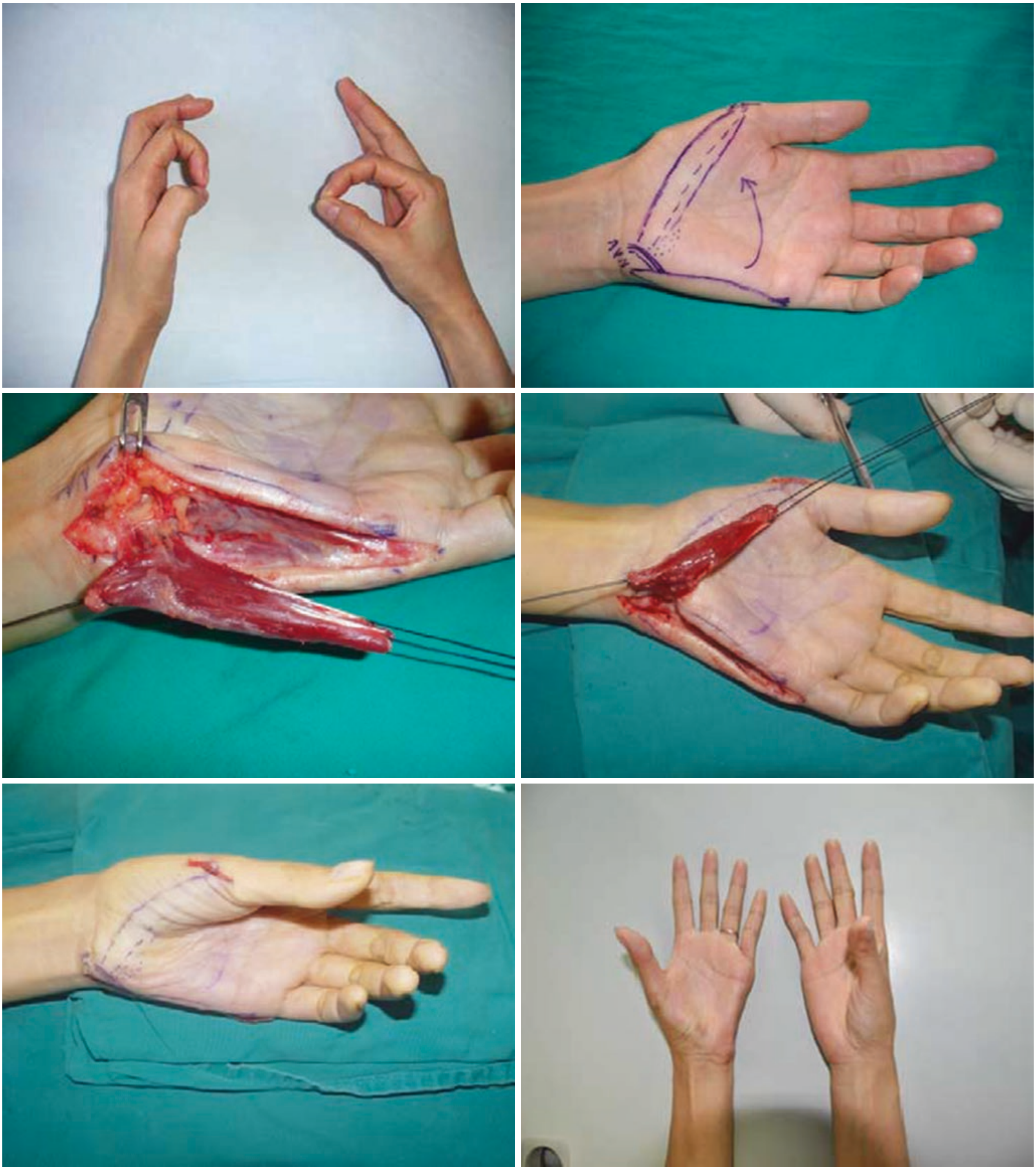


Fig. 14.9 Reconstruction of thumb abduction opposition function by bipolar abductor digitorum minimus transposition with vascular nerve pedicle

Fig. 14.9 (continued)

Muscle transplantation with anastomosis of nerves and blood vessels is an option for delayed brachial plexus injury. Notably, since Doi proposed the double muscle transplantation for hand function reconstruction in 1995 (two-staged operations for elbow flexion and digital movements respectively), the traditional view that free muscle transplantation can only be performed after failure of nerve repair (2–5 years after injury) has been changed. This deeply impacts the treatment of brachial plexus injury. Currently, nerve transfer combined with early double free gracilis muscle transplantation, as well as the contralateral C7 nerve root transfer via the anterior vertebral route to repair low trunk combined with free gracilis muscle transfer has been proved to be effective and promising for total brachial plexus root avulsion. For delayed upper brachial plexus injury, the above-mentioned methods in Sect. 14.2 can still be useful in reconstruction of shoulder abduction and elbow flexion. For delayed lower brachial plexus injury, the above-mentioned methods in Sects. 14.2 and 14.4 can also be useful in reconstruction of finger flexion and thumb opposition. Additionally, functioning free muscle transplantation can be used for elbow extension.

14.7.1 Nerve Transfer Combined with Early Double Gracilis Muscle Transplantation for Total Brachial Plexus Root Injury

This surgery integrates the advantages of Gu YD's multiple nerve transfer and Doi's free muscle transplantation. Nerve transfers which aim to regain preferable shoulder abduction, elbow extension, and hand sensory recovery are followed by early free double gracilis muscle transplantation which reconstructs elbow flexion, and extension and flexion of thumb and fingers. Specifically, (1) phrenic nerve transfer for suprascapular nerve in the first operation, (2) contralateral gracilis muscle transplantation for elbow flexion and digital and thumb extension (innervated by the trapezius branch of accessory nerve) in the first operation, (3) ipslateral gracilis muscle transplantation for thumb and digital flexion (innervated by the fourth, fifth and sixth intercostal nerves) in the second operation, (4) third intercostal nerve transfer to the triceps brachial branch of radial nerve for elbow extension, (5) transfer of the sensory branches of the third, fourth, fifth and sixth intercostal nerves to the lateral part of median nerve for hand sensation in supplementary operations, and (6) infusion of the metacarpophalangeal joints.

1. In the first stage, via the surgical approach for brachial plexus exploration, the external jugular vein and transverse cervical artery are anastomosed with the nutrient vessels of the transplanted muscles, respectively. The phrenic nerve is dissected and anastomosed with the suprascapular nerve for abduction reconstruction. If the phrenic nerve is not available, the contralateral C7-sural nerve grafts are chosen.

   The first-staged contralateral gracilis muscle transplantation (powered by the trapezius branch of accessory nerve) is used for elbow flexion, and thumb and digital extension.
2. In the second stage of operation, via the mid-axillary line approach to identify the lateral branch of intercostal nerve, the main trunk of the intercostal nerve is dissected until between the anterior axillary line and the midclavicular line, including the third, fourth, fifth and sixth intercostal nerves with an average length of 10–12 cm. After the mid-axillary line incision is extended in a Y-shaped way, the lateral portion of median nerve and the triceps branch of radial nerve are dissected and cut off. The motor branch of the third intercostal nerve is anastomosed with the triceps branch of radial nerve. The fourth, fifth and sixth intercostal nerves are anastomosed with the lateral portion of median nerve.

After the ipsilateral gracilis muscular flap is harvested, it is placed at the medial side of upper limb. The proximal side is fixed at the second and third rib. The motor nerves of the muscle are anastomosed with the fourth, fifth and sixth intercostal nerves without tension. The nutrient artery of the muscle is anastomosed with the brachial artery in an end-to-side fashion and the vein of the muscle is anastomosed with the deep brachial vein(s) in an end-to-end fashion. Guide the muscle through the subcutaneous route to the distal portion of the forearm, and then flex the elbow by 45°, and flex the wrist or fingers to adjust the muscles' tension. The muscles' tendon is weaving sutured with flexor pollicis longus and flexor digitorum profundus together. After the operation, immobilize the limb at the elbow flexion and forearm adduction.

Recently, the phrenic nerve can also be harvested under arthroscopy and anastomosed with the motor nerve of the muscle so as to reconstruct thumb and digital flexion. In this case, the muscular flap can be placed at the distal part of the upper limb, with the new origin fixed at the septum of intermuscular brachii medialeta.

3. Postoperative management. (1) Immobilization for 4–6 weeks. (2) Expansion of blood vessels, observation of flap circulation, and intervention of the ischemic crisis (in less than 4–6 h). (3) Using drugs to promote nerve regeneration, such as immune suppressor FK506. (4) Rehabilitation: Passive motion of the elbow and hand starts 4–6 weeks after operation, and active motion begins 3–4 months after operation, and voluntary exercise and anti-resistance exercise start 6–8 months after operation.

14.7.2 CC7 Nerve Transfer Combined With Gracilis Muscle Transplantation for Total Brachial Plexus Root Injury

Contralateral C7 nerve root transfer is an important option for brachial plexus avulsion injury. Gu YD proposes that the contralateral C7 nerve transfer should be performed in two stages. Contralateral C7 nerve root transferred can also be a donor for the gracilis transplanted to establish elbow flexion and digital flexion. Mcguiness and Wang SF propose the contralateral nerve transfer should be performed via the route between esophagus and vertebral body to directly repair the upper or lower trunk, with or without sural nerve as an allograft. They believe the transfer via the pre-vertebral route can shorten the distance of nerve regeneration. Wang SF also investigated the feasibility to directly anastomose the contralateral C7 with the lower trunk in an attempt to shorten the distance of nerve regeneration. Gu L performed a clinical and anatomical study on contralateral C7 nerve transfer via the anterior scalene and anterior vertebral body route which shows that the anterior and posterior divisions of the contralateral C7 nerve root can be as long as 7.71 ± 1.16 and 6.97 ± 1.18 cm, respectively, indicating that the both can be guided through the anterior scalene and anterior vertebral body route to the contralateral side to directly repair the avulsed nerve root (C8 and T1 or C5, 6). Gu L proposes a surgical protocol for total brachial plexus injury in which the contralateral C7 nerve transfer is used (through the anterior vertebral route) to repair the lower trunk directly and combined with the gracilis muscle transplantation in the second stage.

14.7.3 Contralateral C7 Nerve Transfer (Through the Anterior Vertebral Route) to Repair the Lower Trunk in the First Stage

1. Indications: definite diagnosis of total brachial plexus injury by clinical examination, MRI, or CTM; avulsion of C7, C8, and T1 accompanied with C5 and C6 rupture; duration between primary injury and surgery was less than 12 months.
2. Surgical procedures
   (a) Exploration of the brachial plexus. Via the transverse approach above the clavicle, the nerve root is dissected and explored, for confirmation of the avulsion of C8T1 root or lower trunk. In some cases in which the nerve roots or lower trunk retract to underneath the clavicle or the scar tissue extends to the clavicle posteriorly and inferiorly, exploration underneath the clavicle is recommended. In the position of shoulder flexion and adduction, identify the target nerve roots and guide them to the anterior scalene muscle for use.
   (b) Harvest of contralateral C7 nerve root. Via the transverse approach above the clavicle, the C7 nerve root is dissected to the intervertebral foramen and identified. The nerve root is dissected distally until the portion where the lateral cord and posterior cord start so that the C7 nerve root can be harvested as long as possible.
   (c) Directly repair the lower trunk using the contralateral C7 nerve root. The anterior border of anterior scalene muscle and the lateral border of C6 and C7 vertebrae are exposed. The surgeon then uses the index finger to do blunt dissection between the vertebral and esophagus until the ipsilateral side, and then uses a large curved forceps to guide a hose from the contralateral side via the prepared route to the other side. The contralateral C7 nerve root is guided to the deep of scalene anterior through the space medial to scalene anterior which is accommodated for the

index finger before the C7 nerve root is placed in the hose. Draw the hose to guide the contralateral C7 nerve root to the other side (1–3 cm beyond the incision). In the position of shoulder flexion and adduction, the transferred C7 nerve root is anastomosed with C8T1-lower trunk without tension. The 'splint' fashion of nerve anastomosis is applied to relieve the tension, and 9–0 sutures are used for perineurium anastomosis.

3. Key points. With the development of CTM and MRI, early diagnosis of brachial plexus injury is possible, and further early surgical inspection and repair is possible in 1–2 months after injury. In an early stage after injury when the hyperplastic tissues and scars are light, it is more convenient to perform surgical intervention than in a late operation (3 months after injury). In an early operation, it is easy to pull and guide the nerve root. This is favorable for direct repair of contralateral C7 nerve root.

   Microsurgical dissection at the portion where the anterior and posterior cords start helps increase the length of nerve harvested. A sufficient length of contralateral C7 nerve root is favorable for anastomosis without tension.
   Immobilization is necessary to avoid anastomosis failure due to motion of the patient's head during recovery from anesthesia. The immobilization should be continued for 6 weeks.

   Free gracilis muscle transplantation for elbow flexion and thumb and digital flexion in the second stage is the same as described in the first stage operation.

14.7.4 Functional Muscle Transplantation for Lower Brachial Plexus Root Injury

The lower brachial plexus injury (BPI) is uncommon compared with upper and total BPI. There are few methods to repair C8-T1 avulsions, and the outcomes are not satisfactory. The ulnar nerve, medial brachial cutaneous nerve, medial antebrachial cutaneous nerve, median nerve and partial radial nerve are often involved in lower BPI, resulting in severe dysfunction or even loss of hand function, but the functions of shoulder, elbow and wrist was are usually preserved. The sensory deficits are commonly located at the ulna side of the forearm and hand.

Nerve transfer and free muscle transplantation are two procedures commonly used in clinic. Gu Y successfully reconstructed thumb and finger flexion by transferring the brachialis muscle branch of the musculocutaneous nerve (BMBMCN) to the posterior part of the median nerve in treatment of C8T1 avulsions. Nagano A et al. transferred the intercostal nerve to the median nerve or ulnar nerve, and Doi et al. transplanted free gracilis muscle to reconstruct thumb and finger flexion with the intercostal nerve as the donor nerve.

Gu [3] reported using free gracilis muscle transplantation to reconstruct thumb and finger flexion for lower BPI with BMBMCN as the donor nerve in two patients. Their 2 years' follow-up revealed that patients regained noticeable improvement in digital flexion, with the muscle power of M4. In addition, transection of BMBMCN did not cause functional impairment to the elbow or the wrist. The muscle power of the elbow flexion was similar to the preoperative level.

1. Surgical methods

   Free gracilis muscle transplantation innervated by the brachialis muscle branch of the musculocutaneous nerve for reconstruction of thumb and finger flexion.

   (a) Anesthesia: general anesthesia.
   (b) Preparation for the recipient site. A 15-cm longitudinal incision is made in the medial-inferior part of the medial upper extremity. After skin and subcutaneous tissue are incised to expose the basilic vein, median nerve and biceps, the median nerve and biceps are retracted laterally to expose the brachialis, brachial artery and musculocutaneous nerve (MCN). The MCN is dissected carefully to expose the brachialis branch which should be definitely identified by observing contraction of brachialis due to electrical stimulation. Another 7-cm longitudinal incision is made in the distal part of the forearm near the wrist, and skin and subcutaneous tissue are incised to expose the tendon of flexor digitorum profundus and flexor pollicis longus muscle. Finally, a subcutaneous tunnel between the two incisions is made for placement of the gracilis tendon.
   (c) Harvest of gracilis muscle flap, as described before.
   (d) Free gracilis muscle transplantation to reconstruct thumb and finger flexion. The gracilis muscle flap is placed above the elbow, with the proximal site of muscle anchored to the medial brachial intermuscular septum. The distal tendon is then woven into the flexor digitorum profundus and flexor pollicis longus tendons using a Pulvertaft weave. The vascular anastomosis is performed under a microscope; with the artery and vein of the gracilis anastomosed to the brachial artery and basilic vein, respectively. The gracilis motor nerve is sutured with BMBMCN using 9–0 nylon sutures with the assistance of microscope.

2. Postoperative protocol. After surgery, the upper extremity is immobilized by plaster for 6 weeks.
3. Outcomes. In the present study, free gracilis muscle transplantation was used to reconstruct thumb and finger flexion with BMBMCN as the donor nerve in two patients. After 2 years, the patients regained a noticeable improvement in digital flexion and a muscle power of M4

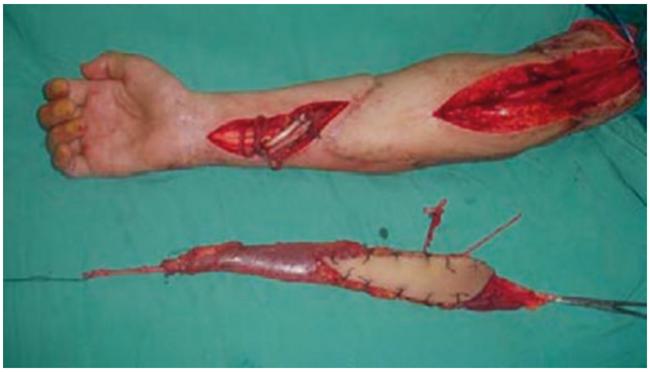


Fig. 10 Gracilis muscle transplantation with vascular nerve anastomosis for reconstruction of thumb abduction opposition function

(Fig. 14.10). However, a secondary surgery was still needed to reconstruct the sensation of the ulna side of the hand and function of the intrinsic muscle.

Bibliography

1. Sixth People's Hospital of Shanghai. Free muscle transplantation by microsurgical neurovascular anastomoses: report of a case. Chin Med J. 1976;2:47.
2. Ikuta Y, Kubo T, Tsuge K. Free muscle transplantation by microsurgical technique to treat severe Volkmann's contracture. Plast Reconstr Surg. 1976;58:407–11.
3. Tamai S, Komatsu S, Sakamoto H, Sano S, Sasauchi N. Free muscle transplants in dogs, with microsurgical neurovascular anastomoses. Plast Reconstr Surg. 1970;46:219–25.
4. Harii K, Ohmori K, Torii S. Free gracilis muscle transplantation, with microneurovascular anastomoses for the treatment of facial paralysis, a preliminary report. Plast Reconstr Surg. 1976;57:133–43.
5. Manktelow RT, McKee NH. Free muscle transplantation to provide active finger flexion. J Hand Surg Am. 1978;3:416–26.
6. Manktelow RT, Zuker RM, McKee NH. Functioning free muscle transplantation. J Hand Surg Am. 1984;9:32–9.
7. Doi K, Sakai K, Ihara K, Abe Y, Kawai S, Kurafuji Y. Reinnervated free muscle transplantation for extremity reconstruction. Plast Reconstr Surg. 1993;91:872–83.
8. Doi K, Kuwata N, Kawakami F, Hattori Y, Otsuka K, Ihara K. Limb-sparing surgery with reinnervated free-muscle transfer following radical excision of soft-tissue sarcoma in the extremity. Plast Reconstr Surg. 1999;104:1679–87.
9. Ihara K, Shigetomi M, Kawai S, Doi K, Yamamoto M. Functioning muscle transplantation after wide excision of sarcomas in the extremity. Clin Orthop Relat Res. 1999;358:140–8.
10. Doi K, Hattori Y, Kuwata N, Soo-heong T, Kawakami F, Otsuka K, et al. Free muscle transfer can restore hand function after injuries of the lower brachial plexus. J Bone Joint Surg Br. 1998;80:117–20.
11. Doi K, Muramatsu K, Hattori Y, Otsuka K, Tan SH, Nanda V, et al. Restoration of prehension with the double free muscle technique following complete avulsion of the brachial plexus. Indications and long-term results. J Bone Joint Surg Am. 2000;82:652–66.
12. Doi K, Sakai K, Kuwata N, et al. Double-muscle technique for reconstruction of prehension after complete avlusion of the brachial plexus. J Hand Surg (Am). 1995;20:408.
13. Doi K. New reconstructive procedure for brachial plexus injury. Clin Plast Surg. 1997;24:75–85.
14. Frey M. Avulsion injuries to the brachial plexus and the value of motor reinnervation by ipsilateral nerve transfer. J Hand Surg (Br). 2000;25:3323–4.
15. Leffert RD. Brachial plexus injuries. 1st ed. New York: Churchill Livingstone; 1985.
16. Kline DG, Hudson AR, Kim DH. Atlas of peripheral nerve surgery. Philadelphia: WB Saunders; 2001.
17. Lundborg G. A 25-year perspective of peripheral nerve surgery: evolving neuroscientific concepts and clinical significance. J Hand Surg (Am). 2000;25:391–414.
18. Midha R. Epidemiology of brachial plexus injuries in a multitrauma population. Neurosurgery. 1997;40:1182–9.
19. Millesi H. Brachial plexus injuries, nerve grafting. Clin Orthop. 1988;(237):36.
20. Millesi H. Trauma involving the brachial plexus. In: Omer GE, Spinner M, Van Beek AL, editors. Management of peripheral nerve problems. 2nd ed. Philadelphia: W.B. Saunders; 1998. p. 344–444.
21. Narakas AO, Hentz V. Neurotization in brachial plexus injuries, indications and results. Clin Orthop. 1988;(237):43.
22. Narakas AO. Brachial plexus injuries. In: McCarthy J, editor. Plastic surgery, vol. 7. Philadelphia: WB Saunders; 1990. p. 4776.
23. Oberlin C, Beal D, Leechavengvongs S. Nerve transfer to biceps muscle using a part of ulnar for C5-C6 avulsion of the brachial plexus: anatomical study and report of four cases. J Hand Surg (Am). 1994;19:232–7.
24. Sungpet A, Suphachatwong C. Transfer of a single fascicle from the ulner nerve to the biceps muscle after avulsions of upper roots of the brachial plexus. J Hand Surg (Br). 2000;25:325–8.
25. Lu Q, Gu L, Jiang L, Qin B, Fu G, Li X, Yang J, Huang X, Yang Y, Zhu Q, Liu X, Zhu J. The upper brachial plexus defect modal in rhesus monkeys: a cadaveric feasibility study. Neuroreport. 2013;24:884–8.
26. Yang J, Qin B, Fu G, Li P, Zhu Q, Liu X, Zhu J, Gu L. Modified pathological classification of brachial plexus root injury and its MR imaging characteristics. J Reconstr Microsurg. 2014;30:171–8.
27. Baker PA, Watson SB. Functional gracilis flap in thenar reconstruction. J Plast Reconstr Aesthet Surg. 2007;60:828–34.
28. Herrero F. Extensor digitorum brevis free flap: anatomic study and further clinical applications. Plast Reconstr Surg. 2000;105:1347–56.
29. Hirase Y, Kojima T, Fukumoto K, Misu H, Yamaguchi T. Indication and practice of reverse flow extensor digitorum brevis muscle flap transfer. Ann Plast Surg. 2003;51:273–7.

15 Functional Anatomy of Brachial Plexus

Jie Lao and Kaiming Gao

Traumatic brachial plexus injury represents a severe handicap for the patient because it is very difficult to treat, especially the spinal nerve-root avulsion. Recent advances in microsurgical repair and diagnosis, but the prognosis of the injury is still not optimistic. The complicated anatomy of brachial plexus is one of the main reasons. In order to achieve satisfying outcomes after treatment, it is necessary to be fully familiar with the detailed functional anatomy of brachial plexus.

15.1 Combination and Location of Brachial Plexus

The brachial plexus is formed from the ventral rami of five cervical nerves, including C5, C6, C7, C8 and T1. It is usually divided into five parts in terms of anatomy: roots, trunks, divisions, cords and terminal branches (Fig. 15.1). The five large nerve roots emerge from the foramina as the first section of the brachial plexus. Then the brachial plexus passes through the space of the anterior and middle scalene to form the part of "trunks". The C5 and C6 nerves merge to form the upper trunk; C8 and T1 nerves combine to form the lower trunk; C7 forms the middle trunk alone. The roots and trunk of the brachial plexus above the clavicle form the supraclavicular plexus. The suprascapular nerve emerges at the point of convergence of the C5 and C6 nerves, known as Erb's point. The three trunks go posterior to the subclavian artery and pass through to the distal of the clavicle, each of which divides into anterior and posterior divisions. The anterior divisions of the upper and middle trunks combine to form the lateral bundles; the posterior divisions of all trunks merge into the posterior bundles; the anterior divisions from the lower trunk form the medial bundle separately. The lateral cord is divided into two distal branches, which are the musculocutaneous nerve and the lateral branch of median nerve; the posterior cord splits into the phrenic nerve and the phrenic nerve; the medial bundle emits the ulnar nerve and the medial branch of the median nerve. The cords and the terminal branches together compose the infraclavicular plexus.

Additional branches emerging from the supraclavicular plexus include the long thoracic nerve and the dorsal scapular nerve. Additional branches emerging from the infraclavicular plexus include the thoracodorsal nerve, the upper and lower subscapular nerves, the lateral and medial pectoral nerves, the medial brachial cutaneous nerve, and the medial antebrachial cutaneous nerve.

15.2 The Terminal Branches of Brachial Plexus

15.2.1 Musculocutaneous Nerve

The main part of musculocutaneous nerve is originated from the C6 root. It emerges from the lateral cord at the level of the inferior border of the pectoralis minor, passing the coracobrachialis and continuing through the space between the biceps and brachialis. At the level of elbow, the musculocutaneous nerve continues to be the lateral antebrachial cutaneous nerve. The muscles innervated by the musculocutaneous nerve include coracobrachialis, biceps and brachialis.

15.2.2 Median Nerve

The lateral cord gives off lateral cord contribution to the median nerve and the medial cord gives off the medial cord contribution to the median nerve and the two cords of median nerve merge together anterior to the axillary artery. At the brachial level, the median nerve goes in the medial groove of biceps accompanied with the brachial artery with no braches. Then the median nerve continues through inferior to the aponeurosis of biceps tendon and passes the two heads of

J. Lao (✉) · K. Gao
Department of Orthopedics, Huashan Hospital Affiliated to Fudan University, Shanghai, China
e-mail: laojie222@sina.com; gaokaiming511@163.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_15

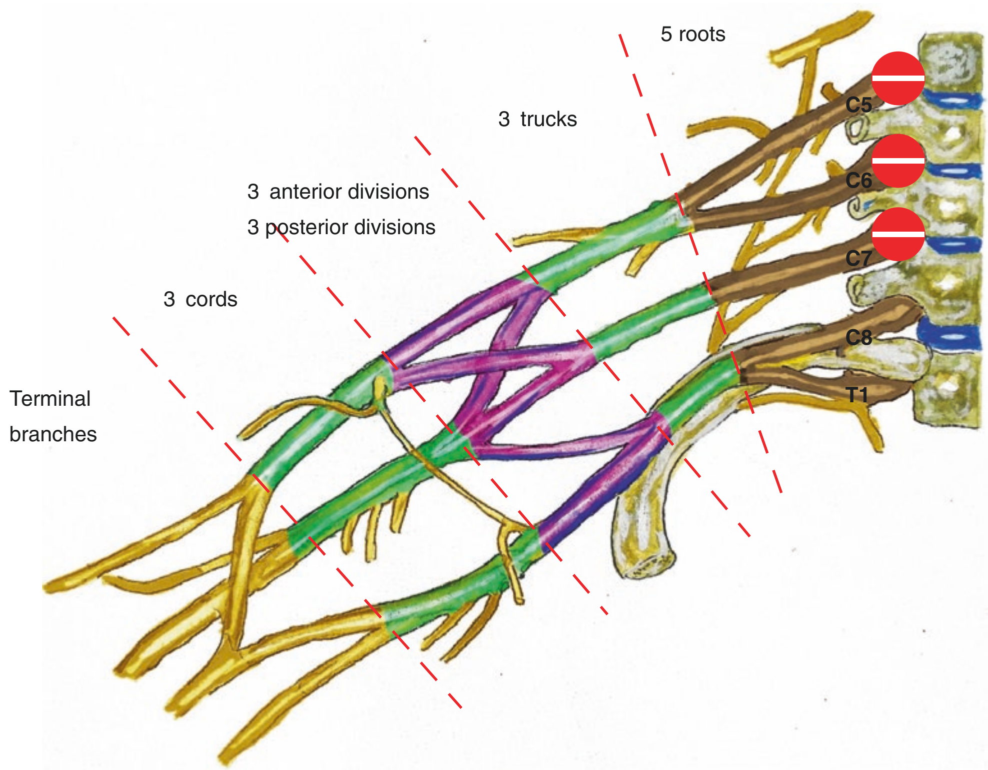


Fig. 15.1 Schematic diagram of brachial plexus

flexor digitorum superficialis. The anterior interosseous nerve (AIN) emerges from the median nerve in the proximal forearm. At the antebrachial level, the median nerve goes in the space between the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP). At this level, the muscles innervated by median nerve include pronator teres (PT), palmaris longus (PL), flexor carpi radialis (FCR), all the finger flexor digitorum superficialis (FDS), index and middle flexor digitorum profundus (FDP), flexor pollicis longus (FPL), and pronator quadratus (PQ) muscles. At the wrist level, the median nerve passes to the palm through the carpal tunnel and then splits to the recurrent branch of median nerve and the common palmar digital nerves to thumb, index finger, middle finger and the radial part of ring finger. At this level, the muscles innervated by median nerve include the abductor pollicis brevis (APB), opponens pollicis, superficial head of the flexor pollicis brevis (FPB), first and second lumbricalis.

15.2.3 Ulnar Nerve

The main part of ulnar nerve is originated from the C8 and T1 roots, emerging from the medial cord. At the brachial level, the ulnar nerve goes in the medial groove of biceps medial to the brachial artery and crosses the medial intermuscular septum with no braches. Then it continues through the ulnar nerve groove posterior to the medial epicondyle of humerus and passes the two heads of flexor carpi ulnaris (FCU). At the antebrachial level, the ulnar nerve goes in the space between FCU and FDP. At this level, the muscles innervated by median nerve include FCU, FDP of ring finger and little finger. The dorsal branch of ulnar nerve emerges from the ulnar nerve about 7 cm proximal to the wrist. At the wrist level, the ulnar nerve continues to the palm anterior to the ligamenta carpi transversum and medial to the pisiform and then divides into its two terminal branches, the superficial and deep branches. The superficial branch of ulnar nerve which is a pure sensory one splits to the little finger and the ulnar part of ring finger, while the deep branch of ulnar nerve which is a pure motor one continues through the Guyon's canal and then splits to different branches to innervate hypothenar muscles (opponens digiti minimi, flexor digiti minimi, abductor digiti minimi), the deep head of the FPB, the adductor pollicis muscle, the lumbricals for the little and ring fingers, and all the interosseous muscles of the fingers.

15.2.4 Axillary Nerve

The main part of axillary nerve is originated from the C5 and C6 roots, emerging from the posterior cord. It goes posterior to the axillary nerve and anterior to the subscapularis and then passes the quadrilateral foramen accompanied with the posterior humeral circumflex artery. At this level, the branches that innervate the teres minor emerge from the axillary nerve. Then the axillary nerve continues to the posterior part of the deltoid via the surgical neck of humerus and splits to several rami to innervate the anterior, middle and posterior parts of the deltoid.

15.2.5 Radial Nerve

The radial nerve is originated from all of the five roots of the brachial plexus (C5 to T1), emerging from the posterior cord. It goes posterior to the axillary nerve and anterior to the subscapularis and the latissimus dorsi and then gradually goes posterior to humerus at the level of the inferior border of latissimus dorsi tendon. At the level of the middle part of humerus, the radial nerve goes through the radial nerve groove in the space between the long head and the lateral head of triceps. At the level of the distal part of humerus, the radial nerve passes the lateral intermuscular septum with and then continues in the space between the brachialis and brachioradialis to the elbow. At the level of elbow, the radial nerve goes in the space between the brachioradialis (BR) and extensor carpi radialis longus (ECRL). The radial nerve innervates BR and ECRL before it branches in two ends, the superficial (sensory) and posterior interosseous (motor) branches. When the posterior interosseous nerve passes through the supinator muscle that locates approximately 8 cm distal away to the elbow joint, it splits into several branches, which are described as the cauda equina. The muscles innervated by median nerve include the long head, the medial head and the lateral head of the triceps, BP, ECRL, the supinator, extensor carpi radialis brevis (ECRB), extensor pollicis longus (EPL), extensor digiti minimi (EDM), extensor pollicis brevis (EPB), abductor pollicis brevis (APL), extensor digitorum communis (EDC), extensor indicis proprius (EIP) and extensor carpi ulnaris (ECU).

15.3 Types and Clinical Manifestations of Brachial Plexus Injury

After we have described the anatomy and function of the brachial plexus, we will illustrate the types and clinical manifestations of brachial plexus injury concerning its location (root, trunk, cord or branch) and range (partial or entire) in this section.

15.3.1 Brachial Plexus Root Injury

Theoretically, clinical symptoms and signs may not occur after a single nerve root is injured or even ruptured, because the upper extremity peripheral nerve is not composed of each of the brachial plexus nerve roots independently. Only damage to two adjacent nerve roots may cause visible clinical symptoms and signs. We call this phenomenon as single-root compensatory phenomenon and dual-root combination phenomenon. Conveniently, we divide the brachial plexus into upper and lower brachial plexus. The upper brachial plexus includes cervical nerve roots 5, 6 and 7 and the lower brachial plexus includes thoracic nerve roots 8 and 1.

The injury to upper brachial plexus roots: When the upper brachial plexus roots (C5–7) are injured, the axillary nerve, musculocutaneous nerve, super-scapular nerve, sub-scapular nerve and the dorsal scapular nerve are paralyzed, and the radial nerve and median nerve partially paralyzed. Consequently, the deltoid, biceps muscle, brachial muscle, sub-scapularis, teres major, supraspinatus and subspinatus, clavicular head of pectoralis major, flexor carpi radialis, pronator teres, brachioradialis muscle, supinator are paralyzed, and the latissimus dorsi muscle and extensor digitorum muscle partially paralyzed (Fig. 15.2).

The clinical manifestations: The functions of shoulder abduction and elbow flexion are absent, but the elbow extension, wrist flexion and extension are still preserved but the muscle strength is decreased. Sensation on the upper limb extensor skin is mostly missing and thumb feeling is decreased, but sensation on 2–5 fingers, hand and the median forearm skin is completely normal. We can find atrophy of the supraspinatus, subspinatus, deltoid and biceps muscles. In addition, the forearm rotation is limited, but the activities of fingers are still normal.

The symptoms are similar to those of the upper brachial plexus (C5–6) injury. Determination of whether the C7 nerve is damaged or not mainly depends on presence of paralysis of the latissimus dorsi, elbow extensor and extensor digitorum communis. In the presence of trapezius atrophy, shrugging disability, paralysis of the levator scapula and rhomboid muscle, and raised scapulas spine edge while the patient flexes the arm forward, the brachial plexus root avulsion can be determined at or proximal to the intervertebral foramina.

Lower brachial plexus root injury: When the lower brachial plexus (C8 and T1) nerve roots are injured, the ulnar nerve, medial cutaneous nerve of the forearm and arm, the medial head of median nerve are paralyzed, and the lateral head of the median nerve and radial nerve partially paralyzed. Accordingly, the flexor carpi muscles, 1–5 finger flexor muscles, thenar, hypothenar, all lumbricales manus and musculi interossei are paralyzed while triceps and finger extensor partially paralyzed (Fig. 15.3).

The clinical manifestations: The hand function is lost or seriously limited but activities of the shoulder, elbow, and wrist are still good. Usually Horner syndrome is present on the affected side. All the internal muscles of the hand are atrophic, especially the interosseous muscle. Deformities of flat hand and claw hand can be detected, and the functions of finger flexion and extension are lost. The metacarpophalangeal joints can still extend (depending on extensor digitorum muscle function) but the palm abduction of the thumb does not exist.

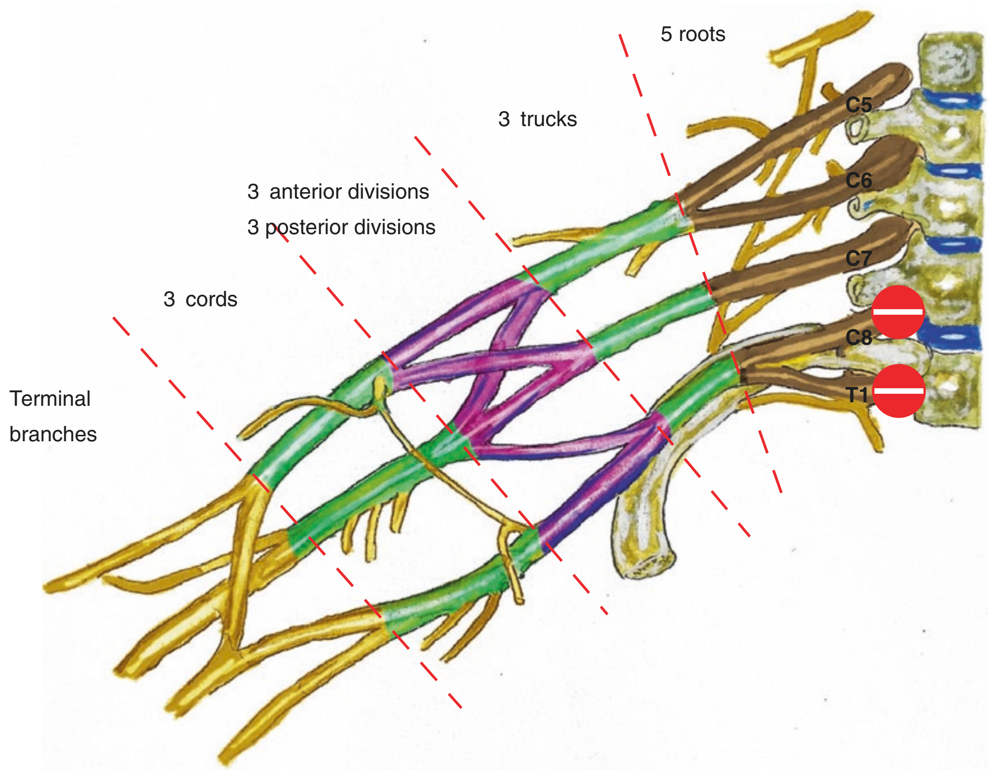


Fig. 15.2 Injury to the upper brachial plexus roots

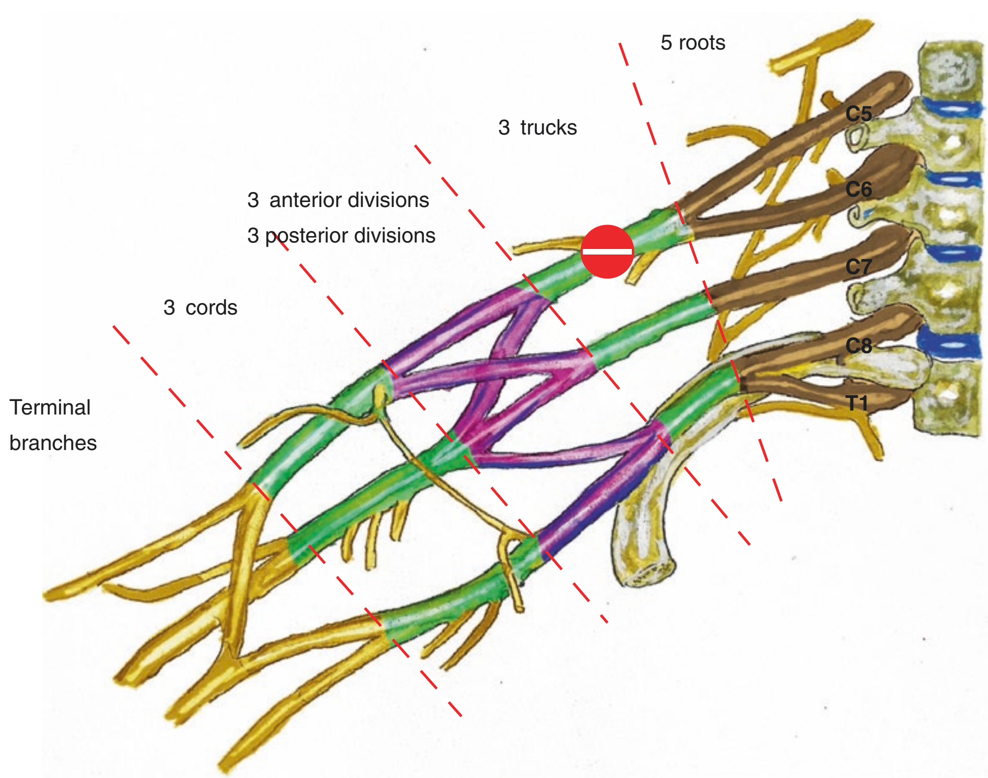


Fig. 15.3 Injury to the lower brachial plexus roots

The sensation on the ulnar part of the forearm and hand skin is lost, and so is the sensation on the medial arm skin.

The above symptoms are similar to those of the injury to lower trunk or medial cord of brachial plexus. Presence of the Horner syndrome proves damage to the sympathetic nerve of T1, often prompting the C8 and TI root avulsion at or proximal to the intervertebral foramina. If Horner sign is negative, atrophy of the sternocostal part of the pectoralis major suggests a diagnosis of injury to the lower trunk of brachial plexus (as sub-clavicle injury), while absence of the pectoralis major muscle atrophy suggests a diagnosis of medial cord injury. Sometimes the injury to the C8 and TI nerve roots can be combined with C7 nerve root injury. The clinical symptoms are similar, but the latissimus dorsi and extensor digitorum communis may become paralyzed or weak while the sensory disturbance can be extended to the radial side.

15.3.2 Brachial Plexus Trunk Injury

The upper trunk of brachial plexus injury: The upper trunk of brachial plexus is composed of C5 and C6. When the upper trunk is injured, axillary nerve, musculocutaneous nerve and super-scapular nerve are paralyzed while radial nerve and median nerve partially paralyzed. The clinical symptoms and signs are similar to those of the upper brachial plexus injury (Fig. 15.4).

The middle trunk of brachial plexus injury: The middle trunk of brachial plexus consists of C7 only. Mere C7 injury which is rarely reported in clinic presents with no obvious clinical symptoms or signs except for a short period of (usually 2 weeks) decreased strength of extensor muscles (Fig. 15.5).

The lower trunk of brachial plexus injury: The lower trunk of brachial plexus consists of C8 and T1. When it is injured, the ulnar nerve, medial head of the median nerve, medial cutaneous nerve of the arm and forearm are paralyzed while the lateral of the median nerve head and radial nerve partially paralyzed. The clinical symptoms and signs are similar to those of the lower brachial plexus injury. Hand functions including flexion, extension, adduction and abduction are totally lost, resulting in disability to grip anything (Fig. 15.6).

15.3.3 Brachial Plexus Cord Injury

The clinical symptoms and signs of brachial plexus cord injury are very regular and easy to diagnose according to the structure of the brachial plexus.

Injury to the lateral cord of brachial plexus: After the lateral cord of brachial plexus is injured, the musculocutaneous nerve, the lateral head of median nerve and the lateral part of nervi thoracales anteriores are paralyzed. Accordingly, the muscles like biceps, radial flexor carpi and the clavicular part of pectoralis become paralyzed (Fig. 15.7).

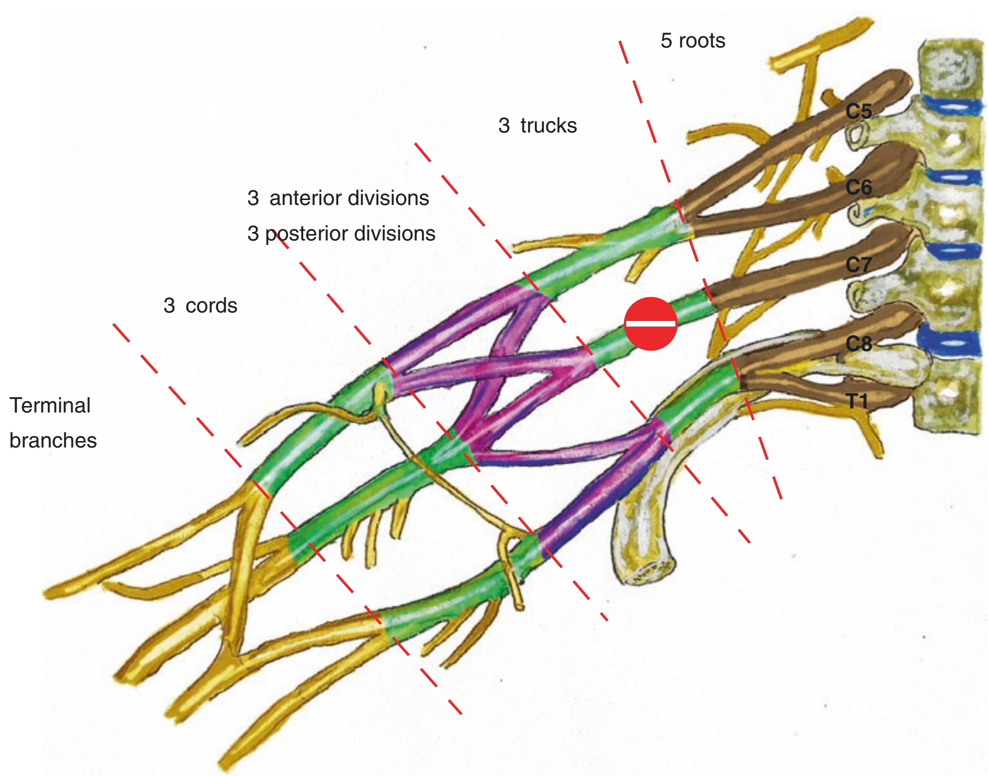


Fig. 15.4 Injury to the upper trunk of brachial plexus

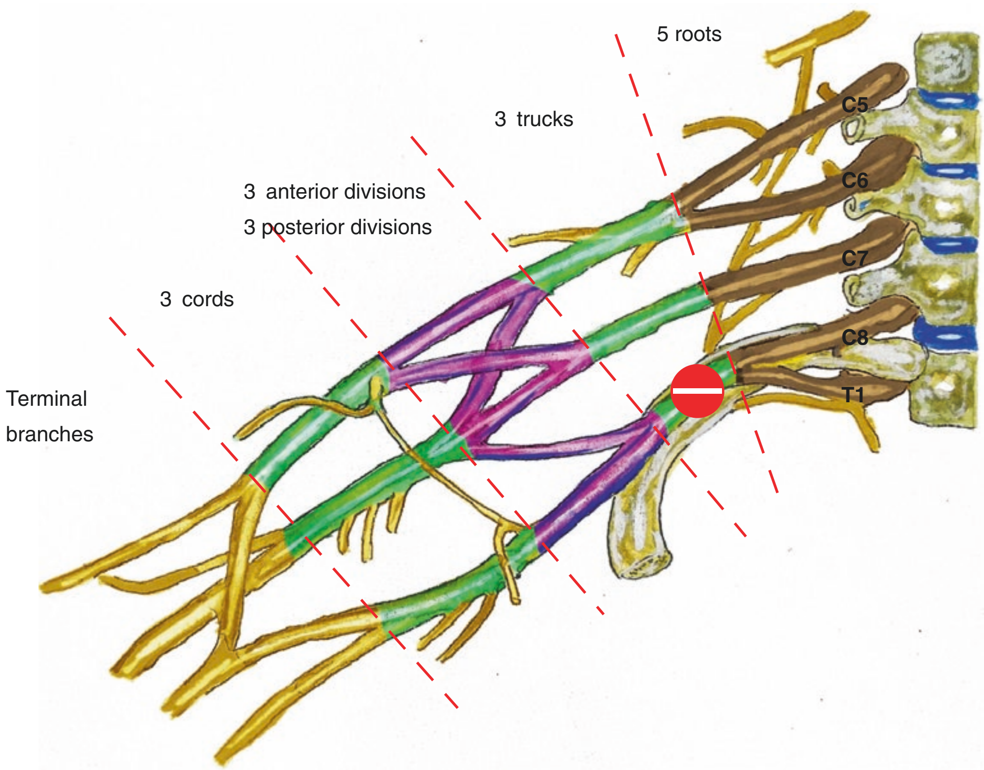


Fig. 15.5 Injury to the middle trunk of brachial plexus

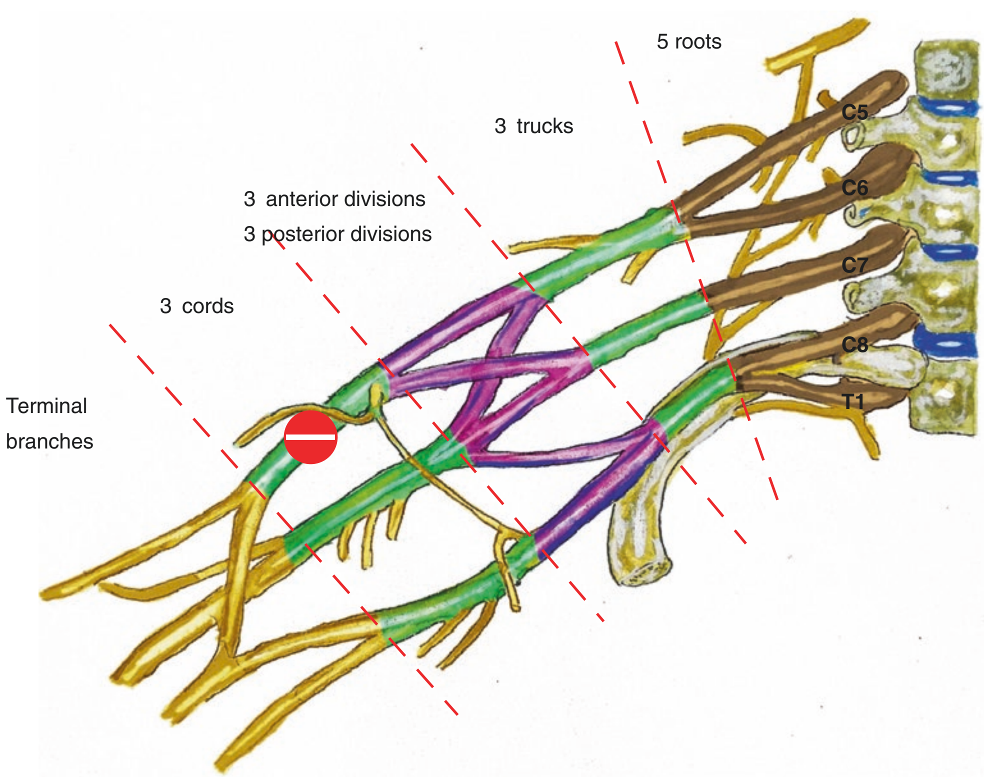


Fig. 15.6 Injury to the lower trunk of brachial plexus

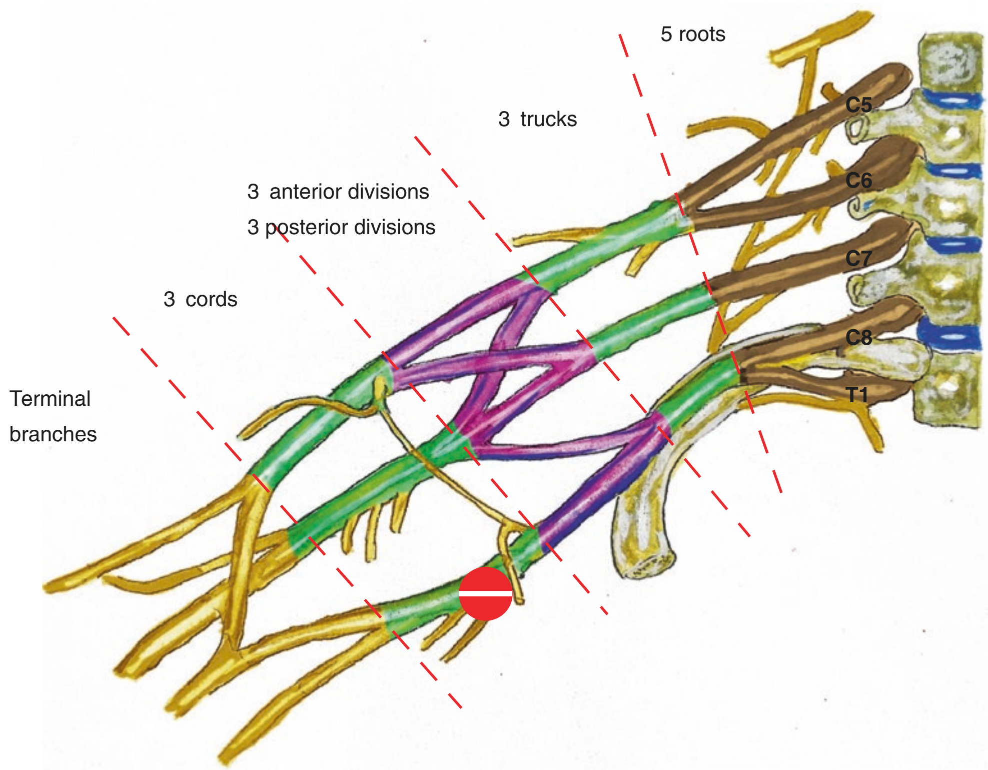


Fig. 15.7 Injury to the lateral cord of brachial plexus

The clinical manifestations: paralysis of biceps and pronator teres, but with normal activities of the shoulder and hand.

Injury to the medial cord of brachial plexus: After the medial cord of brachial plexus is injured, the ulnar nerve, the medial head of median nerve and the medial part of nervi thoracales anteriores are paralyzed. Therefore, the dominated muscles become paralyzed except the radial flexor carpi and pronator teres (Fig. 15.8).

The clinical manifestations: paralysis of all the internal muscles of the hand and finger flexor muscles, leading to disability of the hand, involving finger flexion and extension and thumb abduction (but the metacarpophalangeal joints can extend). Sensory loss is mainly located at the medial of the forearm and the ulnar hand. Significant atrophy can be found of the internal of the hand and forearm flexor muscles, leading to the flat hand and claw hand deformities while the shoulder and elbow functions are still normal.

It is necessary to distinguish medial cord injury from the injury to C8, T1 or the lower trunk, which presents with partial paralysis of the sternocostal part of pectoralis major, triceps, wrist extensors and extensor digitorum communis.

Injury to the posterior cord of brachial plexus: After the posterior cord of brachial plexus is injured, the following nerves and their dominated muscles are paralyzed: teres major and subscapularis innervated by the sub-scapular nerve, the latissimus dorsi innervated by the thoracodorsal nerve, the deltoid and teres minor innervated by the axillary nerve, and the extensor group of the arm and forearm innervated by the radial nerve (Fig. 15.9).

The clinical manifestations: disability of shoulder abduction, arm internal rotation, elbow and wrist dorsiflexion, extension of metacarpophalangeal joints, thumb extension and radial side abduction. The sensory loss is located at the lateral shoulder, the dorsal forearm and the dorsal of the radial side of hand. Atrophy is detected of the deltoid, latissimus dorsi, triceps and forearm extensor group, but the other joint activities are still normal.

15.3.4 Global Brachial Plexus Injury

At the early stage of global brachial plexus injury, the entire upper limb becomes paralyzed gradually. Passive movement at full range of motion can be conducted in all the joints but the active movement cannot. Shrugging movement still exists due to the presence of the trapezius muscle function. In addition, all the sensation is absent at the upper limb except the medial part of the arm which is co-dominated by the ICBN which is distributed from the second intercostal nerve. All of the upper extremity tendon reflections disappear, accompanied by low temperature, limb swelling and Horner syndrome.

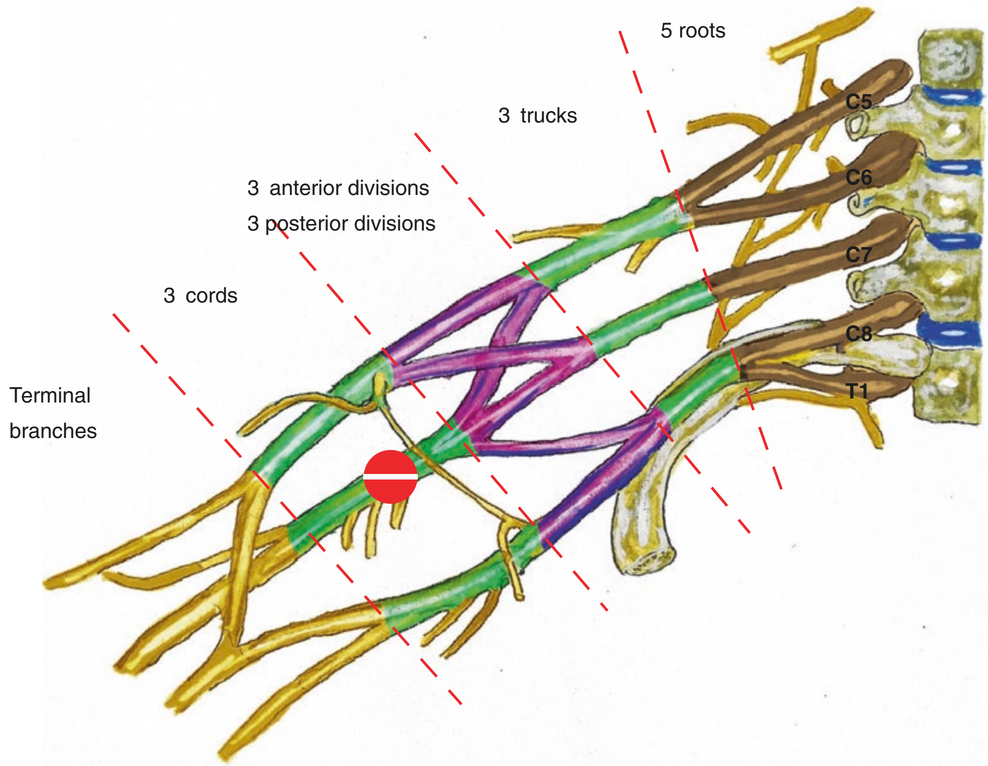


Fig. 15.8 Injury to the medial cord of brachial plexus

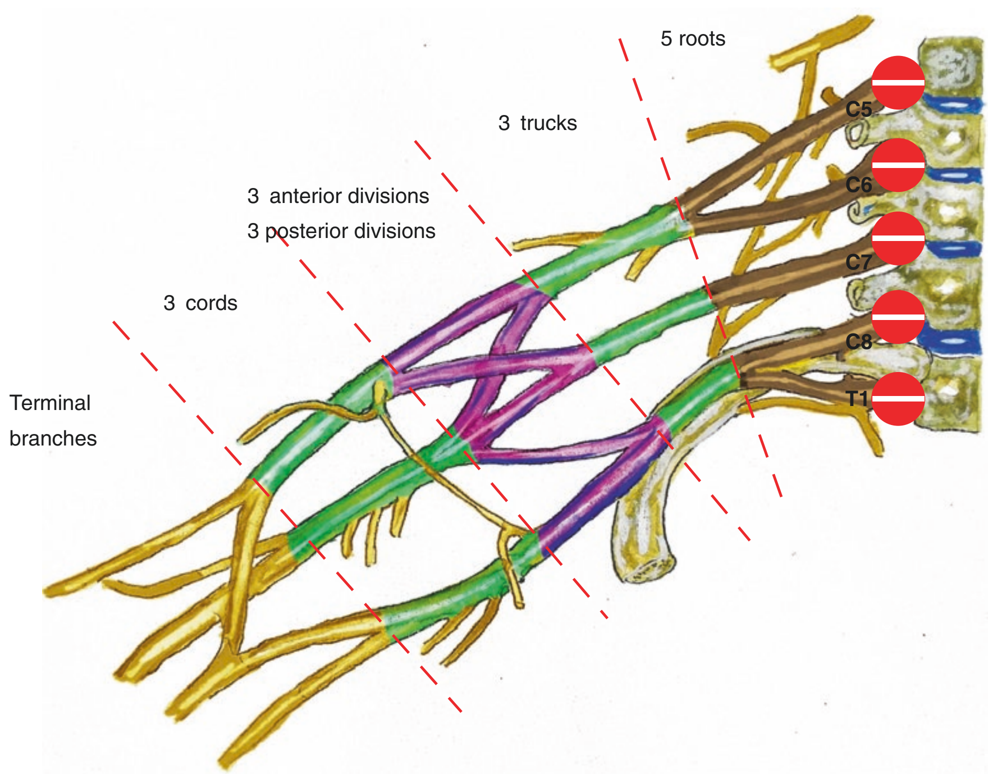


Fig. 15.9 Injury to the posterior cord of brachial plexus

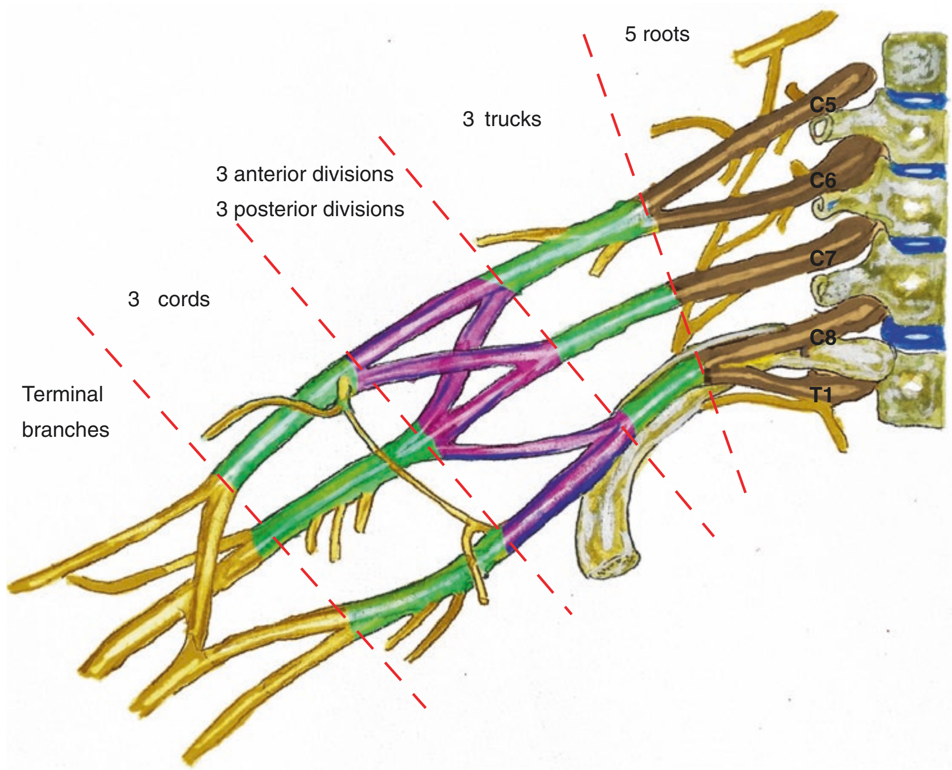


Fig. 15.10 Global brachial plexus injury

At the advanced stage, atrophy of the upper limb muscles is significant, and the passive movement of each joint is limited due to joint contracture, especially the shoulder and finger joints (Fig. 15.10).

15.4 Microsurgery for Brachial Plexus Injury

15.4.1 Diagnosis of Brachial Plexus Injury

Diagnosis of brachial plexus injuries needs detailed medical history, physical examination, and auxiliary examinations. Based on comprehensive analysis of the patient's condition, an experienced doctor can give a precise diagnosis of severity and location of the injury.

15.4.1.1 Medical History

Patients with brachial plexus injury usually have a history of a serious impact on his (or her) neck or shoulder. Many complain of disability of motor and sensory function of their affected upper extremities, usually after a car accident, falling from a height, traction or crush injury in a factory. Severe violent injuries sometimes lead to multiple traumas. Some may have fractures of scapula, clavicle, humerus or other bones in the upper extremity. Some have a history of brief coma. When the patients complain of paresthesia and somewhat disabled movement of upper extremities after other wounds have been treated, we should consider the possibility of brachial plexus injury, if head trauma, spine injury, fracture of upper extremity and tear of tendons or muscles are excluded. The typical and the most severe pan-plexus root avulsion injury turns out to be complete loss of motor function and sense of the affected upper extremity. Other types of brachial plexus injury, such as injury to the upper, middle, and lower trunks and medial, lateral, and posterior cords, show different manifestations. We should consider that there may be injuries both affecting trunks and cords, especially after huge violence. Surgeons may need to explore both supraclavicular and infraclavicular regions in the operation. Careful physical examinations, proper accessory tests are necessary to make a precise localization diagnosis. Furthermore, a patient may have got humerus fracture simultaneously. When he or she has a typical manifestation of radial nerve injury, it is necessary to distinguish if radial nerve injury coexists in the arm to avoid misdiagnosis which may delay treatment.

15.4.1.2 Physical Examination and Clinical Analysis

Nowadays many accessory examinations such as electrodiagnostic evaluation, MRI, and B ultrasound are used in most hospitals to help diagnosis of brachial plexus injury. However, basic physical examination and clinical thinking are also essential. The active and passive ranges of motion of every joint, muscle strength, sensory test can reflect the patient's condition most directly. No modern instruments can replace a doctor's precise physical examination and logical clinical thinking ability.

To analyze and give a localization diagnosis of brachial plexus injury, we need to know functional anatomy of brachial plexus. Understanding sensory and motor dominated regions of different nerves of brachial plexus, in addition to clinical examination, we can make a qualitative and localization diagnosis of brachial plexus injury.

Make Sure That a Patient Does Have Brachial Plexus Injury

Physical examinations usually start from sensory and motor functions. First we get the impression of single nerve function. Then we combine all the functions of every single terminal branch together, arriving at a precise diagnosis. So it is necessary to review manifestations of every terminal branch injury in the upper extremity.

1. Axillary nerve: innervating deltoid and teres minor. Its terminal sensory nerve turns out to be superior lateral brachial cutaneous nerve, innervating the skins of shoulder and lateral brachial area. Injury to the axillary nerve shows atrophy of deltoid, restricting function of shoulder abduction.
2. Musculocutaneous nerve: innervating biceps mainly, and coracobrachialis and brachialis as well. Its terminal sensory nerve is lateral antebrachial cutaneous nerve, innervating the skins of lateral forearm. Injury to the musculocutaneous nerve leads to atrophy of biceps and restricted flexion of one's elbow. One thing we need to pay attention to is that we assess the elbow flexion with the forearm supination to assure the contraction of biceps. Otherwise the flexion can be done by the contraction of brachioradialis with the forearm pronation.
3. Radial nerve: innervating triceps, brachioradialis, extensor carpi, extensor pollicis longus and brevis and extensor digitorum. In the arm, it gives out branches such as posterior brachial cutaneous nerve, inferior lateral brachial cutaneous nerve, and posterior antebrachial cutaneous nerve, innervating the suggesting area. One of the terminals in the antebrachial area is the superficial branch of radial nerve, innervating the radial half of the back of hand and the back of proximal phalanx of thumb, index finger and middle finger (radial side). Injury to the radial nerve leads to restriction of extension of elbow, wrist or fingers, depending on the levels of injury. It should be kept in mind that physical examination of finger extension should be done under wrist extension position, to avoid the influence of tenodesis.
4. Median nerve: innervating all the musculus flexor in the forearm except brachioradialis, flexor carpi ulnaris, ulnar half of flexor digitorum profundus, and also innervating pronator teres, pronator quadratus, muscle of thenar except adductor pollicis, and the first and second lumbricalis. It gives off terminals to control the sense of palm, the palm side of thumb, index finger, middle finger and the radial side of ring finger, and the back side of their middle and distal phalanx. Injury to the median nerve leads to atrophy of thenar eminence, restriction of wrist flexion, finger flexion and palmar opposition. Failure to flex one's thumb and distal interphalangeal joint of index finger, failure of palmar opposition and paresthesia of thumb, index, middle and radial side of ring finger are typical of median nerve injury.
5. Ulnar nerve: innervating flexor carpi ulnar, ulnar half of flexor digitorum profundus, hypothenar, the third and the fourth lumbricalis, interosseus and adductor pollicis. It also innervates the sense of ulnar side of the back of hand, the little finger and the ulnar side of ring finger. Injury to the ulnar nerve leads to atrophy of the innervated muscles, and decreased strength of the flexion of distal interphalangeal joints of ring and little fingers. Such manifestations, as restriction of the side adduction and abduction of the fingers, failure to extend the distal interphalangeal joint, claw hand deformity, and paresthesia of ulnar side of the hand, suggest consideration of ulnar nerve injuries.

Generally, injury of a single nerve suggests the level of injury is below the branches. The following two conditions remind us of consideration of brachial plexus injury: (1) combined injuries of two or more than two nerves mentioned above (axillary nerve, musculocutaneous nerve, median nerve, radial nerve, ulnar nerve); (2) injuries to any one of the median, ulnar and radial nerves and to the medial antebrachial cutaneous nerve (except the incise injury).

Supraclavicular or Infraclavicular Injury

Judgment of Supraclavicular or Infraclavicular Injury

After a patient is diagnosed as having brachial plexus injury, we need to judge if it is supraclavicular or infraclavicular injury in order to further diagnose its localization before a proper treatment is chosen.

To make a localization diagnosis, we need to be familiar with the anatomy. The C5 and C6 roots unite to form the upper trunk, the C7 root alone form the middle trunk, and the C8 and T1 roots form the lower trunk. Each of the three trunks divides into anterior and posterior divisions. The three posterior divisions unite to form the posterior cord, the anterior divisions of the upper and middle trunks form the lateral cord, and the anterior division of the lower trunk continues distally to form the medial cord. The posterior cord divides into the axillary nerve and the radial nerve, the lateral cord gives off the musculocutaneous nerve and lateral cord contribution of the median nerve and the medial cord divides into the medial cord contribution of the median nerve and the ulnar nerve. In this process, the level of posterior, medial and lateral cord is an important division. It determines the type of brachial plexus injury by level above the cord or beneath the cord. After that, further localization diagnosis can be made on this basis. And it is also useful for the surgeons to make decisions on surgical protocols.

To know if the injury level is above or beneath the cord level, we need to review its anatomic characteristics. The lateral cord gives off the lateral pectoral nerve from its origin (which is about the bottom level of the middle of clavicle), innervating the clavicular portion of pectoralis major. The posterior cord gives off superior subscapular nerve, thoracodorsal nerve and inferior subscapular nerve at its proximal part, innervating subscapularis, latissimus dorsi and teres major respectively. Therefore, during a physical examination, if the muscle strength of pectoralis major, latissimus dorsi or teres major is weakened, the injury level is considered above the cord level, also supraclavicular injury, such as injury to the trunks or the roots. The surgical protocol should explore the supraclavicular brachial plexus. Otherwise, infraclavicular injury should be considered. The surgical protocol should explore the infraclavicular brachial plexus.

Infraclavicular Injury

When infraclavicular injury is confirmed, localization of lateral, medial or posterior cord is necessary. We make this diagnosis by clinical manifestations of injury to different nerves. Injury to one single cord is not common. In most cases at least two cords are injured. The severity of injury depends on the magnitude of the violence.

The combined injury of musculocutaneous nerve and lateral part of median nerve (the sensory part mainly) suggest the injury of lateral cord. The combined injury of median nerve (the motor part mainly) and ulnar nerve suggest the injury of medial cord. The injury of axillary nerve and radial nerve suggest the injury of posterior cord.

Supraclavicular Injury

When supraclavicular injury is confirmed, localization of the roots or trunks injured should be further discussed. The suprascapula nerve derives from origin of the upper trunk, innervating supraspinatus and subspinatus. When the suprascapula nerve is injured, injury of roots should be considered.

The combined injury of axillary nerve and musculocutaneous nerve suggests injury of the upper trunk. When the axillary nerve and the suprascapular nerve are affected, C5 root injury should be considered. The complete injury of axillary nerve and musculocutaneous nerve, combined with radial nerve, suggests injury of upper and middle trunks.

When the musculocutaneous nerve is totally paralysed, it should be considered that all of the C5, C6 and C7 roots have been injured. When the musculocutaneous nerve is paralyzed in combination with radial nerve injury, it should be considered that C6 root is completely impaired, and all of the C5, C7 and C8 have been somewhat injured.

When the median nerve is totally paralyzed, combined with radial nerve injury, it is suggested that the C8 root is completely impaired and all of the C6, C7 and T1 roots have been somewhat injured. Combined injury of median nerve and ulnar nerve suggests the injury of lower trunk or medial cord.

When the ulnar nerve is totally paralyzed, combined with radial nerve injury, it is suggested that the T1 root is completely impaired and all of the C6, C7 and C8 roots have been somewhat injured.

Preganglionic Injury or Postganglionic Injury

It is necessary to treat the patients with preganglionic injury as early as possible. On the contrary, it is better for the patients with postganglionic injury, except those with complete excision damage, to wait for a period of about 3 months to see if the impaired upper limb can be self-restored.

The following table gives information on how to distinguish preganglionic and postganglionic injuries (Table 15.1).

Table 15.1 Differences between preganglionic and postganglionic injuries

Distinguishing points	Preganglionic injury	Postganglionic injury
Characters of clinical history	1. History of coma	1. Conscious mostly
	2. Severe injury mostly with fracture	2. Relatively simple injury
	3. Causalgia	3. Causalgia rarely
Physical examination	1. Atrophy of the trapezius, restriction of shrug	1. Atrophy of the trapezius is rare
	2. Horner sign (+), contracted palpebral fissure, contracted pupil	2. Horner sign (−)
During surgery	1. The giant neuroma above the supraclavicular region	1. The swollen or nearly normal roots and trunks
	2. Emptiness of interscalene fissure	2. The roots can be seen in the interscalene fissure
	3. The ganglion sometimes can be seen in the vertebral foramen	3. The roots sometimes can be seen thickening or swollen in the vertebral foramen
Electrodiagnostic evaluation	Positive SNAP, negative SEP Sometimes phrenic nerve and accessary nerve are completely injured	Negative SNAP and negative SEP

15.4.1.3 Assistant Examination

Nowadays electrodiagnostic evaluation is a common and essential examination in both diagnosis and surgery for brachial plexus injuries. It provides doctors with much information on localization diagnosis and helps to make proper decisions in the surgery. MRI and B ultrasound are gradually popularized in diagnosis, making sure whether the injury is preganglionic or postganglionic.

15.5 Microsurgical Repair of Brachial Plexus Injury

15.5.1 Treatment of Brachial Plexus Injury

15.5.1.1 Principles for Treatment of Brachial Plexus Injury

Nerve exploration or repair should be carried out within 6 months after brachial plexus injury. Patients with open preganglionic injury should be operated on as early as possible, so are those with closed postganglionic injury who show no sign of recovery after 3–6 months' conservative treatment. Of the surgical methods for brachial plexus injury, direct suturing is better than nerve grafts. For brachial plexus injury, intra-plexus transfer is better than extra-plexus transfer and ipsilateral transfer is better than contralateral transfer. Since the surgical effects depend on the quality of donor nerve in intra-plexus transfer and contralateral extra-plexus transfer, it is important to evaluate the quality of donor nerve before and during the surgery. Protection of neural blood supply, tension free suturing and fixed position of tension reduction are essential to the recovery after nerve repair.

15.5.1.2 Surgical Methods of Brachial Plexus Repair

Exploration of Supraclavicular Area

Incision is made on 21 cm medial to the sternocleidomastoid muscle and 2 cm above the clavicle. The cutaneous branches of the cervical plexus should be recognized and protected. The omohyoid muscle and transverse cervical artery can be seen through the incision of the cervical deep fascia which can be cut off and ligated when necessary. Then the brachial plexus can be found below the fat pad. The phrenic nerve which goes through the surface of scalenus anterior should be protected. Usually the upper trunk can be seen first. C5 and C6 roots are on the proximal side of the upper trunk. C5 is on the lateral side. The suprascapular nerve is on the distal side of the upper trunk before the upper trunk is divided into anterior division and posterior division. C7 root which is deeper than the upper trunk is often located between the scalenus anterior and middle scalene muscle. The inferior trunk which is composed of C8 and T1 root is even deeper and near the subclavian artery.

Exploration of Subclavicular Area

Incision is made between the deltoid and pectoralis major muscle. Outcrop vein and the thoracoacromial vessels can be exposed through intermuscular space. The brachial plexus can be found when pulling the pectoralis minor apart. Lateral bundle which branches itself into musculocutaneous nerve and median nerve lateral head can be seen first and is around the axillary artery and vein. Median bundle which branches itself into ulnar nerve and median nerve median head is on the median side of axillary artery. Posterior bundle which branches itself into radial nerve and axillary nerve is deeper than the axillary artery.

When severe scar is found during the exploration or the axillary vessels are injured before, exploration should begin from the normal tissue (Figs. 15.11 and 15.12).

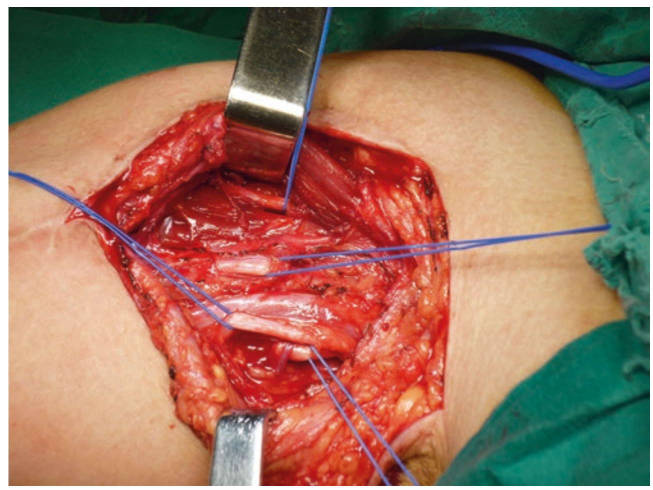


Fig. 15.11 Exploration of subclavicular area

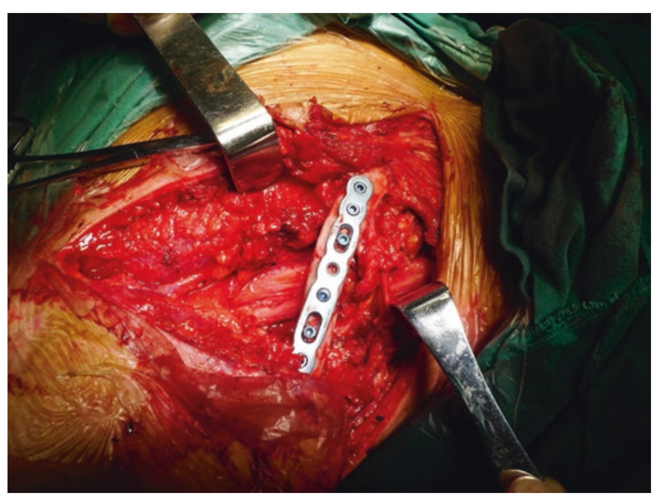


Fig. 15.12 Exploration of supraclavicular and subclavicular areas

Nerve Release

If the exploration finds the existence of conduction together with postganglionic injury, nerve release can be carried out. The nerve release can put the nerve away from the scars around. Sometimes the nerve needs intra-fascicle release which is done by incision on the epineurium and perineurium.

Direct suturing

Direct suturing can only be carried out in some patients with early cutting injury. It needs tension free and is better than nerve craft.

Nerve Graft

Nerve grafts can be applied for postganglionic nerve injury when nerve conduction is absent and direct suturing is unavailable. Common nerve grafts can be sural nerve, superficial radial nerve or other cutaneous nerves. In common, C5 residues can be used to rebuild the abduction and external rotation or stability of the shoulder. C6 residues can be used to rebuild elbow flexion. C7 residues can be used to rebuild elbow extension. Nerve grafts with blood supply can be applied in long-distance (>15 cm) or large diameter nerve grafts.

Nerve Transfer

Nerve transfer is to rebuild the motor or sensor function by transferring a normal or nearly normal nerve branch or bundle to the target motor or sensor nerve when the proximal side of this nerve is unavailable.

Indications

- Unrepairable preganglionic injury
- Some postganglionic injury with damaged proximal side
- Donor nerve for free muscle transplantation

Transfer Methods

Accessory Nerve Transfer

Accessory nerve transfer can be carried out via both anterior approach and posterior approach and is usually transferred to suprascapular nerve. In supraclavicular area exploration, incision is made via the anterior approach. The accessory nerve is located on the surface of trapezius which will contract when stimulated. The suprascapular nerve can be dislocated from the upper trunk and sutured with the accessory nerve. The patient is in prone position or lateral position when posterior approach is applied. Transverse incision is made on the superior margin of scapula. The suprascapular nerve is behind the scapula and the accessory nerve is on the 2/5 between the dorsal midline and acromion. After the surgery a special bracket of plaster is used to keep the neck away from movement in order to reduce the tension for 4–6 weeks.

Phrenic Nerve Transfer

Phrenic nerve transfer, invented by Gu YD, is widely used clinically. It has been proved effective and safe mainly in reconstruction of biceps. In supraclavicular area exploration, an incision is also made. When the phrenic nerve is found, it is dislocated completely and blocked by lidocaine before cutting. Meanwhile the posterior division of upper trunk is dislocated and cut to be sutured with the phrenic nerve. When there is wide adhesion in the supraclavicular area or the upper trunk is totally avulsed towards the subclavicular area, the phrenic nerve can be directly transferred to the musculocutaneous nerve with nerve graft. As an alternative method, a full-length phrenic nerve can be harvested to reduce the distance of nerve regeneration with assistance of video thoracoscopy. After the surgery a special bracket of plaster is used to keep the neck away from movement in order to reduce the tension for 4–6 weeks.

Triceps Branch Transfer

Transfer of triceps branch of radial nerve is worldwide used in patients with strong triceps. It is used to repair the axillary nerve and is usually sutured with the anterior branch of axillary nerve near the quadrilateral foramen. After the surgery the upper extremity should be fixed in the elbow flexion and chest stick position (Fig. 15.13).

Partial Ulnar Nerve Transfer (Oberlin Surgery)

It is suitable for the patients with normal C8 and T1 nerve function to rebuild elbow flexion and usually used with other nerve transfers the functional reconstruction. During the surgery, the target nerve is the biceps branch. A small bundle of ulnar nerve which mainly controls the flexor carpi ulnaris matches the diameter of the biceps branch. After the surgery, an elbow flexion position should be keep for 4–6 weeks.

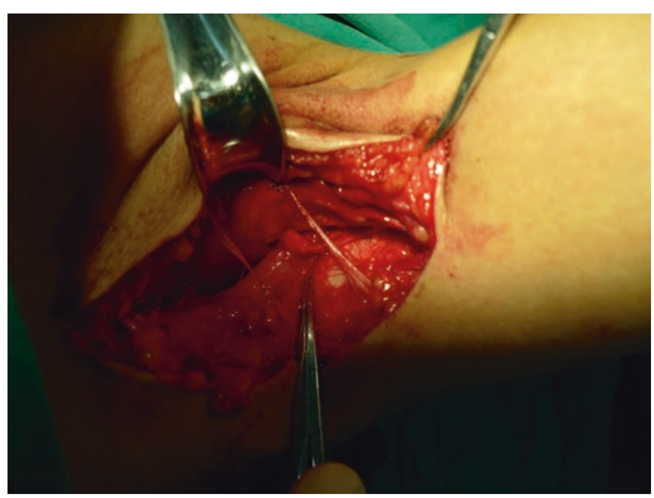


Fig. 15.13 Triceps branch transfer to axillary nerve

Intercostal Nerve Transfer

It was initially applied in musculocutaneous nerve repair and is now applied in triceps, deltoid, latissimus dorsi and free muscle transplantation. Attention should be paid to the patients undergoing a rib fracture, thoracic surgery or chest drainage whose intercostal nerve may be unavailable. Intercostal nerve transfer and phrenic nerve transfer should be conducted separately in children. After the surgery the upper extremity should be fixed in the elbow flexion and chest stick position for 4 weeks (Figs. 15.14 and 15.15).

Brachialis Branch Transfer

It was first applied in Huashan Hospital at Shanghai for patients with inferior trunk injury but normal upper trunk.

Fig. 15.14 Intercostal nerve transfer

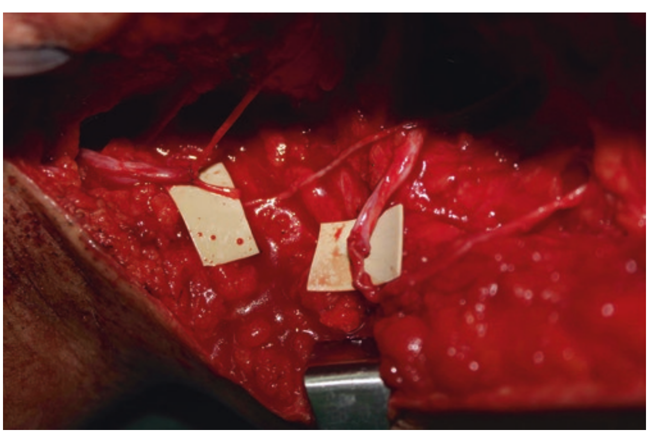


Fig. 15.15 Intercosal nerve transfer to triceps branch and throcadorsal nerve

During the surgery, the brachialis branch can be found in the arm beneath the brachialis muscle. The brachialis branch will be transferred to the posterior 1/3 bundle of median nerve. After the surgery, an elbow flexion position should be keep for 4–6 weeks.

Supinator Branch Transfer

It is also applied in patients with inferior trunk injury but normal upper trunk. It is usually carried out together with the brachialis branch transfer. It is used to repair posterior interosseous nerve. After the surgery, an elbow flexion position should be keep for 4–6 weeks.

C7 Root Transfer

It was invented by Gu YD. from Huashan Hospital at Shanghai and is now widely applied. It is detailed in Sect. 15.6 of Chap. 15.

15.5.1.3 Nerve Transfer Procedures for Brachial Plexus Injury

Injury to Upper and Middle Trunk

- Option 1: Ipsilateral C7 transfer to upper trunk; accessory nerve transfer to suprascapular nerve.
- Option 2: Accessory nerve transfer to suprascapular nerve; phrenic nerve transfer to musculocutaneous nerve; triceps branch transfer to axillary nerve.
- Option 3: Accessory nerve transfer to suprascapular nerve; triceps branch transfer to axillary nerve; partial ulnar nerve transfer to biceps branch of musculocutaneous nerve (Oberlin surgery).
- Option 4: Intercostal nerve transfer to musculocutaneous nerve, axillary nerve or suprascapular nerve.
- Option 5: Ipsilateral C7 or contralateral C7 transfer to upper trunk.
- Others: Motor branch of cervical plexus transfer to posterior division of upper trunk can be an alternative method to rebuild elbow flexion. Anterior or posterior approach in accessory nerve transfer depends on the patient's injury.

Injury to Inferior Trunk

- Option 1: Ipsilateral C7 root transfer to inferior trunk.
- Option 2: Brachialis branch transfer to anterior interosseous nerve; supinator branch transfer to posterior interosseous nerve; cutaneous branch of musculocutaneous nerve transfer to middle bundle of median nerve.
- Option 3: Full-length phrenic nerve transfer combined with accessory nerve transfer and intercostal nerve transfer to median nerve and ulnar nerve.

Total Brachial Plexus Avulsion

- Option 1: Accessory nerve transfer to suprascapular nerve; phrenic nerve transfer to musculocutaneous nerve or anterior division of upper trunk; motor branch of cervical plexus transfer to posterior division of upper trunk; contralateral C7 root transfer to ulnar nerve; intercostal nerve transfer to median nerve and throcadorsal nerve; ulnar nerve transfer to radial nerve after 4–8 months (or other necessary nerve); muscle transfer for function reconstruction.
- Option 2: Accessory nerve transfer to suprascapular nerve; phrenic nerve transfer to musculocutaneous nerve or anterior division of upper trunk; contralateral C7 root transfer to inferior trunk; intercostal nerve transfer to radial nerve and throcadorsal nerve.
- Option 3: Contralateral C7 transfer to upper trunk and inferior trunk; intercostal nerve transfer to suprascapular nerve, radial nerve and throcadorsal nerve; muscle transfer for function reconstruction.

15.6 Contralateral C7 Nerve Transfer

Brachial plexus avulsion injury (BPAI) is very difficult to treat despite advances in technology. Currently, the most successful method to restore affected limb function in patients with total BPAI is nerve transfer. However, the treatment results are not always satisfying, especially for the function of hand. Slow regeneration velocity of the recipient nerve, irreversible atrophy of the target muscle and a limited number of donor nerves are the three main causes for the unsatisfactory results. In this chapter, we will pay special attention on the problem of the limited donors. Modern management of BPAI involves all sorts of neurotizations with extraplexus and intraplexus, contralateral and ipsilateral nerve donors, including the spinal accessory nerve, phrenic nerve, intercostal nerves and contralateral C7 nerve (cC7). The spinal accessory nerve is usually used for direct neurotization of the suprascapular nerve and musculocutaneous nerve. The phrenic nerve is commonly used to transfer to the musculocutaneous nerve. Intercostal nerves are usually used for repair of the biceps branch, triceps branch, and axillary nerve. The number of donors is still extremely limited. Sometimes, a trauma is so serious that the commonly used donor nerves such as the phrenic, spinal accessory, and intercostal nerves are also involved. Under these conditions, contralateral C7 nerve graft is viewed to be one of the best therapies. Since Gu initiated the application of contralateral C7 nerve graft in 1986, its effectiveness has been admitted by many medical institutions around the world. The C7 nerve translocation from the healthy side is one of the most commonly used methods for the treatment of brachial plexus avulsion. The total axonal count for the C7 nerve is approximately 24,000 which are not all involved in the initial injury in most cases. This makes C7 one of the best donors for transfer. However, its surgical details differ between different surgeons. Some surgeons even modified this procedure. Some achieved satisfying results while some not. Here the authors give a brief review of the contralateral C7 nerve transfer.

15.6.1 Regular Surgical Techniques for Contralateral C7 Nerve Transfer

- Stage 1 (Fig. 15.16): The patient is in the supine position and the upper limb to be repaired is placed on the arm table. The sterile areas include bilateral upper and lower limbs, anterior and posterior chest up to the median line, and both sides of the neck are up to the mandible. The two teams undergo surgery simultaneously under a microscope with a magnification of 2.5 times. One team revealed the contralateral nerve plexus while another team probed and stripped the ulnar nerve which is pedicled by the superior ulnar collateral artery from the affected side. The C7 nerve of the normal side is spotted to show its divisions' level and cut. The vascularized ulnar nerve reaches the contralateral neck through the subcutaneous tunnel of the chest wall. The entire root or part of the nerve bundles of C7 are sutured to the ulnar nerve with a 8-0 suture under a microscope.
- Stage 2: The distal end of the transplanted ulnar nerve is cut and anastomosed with the ipsilateral receptor nerve to make it neuralization.

15.6.2 Blood Supply of the Grafted Nerve

For patients with total BPAI, the most commonly used graft for contralateral C7 nerve transfer is the pedicled ulnar nerve. Core necrosis often occurs in nerve grafts with a large diameter, leading to poor outcomes. Hence, in the initial procedure, the ulnar nerve is pedicled by the ulnar artery to guarantee the blood supply of the grafted nerve while sacrifice of the ulnar artery might impair the recovery of the target muscle in the affected limb. Experimental and anatomic researches by Gu et al. reported that only the superior ulnar collateral artery could provide enough blood supply for the grafted ulnar. Clinical study also reported no significant difference between the group using the ulnar artery and the group using the superior

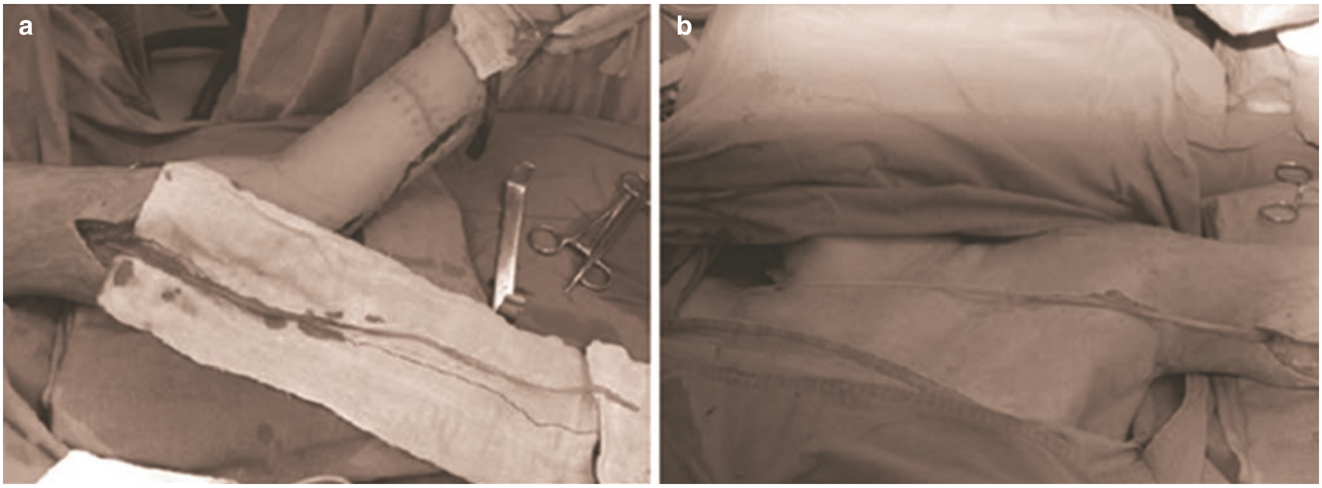


Fig. 15.16 The first stage of contralateral C7 nerve transfer. (**a**) The ulnar nerve of the upper limb of the affected side is cut at the level of the wrist and taken to its full length. (**b**) The distance from the ulnar nerve to the contralateral neck is measured

ulnar collateral artery as the pedicle. The superior ulnar collateral artery instead of the ulnar artery is used as the pedicle to modify the procedure.

15.6.3 Staging of Contralateral C7 Nerve Transfer

Staging of this procedure is one of the key factors that affect its results. In the study on SD rats, we have found that the two-staged contralateral C7 nerve grafting can improve better recovery rate of the muscular tension, more nascent nerve fibers of the recipient nerve, integrity of the structures of Schwann cells' body and medullary sheath and the Schwann cells similar to normal nerve axons in morphosis. So we emphasize that this procedure be divided to two stages. Waikakul et al. reported the result of one-staged contralateral C7 transfer in 96 cases. Only 29% of the median nerve achieved effective recovery. We speculate that losing the blood supply from the core ulnar artery is a possible reason why one-staged contralateral could not achieve satisfying results.

The interval between the two operative stages is another core component that determines the recovery of postoperative function. The early or late of the second stage of surgery will affect functional recovery. In a clinical study involving 51 total BPAI patients, those with a surgical interval of 4–8 months performed best in terms of sensory and motor function restoration. If the second stage of surgery begins prematurely, the anastomotic branches of the recipient nerve and the ulnar nerve will be oppressed by the scars. If the operation begins too late, the recipient's corpuscula tactus and innervating muscles will atrophy. Therefore, we believe that 4–8 months may be the optimal interval for the second surgery.

15.6.4 Should Entire or Partial Contralateral C7 Nerve Be Transected?

Immunohistochemistry examination shows that there are more motor fibers in the posterior division of the C7 nerve root than in the anterior division, and the medial part of the anterior division accounts for the largest proportion of sensory fibers compared with the other parts. As a result, more and more surgeons use part of the contralateral C7 nerve instead of the entire root as a donor nerve for transplantation, thereby allowing more sensory function of the contralateral limb to be preserved.

The clinical outcomes of the part of contralateral C7 nerve transfer, however, are not satisfactory. In a clinical study involving 51 total BPAI patients, 81.8% of those who had received entire C7 nerve transfer achieved effective recovery of both motor and sensory function of the median nerve while only 40% of those who had received partial C7 nerve transfer achieved effective motor function recovery and 57.5% effective sensory function recovery. Using the entire C7 root transfer can obtain significantly better recovery.

The number of partial contralateral C7 nerve fibers is not less than that of ulnar nerve fibers in the affected side, but it is still significantly less than the number of nerve fibers in the entire contralateral C7 root. Using the whole contralateral C7 for nerve transfer will offer more nerve fiber donors. Anatomical variations in C7 nerve roots may lead surgeons to make errors in choosing sensory and motor fascicles, thereby transferring more of the sensory beam as a donor. Based on these facts, we advocate using the entire root as a donor rather than a partial to graft.

15.6.5 Simultaneous Contralateral C7 Nerve Transfer to Multiple Recipient Nerves

The total axonal count for the C7 nerve is approximately 24,000. Thus, if the C7 nerve is intact, it is reasonable to use it as a donor for repair of more than one recipient nerve. Gu reported a successful contralateral C7 nerve transfer to more than one recipient nerve in 2004. In a clinical study involving 22 total BPAI patients, the recipients were the median nerve and biceps branch in 12 patients and the median nerve and triceps branch in the other 10. The recovery rate was 68.18% for the wrist and finger flexor, 45.45% for the median nerve area sensation, 66.67% for the elbow flexor, and 20% for the elbow extensor. The recovery of median nerve in biceps and triceps groups was equal whereas the recovery of biceps branch was significantly better than that of triceps branch ($P < 0.05$). It is concluded that simultaneous contralateral C7 nerve transfer to two recipient nerves is one option for the treatment of total BPAI, but the two recipient nerves should be collaborative in motor function.

15.6.6 The Route of Grafted Nerve in Contralateral C7 Nerve Transfer

In a regular procedure, the pedicled ulnar nerve was passed across the chest through a subcutaneous tunnel to the healthy side of the neck. The average length of the grafted ulnar nerve was 20 cm which takes a long time (6 months on average) for the nerve to regenerate from the healthy side to the affected side. To shorten the distance of nerve regeneration, some surgeons modified the route of grafted nerve. The pre-spinal route was reported through which the contralateral nerve could be neurotized into the recipient nerve with no grafted nerve. Xu et al. described the technique of C7 transfer through the pre-spinal and retropharyngeal route to repair the upper trunk. However, we do not recommend the pre-spinal route because the blood supply may not be guaranteed when the nerve crosses through the spine. Lacking of blood supply always leads to poor outcomes of nerve regeneration. So, subcutaneous and submuscle routes will be a relatively reliable choice.

In summary, the contralateral C7 transfer is an effective option in treatment of BPAI patients. Using this procedure properly can achieve satisfying outcomes.

15.7 Intraplexal Nerve Transfer

15.7.1 Ipsilateral C7 Transfer

Since ipsilateral C7 transfer was firstly introduced by Gu et al. in 1996, it has become a widely used surgical procedure for repair of brachial plexus avulsion injury, especially injury of only upper or lower trunk, when extraplexal donor nerves are insufficient.

C7 root, containing 40,000 nerve fibers, is the strongest donor nerve. The lateral portion from the anterior division of the C7 root is dominated by sensory fibers stretching into the median nerve, while the posterior portion from the posterior division is dominated by motor fibers stretching into the radial nerve. The anterior division innervating the forearm flexor muscle group is always used to repair median nerve, and the posterior one innervating the extensor muscle group is used to repair radial nerve.

Ipsilateral C7 root transfer is applied to restore upper trunk or lower trunk injury, especially when ipsilateral active donor nerve is insufficient. However, when physical examination reveals decreased muscle power of latissimus dorsi, indicating the upper and middle trunk has been injured, the ipsilateral C7 cannot be selected as donor nerve for reconstruction. Gu et al. applied ipsilateral C7 root transfer to repair upper trunk injury in four cases. After follow-up of 1–2.5 years, the power of bicep muscles reached M4 in all the cases. Shoulder abduction reached 90° and external rotation reached 30–40° in 2 cases. The treatment outcomes were much better compared with transfer of spinal accessory nerve to suprascapular nerve, except that the power of muscle innervated by C7 decreased by 1 level temporarily. Xu et al. used selectively the lateral portion of ipsilateral C7 containing more motor fibers to treat brachial plexus avulsion injury in eight cases. At 6 months postoperatively, 4 cases recovered elbow flexion significantly, with little functional loss. The ipsilateral C7 partially cut can provide sufficient motor donor innervation and may not lead to permanent damage to the upper extremity.

Using ipsilateral C7 root to repair upper or lower trunk injury results in little surgical trauma, a simple operation, and good outcomes. However, its strict indications limit its wide application.

15.7.2 Ulnar Nerve Transfer

In 1994, Oberlin et al. reported repair of C5-C6 avulsion of the brachial plexus in four cases using transfer of 10% of ulnar nerve to biceps muscle. After 2 years' follow-up, the biceps muscle power in all cases recovered from M3 to M4, and the donor sites did not show any sensory or motor disorder.

Sungpet et al. used the Oberlin's surgical method to restore biceps muscle's power in 36 patients with upper or upper and middle trunk injury. An average follow-up of 22 months revealed their biceps muscle power reached to more than M3 in 34 cases. The report showed that the treatment outcomes for only upper trunk injury were much better than those for upper and middle trunk injury. The patients' muscle power of grip, pinch and wrist flexion were not affected.

Using partial ulnar nerve transfer to reconstruct elbow flexion function has advantages of little surgical trauma, reliable treatment effect, shortened distance of nerve regeneration, leading to satisfactory functional recovery. The donor ulnar nerve should not be over 1/10.

15.7.3 Median Nerve Transfer

MacKinnon et al. modified the Oberlin's method by applying transfer of partial ulnar nerve to biceps muscle branch of musculocutaneous nerve and transfer of partial median nerve to brachial muscle branch to obtain maximal elbow flexion power. The median nerve in arm is approaching to the musculocutaneous nerve. Therefore, part of the median nerve can also be used to repair biceps muscle branch of musculocutaneous nerve to reconstruct elbow flexion. The surgical operation is suitable for patients with healthy lower trunk. Sungpet et al. reported five cases of C5-6 injury treated by this operation. After an average follow-up of 32 months, the biceps muscle power in 4 cases recovered to M4 and in one case to M3 while the patients' muscle power of grip, pinch and wrist flexion were not affected.

Transferring partial median nerve to biceps muscle branch of musculocutaneous nerve can effectively restore elbow flexion function. The operative procedure is simple and effective. The key point is to identify the position and range of the partial median nerve as donor nerve. Some researches demonstrate that since pronator teres muscle branch and flexor carpi radialis branch of median nerve are relatively unimportant, they can be sacrificed as donor nerves to achieve nerve transfer repair.

Recently, the procedure, transfer of partial median nerve to extensor muscle branch of radial nerve, has been introduced as an alternative method for patients with radial nerve injury. The donor nerves includes the branches of flexor carpi radialis muscle, flexor digitorum superficialis muscle and the palmaris longus muscle while the recipient nerves the branch of short radial carpal extensor muscle or posterior interosseous nerve. Moreover, the sensory branch of radial nerve can be end-to-side coated with the distal part of median nerve for sensory reconstruction.

When the ulnar nerve is injured but the median nerve is intact, the pronator quadratus muscle branch of median nerve can serve as donor nerve to be transferred to the deep branch of ulnar nerve. The operation can improve the motor function of the ulnar side, enhance the pinch strength, and prevent grasping hand deformity, but can hardly achieve complete recovery of hand function without other interventions.

15.7.4 Radial Nerve Transfer

The research into radial nerve transfer is always focused on transferring triceps muscle branch of radial nerve to repair upper trunk injury. The deltoid muscle's function can be recovered by transferring long head branch of triceps to axillary nerve through the posterior approach. The positions of the two nerves are close and their fiber counts are similar. In an effort to achieve better shoulder stability, the teres minor muscle branch of axillary nerve should be included in repair.

Transfer of the superficial branch of radial nerve can restore protective sensory function of the hand. The superficial branch of radial nerve can be transferred to the distal part of sensory branch of median nerve to treat incurable median nerve injury. Also, the superficial branch of radial nerve can be transferred to thumb or index finger's digital nerve to restore finger sensory.

15.8 Obstetric Brachial Plexus Palsy

15.8.1 Definition

Obstetric brachial plexus palsy (OBPP) is a condition caused by the injury to the brachial plexus nerve in the shoulder during birth process. Its incidences vary in different countries (0.6–4‰). About 5400 newborns suffer OBPP in America every year.

15.8.2 Cause

OBPP can result from neonatal factors, maternal factors, mode of delivery, labor factors, vacuum extraction, and forceps delivery.

OBPP is mainly caused by excessive side traction related to shoulder dystocia and forceful separation of the fetal head and body. Large babies in difficult deliveries are particularly prone to this injury. The brachial plexus can also be injured when the nerves are stretched by a blow to the shoulder or when bones around them are broken. Abnormal fetal position such as shoulder dystocia may make the front shoulder of fetus directly press on the pubic symphysis, leading to damage to the brachial plexus. As the pelvic adipose tissue in obese pregnant women is too thick, the narrow available space may lead to delay or disproportion of fetal head through the pelvis. Moreover, the slowing down cervical dilation and the stenosis of soft birth canal may increase birth resistance, resulting in a prolonged labor. The fat accumulation in perineum also impedes the delivery of a baby.

15.8.3 Classification

The classification of OBPP dated back to 1872 when Erb, Duchenne, Seeligrnuller and Klumpke reported upper, lower and total brachial plexus palsy in infants. They divided OBPP into three types: Erb type, Klumpke type and Seeligrnuller type, corresponding to the upper, lower and total brachial plexus palsy. Erb type is the most common, accounting for 62.1% of the total OBPP.

According to the extents of nerve injury, Narakas classified OBPP into four types. Type I: cervical 5 & 6 nerve roots injured, presenting as paralysis of shoulder abduction and external rotation muscles, and elbow flexion and forearm supination muscles. Type II: cervical 5, 6 & 7 nerve roots injured: in addition to muscle paralysis in type I, paralysis of the extensor carpi muscle and extensor muscle. Type III: cervical 5, 6, 7 & 8 nerve roots and thoracic 1 nerve root injured: complete paralysis of upper limb muscles without Horner syndrome. Type IV: cervical 5, 6, 7 & 8 nerve roots and thoracic 1 nerve root injured: complete paralysis of upper limb muscles with Horner syndrome.

According to the anatomy of the brachial plexus, Gilbert classified OBPP into 3 types: upper brachial plexus palsy (Erb): C5 & C6 injured, sometimes C7 damaged; middle brachial plexus palsy: C7 damaged with or without C8 and T1 injured; lower brachial plexus palsy (Klumpke): C8 & T1 injured; total brachial plexus palsy: C5–C8 damaged with or without T1 injury.

15.8.4 Diagnosis

Diagnosis of obstetric brachial plexus injury often relies on the history, clinical symptoms and examinations.

Excessive child birth weight, a history of forceps-aided labor, flaccid paralysis of an upper limb, color Doppler ultrasound and MRI examinations and nerve electrophysiology tests can help us determine the nerve damaged, the extent of damage and the prognosis. Color Doppler ultrasound can accurately identify the nerve tissue structure and show the location and shape of brachial plexus, providing accurate position information for clinical diagnosis. MRI can directly observe changes in brachial plexus outside the spinal canal and make a more accurate diagnosis, clearly showing whether the preganglionic nerve damage exists or not. EMG not only identifies nerve damage and location of the damage, but also observes dynamic recovery of the nerve.

15.8.5 Treatment

1. Nonoperative treatment
   (a) Rehabilitation exercise
   Passive activities on the limb joints to prevent contracture: hold the elbow, do shoulder passive external rotation and lift with shoulder adduction to reduce the medial rotation contracture of the shoulder; lift the limb and press down the inferior angle of the scapula to reduce contracture of the teres major and latissimus dorsi muscle; put the hand on the other shoulder and push the scapular spine margin toward the rib direction to alleviate shoulder external rotation contracture.
   (b) Electrical stimulation can promote nerve regeneration.
   (c) Hyperbaric oxygen is effective in the treatment of obstetric brachial plexus palsy.
2. Operation treatment
   (a) Operation indications
   Shoulder and elbow joints show no functional improvement after conservative treatment of obstetric brachial plexus palsy for 3 months. EMG shows presence of obvious denervation potentials and significant decrease in action potentials. Significant Horner 's syndrome appears and EMG suggests preganglionic injury (SEP disappears and SNAP saves).
   (b) Neurolysis
   If nerve continuity is intact in surgical exploration and EMG shows extractable SEP and presence of CMAP in nerve roots, neurolysis of the brachial plexus can be performed. The postoperative observation period is 3–6 months.
   (c) Brachial plexus reconstruction
   Brachial plexus reconstruction includes neuroma resection, nerve graft and nerve transfer. Traumatic neuroma ought to be resected no matter its conductivity exists or not. For brachial plexus avulsion, nerve transfer is a major way of reconstruction and forearm cutaneous nerve or sural nerve may be used as nerve grafts. C5 & 6 broken: C5-posterior division of superior trunk, C6-anterior division of superior trunk, accessory nerve–superascapular nerve; C5 & 6 broken and C7 avulsion: C5-posterior cord, C6-lateral cord, accessory nerve–superascapular nerve; C5-7 broken and C8T1 avulsion: C5-posterior cord, C6-lateral cord, C7-medial cord, accessory nerve–superascapular nerve. If only two nerve roots are available for suturing, the lateral and medial cords should be repaired before the accessory nerve is transferred to superascapular nerve, and intercostal nerves are used to repair radial nerve and thoracic dorsal nerve. If only one nerve root is available for repair, the medial nerve should be repaired first by

nerve graft. Next, the accessory nerve is transferred to superascapular nerve, and intercostal nerves are used to repair the lateral cord. If C5-T1 are all avulsed, the accessory nerve is transferred to the superascapular nerve, the intercostal nerves are used to repair lateral cord and the contralateral cervical 7 nerve root is used to repair the median nerve. Phrenic nerve transfer should be avoided as much as possible in child patients, especially infants less than 2 years old. It should not be used together with the intercostal nerve transfer, to prevent pulmonary function damage and recurrent pneumonia by diaphragmatic lift, or even respiratory failure.

(d) Functional reconstruction

Medial rotation contracture of the shoulder: The subscapularis muscle dissection, anterior shoulder joint lysis, and osteotomy should be performed for this condition.

Poor shoulder abduction and external rotation: Reconstruction of shoulder abduction and external rotation should be performed, in which latissimus dorsi and teres major muscle are shifted to the infraspinatus tendon or trapezius muscle is transferred to the infraspinatus tendon.

Forearm rotation deformity, radial head or elbow joint dislocation by secondary elbow flexion contracture: open reduction of the elbow joint.

Elbow flexion dysfunction: If the elbow flexion is completely lost, bi-pedicled latissimus dorsi muscle transfer is the first choice and transfer of the pectoralis major muscle is also feasible. If the elbow flexion exists preoperatively but the strength is weak (M2-M3), transfer of the pectoralis minor muscle or elevation of the starting point of flexor muscle in the forearm is feasible.

Forearm supination deformity: If triceps muscle function is good without the interosseous membrane contracture or dislocation of distal radioulnar joint, biceps muscle bypass is feasible. If the radial head is dislocated, pronation osteotomy of the radius can be performed, but the wrist drop is the absolute contraindication of the operation.

Ulnar deviation deformity of the wrist: Brace fixation, wrist joint fusion, tendon transfer (flexor or extensor carpi ulnaris—extensor carpi radialis longus or abductor pollicis longus) can be performed.

Wrist or finger extensor disorder: flexor carpi ulnaris–extensor carpi radialis muscle or flexor digitorum superficialis of index finger–extensor carpi radialis brevis, flexor digitorum superficialis of middle finger–extensor pollicis longus, flexor digitorum superficialis of ring and little fingers–extensor digitorum communis. Tendon fixation or wrist fusion in the functional position of the wrist is suitable for the children without proper dynamic muscle.

15.8.6 Prognosis

According to Narakas's classification, Type I has the best prognosis: 80% of the patients can recover completely. Type II has worse prognosis than Type I: 70% of cases restore elbow flexion and wrist extensor function. Type III has worse prognosis than Type II, but most of the cases are satisfied with restoration of hand function. Type IV has the worst prognosis because it does not have natural recovery.

15.8.7 Summary

Obstetric brachial plexus palsy in newborns is still a serious problem. Although most patients recover some function owing to the positive operative treatment, some children are left with varying degrees of dysfunction, especially those with total brachial plexus injury. Due to the limited number of donor nerves, functional recovery of intrinsic muscle is still poor. Therefore, prevention of obstetric brachial plexus palsy is significant.

15.9 Functional reconstruction of brachial plexus injury

15.9.1 General Principles for Motor Function Reconstruction

Wide application of microsurgical techniques has significantly improved the efficacy of peripheral nerve repair. But some patients with severe nerve damage do not have a chance to repair the nerve or restore nerve function, even partially, after the nerve surgery. They need surgery for tendon transposition, tendon fixation, arthrodesis, bone block technique and joint capsule plication and other operations to reconstruct limb function. Of these methods the most common one is tendon transposition.

One should comply with the following principles in tendon transfer surgery.

15.9.1.1 Operation Time

Tendon transposition time should be based on a comprehensive analysis of the causes of nerve injury, location, extent, postoperative observation time and age. In cases of high level injury, large damage range, massive defects without nerve repair after injury, tendon transposition shall be carried out as soon as possible. If the nerve injury is repairable, the functional restoration should be followed up regularly. Observation time should be based on the severity of injury, generally 6 months or more. In cases of late stage brachial plexus injury, the observation time should be 1.5–2 years from the original injury to the first nerve surgery. If the clinical and electrophysiological evidence has confirmed that there is no sign of nerve recovery, tendon transposition should be carried out as soon as possible. If the nerve recovery is going on, the observation time should be extended. Since infants and children are less cooperative in physical examination, their preoperative muscle strength level is inaccurate. Moreover, they cannot cooperate with postoperative functional training. As a result, the tendon surgery should be delayed until 4–5 years old.

15.9.1.2 Choice of Donate Tendons

Four aspects should be considered when a donor tendon is chosen:

1. Muscle strength

   Donor muscle should have sufficient strength. As postoperative muscle strength usually degrades 1°, you should select a MRC 5 muscle as a donor to get satisfactory results.
2. Range of motion (ROM)

   The range of motion of the donor tendon directly affects the operation outcome. According to the known data, the range of motion was 33 mm for carpal extensor and carpal flexor muscle, 70 mm for FDP, 64 mm for FDS, 50 mm for EDC, 52 mm for FPL, 58 mm for EPL, and 28 mm for EPB and APL. The range of motion of the donor muscle should match that of the receptor.
3. Tendon choice

   Donor and receptor should be the same kind of muscle. Without this condition, you should choose synergistic muscle. Selection of antagonistic muscles for transposition will result in long time functional training after surgery. Therefore, transfer of synergistic muscles should be a better choice.
4. Damage of donor function

   There should not be more harmness of the donor function after tendon transposition surgery.

15.9.1.3 Joint Activity

The ROM of the joint should be normal before tendon surgery. Stiffness, restriction or instability of the joint should be excluded. In cases of poor ROM, the joint activity should be corrected before the tendon transposition surgery. When the peripheral nerve is injured, muscle paralysis and strength loss may cause muscle strength imbalance which usually results in restriction deformity of the joint. Therefore splint support and passive exercise should be carried out to protect the ROM of the affected joint. If scar adhesion and constriction occur, a release surgery should be performed.

15.9.1.4 Tendon Transposition Tissue Bed

The transferred tendon must be within a healthy soft tissue bed, and has a good skin coverage. The tendon tunnel should be under the skin, and must be wide enough to facilitate sliding. If a transferred tendon is located within the scar tissue, postoperative adhesion may cause surgical failure. Tendon junction can not be placed inside the carpal tunnel to avoid adhesion.

15.9.1.5 Direction and Tension of the Transferred Tendon

The direction of transferred tendon should be straight to avoid angulation. This prevents occurrence of loss of strength. If angulation can not be avoided, a pulley should be used. Sufficient proximal dissociation of the donor muscle is necessary for a satisfactory tendon direction. But the nutritional nerve and blood vessels of the muscle should be precisely protected when the upper middle part of the muscle is dissociated. Otherwise tendon transfer will fail.

The tension of the transferred tendon should be appropriate, neither too tight nor too loose. If one donor tendon is transferred to several receptor tendons, the tendon tension to each receptor should be equal. The same tendon should not be divided into two halves in two completely different muscles. Tendon surgery performed under local anesthesia is in favor of the right to master the tension.

15.9.2 Motor Function Reconstruction of Median Nerve

15.9.2.1 Reconstruction of Forearm Pronation Function

Forearm pronation functional reconstruction generally uses the FCU or ECU as donor muscle, the tendon of which is transpositioned at the distal part of the radius with the forearm pronated. The outcome of using the FCU is better than that of using ECU due to the muscle anatomy. If the function of carpal flexors other than the FCU is not restored, a wrist arthrodesis surgery should be performed when the FCU is used as the donor muscle. In this situation wrist flexion function can be preserved by choosing the ECU as the donor although its outcome is not excellent.

15.9.2.2 Reconstruction of Thumb and Finger Flexion

The brachioradialis (BR) and ECRL are usually transferred to the FPL to restore the thumb flexion.

To restore the index and middle finger flexion, the FDP tendon of the index and middle fingers should be cut at a higher level and sutured to the ulnar part of the FDP. The tension of ulnar part of the FDP tendon should be tighter than that of the radial part. If necessary, the ECRL can be transferred to the FDP to enhance the flexion force.

15.9.2.3 Reconstruction of Thumb Palmar Opposition

Loss of function of the thumb palmar opposition has a great influence on the hand function. If the carpometacarpal joint has not only a fine passive activity but also ideal tendons for use, tendon transfer surgery should be performed to reconstruct the thumb palmar opposition. If there are no ideal conditions for tendons transfer (such as carpal metacarpal joint stiffness), you should make bone reconstruction surgery to restore the palmar opposition, such as making the first and second metacarpal bone bridge, so that the thumb is in place on the palmar opposition position.

FDS of the Ring Finger as Dynamic Muscle

The commonly used surgical procedure in clinical practice is as follows.

1. Make a 2 cm vertical incision in the ring finger proximal phalanx radial side. Cut the skin and subcutaneous tissue, and dissociate the flap to the palm side. Retract the flap and neurovascular bundle to the palm side to expose the flexor tendon sheath. Make a longitudinal incision of the tendon sheath, find out FDS tendon, and cut the tendon at a distance of about 0.5 cm to its ending point.
2. In the wrist flexor surface at the wrist flexor carpi stripes level make a "L" shaped incision, about 5 cm, cut the skin, subcutaneous tissue and deep fascia, find out ring finger FDS tendon, withdraw its distal ends from this incision, and then dissociate upward to muscle belly. Find out the FCU tendon in the carpal incision, cut distal radial side of the FCU tendon strips about 2.5 cm in length, do not cut off the distal end, and then suture the tendon strip reversely to form an artificial pulley.
3. Make a vertical incision, about 2 cm, on the dorsal ulnar side of the first metacarpophalangeal joint, revealing the bone surface of the proximal phalanx, and drill a hole in the ulnar to the radial side with a hand drill at the base of the proximal phalanx bone. Make a subcutaneous tunnel between the incisions of thumb and wrist. Make sure that the FDS tendon of the ring finger through the pulley, withdrawn from the thumb incision, suture ring finger and wrist incision.
4. Fix the thumb on the abduction and opposition position, suture the FDS tendon to the bone cave and then suture thumb incision.
5. Postoperatively use dorsal forearm plaster to immobilize the thumb in abduction and opposition positions. Four weeks later unplug the wire, and begin functional training.

Choice of ring finger FDS as dynamic muscle to reconstruct the thumb opposition function has these advantages: enough tendon length, good muscle strength, large slide range and easy proceeding.

Since transferred tendon direction is the key point, it should be consistent with the direction of the abductor pollicis brevis.

FCU, ECU and PL as Dynamic Muscle

The surgical procedure is as follows:

1. Make a dorsal forearm vertical incision, about 4–5 cm long, identify EPB tendon and cut it off at the muscle belly transitional portion.
2. In distal dorsal part of the first metacarpal make a vertical incision, about 3 cm long, and pull out the EPB tendon.
3. Make a volar forearm wrist crease level incision, about 3 cm long, through subcutaneous tunnel to the second incision, and pull the EPB tendon to the pisiform bone.
4. Make an ulnar volar forearm vertical incision, about 5–6 cm long, find the FCU tendon, cut it off at 2 cm to the attaching ending, fold and suture the distal ending to the pisiform bone to create a pulley. Suture the EPB to the FCU though the artificial pulley in thumb opposition position.

Postoperative plaster should be used in wrist flexion and thumb abduction position. Four weeks after the immobilization, functional exercises should begin.

Adductor Digiti Minimi as Dynamic Muscle for Thumb Opposition Reconstruction

Littler and Cooley reported the ADM transfer method (1963) explained in detail. Shanghai Ninth People's Hospital has applied this surgical treatment for various causes of thenar paralysis, achieving satisfactory results. Surgical steps are as follows:

1. Make an incision from little finger metacarpophalangeal joint to ulnar proximal phalanx base, upstream along the hypothenar ulnar edge, and turn the wrist crease to the wrist.
2. Cut the skin to reveal hypothenar muscles. Locate ADM muscle, dissociate the muscle from the ulnar side to avoid the nerve vascular bundle. Cut the attaching ending, dissociate the muscle proximally and cut the ulnar part attaching to the pisiform bone.
3. On the radial side of the thumb metacarpophalangeal joint to make a 3 cm longitudinal incision to expose the APB fascia. Between the two incisions made a subcutaneous tunnel. Flip the ADM, make it through the subcutaneous tunnel, suture it to the APB attaching point at thumb opposition position. Make sure to protect the neurovascular bundle of the ADM from twisting or pulling too tight.
4. Postoperative forearm plaster immobilization is necessary. Hold thumb abduction and opposition three weeks after the surgery, and then start functional training.

Advantages of this procedure are quick recovery, power lines fit, good shape and appropriate length.

FPB as Dynamic Muscle

Orticochea reported the use of deep head of the flexor pollicis brevis transfer to reconstruct the thumb opposition function. Dissociate the FPB proximal phalanx base, radial sesamoid, metacarpophalangeal joint capsule and EPL completely separated, pass the FPB tendon under through the EPL tendon from radial to ulna side, re-attach it to the proximal MPJ base of the thumb to cross-shaped and oblique attachment of the adductor pollicis. Advantages of this procedure are: using the previous multi-incisions, a small incision about 2 cm, the trauma, the effect of the thumb on the palm, and reliable function reconstruction.

15.9.3 Radial Nerve Function Reconstruction

Radial nerve paralysis presents disability of the wrist, finger and thumb extension. The purpose of reconstruction is to use the flexor side muscle as dynamic muscle to restore the hand extension function. In order to keep the wrist stable, at least one carpal flexor muscle and carpal extensor should be spared. The radial nerve injury high above the elbow joint plane will be required to transfer the pronator teres to the ECRL and ECRB to keep the wrist stability. For the interosseous dorsal branch (i.e. the deep branch of radial nerve) also known as low level radial nerve injury, as ECRL function was preserved, so there is no need for pronator teres transfer. Keep a flexor muscle of wrist and the long extensor carpi antagonism, the wrist can be stable on the function position.

There are plentiful procedures to choose which can all achieve satisfying results.

15.9.3.1 Method One

The pronator teres is transferred to the ECRL and ECRB to restore wrist extension function, and the FCU transferred to EDC, EDM and EDI to restore finger extension function. Transfer the FCR or the PL to the EPL, EPB and APL to restore thumb extension function. Surgical steps of the procedure are as follows.

1. Separate FCU tendon: In the wrist flexor carpi stripes make a 2 cm transverse skin incision to expose the FCU, cut off near its end point, and dissociate the proximal tendon. In the middle of the ulnar forearm flexor surface make a longitudinal skin incision about 5 cm in length to expose FCU so that its distal part can be stripped out in this incision.
2. Separate FCR tendon: In the wrist radial side stripes make a transverse skin incision to expose the FCR tendon and cut off near its attaching point, dissociate it proximally carefully.
3. By subcutaneous tunnel transfer the FCU or FCR in the middle dorsal forearm, proximal to the dorsal wrist ligament for a length of about 6–8 cm of the “S” shaped skin incision to expose the finger extensor tendon, intrinsic index finger extensor tendon, little finger extensor tendon inherently, EPL and APL tendon. Thus the subcutaneous tunnel is made towards the middle of the forearm flexor surface of the radial and ulnar incision, and the FCR and FCU are pulled by the radial and ulnar subcutaneous dorsal carpal tunnel incision.
4. Suture all incisions at forearm flexor side.
5. Pronator teres transfer: Make a longitudinal incision up-middle of the forearm radially to reveal the distal part of PT muscles. Cut it off together along with the periosteum at the attaching point. Expose the ECRL and ECRB tendon in the same incision, suture the PT tendon to ECRB and ECRL tendon at appropriate tension with weaving stitching. Suture the incision.
6. Finger and thumb extension reconstruction: Keep the wrist, thumb and fingers in dorsiflexion position. Make the transfer under proper tension. Suture the FCU to EDC EDI and EDM by weaving stitching and suture the FCR to the EPL EPB and APL by weaving stitching in the dorsal incision. Suture the dorsal wrist incision.

Postoperative long arm cast immobilization is conducted, keeping elbow flexion 90°, pronation, and the wrist, thumb and fingers at dorsiflexion position. Four weeks later functional training begins.

15.9.3.2 Method Two

Transfer the pronator teres to extensor carpi, and then split the extensor carpi tendon in half, and transfer the half to APL tendon to reach the wrist and carpometacarpal joint stability. PL is transferred to EPL, FCU to EDC, and FCR retained in situ.

15.9.3.3 Method Three

Transfer PT to ECRL and ECRB to restore wrist extension function. Transfer FCU to EDC, EDI and EDM, PL to APL and EPB, FCR to EPL to restore the digital extension function. FDS of the ring finger is cut off at the PL level, the distal ending of which is transferred to the FDS tendon of the middle finger. The proximal part is sutured to the PL tendon to restore wrist flexion function.

15.9.4 Ulnar Nerve Function Reconstruction

In cases of low level ulnar nerve paralysis, the adductor pollicis and the first dorsal interosseous muscle present weakness, and finger pinch clamp function is lost. Most of the finger intrinsic muscles (all interosseous muscles and three and four lumbricals) are paralysed. There may be uncoordinated finger flexion, decreased hand grip strength and hand deformity of the ring and small finger grip. Functional reconstruction of the intrinsic muscle, thumb adduction and index finger abduction should be considered. In the cases of higher ulnar nerve paralysis, the FCU and FDP of ring finger and little finger are also compromised, so the FDS of the ring finger is not suitable for dynamic muscle any more.

Intrinsic muscle function generally cannot fully restore the original function after ulnar nerve paralysis. However, if the surgery is done correctly and the appropriate surgical procedures are selected, functional reconstructive surgery can still get more significant improvement.

15.9.4.1 Correction of Deformity of Intrinsic Muscle and Claw Hand

Intrinsic muscles are rebuilt in following steps:

FDS of Middle and Ring Fingers as Dynamic Muscle

1. Make a 3 cm-long longitudinal incision in the middle and ring finger on both sides of the proximal phalanx respectively, expose the FDS tendon, and cut off at about 0.5 cm at its proximal point.
2. In the palm along the distal palm stripes make a skin incision about 4 cm long, expose the superficial flexor tendon, split each tendon in half, strip out the tendons in the incision.
3. Make incisions at the radial middle lateral side of the 2–5 fingers, and retract the flap to expose the side beam of extensor tendon.
4. Pass the FDS tendon of the middle and ring fingers respectively through the lumbrical canal from the radial side cut-out of each finger. Stitch the palm incision.
5. Keep the wrist in dorsiflexion position, metacarpophalangeal joint flexion of approximately 70° position, and interphalangeal joint fully extended position. Suture the tendons to the lateral bands of each finger extensor tendons respectively.
6. Postoperative plaster is applied to fix the position for 3–4 weeks before functional training begins.

ECRB as Dynamic Muscle

If the FDS is not available for any reason, the ECRB could be a choice. Meanwhile the PL or plantaris extensor brevis tendon should be used as graft tendon. Postoperative plaster is used for fixation at the same position for three weeks.

15.9.4.2 Functional Reconstruction of Thumb Adduction

Brachioradialis or ECRL as Dynamic Muscle

Cut the brachioradialis proximally and fully dissociate it to enhance the magnitude of the tendon stretching activities. A free tendon (Palmaris longus or plantaris muscle) is extracted using a wire, and attach it to adduction nodules of thumb, or the tendon is sutured to the end in the adductor muscle. Postoperative plaster is used for fixation in thumb adduction and wrist extension positions.

FDS of Ring Finger as Dynamic Muscle

Improved Royles-Thompson tendon procedure: In the ulnar side of the ring finger make the midline incision, dissociate and cut off FD tendon. It will be withdrawn from the palm. At dorsal radial side of the thumb, make a curved incision. A bunch of superficial flexor tendons though the subcutaneous tunnel are sewn to the distal end of the metacarpophalangeal joint of the EPL. The other part of the FDS tendon is sutured to the ulnar edge of attaching point of adductor pollicis. The thumb is placed in an adduction position, and the wrist in moderate flexion fixed with plaster. After 3 weeks the functional training begins.

15.9.4.3 Index Finger Abduction Reconstruction

Index finger abduction movement is essential for the daily life actions, such as writing, using chopsticks, playing the piano and other tasks that require outreach of the index finger. APL and EDI tendon can be used to reconstruct the function of the first dorsal interosseous muscle.

The reconstructive procedures to restore index finger abduction are as follows.

APL as Dynamic Muscle

1. In the carpal radial dorsal side make a small transverse incision on the radial styloid plane to find APL tendon. Determine the attachment point at the base of the first metacarpal and the trapezium bone by pulling. Reserve the first metacarpal base to attach tendon bundle, and cut against the trapezium bone ends (or other parts) of attachment. It is used as the driving force tendon.
2. In the index finger metacarpophalangeal joints make a semicircular radial dorsal incision to expose the dorsal muscle attachment points between the first bones. Use a hemostat between the two incisions to make a subcutaneous tunnel.
3. Cut the PL tendon and suture it to the trapezium bone attachment of APL though the subcutaneous tunnel. Keep the index finger and wrist in a neutral position. Keep appropriate tension on the suture between the points of the first dorsal interosseous muscle attachment. Cast immobilization is applied for 3–4 weeks before functional training.

EDI (Extensor Digiti Index Inherent) as Dynamic Muscle

On the index finger radial side of the proximal phalanx, make a curved incision, extending proximally through the radial side of the metacarpophalangeal joint to the second dorsal metacarpal 1/3. In order to increase the length of the index finger extensor inherent, dissociate to proximal metacarpophalangeal joint extensor expansion portion, separate dorsal fascia, and cut the ending point of the index finger extensor inherent. Suture the area of extensor expansion defect. The index finger extensor inherent is transferred to the distal joints between the attaching points of the first dorsal interosseous muscle.

15.9.4.4 Ulnar Flexor Wrist and Ring Finger, Little Finger Flexion Function

The ring and little fingers' FDP tendon could be sutured to the FDP tendon of the middle finger to restore the DIPJ flexion function of ring finger and little finger. For the patients who need stronger wrist flexion strength, we could transfer the FCR to the attaching point of the FCU.

15.9.5 Multiple Nerves Paralysis

Multiple nerves paralysis may cause severe function loss which often accompanied with blood supply loss, fibrosis, anthrax instability, and muscle ingredient. Such injuries complicate the design of reconstruction. Reconstructive surgery program should be determined according to each patient's condition, if the design is reasonable, partial limb function can be reserved after the reconstructive surgery.

15.9.5.1 Functional Reconstruction of Median Nerve Combined with Ulnar Nerve Paralysis

The median nerve and ulnar nerve injuries can seriously affect hand function, no matter in the upper arm, forearm or wrist.

High level injury of median and ulnar nerves can cause paralysis of all volar forearm muscles and intrinsic muscles. When the whole hand sensation is almost totally lost, it is impossible to restore its full function. We can transfer the ECRL to FPL, FCU to FDP, and ECRB to the interosseous muscles by four graft tendons to restore the hand function after a wrist arthrodesis procedure.

Functional reconstruction of low level paralysis of the median nerve and ulnar nerve should be based on the patient's condition, especially when his or her wrist flexion, finger flexion and thumb flexion functions are spared. Usually we just need to repair the FDP tendon to avoid tendon adhesion. The key point in reconstruction procedure of low level median and ulnar nerve paralysis is the interosseus muscle and thumb opposition function.

15.9.5.2 Functional Reconstruction of High Level Ulnar Nerve Injury Combined with Radial Nerve Paralysis

As the median nerve function is preserved, we can restore the hand functions using these methods:

1. Transfer pronator teres to ECRB to reconstruct the wrist extension function.
2. Transfer middle (or ring) finger FDS tendon to APB and little and ring finger intrinsic muscle to reconstruct the thumb adduction and intrinsic muscle function.
3. Transfer the FDS tendon of index and ring finger to EDC and EPL to restore finger and thumb extension.
4. Ring and little finger flexion reconstruction: Suture the FDP tendon of little and ring fingers to the FDP tendon of middle finger.

15.9.5.3 Functional Reconstruction of High Level Median Radial Nerve Paralysis

After such injury the hand function is only slightly better than the prosthesis. All of the wrist muscles are paralyzed except for the FCU, which is the indication of wrist arthrodesis. Tightly suturing the FDP of index and middle finger to the FDP tendon of ring and little finger to restore the finger flexion. Transfer the FCU dorsally to reconstruct the thumb extension and finger extension function. Transfer the abductor digiti minimi or the APB to restore the thumb opposition function. Meanwhile a fused first metacarpal joint or a fixed FPL tendon is a good choice of accessory surgery for a better thumb function.

15.9.5.4 Functional Reconstruction of Brachial Plexus Paralysis

Basic Principles and Methods

1. Surgery must be carefully planned. Consider the patient's age, sex, occupation, health status and requirements for surgical treatment of limb function. Overall "losses" and "gains" of the surgery should be evaluated.
2. When a limb has got multiple dysfunctions, it needs multi-functional reconstruction. Certain functions must be rebuilt in a correct order. Priority orders are as follows: (1) control of the elbow, (2) wrist and finger flexion and median nerve area sensation, (3) control of shoulder, (4) wrist extension, (5) intrinsic muscle and ulnar nerve area sensation.
3. Dynamic muscle must have a MRC 4 or better strength.
4. Three basic points should be followed in the surgical operation: (1) Dynamic tendon must have sufficient strength. (2) Shift the direction of the tendon according to the principles of mechanics. If necessary, change the direction using a pulley. (3) Attaching points must be securely fixed.

Reconstruction of specific functions of each part refers to the above related contents in this section.

Microsurgical Reconstructive Surgery for Irreversible Brachial Plexus Paralysis

History of Reconstruction Surgery

Before 1960s, brachial plexus root avulsion was considered as an incurable irreversible injury without any surgical indication. The development of microsurgery, especially after the 1970s, made it possible to find a treatment for this type of injury with emerging nerve transpositions. Recovery of limb function became hopeful. However, in patients with long duration (over 2 years) of brachial plexus injury, regardless of the pre or post ganglion injury as a result of long-term denervation, muscle atrophy is significant. For them, limb function reconstruction by nerve surgery was impossible and their brachial plexus injury was regarded irreversible. Since 1980s, new microsurgical techniques have provided new possibilities to restore function for these patients.

Indications for Surgical Reconstruction

1. Those with brachial plexus injury for more than 2 years but without any functional recovery after injury.
2. Those with an injury course of less than 2 years and obviously defected muscle atrophy or muscle belly.
3. Those without any functional recovery after follow-up of more than 3 years in spite of various treatments (including surgery, multiple sets of nerve transfer).
4. Those whose vascular condition above the elbow is available to accept the transplanted tissue.
5. Those whose ipsilateral nerves are available as donors, such as phrenic nerve, cervical plexus motor branch, intercostal nerve, etc. If these nerves are damaged or have been inactive for transfer, the contralateral C7 nerve can be used.

Surgical Methods

According to Gu's experience, the following methods can be used for reconstruction.

Elbow Flexion Reconstruction

Microsurgical techniques with neurovascular pedicle free tensor fascia lata, latissimusdorsi or pectoralis major muscle flap to reconstruct elbow flexion.

Flexion Function Reconstruction

It is very difficult to reconstruct flexor function for irreversible paralysis of the brachial plexus. The key is transfer of the donor nerve to the elbow joint level. For this purpose, the flexion reconstruction should be performed in three steps as follows.

- Step 1: The first phase of the operation is to gain donor nerve at the elbow level. The method is to transfer the ipsilateral forearm medial cutaneous nerve, the phrenic nerve, the cervical plexus motor branch, intercostal nerve or free nerve to the beginning part of the forearm medial cutaneous nerve, usually required for nerve graft. If these ipsilateral donor nerves are not available for use, the contralateral C7 nerve is a good choice.
- Step 2: The second phase of the operation is to transplant the free limb forearm muscle to restore limb flexor function. The method is to choose the contralateral latissimusdorsi flap or pectoralis major muscle flap graft in the forearm.
- Step 3: Finally fix the thumb in opposition position. The EDC of 2–5 fingers and transfer of lateral bundle of 2–5 fingers to restore the finger flexion after the free muscle flap transplantation of the forearm.

Bibliography

1. Gu YD, Cai PQ, Xu F, et al. Clinical application of ipsilateral C7 nerve root transfer for treatment of C5 and C6 avulsion of brachial plexus. Microsurgery. 2003;23(2):105–8.
2. Xu JG, Hu SN, Wang H, et al. The clinical application of selective ipsilateral C7 transfer. Chin J Hand Surg. 1999;15(3):151–3.
3. Sungpet A, Suphachatwong C, Kawinwonggowit V, et al. Transfer of a single fascicle from the ulnar nerve to the biceps muscle after avulsions of upper roots of the brachial plexus. J Hand Surg Br Eur. 2000;25(4):325–8.
4. Sungpet A, Suphachatwong C, Kawinwonggowit V. One-fascicle median nerve transfer to biceps muscle in C5 and C6 root avulsions of brachial plexus injury. Microsurgery. 2003;23(1):10–3.
5. Orticochea M. Use of the deep bundle of the flexor pollicis brevis to restore opposition in thumb. Plastic Reconstr Surg. 1971;47(3):220.
6. Dong Z, Zhang CG, Gu YD. Surgical outcome of phrenic nerve transfer to the anterior division of the upper trunk in treating brachial plexus avulsion. J Neurosurg. 2010;112(2):383–5.
7. Zheng MX, Xu WD, Qiu YQ, Xu JG, Gu YD. Phrenic nerve transfer for elbow flexion and intercostal nerve transfer for elbow extension. J Hand Surg Am. 2010;35(8):1304–9.
8. Xu L, Gu Y, Xu J, Lin S, Chen L, Lu J. Contralateral C7 transfer via the prespinal and retropharyngeal route to repair brachial plexus root avulsion: a preliminary report. Neurosurgery. 2008;63(3):553–8; discussion 558–9.
9. Song J, Chen L, Gu Y. Effect of ipsilateral C7 nerve root transfer on restoration of rat upper trunk muscle and nerve function after brachial plexus root avulsion. Orthopedics. 2010;33(12):886.

10. Kaiming G, Jie L, Xin Z, Yudong G. Outcome of partial contralateral C7 nerve transfer—results of 46 patients. Neurosurgery. 2011;69(5):1153.
11. Chen L, Gu YD, Hu SN, Xu JG, Xu L, Fu Y. Contralateral C7 transfer for the treatment of brachial plexus root avulsions in children—a report of 12 cases. J Hand Surg Am. 2007; 32(1):96–103.
12. Xu W, Lu J, Xu J, Gu Y. Full-length ulnar nerve harvest by means of endoscopy for contralateral C7 nerve root transfer in the treatment of brachial plexus injuries. Plast Reconstr Surg. 2006;118(3):689–93; discussion 694–5.
13. Xu WD, Lu JZ, Qiu YQ, Jiang S, Xu L, Xu JG, Gu YD. Hand prehension recovery after brachial plexus avulsion injury by performing a full-length phrenic nerve transfer via endoscopic thoracic surgery. J Neurosurg. 2008;108(6):1215–9.
14. Yang J, Chen L, Gu Y, Chen D, Wang T. Selective neurotization of the radial nerve in the axilla using a full-length phrenic nerve to treat complete brachial plexus palsy: an anatomic study and case report. Neurosurgery. 2011;68(6):1648–53.
15. Hu SN, Zhou WJ, Wang H, Chen L, Zhu Y, Gu YD, Xu JG. Origination of the brachialis branch of the musculocutaneous nerve: an electrophysiological study. Neurosurgery. 2008;62(4):908–11; discussion 911–2.
16. Dong Z, Gu YD, Zhang CG, Zhang L. Clinical use of supinator motor branch transfer to the posterior interosseous nerve in C7-T1 brachial plexus palsies. J Neurosurg. 2010;113(1):113–7.
17. Feng J, Wang T, Gu Y, Chen L, Zhang G, Zhu Y. Contralateral C7 transfer to lower trunk via a subcutaneous tunnel across the anterior surface of chest and neck for total root avulsion of the brachial plexus: a preliminary report. Neurosurgery. 2010;66(Suppl Operative 6):252–63; discussion 263.
18. Oberlin C, Beal D, Leechavengvongs S, et al. Nerve transfer to biceps muscle using a part of ulnar nerve for C5-C6 avulsion of the brachial plexus: anatomical study and report of four cases. J Hand Surg Am. 1994;19(2):232–7.
19. Zhu W, et al. Anatomic study on reconstruction of thumb abduction with flexor pollicis brevis as dynamic tendon. J Chin Orthop. 1995;15(9):594.
20. Gu YD. Diagnose and treatment of brachial plexus injury. Shanghai: Press of SHMU; 1992. p. 69–74.
21. Zhu XC, et al. Outcome of abductor digiti minimi transfer of reconstruction of thumb opposition a 32 cases serial study. J PLA Med. 1989;14(3):213.
22. Omer GE. Tendon transfers for combined traumatic nerve palsies of the forearm and hand. J Hand Surg. 1992;17B(6):603.
23. Wolfe SW. Green's operative hand surgery. 6th ed. Amsterdam: Elsevier; 2012. p. 997–1054.
24. Waikakul S, Orapin S, Vanadurongwan V. Clinical results of contralateral C7 root neurotization to the median nerve in brachial plexus injuries with total root avulsions. J Hand Surg Br. 1999;24(5):556–60.
25. Gu Y. Functional motor innervation of brachial plexus roots. An intraoperative electrophysiological study. Chin Med J (Engl). 1996;109(10):749–51.
26. Littler JW, Cooley SG. Opposition of the thumb and its restoration by abductor digiti quinti transfer. J Bone Joint Surg Am. 1963;45:1389–96.

16 Microsurgical Repair of Peripheral Nerve Injury

Rui Cong and Liu Yang

16.1 Overview

Since 1970s, rapid development of microsurgical techniques has drawn the attention of surgeons. In 1963, Chen Zhongwei, a Chinese surgeon, successfully accomplished the first replantation of a severed limb in the world. This milestone event in medical history inspired surgeons all over the world to spare no efforts to optimize microsurgical techniques which also revolutionized peripheral nerve surgery.

In recent years, more and more clinicians repair and treat peripheral nerve injury in clinics using microsurgical techniques. Remarkable accomplishments have been made in researches on evaluation of peripheral nerve injury, nerve regeneration and microsurgical suture techniques. Historically, surgical repair of peripheral nerve injury happened six centuries earlier than surgical repair of vascular damage. The progress of surgical repair of peripheral nerve injury, however, has lagged behind. This may be because repair of peripheral nerve is not a decisive factor for limb survival and its outcome will take a long time to be recognized. In recent two decades, the efficacy of surgical repair of peripheral nerve injury has been boosted by more than 80% as a result of application of microsurgical techniques and new techniques for detecting motor nerve tracts and sensory nerve bundles. Meanwhile, great progresses have been made in the basic researches concerning peripheral nerve microsurgery in microsurgical anatomy of the brachial plexus, microscopic nerve implants, microsurgical intraneural release, peripheral nerve microscopic blood circulation, assessment of peripheral nerve microsurgical repair and sensory nerve recovery.

R. Cong (✉) · L. Yang
Department of Orthopaedics, Xijing Hospital, Air Force Medical University, Xi'an, People's Republic of China
e-mail: congrui@fmmu.edu.cn; yangliu@fmmu.edu.cn

16.2 Electrophysiological Diagnosis of Peripheral Nerve Injury

Electrophysiology plays an important role in the diagnosis and treatment of peripheral nerve injury, for it helps confirming a diagnosis, evaluating recovery of nerve injury and staging peripheral nerve entrapment syndrome. Despite of the advantages, electrophysiological diagnosis has its drawbacks and limitations. If used inappropriately or blindly or without other clinical evaluations, the electrophysiological results may be misleading. Therefore, electrophysiological diagnosis should be used with caution in peripheral nerve surgery.

16.2.1 Methods of Electrophysiological Diagnosis

16.2.1.1 Electromyography

Electromyography (EMG) can examine the nerve and muscle disorders by extracting the weak electrical activities in muscles through the electrodes and then magnifying and displaying them on an oscilloscope or EMG recording paper, thus helping diagnosis of peripheral nerve injury.

Normal EMG

1. Electrical silence: The electrical silence refers to a case when a needle electrode is inserted into a completely relaxed muscle and no electrical activity occurs.
2. Motor unit potential: The motor unit potential refers to the myoelectric potential comprehensively produced when the muscle fiber containing the motor unit contracts (Fig. 16.1). Time limit is 5–12 ms, the voltage is 100–500 mV, and the wave types include single phase, two-phase, three-phase and multi-phase (≤12%).
3. Wave types for muscle contraction: A muscle has hundreds or thousands of motor units and various waves can be produced due to quantity of motor units participating into the contraction (Fig. 16.2):

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_16

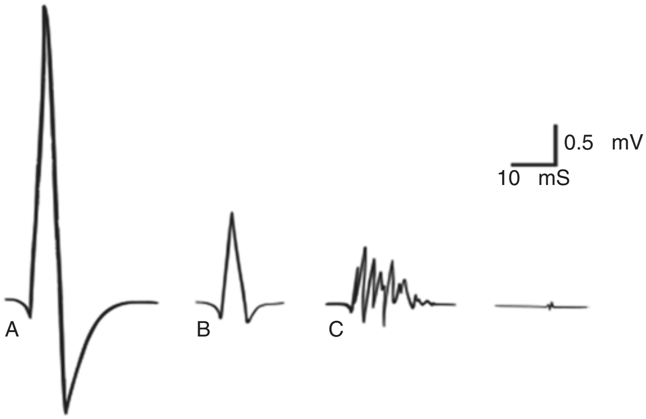


Fig. 16.1 Waveform and amplitude of wave for motor unit potential (MUP) during electromyography (B is the normal MUP)

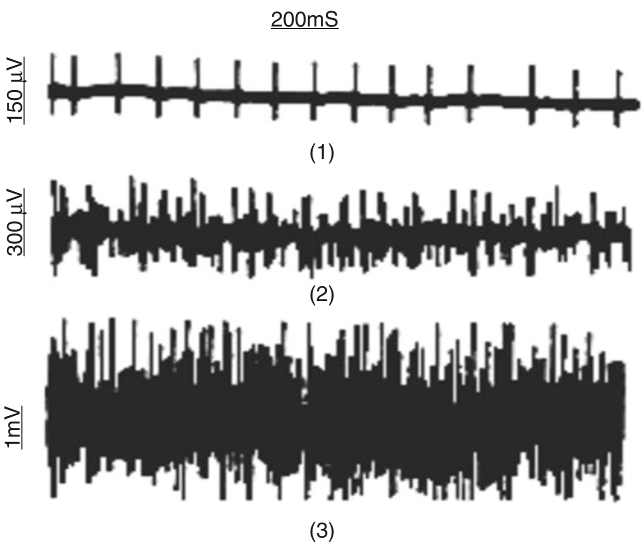


Fig. 16.2 Various muscle waveforms under contractions of different strength. (1) Single phase, (2) mixed phase, (3) interference phase

(a) For mild contraction: Only one or a few motor unit potentials are involved that are separated from each other, which is called simple phase.
(b) For moderate contraction: The potentials of motor units are partially overlapped, which is called mixed phase.
(c) For strong contraction: The potentials of motor units are completely overlapped and interfered with each other, which is called interference phase.

EMG for Denervated Muscle (Fig. 16.3)
After denervation for 2–3 weeks, the fibrillation and positive phase potentials can be seen as the characteristic changes in EMG, and are gradually enhanced after 3–4 weeks and then gradually weakened. The above-mentioned potentials will disappear after complete muscle fibrosis. The reduction in the number of functional motor units or whole destruction of motor units in denervated muscle results in reduction or disappearance of motor unit potentials. For strong contraction, the mixed phase or single phase can be seen, or even no potential of motor unit appears. For partial denervated muscles, multiple phases can be seen.

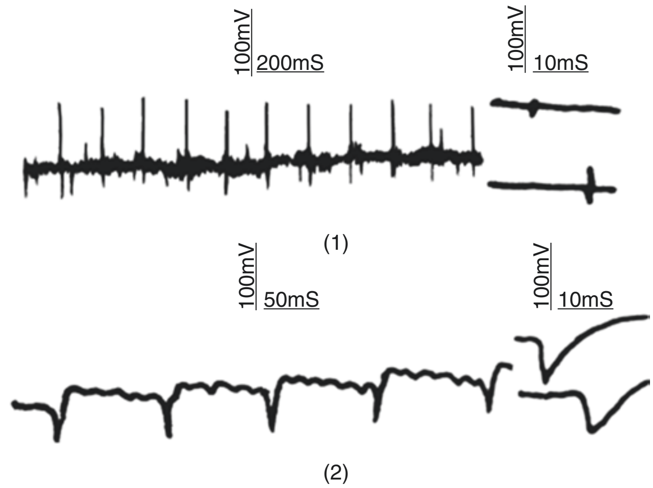


Fig. 16.3 Electromyography for muscles loss of nerves' domination. (1) Fibrillation potential refers to spontaneous potential with short time limit (0.5–4 ms) and low voltage (50–500 µV), and the waveform is simple phase or double-phase, mostly seen when the muscle loses nerves' domination, which is also called as denervation wave. (2) Positive potential is a kind of spontaneous potential with wide positive phase and low negative phase, looking like "V" shape or zigzag, which is frequently seen when electrodes are inserted

EMG of Nerve Regeneration (Fig. 16.4)
In the early nerve regeneration, axons grow into a few muscle fibers while the nerves are not mature yet and the excitabilities are various. The short-time multiple phases produced with low voltage are called fresh potential. Thereafter, with the gradual progress of nerve regeneration multiple-phase potential emerges and the voltage increases significantly. Then the phase is also more complicated and is called complex potential. With nerve collateral formation during nerve regeneration, the dominant muscle fibers increase and the range covered by formed motor units enlarges, resulting in huge potentials, which is also called regenerative potential.

Therefore, EMG has a diagnostic value for peripheral nerve injury. For nerves with loss of conductive function, there is no fibrillation potential or positive phase potential on EMG, and no motor unit potential through contraction either. There are fibrillation potential and positive phase potentials for partial denervation while motor unit potential, fresh potential, complex potential and regeneration potential occur through muscle contraction. There is no motor unit potential except fibrillation potential and positive phase potential for complete denervation. No motor unit potential on EMG after several months usually indicates complete rupture of nerves.

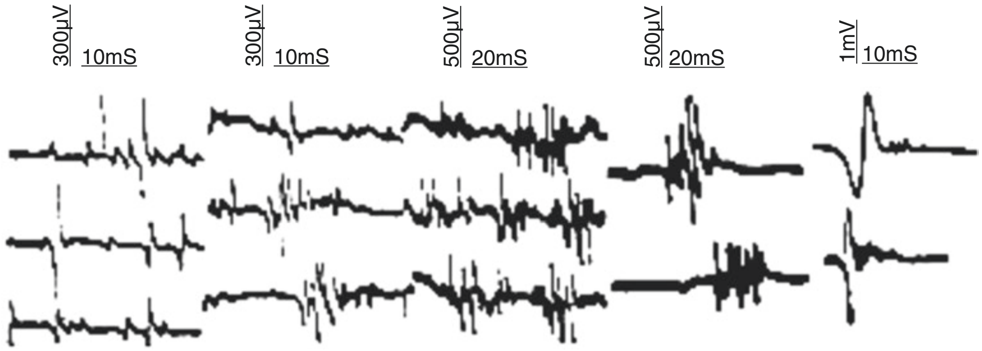


Fig. 16.4 Potential during nerve regeneration. (1) Fresh potential, (2) complex potential, (3) regeneration potential

Furthermore, for injury of nerve root, plexus or cord, location of an injured nerve can be confirmed based on the distribution of abnormal myoelectric potentials. For example, abnormal myoelectric potential that occurs in sacrospinous muscles after brachial plexus injury indicates that the injury is located in the intervertebral foramen while no abnormal myoelectric potential in these muscles suggests that the injury is located outside the intervertebral foramen. Thus this helps clinical treatment. When nerve regeneration occurs, emergence of fresh potentials on the EMG is much earlier than clinical signs of sensory and motor recovery; the fresh potential that appears but retains at a certain stage indicates frustration of regeneration.

16.2.1.2 Measurement of Nerve Conduction Velocity

Nerve conduction velocity measurement is a method combining electrical diagnosis and EMG, and also a diagnostic technique calculating propagation velocity of excitability along nerve by irritating muscles with electricity and recording muscle potentials (measuring motor nerve conduction velocity) and nerve potentials (measuring sensory nerve conduction velocity).

Motor Nerve Conduction Velocity

Determination of motor nerve conduction velocity can evaluate the function of the low motor neurons. During measurement, the distal point and proximal point of a nerve trunk are stimulated respectively by pulse current (Fig. 16.5). The stimulus intensity is gradually increased until a super-strong stimulus simultaneously depolarizes all nerve fibers within the nerve trunk. As a result, the action potential produced directly conducts along the nerve trunk to motor end plate leading to muscle contraction. For the muscles dominated at the distal point, the induced action potential recorded by EMG is called as compound action potential of muscle (or M wave). The incubation period at the proximal point is measured as T1, the incubation period at the distal point is measured as T2, and the distance between the two points on body surface is measured as S, which are inserted into the formula: motor nerve conduction velocity V (m/s) = S (mm)/(T1 − T2) (ms).

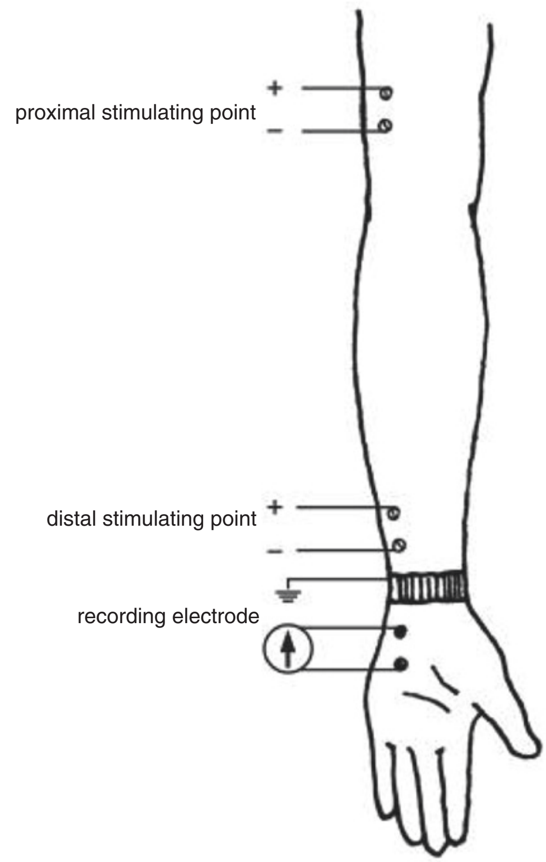


Fig. 16.5 Schematic diagram for determination of conduction velocity of nervus motorius of ulnar nerve

Sensory Nerve Conduction Velocity

Determination of sensory nerve conduction velocity can evaluate the function of sensory nerve, even the function of dorsal root ganglia. During measurement, the sensory nerve on the end of a finger (toe) can be simulated by a ring electrode, and then the surface electrode/pin electrode are placed correspondingly in the nerve trunk to record sensory nerve action potential (SNAP). The same method is used to calculate the incubation period and conduction velocity (Fig. 16.6).

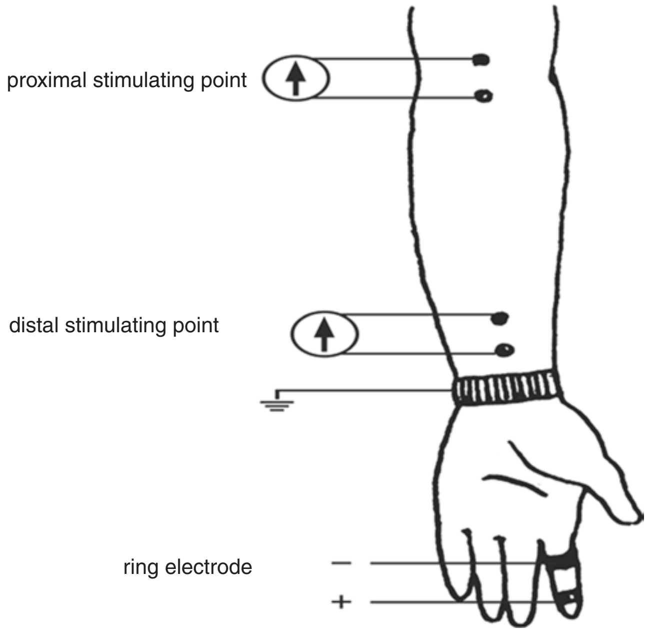


Fig. 16.6 Schematic diagram for determination of conduction velocity of sensory nerve of median nerve

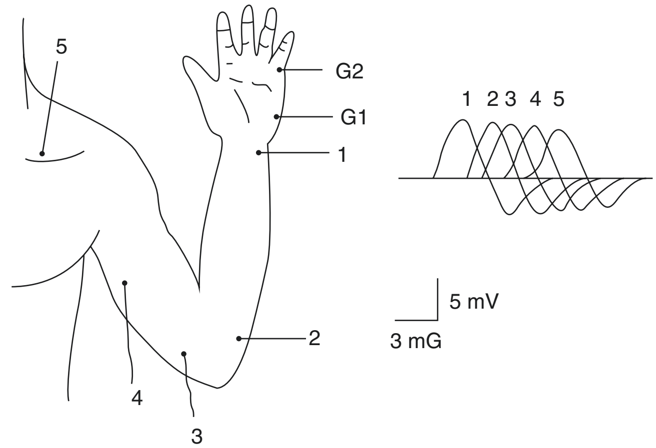


Fig. 16.7 Stimulate the motor components of ulnar nerve along various points of ulnar nerve trunk, and record the M wave at hypothenar muscle. The amplitude of M wave reduces slightly following the stimulating points forwarding to proximal limb with similarly same area. (1) wrist, (2) below elbow, (3) above elbow, (4) below fossa axillaris, (5) above clavicle, (G1) recording electrode, (G2) reference electrode

Usually, nerve conduction velocity changes after nerve injury. It is partially considered that the conduction velocity will slow down if a nerve is partially injured, and a nerve will completely lose its conductivity in case of transverse injury. The site of lesion can be determined by the slowed down conduction at a lesion segment but the normal velocity at the segment above the lesion one. Further, changes in conduction velocity can still reflect nerve regeneration and recovery. However, recent studies and clinical examinations also find that the results for nerve conduction velocity can be sometimes contradictory to the actual state of an illness.

16.2.1.3 Direct Electrical Nerve Stimulation

Penetrate the skin using two electrodes to directly simulate some superficial nerves and observe whether the muscle contracts or not. In determining abnormal neurological domination, it can supplement EMG. For the patients with hand median nerve injury and still partial function of greater thenar muscles, simulating the ulnar nerve can induce the muscle contraction of partial thenar, indicating abnormal nerve domination. Direct nerve stimulation is helpful in peripheral nerve surgical procedure for identification of false neuroma, and functional properties of nerve branches and nerve tracts.

16.2.1.4 Amplitude and Area of Compound Action Potential (Amplitude Integral)

Traditional electrophysiology diagnosis focuses on nerve conduction velocity and incubation period of distal point but overlooks compound muscle action potential such as M wave and SNAP, etc. Application of computer technology can quickly analyze a number of parameters of M wave: Area (amplitude integral), amplitude, time limit, and waveform. Of them the area and amplitude are of most importance. They represent the sum of all the depolarization of the muscle fibers, and are also indexes for the number of nerve fibers excited. If the number of muscle fibers or excitation conducted axons reduces, the amplitude and area of M wave also decreases. Therefore, detection of amplitude and area of M wave is vital in the evaluation of functional recovery and prognosis after nerve injury (Daube 1980). The shape, size and amplitude of M waves are substantially identical on each motor nerve stimulation point (Fig. 16.7). A change to M wave area suggests that neural cord cannot conduct action potential resulting in conduction block. A change in M waveform indicates that the uniform conduction along the axon slows down, resulting in partial demyelination rather than conduction block.

16.2.1.5 Delayed Reaction

F Wave

Traditional motor nerve conduction velocity can accurately provide information for distal nerve stimulation points, but not information for nerve proximal segments. The F wave can provide this information to a certain extent because it evaluates the full length from the motor nerve to the spinal cord anterior horn cells. When the simulation applied on distal motor nerve exceeds the maximum the nerve can tolerate, all axons are depolarized and the anterograde conduction of nerve action potential can produce a standard M wave. Meanwhile, the action potential is also retrogradely conducted from the nerve root to the anterior horn cells, and the

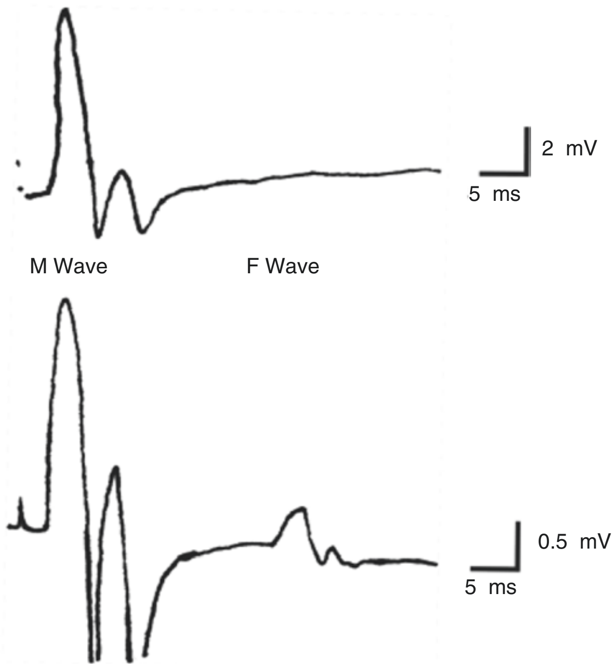


Fig. 16.8 The M wave and F wave recorded at thenar muscles when simulating median nerve at wrist. The top figure means standard waveform, and the bottom figure means magnified waveform

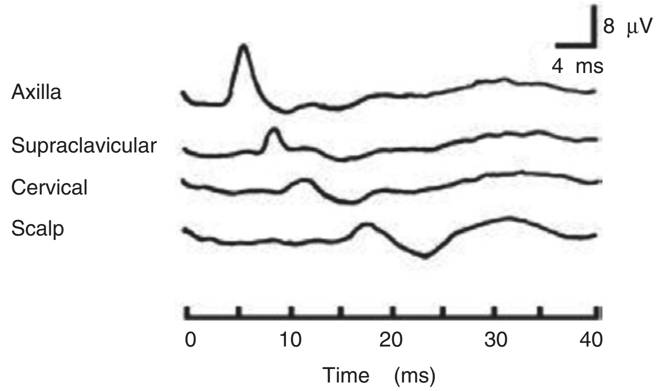


Fig. 16.9 Upon stimulating median nerve of wrist, the wave of somatosensory evoked potentials (SEPs) is recorded on axilla, above claviculate and scalp above contralateral sensory cortex. The reference electrode is placed on scalp of forehead and the stimulating record is overlaid for 500 times. Time (ms)

exciting of anterior horn cells results in an anterograde conduction of action potential returning to muscles. Thus a small F wave can be recorded following M wave (Fig. 16.8) with waveforms and incubation periods. In order to determine slow proximal conduction along the nerve trunk, the measured F-wave should be compared with estimated F wave (the measured distal nerve conduction velocity shall be uniform with estimated conduction velocity of the whole nerve trunk). The incubation period of F-wave can be used to evaluate conduction of entire nervous length, the number of excited axons, and conduction block or proliferation, etc.

H Reflection

The incubation period of F wave can be used to estimate proximal nerve conduction rather than evaluate the reflex arc of proximal sensory segment or within spinal cord. Stimulating sensory nerves and activating afferents fibers of muscle spindle to produce SNAP also results in conduction from proximal to synapses of anterior horn cells and reentry to convert into action potential conducting to muscle leading to muscle depolarization. This is called H reflex. By motor threshold stimulation, the H reflected wave is larger than M wave, but with the increase in the intensity of stimulation, M-wave amplitude tends to reach the maximum, and the H reflected wave weakens.

Usually, stimulating tibial nerve component in popliteal fossa to excite afferent fibers from gastrocnemius muscle spindle to obtain H reflexed wave, so as to evaluate nerve root and sensory nerve disorders on S1 plane. Secondly, the H reflected wave can be obtained by stimulating the afferent fibers of radial flexor muscle of the wrist and muscle spindle dominated by nervus peroneus communis in leg.

16.2.1.6 Somatosensory Evoked Potentials (SEPs)

Given a particular sensory irritation, a potential change with fixed time relation with simulation can be recorded in any part of the sensory pathways. This is called sensory evoked potential. It reflects the active process of afferent sensory impulsivity and functional status of related structure. If cutaneous nerves of fingers and toes or sensory fibers in mixing nerve trunk of limb are stimulated by current pulses, the potential change recorded on nerves of limbs, skin surface of the spine and scalp corresponding to projection of brain sensory is called somatosensory evoked potentials (Fig. 16.9).

Stimulation method and parameters are similar to those for measuring conduction velocity of peripheral nerves. The waveforms recorded and parameters after 500 times of overlaps of supramaximal stimulus are required. Since this technique is more sensitive than that for measuring SNAP's waveform and amplitude, it can be used to determine slowdown and block of conduction as well as loss of conduction, to estimate the extent of injury to peripheral sensory nerve fibers, to some extent, to reflect the functional status of mixed neural trunk.

Indications for Electrophysiological Diagnosis

Before electrophysiological examination, detailed history and clinical evaluation results of the patient must be clear. The electrophysiological examination can be considered only when clinical evaluation is difficult, diagnosis cannot be made of the problems of the patient, or for the purpose of excluding secondary or combined systemic disease. These are the main indications for electrophysiological examination. Meanwhile, coordination between clinicians and physicians responsible for electrophysiological examination is required. Clinical condition, diagnosis considered and other possibilities to be excluded should be specified in the application form. It should also be considered whether one nerve or two nerves of one side of limb, or both sides, or all nerves for both upper limbs and lower limbs should be examined. For the patient with entrapment disorders of multiple peripheral nerves, it is necessary to exclude the possibilities of systemic diseases (such as diabetic neuropathy, or alcoholic neuropathy). Electrophysiology diagnosis is helpful in defining a diagnosis and identifying peripheral neuropathy and muscle disease as well as neck radiculopathy, etc.

Electrophysiological examination also helps to evaluate the possibility of recovery after nerve injury. In clinical assessment of brachial plexus stretch injury or crush injury, the muscular electrophysiological parameters can be used to identify the functional recovery of neuromuscular system, so as to guide clinicians to choose the time for surgical repair of peripheral nerve injury.

Electrophysiology diagnosis has can be used to determine peripheral nerve entrapment syndrome, of loss of nerve and injury to sensory and motor function. In most cases, electrophysiology diagnosis is as important as clinical evaluation for severe nerve entrapment, and consistent with indications for surgical decompression. When clinical evaluation of a patient is difficult, electrophysiological examination can provide useful information, especially, during multiple examinations. The results can be compared, providing an approach to clinical assessment and handling difficult problems.

Properly Understand the Value of Electrophysiological Diagnosis of Peripheral Nerve Injury

We should also note that traditional electrophysiological examinations (such as measurement of nerve conduction velocity, EMG, etc.) have limitations. Moreover, other influences, such as technical errors in actual operation, anatomy variations and physiological factors, are likely to make electrophysiological diagnostics results contradictory to clinical findings. During many electrophysiological diagnoses like measurement of nerve conduction velocity, the recording electrodes used can only detect the electrical activity in the fibers of a normal nerve tract that conducts the fastest, but cannot display the problem in one or two nerve tracts with severe injury. Consequently, the results measured, such as conduction velocity of sensory nerve and motor nerve, can fall within a normal range while some nerve tracts are injured enough to induce obvious symptoms in the patient. In addition, the recording needles of MG can only detect 6–30 muscle fibers near the needle tip but cannot detect the muscles in the other parts of muscle belly which lose nerve domination. Such a detective error is the most obvious limitation of electrophysiological examination which affects its accuracy.

It is common that a patient suffers from significant clinical symptoms of chronic nerve damage (such as chronic nerve entrapment syndrome) but the results of electrophysiological diagnosis indicate "normal". Dellon and Mackinnon (1987) clearly illustrated the pathophysiological basis in patients who have clinical symptoms but normal electrophysiological diagnosis results. Generally speaking, the distribution of lesions in several tracts of peripheral nerve is inhomogenous. In case of the wrist median nerve entrapment syndrome, if the motor nerve tract is entrapped severely, the two-point discrimination is abnormal without contraction of the thenar muscles. Sometimes, the middle finger of a patient is significantly affected while the other fingers are normal. Another example is in forearm median nerve entrapment syndrome, the median nerve dysfunction is various, such as flexor hallucis longus weakness with complete function of the thenar muscles but without paresthesia. Meanwhile, entrapment syndrome in peripheral nerve tends to relate with the arrangement of nerve tracts of peripheral nerve trunks and the position of pressure in neurothlipsis (e.g. fibrous band, fiber muscle-derived pressure). The inhomogenous pressure distribution of neurothlipsis leads to severe compression on some nerve tracts and significant functional loss, resulting in obvious clinical symptoms, while some nerve tracts are slightly compressed, leading to slight dysfunction. Finally, the technique errors, anatomical variations and physiological factors during electrophysiological examination also affect the results of electrophysiological diagnosis.

16.3 Principles of Treatment of Peripheral Nerve Injury

After neurotmesis, the Wallerian degeneration occurs in distal nerve, axon and myelin sheath disintegrate, and schwann cells propagate and arrange in column, so as to accept and support the proximal nerve fiber regeneration. During proximal nerve regeneration, both myelinated fibers and unmyelinated fibers sprout nerve regeneration units, also known as nerve regeneration plexus, which consists of many fibers sprouted by a single axon. These regeneration units, the smallest functional unit of nerve regeneration, are surrounded by the perineurium. A good nerve repair aims to guide these axons regenerated fibers to successfully grow into the distal nerve environment in avoidance of disorientation of nerve regeneration units, since the disoriented nerve fibers will finally form a painful neuroma around the suture site and possibly lose their function. The function of regenerated nerve fibers is unknown, and it is not clear how much the minimum amount of regenerated nerve fibers is required for reinnervation to recover functional muscle strength or cutaneous sensation. It is possible that the quantity of nerve fibers is various between motor system and sensory system and among sensory receptors, since a single sensory nerve fiber dominates several Meckel's cells and several axons can come into one tactile corpuscle.

Effective nerve repair depends on correct connections established between sensory, motor and sympathetic axons and distal organs. Although the final outcomes of nerve repair are impacted by many factors, the surgeon must follow some basic principles when handling all peripheral nerve injury. Here are eight fundamental principles that must be followed during nerve repair, because they are the basis for the treatment of peripheral nerve injury.

1. Careful clinical examination: Preoperative and postoperative evaluations are required for quantitative assessment of movement and feeling so as to accurately assess the effectiveness of treatment. The criteria for motion evaluation include measurement of myodynamia (such as clamping force, grip strength) and muscle atrophy; the evaluation criteria for sensory system include measurement of threshold (stimulation for pallesthesia or piesesthesia), innervation density (static and dynamic two-point discrimination) and sense of pain and temperature sensation (protective sensation).
2. Surgical treatment as early as possible: A one-stage operation should be conducted once the indications are confirmed. The reinnervation should be performed if the nerve defect cannot be directly sutured. The nerve grafting can be made if proximal nerve damage cannot be sutured. A nerve implantation can be made if distal nerve damage cannot be sutured (such as direct implantation of motor nerve into muscles). The neurolysis (endoneurolysis or extraneurolysis) can be made if the nerve is not completely injured, structural continuity remains and fibrosis is present inside and outside the nerve.
3. Use of microsurgical techniques: Microsurgical techniques should be applied in all surgeries for peripheral nerves. Microscopes, microsurgical instruments and microsurgical suture kits can improve surgical accuracy and reduce surgical trauma.
4. Gradual excision of scar tissues from healthy region during nerve tract anatomy: The nerve shall be gradually exposed from the normal tissue around both sides of the lesion, and then a dissociation shall be gradually made from the lesion. Since the anatomical structures in the region of lesion are usually in chaos, especially in the long-term denervation, the nerves and surrounded tissues adhere to a mess by scar tissues. As a result, accidental injury might happen to the nerve if an incision is made around this region. Conversely, on a normal site where the anatomical structures are clear and the nerve is easily identified, a gradual dissociation from the nerve plexus to the lesion can avoid a continuous nerve transection.
5. Thorough resection of neuroma: The stub-end of injured nerve forms a neuroma, in which the nerve fibers that are in chaos and parceled by a mass of fibrous tissues cannot connect to the nerves. The regeneration as well as functional recovery can be ensured only after the neuroma is thoroughly resected and the normal nerve can be reached. At a normal cross-section, the visible nerve tracts exhibit granular process, the tissues are soft among tracts with vascularity and there is some space between tracts. If the neuroma is not thoroughly resected and there are many scar tissues on the stump with disordered nerve fibers that cannot form a sarciniform, the nerve regeneration after suture will be significantly impacted.
6. The nerve stumps should be sutured without tension: After resection of a neuroma, there is a certain defect between two nerve stumps. If the defect is not large, normally, the suture can be achieved without tension by separating, flexing a joint, cutting off some minor branches, rerouting nerves or even shortening a backbone. During suture, the nerve stumps should be aligned and connected in corresponding positions and the methods involved include epineurial suture and perieneurial suture. The neural transplantation shall be conducted if the defect is large, the connection is made reluctantly under tension, and direct suture is not allowed. The tension on anastomotic stomas will prevent nerve regeneration.
7. The nerve anastomotic stomas or implanted nerves are placed on a tissue bed with sufficient blood supply: Good nerve regeneration should be ensured by good blood supply, especially in transplantation of free nerves. In addition to the blood supply that can be expected to reach the both nerve stub-ends, the blood supply to other parts will depend on ingrowth of blood capillaries from surrounding soft tissues. Usually, the surrounding blood supply can be established 3–5 days after transplantation. If the surrounding tissues are stiff scar, skin or bone which lacks blood supply, nerve regeneration will be affected or even scar forms without blood supply. Thus, in case of serious skin scar, the skin flap transplantation shall be considered first. For the skin scar adjacent to bone surface, try to change the transplantation route or transplant a muscle flap to embrace the nerve to ensure good blood supply.
8. After operation, rehabilitation retraining of motor nerves and sensory nerves shall be rigorously carried out to enhance the outcomes of surgery.

16.4 Microsurgical Techniques for Repair of Peripheral Nerve Injury

In recent years, on the basis of microsurgical techniques, laser, cell transplantation, tissue engineering and genetic engineering are used to repair peripheral nerve injury to vastly improve the repair quality. However, nerve regeneration is affected by the nature of peripheral nerve structures and regeneration, as well as by other factors (such as age, location, cause, nature and extent of injury and repair method, etc.). Various techniques for repair of peripheral nerve injury still have limitations which compromise the effectiveness of nerve repair. Especially, satisfactory outcomes have not been achieved yet in recovery of motor function after nerve injury. The current techniques for repair include:

16.4.1 Epineurial Suture and Perieneurial Suture

For many years, many clinical and experimental studies compared the advantages and disadvantages between epineurial suture and perieneurial suture (Fig. 16.10), but no final conclusion was drawn. Theoretically, the perieneurial suture can accurately connect and align the broken ends on proximal and distal ends of various nerves, avoiding or reducing the chance that the regenerated nerve fiber grows out of perineurium and into a wrong path. This benefits the passing of regenerated nerve fibers. Its clinical outcomes are better than that for epineurial suture. But in practice, the possibility of wrong growth and wrong connection still exists. If the nerves are mixed tracts, cross-growth between motor fibers and sensory fibers might happen.

On the other hand, the methods used for identifying nature of nerve tracts with respect to morphology, electrophysiology and histopathology are still not perfect. The blindness in connecting nerve tracts may lead to mispairing of nerves with different functions, resulting in complete loss of function of nerve tracts. The operation for epineurial suture is convenient, time-saving and easy to grasp, because no dissection within a nerve trunk is required during operation, decreasing injury to nerves as well as scar formation among nerve tracts. However, interstitial tissues account for a large proportion of a nerve trunk (33–50% on average for the upper limb), mainly distributed among nerve tracts. Since the distribution of nerve tracts along the route of nerve trunk is fasciculate with a variety of arrangement, location, size and quantity, it is difficult in epineurial suture to ensuring accurate connection of nerve tracts on both ends. Therefore, quite a few axons grow into connective tissues among nerve tracts and never reach corresponding end organs, affecting the functional recovery. It is still believed that in spite of the inaccuracy, the nerve chemotaxis allowed by epineurial suture could influence the orientation of growth of nerve fibers (Mackinnon and Dellon 1988), and within a certain region, the proximally regenerated sensory fibers or motor fibers could alternatively grow through suture sites into sheaths of many distal schwann cells (with same or different natures). These may explain the similar clinical outcomes between epineurial suture and perieneurial suture. Finally, it is believed that the theoretical advantages of perineurial suturing are actually weakened by limited techniques and conditions (Fig. 16.11).

In repairing peripheral nerve injury, microsurgical techniques shall be utilized as much as possible. Epineurial suture and perieneurial suture can be chosen according to their individual characteristics and actual conditions, including nature

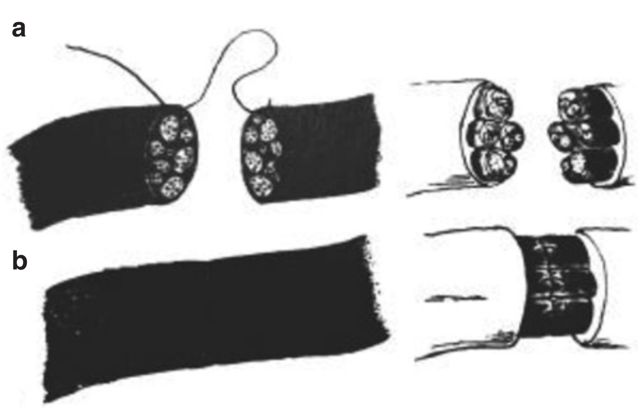


Fig. 16.10 (**a**) Epineurial suture. Coaptation is achieved by single epineurial stitches in the epineurium along the circumference of the nerve. (**b**) Group fascicular suture. Epineurial tissue has been resected and fascicular groups are coated with single sutures in the perineurium or connective tissue surrounding the groups of fascicles

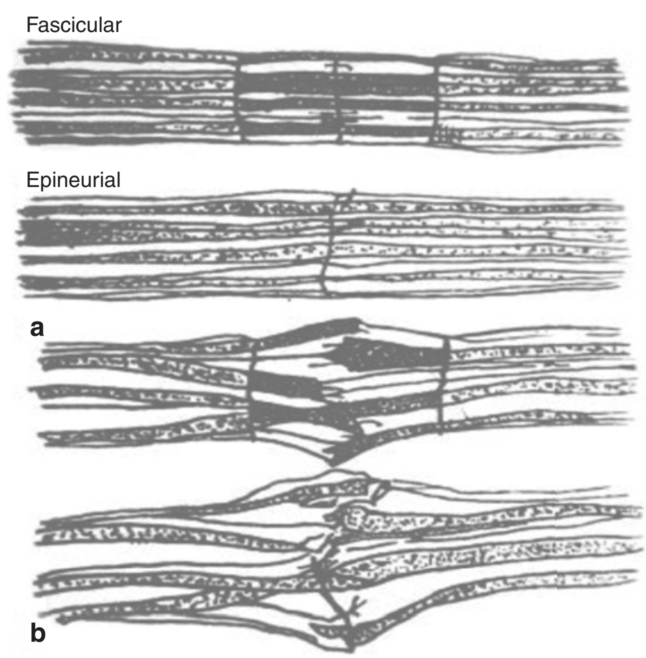


Fig. 16.11 (**a**) For perieneurial suture, take care to connect motor nerve tract (point) and sensory nerve tract (white). For epineurial suture, the suture site is on perilemma epineurium, and using anatomical landmarks such as surface vessels on perilemma epineurium helps to connect corresponding nerve tracts. (**b**) The ideal connection of motor nerve tract and sensory nerve tract (such as **a**) is difficult to achieve in clinical practice. Wrong connection of motor and sensory nerves is commonly on suture site. (The upper figure is perieneurial suture and the lower one is epineurial suture)

of injury, injured part in limbs, anatomy of nerve tracts to be repaired, opportunity for nerve repair and technical merits of an operator, etc. Using these suture techniques to repair nerves aims to connect corresponding nerve tracts with minimal invasion to nerves and maximum recovery of nerve function. During repair, two aspects should be noted:

16.4.1.1 Nature of Nerve Injury

For acute neurological injury such as clean cutting injury by a sharp object, the epineurial suture is usually used in one stage repair because the truncation surface is relatively flat usually with no or little nerve defect and the anatomical positions of various nerve tracts are clear. Anatomic vascular landmarks on the epineurium of both broken ends can be used to easily identify optimal positions for nerve tract connection, especially under a microscope. Of course, if specific function can be determined on a certain nerve tract on both proximal and distal ends, the perieneurial suture shall be used for this nerve tract (such as the dorsal cutaneous branch of the forearm ulnar nerve, the motor deep branch of the ulnar nerve at Guyon canal and the motor recurrent branch of the median nerve at the wrist). In case of incomplete neurotmesis where the location of ruptured nerve tract can be easily recognized, the perieneurial suture shall be used. For electrical injury, chemical injury or serious avulsion with extensive nerve defect, usually, the interfascicular nerve transplantation after thorough debridement or nerve transplantation after vascular anastomosis shall be performed microscopically rather than direct epineurial suture or perieneurial suture. For nerve injuries in the elderly, children, pregnant women and those with other fatal complications like craniocerebral trauma and abdominal injury, surgical procedures should be simplified as much as possible and it is advisable to perform epineurial suture.

16.4.1.2 Levels of Limb Nerve Injury and Anatomical Features of Nerve Tracts in Nerve Trunk to Be Repaired

Microscopical anatomy studies on main nerves of extremities (including studies on anatomic separation of naturally separated tracts) show that most proximal tracts of various nerves are mixed nerves usually containing more connective tissues. The internal structure of the nerve trunk is not simply arranged in parallel, but is fasciculate and staggered. Thus, reluctant suture of separated nerve tracts will result in more lesions so that its outcome is inferior to that of perieneurial suture. Since the sensory tracts and motor tracts on distal nerve tracks are clear and the interfascicular communicating branches are few, it is appropriate to connect nerve tracts with the same nature, leading to better outcomes than epineurial suture. During surgery, if the nature of various nerve tracts can be distinguished using morphological and electrophysiological methods, the perieneurial suture can be used to make accurate connection of nerve tracts.

16.4.2 Reinnervation

When end-end nerve suture cannot ensure a suture site free of tension, nerve transplantation must be made. Even though a nerve suture results in a little tension, the success of final functional recovery is still affected. Millesi et al. (1972) demonstrated that when the length of a nerve defect exceeded by 4% of the isolated length of the nerve broken-end, the tension from the suture site increased significantly, inducing connective tissue hyperplasia and then resulting in scar formation. This is the most important factor inhibiting successful axon regeneration. Proliferation of connective tissues is positively correlated with the tension from a suture site. In suture free from tension, connective tissues proliferate on the suture site but seldom invade into the suture site, exerting little impact on regenerated axons. On the contrary, when suture is made under tension, connective tissues proliferate a lot and invade into the suture site, badly impacting the axon regeneration. Moreover, cicatricial contraction will follow. Even after the regenerated axons have successfully grown into the distal nerve canal, the conductive function of axons is also affected by ring-like nerve entrapment.

Observation of peripheral nervous and vascular circulation under an operating microscope can clearly show the impact of tension on blood supply in nerves. It can be easily found that a little tension applied to the nerve by using microsurgical forceps to pick it away from the tissue bed can make it white and block its blood supply. Surely, when a nerve defect repaired at limb flexion exceeds a certain limit, it is inappropriate to repair a peripheral nerve by directly suturing broken ends of two nerves.

It is still controversial how long a nerve defect can be repaired by neural transplantation. One centimeter defect of a digital nerve means that the extreme flexion of proximal interphalangeal joints cannot be overcome (actually, it is not appropriate using extreme flexion of joints to overcome a nerve defect). On the contrary, 1 cm of nerve defect at the forearm can be easily overcome by dissociating proximal and distal nerves. Anterior displacement of the elbow ulnar nerve can often overcome a 5 cm defect. Thus, for various nerve injuries at different parts of a limb, there are no fixed criteria for the appropriate length of a nerve defect that can be overcome by neural transplantation. It is ideal to dissociate the broken ends of two nerves as much as possible and to make efforts to suture one another according to specific situation. However, the principle of “nerve injury repair without tension” shall be strictly followed. Even a very short nerve defect on some part (such as digital nerve) shall also be repaired by neural transplantation. However, neural transplantation needs one autografted nerve. Recently, the scholars proposed that a short nerve defect should be bridged with non-nerve grafts or canals. Autogenous vein bridging, homologous nerve and nerve canal grafts should be used instead of a nerve autograft. It should be pointed out that although the effectiveness of nerve autografts has been confirmed, it is not appropriate to use extensively in clinic other non-nerve grafts or canals because they are still under development.

Many surgical techniques for neural transplantation are similar to those of one-stage neurorrhaphy. For nerve injury of degree IV, the scars that have no function and prevent regeneration must be completely checked and incised. For nerve injury of degree V, the proximal neuroma and distal neurospongioma must be incised to ensure that both proximal and distal broken ends of the nerves ready for suture are healthy enough and microsurgery techniques can be used for repair free from tension. Especially, both suture sites for transplated nerves should be free from tension during limb exercise. Therefore, post-operative immobilization can be no longer than 2 weeks, since long-term immobilization will lead to unnecessary scar formation along the full length of transplated nerves, resulting in adhesion between the nerve graft and its tissue bed (Table 16.1) which limits nerve gliding exercises.

The neural transplantation shall be performed at the proximal and distal suture sites as much as possible. The sensory tracts as well as motor tracts on broken ends of proximal and distal nerves can be accurately connected with various nerve tracts of grafts (Fig. 16.12).

Table 16.1 Mechanical factors affecting nervous longitudinal gliding

	Normal nerve	After injury
Elasticity	Normal	Reduced due to fibrosis
Gliding feature	Complete	Reduced due to fibrosis
Tension	Even distributed	Increased at suture site or wound site

Fig. 16.12 Mackinnon and Dellon modified the reinnervation. The proximal and distal nerve tracts are excised from the normal side. During interfascicular neural transplantation, the anastomotic stomas are slightly staggered (top figure). It is better if the distance variation between interfascicularly transplanted nerve tracts is smaller (although the nerve length is slightly increased). This makes all nerve tracts close to the same suture level, and makes it possible that the regenerated nerve fibers can grow into adjacent neural transplantation segment, but any regenerated nerve fibers in top figure have no such a chance

The tracts of proximal nerves are usually mixed without regular arrangement. At distal nerve segments, the motor and sensor nerve fibers respectively concentrate as motor or sensor nerve tracts with relatively regular arrangements. The above-mentioned anatomic characteristics of nerves of limbs provide a basis for selecting methods for nerve anastomosis in clinical practice.

The outcome for functional recovery following long neural transplantation is often poor. Some scholars believe that the outcome is not ideal if the length of transplanted segment is more than 5 cm, but the outcomes are not only related to the length of grafts but also to other factors. The long neural transplantation is indicated for injury and defect of proximal nerves of limbs (the time for motor end plate to reachieve innervation increases) and serious nerve injury (tractive injury rather than sharp injury), of which the local tissues are often extensively injured with scar formation and loss of central neuron. These factors contribute to poor functional recovery following long neural transplantation.

The common donor sites for neural transplantation include sural nerve, lateral antebrachial cutaneous nerve and medial antebrachial cutaneous nerves, etc.

16.4.3 Repair for Neuroma-Type Incomplete Nerve Injury (VI° Injury)

VI° nerve injury, i.e. neuroma-type incomplete nerve injury, means injuries of various degrees that simultaneously occur in nerve tracts of a nerve trunk but still keep neural continuity. After healing, a tumor shape goitre forms on the nerve trunk, which is different from a traumatic neuroma that forms after complete rupture. It is also a troublesome problem for surgeons of peripheral nerve surgery. Since the nerve still remains continuity but the neuroma might be mixed with or without healthy nerve tracts, its clinical symptoms and signs at an early stage are difficult to distinguish. The final functional recovery and healing of fibers in nerve tracts depend on injury types of nerve tracts (Table 16.2).

The nerve tracts with concussion injury (degree I) can recover complete function within weeks after injury at a growth rate other than 1 mm per day, because the axons are not injured or degenerated and the Tinel's sign is negative. The nerve function will rapidly recover after recovery of local conduction block or repair for regions of demyelination. Therefore, the injury of degree I needs no nerve repair.

In degree II axon injury, the axons are broken off in the middle and degenerated with positive Tinel' signs on the injured portion. As only the axons are injured, the endoneurium is intact and there will be no wrong growth of sensory and motor fibers during nerve regeneration. At a growth rate of 1–1.5 mm per day, the Tinel's signs move forward to the distal portion. The neural function can be completely

Table 16.2 Relationship between degree of nerve injury and functional recovery

Injury degree	Tinel's sign Progress forward during/after injury	Recovery extent	Recovery rate	Surgery
I neuropraxie	−/−	Complete	Rapid from days to weeks	(−)
II axonotmesis	+/+	Complete	Slow (1 in./month)	(−)
III disruption of nerve fiber	+/+	Very different	Slow (1 in./month)	(−) or neurolysis
IV disruption of nerve tract	+/−	None	No recovery	Nerve suture or transplantation
V nerve rupture	+/−	None	No recovery	Nerve suture or transplantation
VI mixed type	The recoveries of various nerve tracts depend on injury severities (see I–V)			

recovered to the normal level as in the case of concussion injury to nerve tracts but the functional recovery is much slower. The sequence of functional recovery for muscles losing nerves and for sensory receptors is related to the progressive nerve regeneration plane, and usually the same with the anatomic sequence. The injury of degree II needs no nerve repair.

In nerve tract injury of degree III, the axons and endoneuriums are ruptured while the nerve tracts are complete. The nerve regeneration is constrained within the perineurium. The positive Tinel's signs progressively move forward distally along with nerve regeneration. The functional recovery varies greatly depending on the injury plane and anatomic characteristics of the nerve tracts, ranging from almost full recovery to nearly no recovery. If the injured nerve tract mixes sensory and motor nerves, cross-growth will happen during regeneration of sensor and motor fibers, resulting in poor functional recovery. On the contrary, if the injured nerve tract consists of merely motor or sensory nerves that dominate the sensation of one specific muscle or skin region, most axons can grow into the terminal points to recover nearly normal function of the nerve, even though the growth of some regenerated nerve is staggered or some nerve fibers are lost in the scar of endoneurium. The cross-growth of regenerated nerve fibers may result from the incomplete regeneration of nerve fibers due to injured basilar membrane, or from various scars on the endoneurium. Although the natural recovery of nerve injury of degree III varies greatly, it is surely better than the prognosis of one-stage nerve suture, or at least comparable, due to the intact perineurium. Thus, the injury of degree III needs no surgical repair either.

In injury of degree IV, all axons, endoneuriums and perineuriums are ruptured but with complete perilemma epineurium. The range of injury is large. Obvious scar tissues can be seen in nerves with stretching injury, and the proximally regenerated nerve fibers are completely blocked by regenerated nerve fibers with no nerve recovery. Thus, surgical repair must be conducted.

In disrupted injury of nerves (injury of degree V), the nerve completely ruptures, neoplasia forms on proximal and distal broken ends, the proximal regenerated nerve fibers cannot grow to the distal nerve. Its outcome is very poor without surgical detection and repair.

Therefore, a surgeon must check the function of injured peripheral nerves by careful clinical examinations as well as by electrophysiological diagnosis. He should develop a three-dimensional profile for injury to the nerve tracts in a peripheral nerve trunk. In assessment of nerve injury, the injury to various nerve tracts or nerve tract groups and the injury extents are also determined. He should keep in mind that the spontaneous recovery of nerve injuries on I, II and III degrees should be kept in mind and is better than the outcome of surgical suture or repair by transplantation, and the injuries on IV and V degrees must be repaired by surgical reconstruction.

To treat nerve injury of degree VI, microneurosurgery techniques must be used in addition to endoneurolysis and various nerve repair surgeries. The nerves should be detected from the normal proximal and distal nerve segments to the injury site. One should distinguish the nerve tracts with injuries of degrees IV and V from those with injuries of degrees I–III. For the former, the neuroma or nervous tissue as well as scar tissue must be surgically incised before the repair by nerve transplantation is performed; for the latter, the neurolysis can be made without nerve ablation or repair. Careful preoperative physical examination in combination with microsurgical detection helps to specify a surgical diagnosis. Sometimes, intraoperative detection for nerve conduction velocity offers a great help. If the injury of distal limb does not recover beyond the maximum time for final functional recovery, a surgical detection shall be made. During operation, electrophysiological diagnosis should be conducted for various nerve tract groups. If no sign of functional recovery can be seen during the first 3 months after operation for the nerve injury on the proximal limb (such as brachial plexus injury), i.e. if there is an indication for surgery, do not waste time continuing observation and conservative treatment.

16.4.4 Neural Transplantation with Vascular Anastomosis

Early in 1945, Tarlor et al. demonstrated via angiography that the blood vessels growing from the proximal and distal nerve ends were observed 3–4 days after operation in the implanted nerve segment, obviously on day 5. The blood vessels from tissue bed grew through epineurium into the implanted nerve segment on day 5 after operation. On days 6–8, more and more blood vessels grew from the peripheral region and became an important vascular source. The study by Weiss et al. (1946) also demonstrated that the implanted nerve segment survived with the nutrients permeated from tissue fluid on the first 2 days, and the blood vessels grew from the third day. Thus, the conventional reinnervation can only make cable grafting with tiny nerves rather than thick ones, or otherwise, avascular necrosis may occur in the central region seriously affecting functional recovery. The implanted nerve segment cannot be wrapped with artificial film or biological film, but is placed on a tissue bed with good blood circulation for blood vessel growth and regeneration. In addition, the outcome of neural transplantation for a long segment defect is poorer than that for a short one, indicating the blood supply to a reconstructed nerve segment is of great importance.

At present, researchers think the indications for clinical application of neural transplantation with anastomotic blood vessels include:

1. reconstruction for proximal nerve injury and thick nerve defect (such as brachial plexus injury);
2. nerve injury repair and reconstruction with damaged tissue bed in the recipient region, massive scars and poor conditions;
3. reconstruction for long-segment nerve defects.

16.4.5 Microscopic Endoneurolysis

On the basis of exoneurolysis, endoneurolysis further lyses the scars among nerve tracts, aiming to excise the fibrosis part of perilemma epineurium outside nerve tracts, isolate perilemma epineurium from nerve tracts, excise or remove scar tissue, hematoma or tumor, so as to dissociate various nerve tracts. Since the extent of intraneural fibrosis depends on the scope of nerve injury or other lesion, the range of endoneurolysis can be determined according to the specific situation. The lesion must be thoroughly excised until the normal nerve tract is exposed. It is ideal if the surface marker on each nerve tract can be clearly seen.

16.4.6 Microscopic Exoneurolysis

The indications for external neurolysis are usually similar to those for endoneurolysis. The difference is that the former is for milder nerve compression and fibrosis which do not result in fibrosis among nerve tracts. Clinically, the symptoms of thickening and hardening nerve trunks include only mild paralysis (mostly), local tenderness or radiating pain, and normally, unaffected myodynamia. More importantly, although the fibrosis and adherence to peripheral scars in thickening nerve trunks can be seen in operation, the healthy nerve tract can be exposed after lysing scars outside the nerves or excising thickened perilemma epineurium. Since no fibrosis is seen on epineuriums among nerve tracts, the lysis is not needed among nerve tracts. Since external neurolysis is often the first step of endoneurolysis, many indications for endoneurolysis are also suitable for external neurolysis, including:

1. Nerve crush injury, such as minor ulnar nerve injury or nervus peroneus communis injury caused by crush injury to posterior elbow or fibular head; nerve compression, such as medium-stage carpal tunnel syndrome without abnormal feeling or muscular atrophy.
2. Incomplete nerve injury resulting from joint dislocation which can spontaneously recover in most cases, and recover incompletely with mild symptoms in a few cases, such as injury to sciatic nerve resulting from hip dislocation, contusion of axillary nerve resulting from shoulder dislocation, and median nerve as well as radial nerve injury resulting from elbow and capitulum radii dislocations. In most cases the injury can spontaneously recover. The external neurolysis can be performed in case of incomplete functional recovery resulting from thickened nerve epineuriums in a few cases.

16.5 Factors Affecting Efficacy of Peripheral Nerve Injury Repair

There are objective and subjective factors that can explain why the surgical outcomes for peripheral nerve injury are not good enough. However, in many cases the subjective ones, like personal effort, play an important role. A surgeon can improve surgical effects and avoid errors to achieve satisfactory recovery of neural function.

The factors that impact the effectiveness of repair for peripheral nerve injury include the followings.

16.5.1 Objective Factors

16.5.1.1 Serious Injury with a Complex Nature

The poor outcomes following nerve injury repair often result from a powerful traumatic force with a complex nature. A traffic accident, house collapse or striking by a sharp or heavy object often result in serious stretching, extrusion, contusion or laceration of limbs, accompanied by serious nerve injury beyond degree III in addition to lesions of other tissues, like skin, bone and tendon. The surgical repair is difficult, sometimes time-wasting and needs to be performed by stages. The scar adhesion from old injury is tight with disorganized structures. Dissociation for nerve exploration is difficult. Neural transplantation needs to be performed if a nerve defect exists after neuroma excision. Sometimes, when the proximal or distal nerve stumps cannot be found, or stiff scars are left after nerve separation without appropriate soft tissue repair, the surgical repair is more difficult, and its final outcomes are commonly not ideal.

16.5.1.2 Age

The association between age and effectiveness of nerve impair is controversial. However, more satisfactory functional recovery can be usually achieved in children because their limbs are short and the distance of nerve growth is also short, which saves the time for regenerated axons to reach end organs. In addition, the organ atrophy under the same condition can be mitigated. On the contrary, less satisfactory functional recovery is common in the elderly who are characterized by low response and flexibility, weak compensative and adaptive capacity, poor nutritional status, local angiosclerosis, poor blood circulation, necessary long-term limb immobilization, and lack of exercise.

16.5.1.3 Others

The nerve injury recovery is also affected, if the patients suffer from systemic diseases such as diabetes and tuberculosis, dysfunction of multiple tissues and organs, concomitant local or systemic complications like infection or anemia.

16.5.2 Intraoperative Errors

If a surgeon neglects the principles that need to be followed during operation due to subjective reasons, he may usually make the following mistakes.

1. Missing an operation opportunity due to overlooking nerve injury

   A surgeon who does not carefully examine the patient before treatment may often overlook clinical manifestations of nerve injury. This case often occurs in the patients with complex injury. When the surgeon is busy with other important tissue lesions, he often overlooks nerve injury which has to be treated in a secondary two-stage repair after it has been found in wound debridement or postoperative examination. Sometimes in an emergency operation, the broken nerve ends are not found because of the limited exposure of the incision, or the injured nerve is deliberately neglected and scheduled for secondary repair due to time limit or surgical conditions. If the injured nerve is repaired after half a year, its chance for recovery is slim because it has been seriously degenerated with scar proliferation and poor regeneration, and the end organs are atrophic due to disuse. In addition, conflict treatments of multiple tissue injuries make the effectiveness unsatisfactory.
2. The broken nerve ends are wrongly connected with tendons or fibrous tissue branches, or different functional branches are wrongly connected. Wrong connections may be made when the surgeon is inexperienced or careless, illumination is insufficient, or exposure is poor, because nerves, tendons and fibrous tissue branches are similar in appearance. They are also likely to happen in an emergency operation due to poor hemostasis or a messy mixture of blood and tissues. They may also happen in the selective operation with presence of tight scar conglutination and disorganized tissue structure.
3. Incomplete excision of the neuroma and reluctant suture of a too large defective gap following neuroma excision will surely hinder nerve injury recovery. A surgeon who in fluke mind fears that too much excision of stumps makes direct suture of the nerve stumps impossible may make a reluctant connection of the nerve stumps in extreme flexion of the joint when the stumps cannot be directly sutured. The reluctant connection made by decompression stretch and thick silk threads will lead to a great tension at the anastomotic stoma, affecting nerve regeneration.
4. Unskilled micromanipulation

   For instances, nerve suture with thick suture kit, incomplete excision of the scar tissue on nerve stumps, retaining too much of the perilemma epineurium, introduction of the nerve fibers during ligation with the intermicellar vascular forceps, and malalignment of the nerve tracts or the nerve trunks, mismatched sizes or diameters of broken ends, and reversed, overlapped, malpositioned or discontinued broken ends, etc.
5. Man-made damage
   (a) Unavoidable objective difficulties: For instances, in incomplete nerve injury complete excision of scars is expected while continuous nerve ports are to be retained; in injuries of degrees III–IV by Sunderland classification, the endoneurolysis is made on condition that the scar exists in the nerve trunk.
   (b) Common iatrogenic nerve injuries: The accessory nerve is cut off in biopsy for cervical lymph nodes; the femoral nerve is wrongly pricked during herniorrhaphy; the femoral nerve is injured during debridement for tuberculosis of the hip joint; the tibial nerve is injured during knee joint fusion; the femoral nerve is injured during abnormity orthopedics for hip joint flexion; the musculospiral nerve is injured after reduction of humeral fracture.
6. No sufficient conditions for nerve regeneration are provided. For instances, reluctant direct suture is made during nerve transplantation; vascular nerve transplantation is not performed because defects are too long; a soft tissue bed cannot be created due to peripheral scar wrap-

ping; skin flap transplantation is not made on first priority after knowledge of skin defect or scar coverage; no appropriate fixation is made after operation; complications, such as wound dehiscence, cutaneous necrosis and infection, occur because of too early exercises after concurrent repair of nerves and tendons.

16.5.3 Insufficient Postoperative Rehabilitation

In recent years, the postoperative rehabilitation draws more and more attention from clinicians because it is very important for nerve functional recovery. Some study showed that frequent postoperative sensory retraining following peripheral nerve injury could achieve good effectiveness. Athletic rehabilitation is also important.

16.6 Effective Evaluation Following Treatment of Peripheral Nerve Injury

The effectiveness following repair of peripheral nerve injury always challenges surgeons. Functional recovery following peripheral nerve injury is virtually a process of axon regeneration. Neuron protection, promotion of axon regeneration and prevention of effectors' atrophy dominated are key points in repair of peripheral nerve injury. Clinically, nerve functional evaluation aims at motor function, sensory function, autonomic nerve function and nerve electrophysiology, etc.

16.6.1 Examination and Evaluation of Motor Nerve Function

Incomplete injury to motor nerves mostly manifests as decreased myodynamia while the complete injury shows loss of myodynamia, followed by gradually aggravated muscle atrophy (including disuse atrophy and trophopathic atrophy, etc). Therefore, examination of motor nerve function involves muscle strength, muscle tension and muscle volume, etc. At present, a frequently used method that comprehensively evaluates nerve motor functions of limbs is proposed by British Medical Research Council (Table 16.3). It classifies the quantitative strengths against resistance produced via muscle contraction as six levels, i.e. BMRC classification.

The strengths of various muscles dominated by injured nerves should be detected and recorded on the muscle table. During muscle function determination via examination of motor nerve function, individual muscle functions shall be measured, and using joint functions instead of various muscle functions is not allowed. For instance, the wrist joint flexion is mainly dominated by flexor carpi radialis, ulnar flexor of wrist and palmaris longus, but the flexor of fingers can also induce flexion of the wrist joint after finger flexion. Thus flexion of the wrist joint cannot stand for the evaluation criteria for the aforementioned muscles. In addition, some joint motor is induced by trick motion. Although the radial nerve injury results in myoparesis of common extensor of fingers, the myoparesis can be passively stretched during flexion of the wrist joint, possibly resulting in extension of the metacarpophalangeal joints. In order to make accurate diagnosis, the examiner shall check various tendons with fingers so as to confirm the contraction.

Table 16.3 Methods to evaluate muscle functions of limbs (BMRC 1954)

M0	Completely loss of muscle contraction
M1	The proximal muscles recover contraction
M2	The proximal and distal muscles recover contraction
M3	All important muscles can overcome resistance
M4	Muscle coordination starts to recover
M5	The muscular movement completely recovers

Table 16.4 Methods to evaluate sensory functions of limbs

S0	Complete sensory deprivation in region dominated by nerves
S1	The deep pain can felt
S2	Superficial pain and some kind of tactile sense can be felt
S2+	There is superficial pain with hyperesthesia
S3	Superficial pain can be felt
S4	Except S3, there is two-point discrimination (7–11 mm)
S5	The feeling is normal, with two point discrimination (<6 mm) and stereognosis

Since the normal muscle has a certain tension with some tensity, its contour can be felt during palpation. With nerve domination, the muscle tension reduces or disappears, and the contour is not clear without tensity and relaxant. During muscle examination, attention shall be paid to the appearance of muscle. The muscle atrophy shall be evaluated by comparing the measured limb perimeter to that of contralateral normal muscle control.

16.6.2 Examination and Evaluation of Sensory Nerve Function

Common evaluation items of sensor nerve function include deep pain, superficial pain, tactile sense, two-point discrimination, thermal sense and stereognosis, etc. The hyperesthesia that mostly occurs during sensory recovery shows as hyperpathia, pain after tickling skin, or even burning-like thermal sense, etc. Clinically, the commonly used evaluation criteria for sensory function were proposed by BMRC (1954) (Table 16.4):

Some people think that since these methods are more subjective, the results obtained by various surgeons under different environments are very different. Thus, many scholars developed various devices to make objective sensory examinations on the basis of specific changes in sensation threshold and densities dominated by nerve endings during sensory disturbances. Especially in incomplete nerve injury, in a case of very early nerve entrapment, the sensation threshold of skin region dominated by sensory nerve fibers changes to hypersensitivity (Dellon 1980, 1983) followed by increased threshold. The measuring methods include using Semmes-Weinstein single fiber sensory measuring device to determine the threshold of skin piesesthesia, using a vibrometer to determine threshold of skin pallesthesia, and using a tuning fork device (e.g. 256 cps, cycles per second) to quantitatively measure skin pallesthesia, etc.

The above-mentioned sensory examination methods are exquisite but burdensome and rarely used during clinical practice. Only the two-point discrimination is very significant. Clinically, the two-point discrimination is frequently used to distinguish the extents of sensory recovery on higher levels, i.e. the boundary between S3 and S4. S2 mostly indicates protective sensation and clinically plays a role in self-protection of limbs, not only preventing accidental injury but also curing trophic ulcer. The boundary between S2 and S3 lies in whether hyperesthesia occurs which is sufficient to clinical practice. Of course, with respect to hand nerve recovery, stereognosis and sensory discrimination for elaborate goods also exist. Thus, many special pickup examinations can be used to check the nerve recovery of hands and train for nerve function so as to promote its rehabilitation.

16.6.3 Examination and Evaluation for Vegetative Nerve Function

A common method to examine vegetative nerve function is to check sweat gland function. After a finger touches the skin, local wetness indicates sweating, and local dryness and smoothness means adiapneustia. Small sweating points can also be observed under microscope for identification. In addition, some chemical reagents can be used for identification, such as starch iodide test (After 1.5% iodine tincture is smeared and the starch is scattered after drying on the test part, and the test part is baked under infrared lamp. If the starch changes to blue, it indicates sweating, or otherwise, indicates no sweating, since the starch will not change to blue if it contacts iodine), and ninhydrin test (Use finger pulp to press on the paper coated with ninhydrin. If there exists sweating, the amino acid of trace amount will gradually change the color of ninhydrin and the fingerprint will appear on the paper.).

16.6.4 Special Examinations

16.6.4.1 Tinel's Sign (Percussion Test of Nerve Trunk)

The proximal broken ends can regenerate following peripheral nerve injury. At beginning, the regenerated nerve fibers look like branch buds without myelin sheath, and can induce allergies such as pain, radiating pain and feeling of electric shock in their distributed region upon response to rapping and decompression, which is called Tinel's sign. If the nerve broken ends are not repaired, the nerve fibers regenerated from the proximal end will irregularly grow all around and are finally wrapped by proliferated schwann cells and connective tissues as nerve pseudoneuroma. The tender nerve branches also regenerate in pseudoneuroma which also induce pain following rapping or decompression. If the nerve anastomosis is made following axon disruption or nerve trunk rupture, the regenerated tender nerve branches will grow forward along Schwann canal to the distal end. Thus the patient will produce above-mentioned feelings if the rap is made along repaired nerve trunk to the leading edge of regenerated nerve axon. The trigger point will also move forward along regenerated nerve fibers, and the progress of nerve regeneration will be acquainted after regularly repeating this check. It shall be noted that forwarding of tenderness can only reflect distal growth of nerve fibers, but cannot indicate the amount of nerve fibers regenerated, or forecast that all fibers regenerate to the distal end. Thus, the corresponding functional recovery cannot be confirmed.

16.6.4.2 Provocative Test

When chronic nerve entrapment happens, the deployable joint simulates the injury mechanism of nerve entrapment to compress nerves or aggravate entrapment so as to induce paresthesia, such as pain or numb in nerve-dominated peripheral region. This is called provocative test and is helpful for interactive diagnosis. For instance, the wrist flexion test can induce median nerve entrapment of the wrist (Phalen's sign) and elbow flexion can produce ulnar nerve entrapment of the elbow.

16.6.4.3 Deep Reflex Test

Following peripheral nerve injury, the deep reflex of corresponding injured nerve segments will weaken or disappear and no pathological reflex will happen due to lower motor nerve injury. The deep reflex is induced due to irritating receptors in muscles, tendons and joints. The commonly used deep reflexes and corresponding nerve segments include bicipital tendon reflex (Neck 6), triceps brachii muscle tendon reflex (Neck 7), radial periosteal reflex (Neck 7–8), ulna periosteal reflex (Neck 8 and Thorax 1), patellar tendon reflex (Waist 2 and 3), and achilles reflex (Sacrum 1). It should be noted that a bilateral comparison shall be made during reflex test. It is significant if the reflex of normal side is positive while that of rupture side is negative. The significance of results is only for reference if the reflexes of both sides are negative.

16.6.4.4 Nerve Block Test

Sometimes, the anatomic variation cross-dominated by median nerve and ulnar nerve may exist in muscles of hand. During single ulnar nerve or median nerve injury, active dyskinesia will not happen in the corresponding muscle of hand due to domination of another nerve. Such variation of nerve domination can be determined by block anesthesia of another nerve trunk, supporting the accuracy of clinical examination. In addition, when two nerves go through in parallel or dominate a limb part, such as ulnar nerve in medial upper elbow and forearm and cutaneous nerve in forearm, it is sometimes difficult for one to determine via clinical check whether the pain on the medial upper level of elbow and forearm is caused by local compression of the elbow ulnar nerve or lesion of forearm medial cutaneous nerve. The source of nervous lesion contributing to pain can be determined by block anesthesia of elbow ulnar nerve.

16.7 Treatment for Pain Sequela Following Peripheral Nerve Injury

The adverse outcomes following peripheral nerve injury include loss of nerve function resulting from failure of nerve regeneration, as well as pain sequela related to incomplete or abnormal nerve regeneration. The treatment of such pain sequela is more difficult than for sensory or motor functional recovery. Generally speaking, various degrees of pain will appear following nerve injury. The treatments for some kinds of pain are intractable, including painful neuromas, sympathetic reflex dystrophy (RSD)/Sympathetic maintained pain syndrome (SMPS), painful neuroma-type incomplete nerve injury, and pain following carpal canal operation.

16.7.1 Terminology for Pain Following Peripheral Nerve Injury

Definitions for terms related to painful sequelae following nerve injury:

- Sensory deprivation refers to complete loss of sensations including non-painful sensations.
- Hypaesthesia refers to the hypaesthesia of non-painful sensations.
- Paresthesia commonly refers to pricking pain that is awful while not very painful.
- Hyperesthesia refers to intense and obvious pain following tickling skin, characterized by reduced pain perception threshold and increased response to normal stimulation.
- Neuroma-like pain refers to scattered regional pain commensurate with local peripheral nerve injury, and paresthesia in injured nerve distributed region will occur following rapping nerve pain spot.
- Causalgia refers to burning pain or hyperpathia limited to injured peripheral nerve distribution region.
- Sympathetic reflex dystrophy (RSD) or Sympathetic maintained pain syndrome (SMPS) is a clinical syndrome manifesting diffused pain, functional reduction, joint stiffness, soft tissue change, accompanied by vasomotion disorder or not. This RSD is induced by multiple factors, while the long-term response can be maintained due to abnormal sympathetic nervous system. Thus, SMPS gives a clearer description than RSD.

16.7.2 Treatment of Painful Neuroma Following Peripheral Nerve Injury

Treatment of painful neuroma refers to the descriptions in Table 16.5 based on clinical and experimental studies. The final purpose of treating painful neuroma is pain relief and functional recovery. Continuity recovery of peripheral

Table 16.5 Surgical principles for treatment of painful neuroma

Excision of neuroma	Forearm	Tranplanted into bone		
	Wrist and forearm	Important sense	Neural transplantation	
		Non-important sense	Transplanted into brachioradialis	
	Hand	Important sense	Distal nerve stump exists;	Neural transplantation
			No distal nerve	Provide dissociated tissue containing nerves
		Non-important sense	Distal nerve exists	Neural transplantation
			No distal nerve	Transplanted into bone
	Lower limbs	Important sense	Neural transplantation	
		Non-important sense	Transplanted into musculi soleus	

nervous system helps to reverse neuropathological outcomes which can occur on various planes of peripheral nervous, spinal nervous and central nervous systems following nerve injury.

Generally speaking, the surgery for painful neuroma will follow three basic principles:

1. If appropriate distal nervous and sensory receptors exist, the neural transplantation can be made to guide proximally regenerated nerve fibers to grow distally into normal nervous and sensory receptors, so as to reverse the changes along peripheral nervous and central nervous systems secondary to cut off of sensory nerves.
2. If no distal nerve exists and functional recovery of injured nerve is difficult (such as thumb), the regenerated nerves derived from sensory nerves can be transferred and received by dissociated tissues containing nerves (e.g. transplantation of thumb containing nerves and blood vessels, transplantation of tubular flap or full-thickness skin containing nerves, flap or neurovascular island flap, etc).
3. If the function of injured nerve is not a problem, the scheduled therapeutic method fails, distal nerve stump cannot be utilized (such as amputation neuroma) or the tissue bed or local environment is inappropriate for neural transplantation (such as sural nerve at the ankle and sensory branch of radial nerve at the proximal wrist joint), neuroma excision is suitable, and the proximal nerve stump can be transferred to the region with minimal mechanical stimulation.

The treatments for painful neuroma of various parts in the body shall follow these principles and can be improved depending on different parts.

16.8 Microsurgical Repair of Upper Limb Nerve Injury

16.8.1 Median Nerve Injury

Median nerve injury is common and ranks as the second in various nerve injuries (accounting for 20%), of which the pathogenic factors are diverse, such as incise injury, stretch injury, crush injury and ischemic injury, etc. It frequently happens on the wrist, forearm, upper arm or axilla. The pathogenic factors vary depending on different parts. The incise injury mainly occurs on the wrist or forearm and the stretch injury frequently happens on the upper arm or axilla, mostly caused by the upper arm rolled into a machine.

The operation opportunities and therapeutic methods are as follows.

(1) For open injury, if the conditions permit, make efforts to perform neural restoration in emergency treatment. (2) For closed injury, early conservative treatment is carried out first, including electrical stimulation, physiotherapy, physical therapy and neurotrophic drugs (such as Vitamin B1, B6 and B12 as well as bendazol, etc), for observation of 3 months. If there is a sign of recovery, the conservative treatment continues; otherwise the surgical exploration as well as nerve repair shall be performed.

The repair methods are as follows. According to the exposure, if nerve adhesion and scar compression are observed, neurolysis is conducted. In case of nerve rupture with a defect not exceeding fourfolds of the nerve diameter, direct neuroanastomosis can be made; if a nerve defect exceeds fourfolds of the nerve diameter, reinnervation shall be made.

In patients who have lost the opportunity for nerve repair or achieve unsatisfactory recovery of median nerve following nerve repair, the tendon transposition shall be made to improve limb function.

16.8.2 Ulnar Nerve Injury

Various mechanisms can contribute to ulnar nerve injury, such as incise injury, laceration, firearm injury, crush injury, stretch injury, friction injury and ischemic injury, etc. Based on the anatomical features of ulnar nerve, the ulnar nerve injury is mostly caused by incise injury on the forearm. It also commonly results from fracture of internal epicondyle of humerus accompanied by ulnar nerve injury. The traumatic ulnar neuritis, i.e. cubital tunnel syndrome, resulting from the osteoproliferation at sulcus nervi ulnaris of humerus as well as varus deformity of the elbow joint also contributes to the injury.

For surgery opportunity and therapeutic method, in case of open injury, if allowable, one-stage direct suture rehabilitation for ulnar nerve without tension shall be made during emergency treatment. Generally speaking, if the rupture of ulnar nerve is close to cubital tunnel, the anterior transposition of ulnar nerve following cubital tunnel incision while suture rehabilitation of ulnar nerve. On wrist plane, the ulnar nerve can divide into deep branch and superficial branch which should respectively sutured as much as possible so as to benefit the functional recovery. During two-stage repair, when the ulnar nerve has long segment defect (the defect length exceeds fourfolds of nerve diameter) and if the flexed joint still cannot mitigate the tensions from both nerve ends, the reinnervation shall be considered.

Overall, the outcome following repair of ulnar nerve injury is poor, especially for the high level injury, the recovery will cost long time, and the muscle volume in hand is small and easily degenerative during nerve regeneration, and the recovery is impossible. For patients with unsatisfactory recovery, the interosseus reconstruction as well as volar plate constriction for capsulae articulares metacarpophalangeae can be made to improve hand function.

16.8.3 Radial Nerve Injury

The injury rate of radial nerve tops the list among various nerves in upper limbs. Basing on case statistics, the injury rate is about 21%, which is contributed by violent stretch during fracture, pricking and cutting by bone stump or squeezing resulting from embedding of nerve into the crack of fracture sites due to specific anatomical relationship between radial nerve and humeral shaft as well as direct relationship between radial nerve injury and humeral shaft fracture. In addition, the radial nerve injury can also be caused by stretch injury during manual reduction, incise injury during open reduction and crush injury made by steel plate, etc. The radial nerve of forearm is divided into deep branch and superficial branch under common extensor of fingers, and the former goes through musculi supinator and emits a few muscular branches dominating extensor digitorum and extensor pollicis. Most radial nerve injuries on this part are puncture injury or incise injury.

The operation opportunities and therapeutic methods are as follows.

In case of nerve rupture injury with a clean wound and clear boundary, one-stage nerve suture free from tension can be made. For patients on request for two-stage radial nerve repair, such as neuroma excision, if the proximal and distal broken ends of radial nerve are within 3 cm, direct suture can be made; if the length of defect is more than 3 cm, or if the elbow flexion is more than 90°, reinnervation shall be performed while the broken ends of radial nerves are directly sutured, or if the length of defect is more than 5 cm, small saphenous venous arterialization reinnervation shall be made.

As the chance for posterior interosseous nerve (deep branch of radial nerve) to shorten the defect gap via elbow flexion is slim, usually the defect of 1.5 cm requires neural transplantation.

For patients who have lost the opportunity for nerve repair or achieve unsatisfactory recovery following radial nerve repair, tendon transposition can be carried out to improve limb function.

16.9 Microsurgery Repair for Nerve Repair of Lower Limbs

Of all the patients who have undergone nerve injury repair in the last few years, those who have the nerve injury of lower limbs only account 10%. With the development of examination for nerves of lower limbs and increased proficiency in peripheral nerve surgery, more and more nerve injury of lower limbs will be diagnosed and treated.

16.9.1 Injury of Sciatic Nerve

The injury of sciatic nerve is the most common in lower limbs, seriously affecting lower limb function as well as the patients' quality of life. Its surgical treatment is of the first priority. After the sciatic nerve trunk is injured, because it is far away from its dominated muscles and sensory regions, its repair often needs a long time. Depending on different injury mechanisms, the treatment targets are specific. Early definitive therapy is very important.

Most direct incising injury to the sciatic nerve is open sharp injury, such as knife cutting and electric saw cutting, etc. The proportion of complete nerve rupture is large. Since it usually has a clean wound and the nerve injury is not complex, most cases can be debrided during emergency treatment and sutured. In a few cases which shows synaptic cleft of normally less than 2.5 cm following debridement, one-stage suture free of tension by nerve dissociation and joint flexion can be performed. The outcomes following repair are satisfactory.

The firearm injury is common during wartime but the injury to sciatic nerve caused by shotguns such as a civil sporting gun and self-made iron ore gun is also common during peacetime. Usually, the firearm injury is severe with a large damage scale commonly accompanied by fracture and vascular injury. The nerve defect is large, the condition of peripheral soft tissue is poor, and even the skin defect can be seen. The injury to sciatic nerve resulting from firearms often implicates damages to both tibial nerve and nervus peroneus communis. Single injury of tibial nerve or nervus peroneus communis is rare. Most nerve injury is of degree IV or degree V by Sunderland classification. During one stage treatment, it should be noted that thorough debridement is made for the wound without nerve suture. No excision is made of the nerve defect, no broken ends are dissociated, and no wound debridement is conducted to avoid spreading contamination. Use normal tissues to cover dissociated nerves, make the wound heal as soon as possible, and passively move joints to provide basis for two-stage repair. The two-stage repair is carried out 2–3 months after injury. Wound debridement is conducted during exploration. The separation is performed from the normal part to the injured part until two broken ends are dissociated. The neural transplantation and nerve suture are made according to the length of nerve defect following neuroma excision. In a case of long sciatic nerve defect, the defects of tibial nerve and nervus peroneus communis cannot be repaired concurrently with sural nerves of two legs, usually the less important nervus peroneus communis trunk is transplanted to the site of important tibial nerve to recover the sense of planta pedis. In addition, it is difficult for the cable graft with multiple strands of sural nerve to achieve the same diameter for each suture.

16.9.2 Tibial Nerve Injury

The single tibial nerve injury can result from firearm injury, knife stab wound, accidental injury during operation, dislocation of the knee joint or fracture, chondroma on the terminal femur, myositis ossificans, popliteal cyst and posterior leg compartment syndrome, etc.

For open injury of tibial nerve such as incising injury or surgical injury, if the tissue boundary is clear without serious wound response, the operation is easy. Direct one-stage suture free of tension can be performed to repair nerves. The posterior tibial vessels are the main source for blood supply of tibial nerves. The posterior tibial artery and its branches go through the nervous mesenterium and segmentally enter into nerves. Therefore, repair of the tibial nerve should be conducted together with repair of the accompanied injury to posterior tibial vessels to improve blood supply and promote the nervous recovery.

The principles for treating tibial nerve injury and ischiadic nerve injury resulting from firearms are the same. In one-stage surgery, the wound debridement and coverage is performed and the nerve repair is conducted in two-stage surgery.

For advanced injury to the tibial nerve that loses nerve repair value or the tibial nerve injury with unsatisfactory functional recovery, the functional reconstruction by tendon transfer can be made. In patients suffering from long-term tibial nerve injury, since the muscle strengths of peroneus longus and brevis muscles are normal, the talipes calcaneovalgus will happen. The peroneus longus and brevis muscles can be incised and transferred to replace achilles tendon to balance internal and external muscle strengths. The triple arthrodesis can be carried out for children at an age above 12 years and adult patients.

16.9.3 Nervus Peroneus Communis Injury

The simple nervus peroneus communis injury is mainly caused by fracture of lateral tibial plateau, fracture and dislocation of caput fibulae neck, soft tissue contusion or stretch injury of lateral popliteal space, knife cutting, compression of gypsum and small splints, and long-term immobilized stress position, etc.

For nervus peroneus communis injury resulting from sharp incising, if the wound tissue boundary is clear, one-stage direct suture free of tension can be indicated. Notably, on the plane of capitula fibula, the nervus peroneus communis has differentiated into superficial peroneal nerve and deep fibular nerve, which should be separately sutured to achieve ideal functional recovery. The treatment principles and repair methods for nervus peroneus communis injury resulting from firearms are as the same as those for ischiadic nerve and tibial nerve.

For advanced injury to the nervus peroneus communis that loses nerve repair value or the nervus peroneus communis injury with unsatisfactory functional recovery following repair, functional reconstruction by tendon transfer can be made. Usually, the tibialis posterior is forwarded as the dynamic muscle for dorsiflexion foot, while the triple arthrodesis is performed to stabilize the hindfoot in a neutral position to substitute feet for normal walk.

Bibliography

1. Korompilias AV, Lykissas MG, Kostas-Agnantis IP, et al. Approach to radial nerve palsy caused by humerus shaft fracture: is primary exploration necessary? Injury. 2013;44(3):323–6.
2. García-López A, Navarro R, Martinez F, et al. Nerve transfers from branches to the flexor carpi radialis and pronator teres to reconstruct the radial nerve. J Hand Surg Am. 2014;39(1):50–6.
3. Singh R, Mechelse K, Hop WCJ, et al. Long-term results of transplantations to repair median, ulnar, and radial nerve lesions by a microsurgical interfascicular autogenous cable graft technique. Surg Neurol. 1992;37(6):425–31.
4. Niver GE, Ilyas AM. Management of radial nerve palsy following fractures of the humerus. Orthop Clin North Am. 2013;44(3):419–24.
5. Lee YH, Chung MS, Gong HS, et al. Sural nerve autografts for high radial nerve injury with nine centimeter or greater defects. J Hand Surg Am. 2008;33(1):83–6.
6. Pederson WC. Median nerve injury and repair. J Hand Surg Am. 2014;39(6):1216–22.
7. Mavrogenis AF, Spyridonos SG, Antonopoulos D, et al. Effect of sensory re-education after low median nerve complete transection and repair. J Hand Surg Am. 2009;34(7):1210–5.
8. Roganovic Z. Missile-caused median nerve injuries: results of 81 repairs. Surg Neurol. 2005;63(5):410–8.
9. Lundborg G, Rosén B, Dahlin L, et al. Tubular repair of the median or ulnar nerve in the human forearm: a 5-year follow-up. J Hand Surg Br. 2004;29(2):100–7.
10. Woo A, Bakri K, Moran SL. Management of ulnar nerve injuries. J Hand Surg Am. 2015;40(1):173–81.
11. Vordemvenne T, Langer M, Ochman S, et al. Long-term results after primary microsurgical repair of ulnar and median nerve injuries: a comparison of common score systems. Clin Neurol Neurosurg. 2007;109(3):263–71.
12. Bolitho DG, Boustred M, Hudson DA, et al. Primary epineural repair of the ulnar nerve in children. J Hand Surg Am. 1999;24(1):16–20.
13. Pfaeffle HJ, Waitayawinyu T, Trumble TE. Ulnar nerve laceration and repair. Hand Clin. 2007;23(3):291–9.
14. Magdi Sherif M, Amr AH. Intrinsic hand muscle reinnervation by median-ulnar end-to-side bridge nerve graft: case report. J Hand Surg Am. 2010;35(3):446–50.
15. Hillyard RF, Fox J. Sciatic nerve injuries associated with traumatic posterior hip dislocations. Am J Emerg Med. 2003;21(7):545–8.

16. Gauthier L, Allen D, Kim P. Late transection of the sciatic nerve in association with an acetabular reconstruction cage. J Arthroplast. 2010;25(2):333.e21–4.
17. Rodríguez-Lorenzo A, Gago B, Pineda AF. Superficial peroneal and sural nerve transfer to tibial nerve for restoration of plantar sensation after complex injuries of the tibial nerve: cadaver feasibility study. J Plast Reconstr Aesthet Surg. 2011;64(11):1512–6.
18. IJkema-Paassen J, Jansen K, Gramsbergen A, Meek MF. Transection of peripheral nerves, bridging strategies and effect evaluation. Biomaterials. 2004;25(9):1583–92.
19. Tzika M, Paraskevas GK, Kitsoulis P. The accessory deep peroneal nerve: a review of the literature. Foot. 2012;22(3):232–4.
20. Wechselberger G, Schoeller T, Bauer T, et al. Increased peroneal nerve injuries caused by ski edges. Lancet. 1999;353(9154):753–4.
21. Iorio J, Criner K, Rehman S, et al. Nerve and tendon injury with percutaneous fibular pinning: a cadaveric study. Injury. 2014;45(12):2051–4.
22. Katirji B. Peroneal nerve. Encyclopedia of the neurological sciences. 2003. p. 849–55.
23. Phillips LH 2nd, Daube JR. Lumbosacral spinal evoked potentials in humans. Neurology. 1980;30(11):1175–83.
24. O'Brien JP, Mackinnon SE, MacLean AR, Hudson AR, Dellon AL, Hunter DA. A model of chronic nerve compression in the rat. Ann Plast Surg. 1987;19(5):430–5.
25. Dellon AL, Mackinnon SE. An alternative to the classical nerve graft for the management of the short nerve gap. Plast Reconstr Surg. 1988;82(5):849–56.
26. Millesi H, Meissl G, Berger A. The interfascicular nerve-grafting of the median and ulnar nerves. J Bone Joint Surg Am. 1972;54(4):727–50.
27. Weiss P, Taylor AC. Guides for nerve regeneration across gaps. J Neurosurg. 1946;3:375–89.
28. Dellon AL. Clinical use of vibratory stimuli to evaluate peripheral nerve injury and compression neuropathy. Plast Reconstr Surg. 1980;65(4):466–76.
29. Dellon AL. The vibrometer. Plast Reconstr Surg. 1983;71(3):427–31.

17 Treatment of Peripheral Nerve Entrapment

Can-Bin Zheng and Qing-Tang Zhu

17.1 Thoracic Outlet Syndrome

Thoracic outlet syndrome (TOS) is a series of symptoms which is caused by the compression of brachial plexus and subclavian arteries and veins at the thoracic outlet and the attachment of the pectoralis minor muscle and the condyle. The symptoms include the upper limbs with varying degrees of sensory, motor and circulatory disorders, which are caused by the compression of the brachial plexus and the subclavian blood vessels.

17.1.1 Pathogenesis

The pathogenesis of TOS is anatomical variation of bone tissue and soft tissue at the outlet of thorax, of which bone tissue variation accounts for about 30%. The anatomical variation includes the long seventh cervical transverse process, the variation of the cervical rib and the first rib, the formation of callus caused by the fracture of the first rib and clavicle. The fracture results in brachial plexus nerve and subclavicular vascular compression. Soft tissue variation includes congenital or acquired changes in the abnormal fibrous fascia and the anterior and middle scalenus. Owing to the various anatomical variations of bone tissue and soft tissue at the outlet of thorax, various degrees of compression of brachial plexus nerve and subclavian arteriovenous vein resulted in a series of syndromes of nerve provocation and vascular compression.

17.1.2 Clinical Presentation and Diagnosis

Thoracic outlet syndrome is more common in young and middle-aged women, mostly unilateral, and generally has no obvious history of trauma. The most common syndrome is the medial cutaneous nerve of the forearm and the underarm brachial dysfunction when the brachial plexus is compressed. Patients with fifth and sixth cervical nerve root compressions showed fatigue associated neck and shoulder discomfort, pain, dysfunction of scapular nerve, sacral nerve, and musculocutaneous nerve. Raynaud's phenomenon occurs in patients with sympathetic dysfunction. Most patients have positive anterior scale muscle tone test. The examination method is that the patient's head is turned to the healthy side when he or she is seated. The neck is overextended, and the contralateral arm is pulled downward. Positive signs are the aggravated numbness and pain of the affected limb and pain radiation to the distal end. When the blood vessel is compressed, the patient does not have severe blood flow disorder. When the lesion stimulates the blood vessel, the upper limb sleeve sensation abnormality may occur, and the affected limb is cold when it is lifted. The color of skin is pale, and the radial artery beats weakly. When the subclavian vein is severely compressed, distal limb edema and cyanosis appear. When blood vessels are under severe pressure, subclavian blood vessel thrombosis can occur, and the distal part of the limb will present blood transport disorder.

The X-ray examination of the cervical spine and chest is useful for discovering bony abnormalities, especially degenerative changes in the cervical ribs and bones. For those with severe dysplasia, subclavian artery and venography can be performed to understand the position of compression, occlusion or stenosis and the situation of collateral circulation. The diagnosis and localization of the compression site can be obtained by the cathode stimulation along the nerve. The specific method is to measure the conduction velocity of the movement in different parts of the ulnar nerve, the median nerve, the phrenic nerve, and the musculocutaneous nerve.

C.-B. Zheng · Q.-T. Zhu (✉)
Department of Orthopedics, The First Affiliated Hospital of Zhongshan University, Guangzhou, China
e-mail: zhengcanbin@qq.com; qtzhu@qq.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_17

17.1.3 Treatment

If the patient has mild symptoms and no symptoms of nerve damage and vascular compression, non-surgical treatment can be used. Massage can also be used to relax all the muscles that are tight, and the pain points are partially closed. Some symptomatic drugs, such as painkillers, muscle relaxants, etc. can also be used. If conservative treatment is not effective, it should be treated with surgery. Surgical method includes: (1) upper cranial plexus lysis to remove compression factors around the brachial plexus; (2) the first ribectomy, the first rib is removed, the anterior, middle and small scalene muscles lose their dead points, and the bottom-up pressure on the brachial plexus was completely relieved; (3) endoscopic release, under the aid of endoscope, cutting the anterior and middle scalene muscles of the anterior and middle scalene muscles through the micro-incision of the neck, and relieving the compression of the brachial plexus by the scalene muscle, which can achieve better clinical effect.

17.2 Carpal Tunnel Syndrome

Carpal tunnel syndrome, due to increased pressure in the carpal tunnel, causes the median nerve to be compressed, resulting in symptoms and signs of neurotransmission. This symptom is common in women, especially in middle-aged women.

17.2.1 Pathogenesis

The carpal tunnel consists of the carpal bone and ligament, with nine tendons and median nerves passing through it. The pathogenesis of carpal tunnel syndrome is that the median nerve is mechanically compressed by the transverse ligament of the wrist, causing ischemia and hypoxia, leading to nerve conduction disorder. Repeated ischemia and hypoxia of the nerve can cause demyelination of the nerve, hyperplasia of fiber between the bundles, and even severe Wallerian degeneration. All factors that increase the pressure in the carpal tunnel can cause disease, such as the transverse ligament of the wrist, fracture, dislocation and space-occupying lesions.

17.2.2 Clinical Presentation and Diagnosis

Carpal tunnel syndrome is more common in middle-aged women. The clinical diagnosis is mainly based on the symptom that the numbs of three hemiplegia on the temporal side, the history of nighttime awakening, the positive Tinel sign on the wrist, and the positive Phalan sign. The positive Phalan sign refers to the symptoms that if the wrist is over-grip or stretched for 1 min, there will be numbness or numbness in the hand. Neurophysiological examination and high-frequency ultrasound examination play an important role in definitive diagnosis. According to the time of compression of the median nerve, the intrinsic can be divided into early, middle and late stages. According to the severity of the lesion, it can be divided into mild, moderate and severe. The longer the nerve is compressed, the more severe the lesion will be, and the more obvious the symptoms and signs of the patient will be.

17.2.3 Treatment

The treatment plan for carpal tunnel syndrome is mainly based on the severity of the disease. The light type should be based on conservative treatment, while the medium and heavy cases should be based on surgical treatment. Conservative treatments include carpal tunnel neutral bracing, non-steroidal antipyretic analgesics, vitamins B, and partial closures. Surgical treatment includes open and minimally invasive endoscopic neurodecompression.

Open carpal tunnel release (OCTR) is operated under direct vision. A 2.5-cm incision is made in the proximal palm over the transverse carpal ligament, distally beginning at the intersection of a line drawn along the radial border of the ring finger and Kaplan's cardinal line (Fig. 17.1). After skin incision, the subcutaneous tissue is incised to expose the transverse carpal ligament. Then the distal portion of the ligament is divided and the ligament is released from distally to proximally (Fig. 17.2). The advantages of OCTR include but not limited to direct visualization of the thenar motor and sensory branches of the median nerve, and feasibility to deal with the lesions within the carpal tunnel. Care should be taken not to injure the superficial palmar arch.

We prefer to release the carpal tunnel under endoscopy (ECTR) using the single-portal technique introduced by Dr. Ip. A 1.5 cm incision is made along the wrist crease, starting at the ulnar border of palmaris longus tendon (Fig. 17.3). After the skin incision is made down to the deep fascia, the palmaris longus tendon is retracted radially and the median nerve at the entrance of carpal tunnel is identified. A subcutaneous tunnel is made over the transverse carpal ligament from the proximal to the distal end of the carpal tunnel using a curved mosquito hemostat. Different from the standard endoscopic carpal tunnel release in which the scope is introduced into the carpal tunnel, the technique described here is to place a 2.7 mm endoscope above the ligament, and scissors are used to divide the transverse carpal ligament proximally to distally under endoscopic observation (Fig. 17.4). The completeness of the distal cut is confirmed by checking for remaining cross bands and the yellow fat at the end of the carpal tunnel. Be careful to avoid any injury to the median nerve, especially its recurrent branch.

Endoscopic minimally invasive treatment of carpal tunnel syndrome is more effective than open surgery. ECTR is less invasive than OCTR but leads to a better cosmetic outcome

Fig. 17.1 The incision for open carpal tunnel release. A 2.5-cm incision is made in the proximal palm over the transverse carpal ligament, beginning distally at the intersection of Kaplan's cardinal line and a line drawn along the radial border of the ring finger

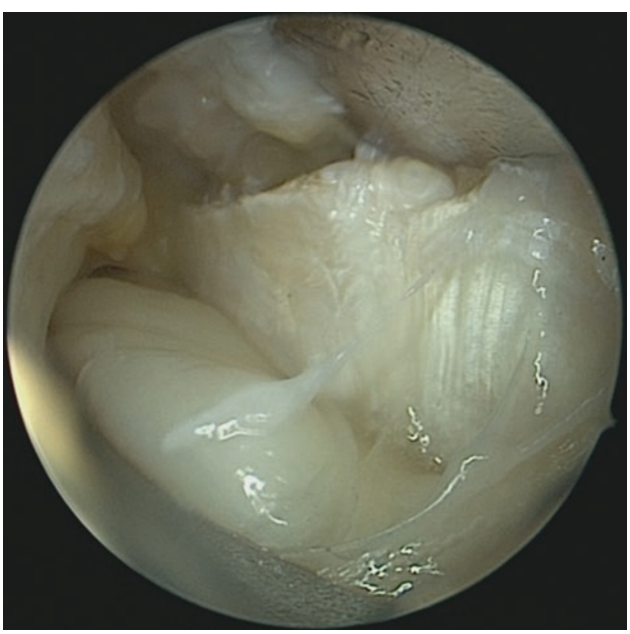


Fig. 17.2 The carpal tunnel is opened and the median nerve and its branches are released under direct observation

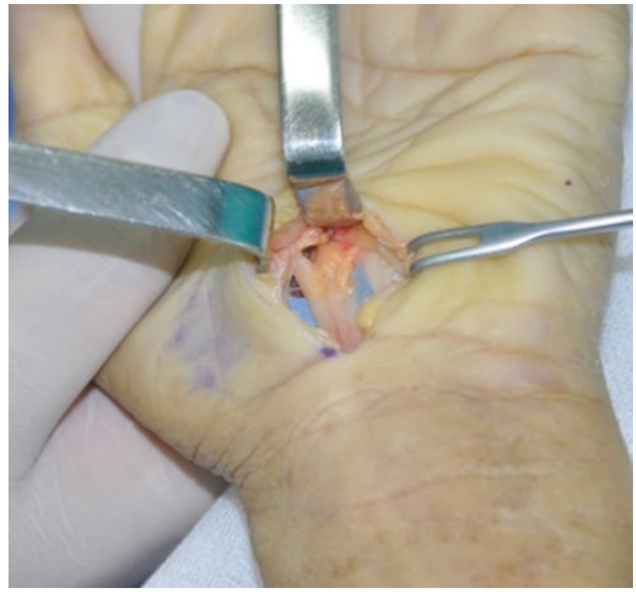


Fig. 17.3 The incision for single-portal endoscopic carpal tunnel release. A 1.5 cm-incision is made along the wrist crease, starting at the ulnar border of palmaris longus tendon

Fig. 17.4 The transverse carpal ligament is divided under endoscopic observation

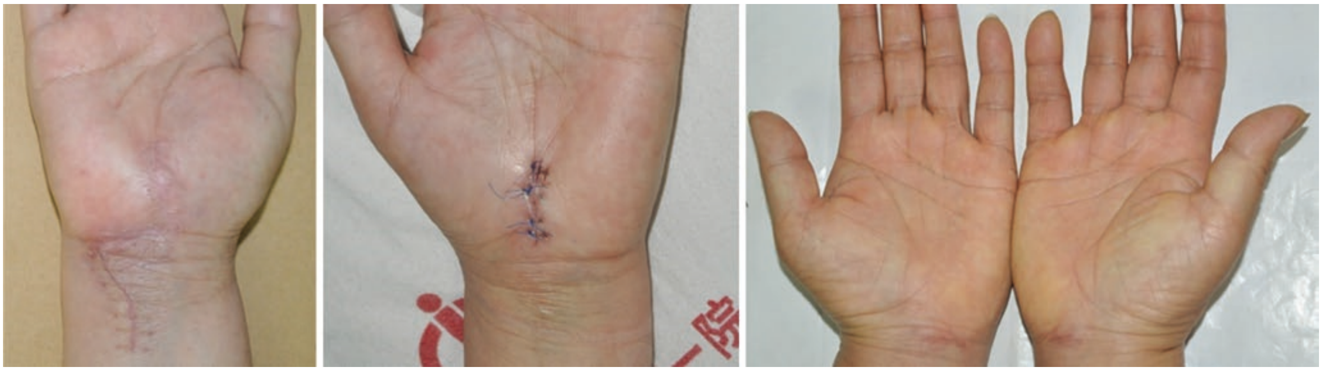


Fig. 17.5 Surgical scar for extended open carpal tunnel release (left), standard open carpal tunnel release (middle) and endoscopic carpal tunnel release (right)

(Fig. 17.5). To many, its disadvantages are steep learning curves and limited visualization for the endoscopic or blinded mini-open techniques. Despite the fact that the risk of neurovascular injury treated using the endoscopic technique is not higher in most of the comparative studies, there is a higher risk that the ligament is not completely released.

17.3 Cubital Tunnel Syndrome

Cubital tunnel syndrome refers to the ulnar nerve being compressed by various factors in the special anatomy of the elbow, resulting in symptoms and signs mainly based on ulnar nerve palsy.

17.3.1 Pathogenesis

Cubital tunnel is a bony fiber tube located behind the upper iliac crest of the humerus. It consists of the ulnar nerve groove and arched ligament. The arched ligament is the ulnar wrist flexor which starts from the humeral head and ulnar head. The arcuate ligament is an important anatomical factor for the ulnar nerve to be compressed in the cubital tunnel. The humerus head side of ulnar wrist flexor muscle start from the common tendon of the extensor condyle in the humerus. The ulnar head side of ulnar wrist flexor muscle starts from the inner edge of the olecranon and the posterior edge of the ulna. The tarsal membrane is connected between the two ends to form an arcuate tough free edge. The main cause of ulnar nerve compression is that the space of the cubital tunnel is narrowed or the content is increased, and the internal pressure of the cubital tunnel is increased. As a result, the neurotrophic blood vessels are compressed, the nerve is hypoxic, and the symptoms of nerve paralysis are caused.

17.3.2 Clinical Presentation and Diagnosis

Symptoms include: (1) soreness or tingling from the ulnar nerve groove, along the lateral ring of the forearm ruler, and the radiation of the little finger; (2) forearm and palm ulnar side, little finger and ring finger ulnar side half numbness discomfort.; (3) symptoms of atrophy in the small intermuscular and interosseous muscles of the hand; (4) Minor finger adduction dysfunction, claw-shaped hand deformity, Froment sign positive. Electromyography (EMG) is an important diagnostic tool for the reduction of ulnar nerve conduction velocity across the elbow. Diagnosis needs to be differentiated from cervical spondylosis, thoracic outlet syndrome and carpal tunnel syndrome.

17.3.3 Treatment

Conservative treatment may be considered for early and mild cases. The methods include splint elbow joint brake, oral analgesic and local steroid injection. In patients with inefficacy of conservative treatment, progressive exacerbation of symptoms and muscle atrophy, early surgical treatment should be performed.

17.3.3.1 Ulnar Nerve Release and Anterior Subcutaneous Transposition

A 10- to 12-cm curvilinear incision centered over the course of the ulnar nerve is made between the medial epicondyle and the olecranon. It is safer to identify the nerve proximal to the ligament of Osborne. The ligament becomes tighter as the elbow is brought into flexion, confirming a dynamic compression of the ulnar nerve. It should be incised proximally to distally to minimize the chances of injury. The nerve is then followed along the postcondylar groove and between the two heads of the flexor carpi ulnaris (FCU) to exclude other sites of compression. If there is no bony deformity such as cubitus valgus, the nerve can be released in situ and should not be mobilized from the groove because doing so would increase the risk of subluxation. Another dynamic test of flexion of the elbow is performed to ensure that the nerve is not compressed or does not tend to subluxate from the cubital tunnel during flexion. In the positive cases, an anterior transposition would ensure a better long-term result.

The medial triceps could also represent a site of compression, with the nerve being compressed between the belly of the muscle and the medial intermuscular septum (MIS). In this case, the MIS is dissected and excised. The FCU is also partially divided. The fascia of the flexor pronator origin is used to contain the mobilized nerve and attached to the superficial subcutaneous layer.

17.3.3.2 Endoscopic Cubital Tunnel Release

The course of the ulnar nerve around the elbow and the range of dissection are marked (Fig. 17.6). A 1.5 cm incision is made just over the cubital tunnel behind the medial epicondyle, and the initial dissection is to identify the ulnar nerve proximal to the entrance of cubital tunnel. Then the ligament of Osborne is divided and the cubital tunnel is released (Fig. 17.7). A 8 cm subcutaneous tunnel in the proximal forearm is made along the course of the ulnar nerve, and a cannula made from a 10-mL syringe is placed. Next a 30° scope is introduced, the FCU is split and the ulnar nerve is released under an endoscopic monitor (Fig. 17.8). Release of the ulnar nerve proximal to the cubital tunnel is performed in a similar manner, being aware that the medial intermuscular septum needs to be dissected (Fig. 17.9).

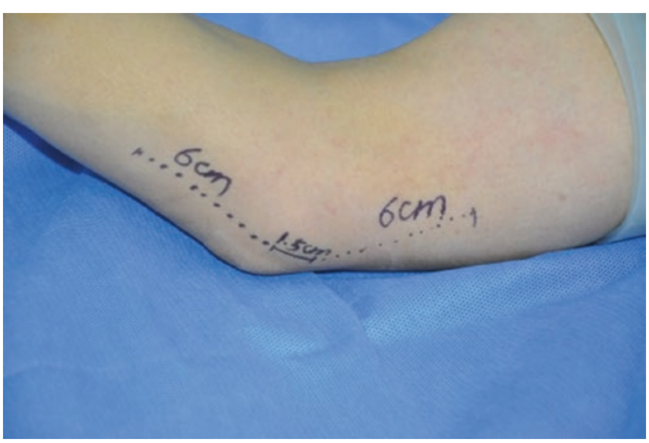


Fig. 17.6 The course of ulnar nerve around the elbow and the range of dissection are marked. A 1.5 cm incision over the cubital tunnel is made for endoscopic cubital tunnel release

Fig. 17.7 The ligament of Osborne is divided and the cubital tunnel is released, revealing a notch on the ulnar nerve caused by chronic compression of the ligament of Osborne

Fig. 17.8 A subcutaneous tunnel in the proximal forearm is made and a cannula made from a 10-mL syringe is placed before a 30° scope is introduced to monitor the dissection of flexor carpi ulnaris (FCU) and release of ulnar nerve.

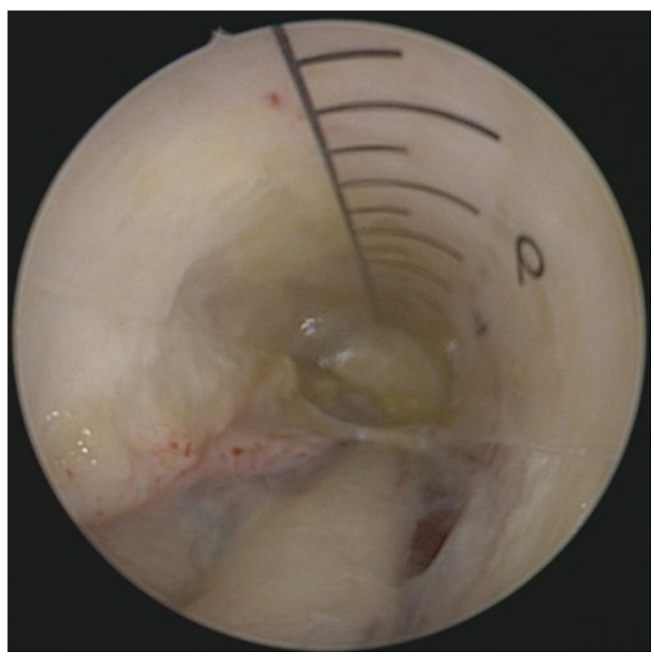


Fig. 17.9 Release of the ulnar nerve proximal to the cubital tunnel is performed with an endoscopic monitor

17.4 Ulnar Tunnel Syndrome

The carpal ulnar tube, which is also called the Guyon tube, is a bone fiber sheath, surrounded by the ulnar side of the transverse ligament of the wrist and its superficial palmar carpal ligaments. In the tube, there are the ulnar nerve, the ulnar artery and its accompanying vein. The ulnar nerve is compressed in the ulnar tube which leads to hand movement and sensory dysfunction, and the intrinsic muscular atrophy syndrome, is called Guyon tunnel syndrome or Guyon syndrome.

17.4.1 Pathogenesis

The part of the superficial layer of the transverse ligament of the wrist is the anterior wall of the carpal ulnar tube, and its deep layer is the posterior wall. The inner side wall is the pea bone and the pisohamate ligament, and the outer side wall is the hook bone. There are ulnar nerve and the ulnar artery passing through. There is a hook-and-loop ligament connection between the uncinate process of hamate and the pea bone. The short flexor of the little finger has two attachment points to the pea bone and the hook uncinate process, and a tough tendon arch is formed between the two points. The bow and the bean ligament form a narrow and slanted bean hook crevice on the side of the ulnar, and the deep branch of the ulnar nerve and the deep branch of the ulnar artery pass through it.

The causes of the ulnar tube syndrome include hypertrophy of the volar ligament, space-occupying lesions, and chronic strains, and so on, which lead to compression of the ulnar nerve in the tube.

17.4.2 Clinical Presentation and Diagnosis

The pain of the ulnar side of the wrist, the sensory abnormalities of the little finger, and half of the ring finger side of the ulnar side, the hands fine movement disorders. The ulnar side buckle pain, Tinel sign (+), ring and small fingers claw-shaped hand deformity, Froment sign (+), Wartenberg sign (+), small fish muscle and interosseous muscle atrophy, muscle strength decreased. B-ultrasound shows the ulnar nerve compression at the ulnar canal. The ulnar nerve injury potential was found by electromyography. The disease should be distinguished from the elbow ulnar nerve compression, thoracic outlet syndrome, cervical spondylosis, carpal tunnel syndrome, and so on.

17.4.3 Treatment

The Guyon tunnel syndrome which is leaded by non-occupational lesions, can receive non-surgical treatment in the early stage, such as partial closure, physical therapy, oral vitamins, and so on. The course of the disease is more than 1 month, if the non-surgical treatment is not effective, or the course of disease is more than 3 months, the patients whose hypothenar muscles and interosseous muscles atrophied should be treated surgically. Surgery removes the cause of compression and neurolysis. Including the ulnar tube incision, resection of the internal mass, hyperplasia of the arcus tendineus, chorda, scar and osteophyte, if there is a fracture, it should be reset, etc.; the epineurium is debonded under the microscope. The bleeding should be completely stopped before the end of the operation to prevent the hematoma from forming and compressing the nerve again.

17.5 Radial Tunnel Syndrome

The deep branch of the sacral nerve is forced to undergo different degrees of paralysis due to traction, friction or mechanical pressure, which lead to dysfunction of the thumb and extension fingers. It is clinically known as supinator syndrome and interosseous dorsal nerve palsy or radial tunnel syndrome.

17.5.1 Pathogenesis

The musculospiral nerve, where from 10 cm from the proximal end of the lateral epicondyle of the humeru, passed from the lateral muscles interval of the upper arm into the diaphragm between the brachioradialis and the musculus biceps brachii and brachialis. It is divided into two branches which are deep and shallow ones where is about 3 cm above and below the humeroradial joint. The superficial branch descends along the surface of the supinator muscle and leaves the gap; the deep one passes through the supinator muscle bow (Frohes bow) into the position where is between the deep and shallow layers of the supinator muscle. The deep branch of the musculospiral nerve bypasses the radius neck to the dorsolateral side of the forearm and enters the front of the supinator muscle. The muscle branch of it supports the musculi extensor carpi radialis brevis and musculi supinator. At the lower edge of the supinator muscle, it is divided into two branches which dominate the extensor carpi ulnaris muscle, extensor digitorum brevis tendon and musculi of fingers and the abductor pollicis longus, respectively. The segment of the phrenic nerve from the lateral muscle of the penetrating arm to the posterior circumflex muscle is called the radial tunnel, where the nerve is susceptible to compression.

17.5.2 Clinical Presentation and Diagnosis

The symptoms of radial tunnel syndrome are tenderness and pain on the outside of the elbow. There is no relief at rest. There is pain at night. The tenderness point is most obvious at the head and neck of radius, especially at the proximal part of supinator muscle along the direction of nerve. The strength of the extension of the thumb and the fingers is weakened or even disappeared, and the movement of the metacarpophalangeal joints is also limited, especially in the last 45°. But there's no sensory obstacles. Electromyography: The musculospiral nerve conduction velocity is slowed or the latency is prolonged, and the fibrillation potential is present in the forearm extensor muscle group.

The symptoms of radial tunnel syndrome are very similar to those of a tennis elbow. As in a tennis elbow, pain in radial tunnel syndrome often starts near the lateral epicondyle. The pain gets worse when the patient bends his or her wrist backward, places the forearm in supination position, or holds something with a stiff wrist or straightened elbow.

The diagnosis of radial tunnel syndrome can be difficult. Many of the cases are initially diagnosed as a tennis elbow. Tests do not always help tell the two conditions apart. Doctors need to take a detailed medical history and do a physical examination to look for the most painful spot.

17.5.3 Treatment

Treating radial tunnel syndrome can be frustrating. Getting the patient's symptoms under control and helping the patient regain the use of his or her elbow can be a great challenge. The most important part of the patient's treatment is to avoid the activity that caused the problem in the first place. The patient needs to avoid repetitive activities that require the wrist to bend repeatedly backwards. Repeated use of the wrist in twisting motions (such as using a screwdriver) also makes the problem worse. If the patient's occupational tasks caused his or her condition, the patient should change his or her job. This is crucial for a successful treatment. The patient needs to take frequent breaks as he or she works and plays. Forceful pushing, pulling, and grasping should also be limited.

If symptoms are worse at night, the patient may want to wear a lightweight plastic arm splint while sleeping. This may limit the movements of the patient's elbow at night, ease further irritation, and keep the elbow at rest, giving the nerve more time to recover from irritation and pressure.

If conservative treatment is ineffective, surgery is required. The Frohse arch and the supinator tube are incised to allow the compressed musculospiral nerve to be fully decompressed. If the Tendinous portion of the extensor carpi radialis brevis is oppressive to the nerve, it should be removed together.

17.6 Piriformis Syndrome

The acute and chronic injury of the piriformis and its surrounding soft tissues, aseptic inflammation and other factors lead to the sciatic nerve and nervus cutaneus femoris posterior to be compressed, causing pain in the buttocks and back of the thigh, called piriformis syndrome.

17.6.1 Pathogenesis

The piriformis starts from the pelvic surface of the second to fourth sacral bone. After coming out of the greater sciatic foramen, the muscle fibers become tendons, and stop above the femoral trochanter. It is the external rotation muscle of the hip joint. The upper edge has the superior gluteal artery and the superior gluteal nerve. The lower edge has vascular nerves such as the inferior gluteal artery, the inferior gluteal nerve, the sciatic nerve, and the nervus cutaneus femoris posterior. The sciatic nerve passes slightly outside, from the anterior and posterior aspect of the gluteus maximus to the posterior side of the thigh, where it is divided into the tibial nerve and the common peroneal nerve, which dominates the skin of the thigh, calf and foot. Trauma, strain and anatomical variation can cause traction and compression of the sciatic nerve.

17.6.2 Clinical Presentation and Diagnosis

Piriformis syndrome is mainly characterized by pain in the buttocks, the posterior side of the thigh, the lateral side, and the inside of the calf. It can also be radiated to the sole of the foot with numbness and tactile dysfunction. The severe pain is hard to bear, and the general painkillers are difficult to work. Examination revealed tenderness and radiation pain in the piriformis. In the chronic phase, the hip muscles are atrophied, the piriformis is diffusely thickened, or the muscle fibers are localized and hardened, and the piriformis test is positive. Straight leg raising test is mostly negative. Ultrasound examination showed that the piriformis muscles were thickened, widened, and the surface was uneven, and the morphology of the sciatic nerve was observed at the same time.

17.6.3 Treatment

The syndrome is mainly received non-surgical treatment, the purpose is to relieve piriformis tendon, promote inflammation absorption, relieve nerve compression, and improve blood circulation. In the acute phase, it is feasible to treat ultraviolet rays or ultrashort wave direct current ion permeation, and it is feasible to treat wax therapy, mud therapy or cupping in the chronic phase. Ultrasound treatment also has a good effect. Partial closure with a mixture of lidocaine and prednisolone relieves symptoms. Surgical treatment should be considered if the non-surgical treatment is not effective for more than 4 weeks. Surgery is performed to relieve nerve compression. If the piriformis is hypertrophy, variability or Tendinous press-fitting, the muscle and tendon are cut; if the scar is adhered, the scar is relieved; If the sciatic nerve sheath is found to be thick and hard, the neurolysis should be performed according to the principles of microsurgery.

17.7 Peroneal Nerve Entrapment

The common peroneal nerve compression syndrome is a symptom of a series of common peroneal nerve injuries caused by the compression of various factors after the peroneal nerve passes through the popliteal space and bypasses the neck of fibula into the peroneus longus. Because this section of the common peroneal nerve position is superficial, and the anatomical relationship around it is adjacent to the hard tissue such as tendon, ligament and bone, there are more cases of clinical compression.

17.7.1 Pathogenesis

The common peroneal nerve passes through the lateral groove of the popliteal fossa and closes to the collum fibulae into the fibular bone. The fibular bone refers to a bone fiber tunnel composed of the transitional part of the iliac crest muscle and the transitional part of the popliteal fossa fascia and the neck of fibula. In the fibular bone, the common peroneal nerve is closely attached to the periosteum of the fibula. The common peroneal nerve passes through the narrow tunnel and enters the calf, where it is divided into superficial peroneal nerve and deep peroneal nerve. Bad body position, improper traction and local compression can increase the pressure inside the fistula, make the blood supply to the common peroneal nerve, causing congestion, edema, nerve demyelination and other changes.

17.7.2 Clinical Presentation and Diagnosis

The patient presented with numbness in the anterior and lateral of crus, the back of the foot is numb, hypoesthesia or even feeling loss. Foot and toe extension, foot valgus fatigue, muscle weakness, tibialis anterior muscle and fibula long and short muscle atrophy. Severe cases can have the symptoms like foot drop, varus deformity. The Tinel sign at the fibular head is positive. Ultrasound examination can show the shape of the nervus peroneus communis, the location and extent of nerve impingement. X-ray film can show the presence or absence of tumor, fracture or poroma of fibula's head and neck. Electromyography: It has a certain significance on the degree and location of nerve impingement. Dynamic nerve impingement should be differentiated from chronic anterolateral or anterior fascial compartment syndrome.

17.7.3 Treatment

Generally, non-surgical treatment is given for 3–4 months. Without external compression and tumors, tumors, fractures, and osteotylus, the patients should be avoided pressure, pay attention to sitting posture, and do not across your legs. If the nerve pressure is caused by the calf compartment syndrome, an emergency incision decompression should be performed immediately, and a neurological decompression surgery should be performed. If there is no emergency, the skin sensory disturbance will be restored, to a certain extent, after 4 weeks of conservative treatment. If there are signs of recovery of motor function, the conservative treatment can be continued. If the treatment is ineffective or poor in function and the neurological function is not complete, surgical exploration and neurolysis are needed.

17.8 Tarsal Tunnel Syndrome

Metatarsal tunnel syndrome, which also known as posterior tibial nerve impingement syndrome or malleolar canal syndrome, is a series of symptoms and signs caused by compression when the posterior tibial nerve supports the underlying fibrous tube through the flexor muscle.

17.8.1 Pathogenesis

Any disease and trauma can reduce the fistula gap, causing the posterior tibial nerve or branch to be pulled, rubbed or compressed to cause fistula syndrome.

17.8.2 Clinical Presentation and Diagnosis

Pain and paresthesia appear in the head of metatarsal bone which is obvious when standing or walking. When have a rest or there's no weight, it can be anesis, but there are also those who wake up at night which because of the pain. There is tenderness at the foot flexor retinaculum and Tinel sign is positive; when the tarsal tunnel is pressed, the symptoms are induced or aggravated; the plantar sensation is reduced, and in severe cases, the claw-toe deformity may occur due to atrophy of the intramuscular muscle. Electrophysiological examination sometimes reveals that the tibial nerve conduction velocity is slowed down. The metatarsal tunnel syndrome should be differentiated from Plantar fasciitis.

17.8.3 Treatment

For the early symptoms of this disease is mild, or the initial attack, Mainly rest and brake, timely release of external stimuli, such as wearing loose wide shoes and socks, local physiotherapy, wax therapy, hot water bath, medication, closure, etc. which can alleviate edema and adhesion can significantly relieve symptoms, but it is easy to relapse. If the conservative treatment is ineffective, the tarsal tunnel can be opened and the phrenic nerve can be released.

Microsurgical Repair of Peripheral Vascular Injury

18

Guangyue Zhao and Long Bi

Peripheral vascular injury is common in both peacetime and wartime. It is mostly injury to both artery and vein, complicated with fracture of limbs and nerve damage. Improper treatment of peripheral vascular injury will lead to fatal massive hemorrhage and ischemic gangrene or dysfunction of limbs. Before appearance of microscopic orthopaedics, perstriction was frequently used to save the life of patients with peripheral vascular injury but the amputation rate was up to 49%. Along with the developing techniques of vascular repair in recent years, treatment of peripheral vascular injury has changed to be aimed at repair. Moreover, thanks to update first-aid concepts and technical enhancement, mortality and amputation rate associated with peripheral vascular injury have decreased significantly.

18.1 Applied Anatomy of Peripheral Vessels

18.1.1 Applied Anatomy of Peripheral Vessels

18.1.1.1 Classification of Peripheral Arteries

According to the structure and anatomical features, peripheral arteries are classified into three types: large, middle and small.

Large Arteries

Large arteries include brachial artery, femoral artery and popliteal artery. They have a very thick tunica media composed of 40–70 layers of elastic membrane (adults: about 70 layers; newborn: about 40 layers). There are many pores on the membrane. Elastic membranes are connected with each other via elastic fibers. Between elastic membranes are circular smooth muscles and a few collagen fibers and elastic fibers. The main component of membrane matrix is chondroitin sulfate. Adventitia is relatively thin and constituted by connective tissues, most of which are collagen fibers. A small quantity of elastic fibers also exists. There is no obvious external elastic membrane. Adventitia is rich in nutritional vessels, lymph vessels and nerves. Sometimes, a few smooth muscles can be seen. Large vessels are good in elasticity but poor in contractility, thus also known as elastic arteries.

Middle Arteries

Except large arteries, most arteries that have a name in anatomy are middle ones. Both the wall thickness and lumen diameter of a middle artery are smaller than those of a large artery. Intima of a middle artery has thin subendothelial layer and obvious internal elastic membrane. Tunica media is composed of 10–30 layers of circularly-arranged smooth muscles. Some elastic fibers and collagen fibers exist between muscles. Adventitia is mainly loose connective tissue, and has a thickness equivalent to tunica media. For most middle arteries, obvious external elastic membrane exists at the junction of tunica media and adventitia. A middle artery has a vessel wall rich in smooth muscles, so it is also called as a muscular artery.

Small Arteries

Small arteries have a diameter of 0.3–1 mm, including several levels of branches with varying thickness. They also belong to muscular arteries. The intima of a larger small artery has obvious internal elastic membrane. Tunica media has several layers of smooth muscles. Adventitia has a thickness close to tunica media and usually has no external elastic membrane. Their wall structure is similar to that of a middle artery, but each layer is thinner. Internal elastic membrane is obvious. Tunica media contains several layers of smooth muscles. External elastic membrane is not obvious. Contraction and relaxation of smooth muscles can reduce lumen diameter and increase blood flow resistance. Therefore, a small artery is also called as a resistance artery.

G. Zhao (✉) · L. Bi
Department of Orthopaedics, Xijing Hospital, Air Force Medical University, Xi'an, People's Republic of China
e-mail: zhaogyue@fmmu.edu.cn; bilong@fmmu.edu.cn

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_18

18.1.1.2 Applied Anatomy of Main Arteries of Upper Limb

Main arteries of upper limb include: axillary artery, brachial artery, ulnar artery and radial artery (Fig. 18.1).

Axillary Artery

Axillary artery is originated from subclavian artery (aortic arch as left-side starting point and brachiocephalic trunk as right-side starting point), dividing into three segments with pectoralis minor muscle as the mark. The first segment is from lateral margin of the first rib to upper margin of pectoralis minor muscle; its branch is superior thoracic artery. The second segment is enveloped by three cords of brachial plexus like a Chinese character "Pin", and covered by pectoralis minor muscle; its branches include lateral thoracic artery and thoracoacromial artery. The third segment is located between inferior margin of pectoralis minor muscle and inferior margin of teres major; its branches include subscapular artery and anterior and posterior humeral circumflex arteries.

Brachial Artery

At inferior margin of latissimus dorsi, axillary artery is renamed as brachial artery, which runs in medial bicipital sulcus together with median nerve. The superior segment of brachial artery locates at the medial to median nerve; through the rare region of median nerve, it goes to the lateral side of median nerve and reaches cubital fossa via deep surface of bicipital aponeurosis. At the height of radial neck, it is divided into radial artery and ulnar artery. Brachial artery is situated at superficial part of cubital fossa. Its pulse can be palpated clearly. In clinical practice, it is usually used as the auscultation part during blood pressure measurement. The main branches of brachial artery include the three. (1) Deep brachial artery: It is beneath the inferior margin of teres major and originated from posterior–medial wall of brachial artery. Deep brachial artery and radial nerve pass through between the medial and lateral head of triceps brachii muscle into sulcus of radial nerve at posterior brachial region. Fracture of middle humerus may easily damage deep brachial artery and radial nerve. (2) Superior ulnar collateral artery: It starts from brachial artery slightly below the origin of deep brachial artery, passes through medial brachial intermuscular septum together with ulnar nerve to dorsal surface of medial epicondyle, and is anastomosed with ulnar recurrent artery and inferior ulnar collateral artery. (3) Superior ulnar collateral artery: It is originated from brachial artery about 3–4 cm above medial epicondyle, distributing anterior and posterior to medial epicondyle, and involved in composition of arterial rete of elbow joint.

Ulnar Artery

Ulnar artery descends between musculus flexor carpi ulnaris and musculus flexor digitorum sublimis, passes through the radial side of pisiform bone to palm. It is anastomosed with superficial palmar branch of radial artery to form deep palmar arch. During its course, ulnar artery has main branches besides branches into ulnar muscles of forearm and articular cubital rete. (1) Common interosseous artery: It is divided into anterior and posterior interosseous arteries, which respectively descends along the anterior and posterior surface of forearm interosseous membrane. During its course, common interosseous artery branches out into forearm muscle, ulna and radius. (2) Deep palmar branch passes through

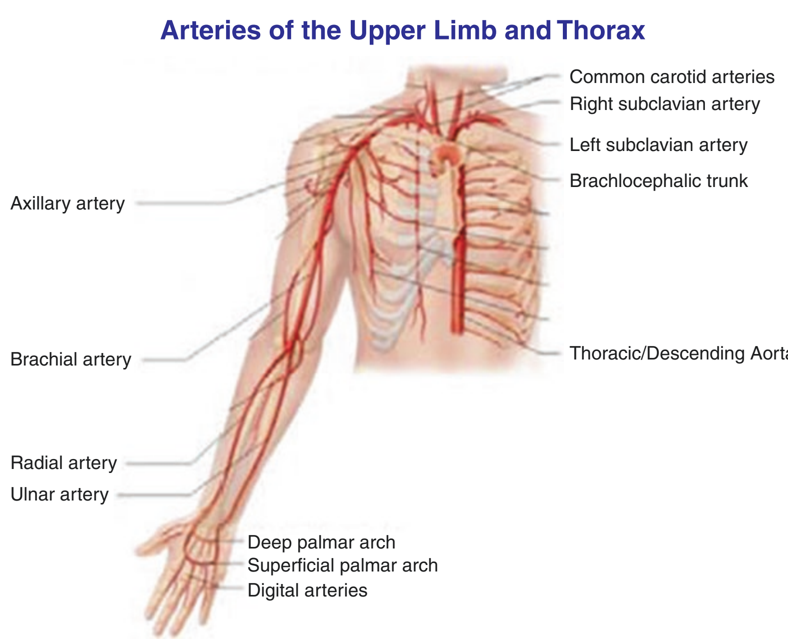


Fig. 18.1 Schematic diagram showing applied anatomy of upper-limb arteries

hypothenar to deep palmar part, and is anastomosed with the terminal of radial artery to form deep palmar arch.

Radial Artery

Radial artery firstly goes through between brachioradialis and pronator teres. Then, it descends between brachioradialis tendon and flexor carpi radialis tendon and bypasses styloid process of radius to reach opisthenar. Finally, it passes through the first metacarpal bone space to palm, where it is anastomosed with deep palmar branch of ulnar artery to form deep palmar arch. Since inferior segment of radial artery is only covered by skin and fascia, it is a part for pulse palpation in clinic. During its course, radial artery has main branches besides branches that are involved in articular cubital rete and provide nutrition to forearm muscle: (1) Superficial palmar branch: It is anastomosed with terminal of ulnar artery to form superficial palmar arch. (2) Principal artery of thumb: It is divided into three branches distributing at both lateral margins of palmar surface thumb and radial margin of index finger.

18.1.1.3 Applied Anatomy of Main Arteries of Lower Limb

Main arteries of lower limb include femoral artery, deep femoral artery, popliteal artery, anterior tibial artery, posterior tibial artery, peroneal artery, and etc. (Fig. 18.2).

Femoral Artery

Femoral artery descends in femoral triangle, goes through adductor canal, and then reaches popliteal fossa via adductor tendinous opening. At popliteal fossa, it is connected to popliteal artery. Slightly below inguinal ligament, femoral artery locates superficially. In a living body, its pulsation can be palpated. In case of bleeding at a lower limb, we can press femoral artery toward inferior ramus of pubis to achieve hemostasis by compression. The main branch of femoral artery is deep femoral artery.

Deep Femoral Artery

Deep femoral artery is originated from femoral artery about 2–5 cm below inguinal ligament. It passes behind femoral artery, goes toward the medial-inferior direction. It gives off medial femoral circumflex artery into medial femoral muscles, lateral femoral circumflex artery into anterior femoral muscles, and perforating arteries (3–4) into posterior femoral muscles, medial muscles and femur.

Popliteal Artery

Popliteal artery descends from deep popliteal fossa to inferior margin of popliteus, where it is divided into anterior tibial artery and posterior tibial artery. Inside popliteal fossa, popliteal artery gives off multiple articular branches and muscular branches, which are distributing at the knee joint and adjacent muscles and involved in genicular articular rete.

Anterior Tibial Artery

Anterior tibial artery is a terminal branch of popliteal artery. It starts from upper part of crural interosseous membrane to anterior part of crus. Then, it immediately gives off anterior tibial recurrent artery, which contributes to the arterial network of the knee joint.

Posterior Tibial Artery

Posterior tibial artery descends along posterior crural superficial and deep flexors, and goes through rear of medial malleolus to reach planta pedis, where it is divided into two terminal branches—medial and lateral plantar arteries. Main branch of posterior tibial artery is peroneal artery.

Peroneal Artery

Peroneal artery originates from upper part of posterior tibial artery and descends along medial side of fibula. Its branches provide nutrition to adjacent muscles, tibia and fibula. Clinically, peroneal artery at middle fibula and fibular nutrient artery (starting from the middle-superior segment of fibula) are frequently used for vascularized dissociation.

18.1.2 Applied Anatomy of Peripheral Vessels

Peripheral veins mainly refer to vein vessels of arms and legs. Based on their course level in body, peripheral veins can be classified into deep and superficial ones. Deep veins which are closer to the proximal end of limb will have a greater effect. On the contrary, superficial ones closer to the distal end of limb always have a greater effect. Below the wrist joint of upper limb and below the ankle joint of lower limb, superficial venous return is the main basis. The wall of superficial vein is thick and the deep vein is thin.

Venous wall is composed of three layers: intima, tunica media and tunica adventitia. Intima is constituted by endothelial cells and has a smooth surface. Tunica media mainly contains circular smooth muscle fibers and elastic fibers. Tunica adventitia is mainly composed of loose connective tissues and rich in nutrient vessels. Vegetative nerve fibers dominating vascular contraction and dilation distribute mainly in this layer. Intima and tunica media of venous vessel are relatively thin, and tunica adventitia is thick.

18.1.2.1 Deep Vein

Deep veins, also known as accompanying veins, run together with deep artery in a course which is as same as that of deep artery. Its drainage range is basically identical with that of deep artery.

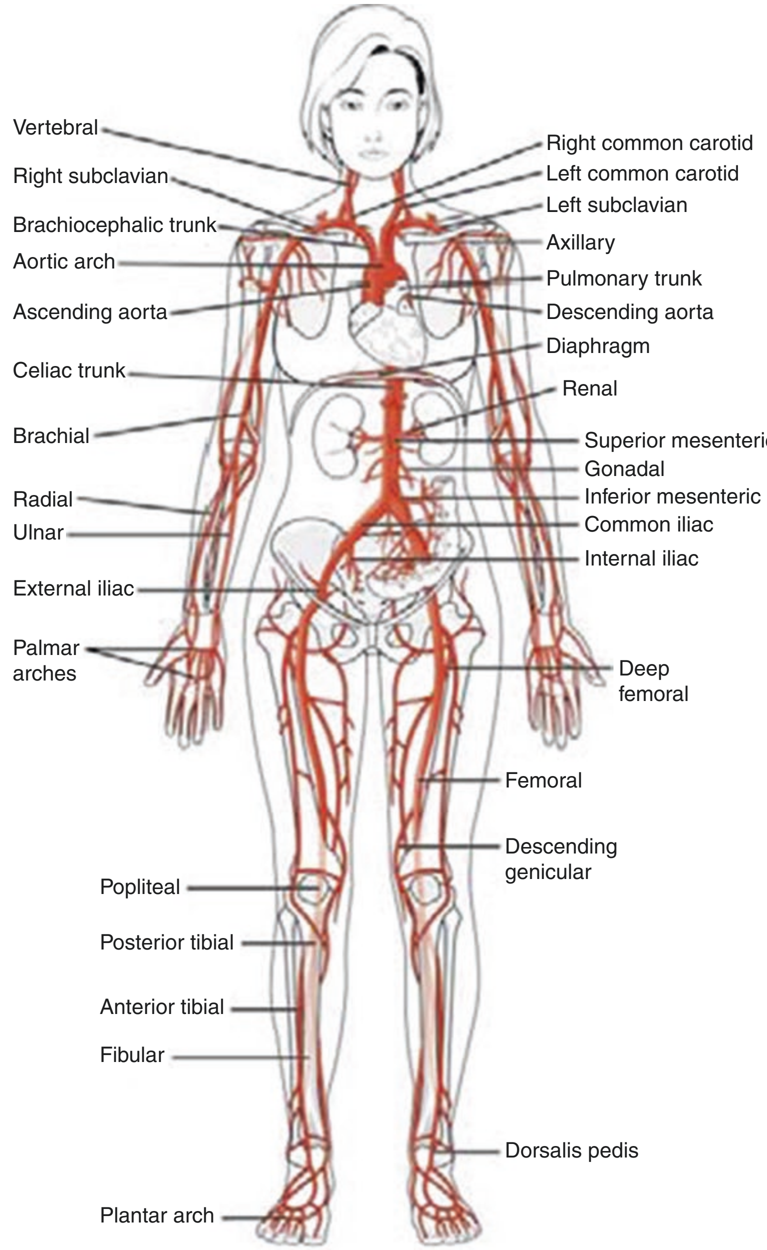


Fig. 18.2 Schematic diagram showing applied anatomy of lower-limb arteries

18.1.2.2 Superficial Vein

Superficial veins, also known as subcutaneous veins, are located in subcutaneous superficial fascia. They do not run together with any artery. They finally enter deep veins.

18.1.2.3 Applied Anatomy of Main Veins

Main Veins of Upper Limb

Deep veins of upper limb mostly accompany deep arteries and finally converge into axillary vein. At lateral margin of the first rib, axillary vein becomes subclavian vein, which accompanies subclavian artery. Superficial veins have two main veins: cephalic vein and basilic vein, which are connected at the center of cubital fossa.

Main Veins of Lower Limb

All deep veins of lower limb accompany corresponding arteries, and finally converge into femoral vein. Femoral vein is medial to femoral artery. It goes through deep surface of inguinal ligament, and is then transmitted to external iliac vein, which accompanies external iliac artery. There are two superficial veins of lower limb: great and small saphenous veins.

18.2 Classification of Peripheral Vascular Injury

18.2.1 Classification Based on Injury Cause

Like vascular damages to other parts, peripheral vascular injuries can be classified into the following types according to their causes. Firstly, direct injury, including sharp injury, like knife wound, puncture wound and gunshot wound, damage caused by surgery or endovascular manipulation, and so on. Most direct injuries are open wounds. Blunt injury, including crush injury, contusion, external compression (exogenous factors such as tourniquet, bandage and plaster immobilization), broken end of fracture, joint dislocation, joint compression, and etc. Most blunt injuries are closed wounds. Secondly, indirect injury, including vascular laceration induced by hyperextension or intense and persistent artery spasm due to traumatic stimulation and secretion of inflammatory factors, vascular concussion injury caused by sudden deceleration in a fast movement, and so on.

18.2.2 Classification Based on Pathological Changes

According to pathological changes after vascular damage, peripheral vascular injury can have the following manifestations. (1) Destruction to vascular continuity, e.g., vascular wall perforation, partial or complete breakage, or even loss of a segment of vessel. (2) Vascular wall injury without interruption of vascular continuity, manifested as adventitial injury, vascular wall hematoma, intimal lancination or crispation. It finally leads to vessel obstruction as a result of secondary thrombosis. (3) Vascular injury caused by high heat, commonly seen in gunshot injury. It results in not only directly vessel rupture but also extensive burn of vascular wall. (4) Secondary pathological changes, including secondary thrombosis, hematoma around the vascular injury site, traumatic aneurysm, traumatic arteriovenous fistula, and etc.

18.2.3 Classification Based on Anatomic Manifestations

In vascular injury, different acting forces lead to different situations of vascular damage. Different degrees of pathological changes cause different clinical manifestations and prognoses of vascular injury. Generally, sharp injury may result in complete or partial vascular rupture, mainly manifested as bleeding. Blunt injury may lead to different degrees of intima or tunica media damage and further thrombosis, mainly manifested as obstructive change.

18.2.3.1 Artery Spasm

Artery spasm is mostly caused by void effect arising from blunt violence or a high-speed bullet (600 m/s). Upon such an effect, sympathetic nerve net causes vascular smooth muscle to contract, ultimately leading to long-segment and long-time artery spasm. Insufficient collateral circulation may also lead to limb ischemia or even necrosis. It is mostly seen in an artery and frequently alleviated in 1–2 h. In some cases, it lasts for 24 h.

18.2.3.2 Artery Contusion

Arterial contusion is mostly caused by blunt violence and commonly seen in fracture. Other causes include shearing stress arising from joint dislocation or acceleration-deceleration. Due to poor endurance of vascular intima and tunica media to excessive extension, traction and warping, intima and tunica media always rupture, leading to extensive hematoma of arterial wall. Ruptured arterial intima drops into the lumen and leads to formation of thrombus.

18.2.3.3 Artery Rupture

1. Partial rupture mainly refers to partial vascular rupture caused by penetration of a sharp object into the outer vascular wall or iatrogenic intubation. Its pathological change is completely different from that of complete rupture. A partially ruptured artery cannot be fully retracted into its surrounding tissues. Furthermore, due to enlargement of gap induced by partial arterial retraction, bleeding is more severe. If a direct path connected to an in vitro device or body cavity exists, severe massive hemorrhage will endanger the patient's life in a short time. Bleeding caused by partial rupture is unlikely to stop automatically, or re-bleeding may occur shortly after hemorrhage is stopped. Sometimes, a curled intimal flap which covers the split may result in local thrombosis while other arterial walls are intact. In consequence, about 20% of the distal pulse persistently exists and covers up arterial injury.
2. Complete Rupture: Completely ruptured vessels can be subject to self-retraction or withdrawn into surrounding tissues. In addition, ruptured intima curls inward and leads to thrombosis. Therefore, bleeding is mild. However, ischemia of limbs and internal organs may occur due to interruption of blood supply, finally giving rise to necrosis of limbs and organs.

18.2.3.4 Traumatic Pseudoaneurysm

After partial rupture of artery, hematoma forms around the gap. After organization of hematoma, blood flow still communicates with hematoma cavity, and passes through the cavity via central arterial foramen to form false aneurysm.

Aneurysm does not contain normal three-layer structure. Its outer layer is organized fibrous tissue, and its inner layer is organized thrombus. It can not only rupture at any time, but also cause distal thrombus growth, leading to distal ischemic change.

18.2.3.5 Arteriovenous Fistula

If adjacent veins and arteries are also injured, arterial blood will flow to low-pressure veins, resulting in traumatic arteriovenous fistula. Delayed treatment of such conditions may cause disorders of circulatory system and heart failure.

18.3 Microsurgical Repair Skills for Peripheral Vascular Injury

The therapeutic aims of peripheral vascular injury include: (1) saving life of the injured by stopping bleeding timely and correcting shock, (2) striving to restore blood circulation and treat vascular injury and concurrent damages in order to preserve limbs and reduce disability, and (3) carefully dealing with concurrent injuries of bone, joint and nerves to create conditions for recovery of limb function.

18.3.1 Principles for Treatment of Damaged Vessels

For vascular injury of limbs, hemostasis by compression bandage is mostly used. For massive hemorrhage induced by femoral artery, popliteal artery and brachial artery, tourniquets shall be used promptly if bleeding cannot be stopped by compression bandage. Improper use of tourniquet may cause severe complications such as limb necrosis, renal failure and even death. If vascular repair is infeasible and long-distance transportation of the injured person is required, it is necessary to perform preliminary debridement, ligate broken ends of vessels, and suture the skin. A tourniquet cannot be used. Then, the injured is rapidly sent to a hospital which has the ability to perform vascular repair. In this way, risk of infection will be reduced and bleeding and adverse effects of long-term tourniquet use can be prevented. For injuries to main arteries or veins, try actively to make repair if the patient's condition and technical conditions permit. If non-major arteries and veins are damaged or the patient cannot endure vascular reconstruction, it is feasible to ligate injured vessels. Ligation of superficial limb vein, external carotid artery/vein, internal carotid vein, internal iliac artery/vein or any one of the distal arteries/veins of the knee or elbow will not lead to adverse outcomes.

18.3.1.1 Emergent Hemostasis

1. Pressure dressing. For vascular injury of limbs, hemostasis by compression bandage is mostly used. Fill and cover the wound with sterile gauzes or clean cloth, and perform pressure dressing with bandages. The dressing should not be too tight. The principle is to stop bleeding without influence on the distal circulation of limbs. After dressing, elevate the affected limb, closely observe distal blood supply and timely transport the injured for further treatment.
2. Finger-pressing is a hemostatic measure for temporary emergency. Press the proximal end of hemorrhagic artery with fingers or palm promptly after vascular rupture, and then stop bleeding by dressing or other methods.
3. Hemostasis with tourniquet. Tourniquet is an effective tool to stop bleeding of limbs. Appropriate use of tourniquet has a good effect on stopping bleeding and can save the life of the patients with massive hemorrhage. However, improper use may bring severe complications and lead to limb necrosis, renal failure or even death.

   An ideal pneumatic tourniquet should have uniform pressure and adjustable pressure values. A wide rubber-belt tourniquet should have large contact surface and good elasticity. A rubber-tube tourniquet should be easy to use and have good hemostatic effects. However, the contact surface should be small, otherwise tissues will be damaged easily. It is unsuitable to use tourniquet substitutes such as cotton tape and rope, which may cause severe injury to tissues due to difficult control over the pressure. Hemostasis with tourniquet is indicated for an injured person who has massive hemorrhage caused by femoral, popliteal and brachial arterial damage and is not suitable for pressure dressing. Generally, it is applied to superior 1/3 of the upper arm or middle part of thigh. The position to apply a tourniquet should be lined with cushion to prevent skin damage. Duration of using a tourniquet should be minimized. Try best to take further hemostatic measures in 1.5–2 h.
4. Hemostasis with forceps. If possible, clamp the bleeding broken ends of a great vessel with hemostatic forceps, bind up the forceps in the wound, and then quickly transfer the injured for further treatment. During this process, be cautious not to damage the adjacent nerves and normal vessels.
5. Vascular ligation. In the event when vascular repair is infeasible and long-distance transportation of the injured person is required, it is necessary to perform preliminary debridement and ligation of broken vascular ends. Do not use any tourniquet. Rapidly transport the injured.

18.3.1.2 Timely Debridement

Timely completion of debridement is the foundation for prevention of infection and successful repair of tissues. For the sake of preventing infection, try to accomplish debridement and remove contaminants, foreign objects, inactivated tissue and necrotic tissue within 6–8 h. Even if vascular repair is completed, failure may happen due to vascular exposure, infection and bleeding caused by wound infection or tissue necrosis if debridement is not thorough. In case of a firearm wound, range of actual injury of broken vascular ends may be larger than what is visible. Perform an additional 3-mm resection beyond the visible range to prevent post-repair thrombosis caused by incomplete debridement.

18.3.1.3 Vascular Injury Repair

Duration of repair should be limited to 8–12 h after injury, and preferably within 4–6 h. For the injured with definite diagnosis of vascular injury, surgery should be done promptly. For the suspected with uncertain diagnosis of vascular injury, conduct dynamic observation for a limited time. Probe early when necessary in order to make a definite diagnosis and use effective therapeutic methods. Before cutting hematoma or false arterial or venous aneurysm, clamp distal and proximal broken ends of vessels to prevent bleeding.

Arterial Vascular Injury Repair

Irrespective of complete or partial rupture or post-contusion embolism, for arterial vascular injury, the best effect is achieved after the damaged part is removed and end-to-end anastomosis is performed. When end-to-end anastomosis is infeasible because of an excessive defect, repair by autogenous vein graft should be done. If sharp instrument injury to a limb artery does not exceed 1/2 of the circumference, local suturing is appropriate.

Arteries can be divided into three classes based on their importance. Class-1 arteries are vessels which inevitably cause severe complications if ligated. For example, ligation is absolutely forbidden of an injured aorta, brachiocephalic trunk, common carotid artery, renal artery, common iliac artery, femoral artery and popliteal artery. In such cases, these arteries must be repaired. Class-2 arteries are the vessels which sometimes lead to serious consequences if ligated, like subclavian artery, axillary artery, brachial artery and most arteries inside the abdominal cavity. Try best to make them repaired rather than ligated. Class-3 arteries are simple ulnar or radial, anterior or posterior tibial arteries. For the arterial injuries except the above-described ones, simple ligation can be performed if conditions are limited.

Vascular Injury Repair

Repair is appropriate for injury to vena cava such as external iliac vein, femoral vein and popliteal vein. Especially, if serious soft tissue damage and superficial vein injury also exist, arteries and veins should be repaired simultaneously so as to avoid limb necrosis caused by insufficient blood return, limb swelling, hematoma formation and muscle necrosis.

Repair of Vascular Injury with Other Tissue Damages

Arterial or venous fistula or false aneurysm with vascular injury should be removed and vascular transplantation and repair should be done. For tissue damages besides vascular injury, proper treatment should be offered simultaneously, such as fixation and reduction of fracture, suturing of tendon rupture, suturing of nerve rupture and closure of wound. For limbs with vascular injury, after pressure in fascia and intermuscular septum is estimated correctly, incision and decompression of fascia or (and) sarcolemma should be conducted.

18.3.1.4 Ligation of Blood Vessels

For injuries to main limb vessels, vascular repair and limb circulation recovery rather than vessel ligation is the first choice, because amputation rate after ligation of main limb arteries is very high. Even if no limb necrosis occurs, such ligation easily causes different degrees of disability due to limb ischemia. The following are the indications of arterial ligation. (1) Vessel ligation and amputation should be performed when limb tissue damage is too extensive and severe and vessels cannot be repaired or limb cannot be preserved after repair. (2) The patient's condition is critical. There are injuries to multiple important organs; the injured cannot tolerate vascular repair. However, for injuries to main limb arteries, try best to repair damaged vessels after the patient's condition becomes stable. (3) If there is lack of vascular repair skills or blood source is not enough, it is necessary to perform debridement, ligate the arterial terminal and quickly transport the injured to a qualified hospital for vascular repair. (4) For injury to minor arteries, e.g., rupture of any one of the ulnar arteries and radial arteries or any one of the anterior and posterior tibial arteries with the other one being intact, ligation of damaged vessels can be done. However, repair should be indicated if limb circulation is affected.

Arterial ligation. For larger vessels, double ligations should be employed. Penetrating ligature is suitable for the proximal side to avoid slippage. A partially ruptured artery should be ligated and then cut off in order to prevent distal arterial spasm. It is improper to perform vascular ligation for an infectious wound, so as to prevent secondary bleeding. Vascular ligation should be done at a slightly high position of normal tissue. Accompanying veins without injury should not be ligated.

18.3.1.5 Management of Vasospasm

Management of vasospasm should be focused on prevention. For example, cover the wound with gauze dampened with tepid saline water, reduce stimulation by wound, coldness, dryness and exposure, and timely remove compression on fractured ends and foreign body. If arterial spasm is suspected but there is no wound, sympathetic block by procaine can be tried; oral administration or intramuscular injection of papaverine hydrochloride is also feasible. If no effect is achieved after the above treatments, arterial probing should be done early. If post-anastomosis spasm of artery is detected during surgical exploration or after exposure of open injured vessels, intravascular hydraulic dilatation is a commonly used effective method, i.e., injection of isotonic saline into spastic vascular segment to dilate vessels. In case of vascular dilation and embolism with vasospasm, it is necessary to remove damaged vascular segments and perform end-to-end anastomosis or autogenous vein grafting and repairing.

18.3.2 Microsurgical Repair Techniques for Peripheral Vascular Injury

18.3.2.1 Suturing of Partial Vascular Injury

Principles of Surgery

This method is indicated for vascular incisions caused by a sharp instrument, with regular-edge arterial incision not exceeding 1/3 of the vascular circumference. Vascular debridement is not necessary and there is no post-repair stenosis. For partial vascular ruptures caused by a firearm, thorough debridement of vessels should be done due to large wound range and severe contamination. Therefore, local suturing or repair is not permitted. It is necessary to remove damaged arterial segments before end-to-end anastomosis or autogenous vein grafting is performed.

Operative Steps

Firstly, use non-traumatic bulldog clamps to clamp two ends of an injured vessel to block blood flow. Wash the lumen with heparin solution to eliminate blood clots. Cut off adventitia of the ruptured edge of the vessel. Then, use human hair or 6-0 nylon thread for interrupted or continuous suture of gap, preferably transverse suture. During suturing, pay attention to prevention of stenosis and embolism at stitching positions.

18.3.2.2 End to End Anastomosis

Principles of Surgery

This method is suitable for cutting wounds caused by an edged tool or after debridement in the injured person with vascular defects ≤2 cm. End-to-end anastomosis can be done directly. During operation, pay attention to the proper separation of broken vascular ends as well as to proper tightness of suture traction and ligation. There should be no tension at the anastomosis positions.

Operative Steps

1. Separation of broken vascular ends. First of all, properly separate two ends of the artery. Keep adjacent joints in semi-flexion position to reduce tension. Sometimes, some insignificant branches can be cut off to increase the length of main artery. For young injured persons, an intact artery can be increased by 2–3 cm in length to compensate for the defective space. Direct anastomosis can be done.
2. Check blood flow condition. When a damaged part is cut off according to vascular resection range determined in debridement, active ejection should be available at the proximal end of artery. If ejection is not sufficient, proximal blockage is possible. In this case, insert a plastic tube into the artery for suction and irrigation. If no effect is achieved, cut off another segment again. If ejection is excessive, use vascular clamps to block blood flow. At the same time, temporarily open distal vascular clamps and check whether arterial countercurrent is good or not. Thrombus in the distal segment must be removed by suction. Anastomosis can be performed only after this segment is unobstructed.
3. Remove vascular adventitia. Clamp adventitia of broken vascular ends with vascular forceps, pull outward and then cut off the adventitia so as to prevent thrombosis caused by adventitia brought into the lumen during suturing. Alternatively, use small scissors to cautiously separate and cut off the adventitia of broken vascular ends. Do not damage any vascular wall. Generally, 0.5–1 cm adventitia is separated at each broken end.
4. Wash the lumen of broken ends. After broken ends on both sides are trimmed, wash the lumen of two broken ends with 0.1% heparin saline (or 0.5% procaine solution or 3.8% sodium citrate solution) to eliminate blood clots and prevent thrombosis of anastomotic stoma.
5. Vascular anastomosis. Based on the size of vessel, conduct anastomosis using interrupted or continuous suture. Interrupted suture is optimal for vessels with a diameter <2 mm; continuous suture is optimal for vessel with a diameter >2 mm. Continuous suture has a good hemostatic effect, but excessively tight suture may shrink anastomotic stoma. Usually, a 4-0–8-0 thin silk thread is used for suturing. 8-0–11-0 Kevlar is used for small vessels. Kevlar with non-traumatic suture needle connected on both ends is appropriate. Hair is also proper. However, three knots must be made for ligation. Common two-fixed-point suture is easy, but three-fixed-point suture can prevent the contralateral wall from being sutured.
6. Two-fixed-point interrupted suture. Make vascular clamps of both vascular ends closer. After the opposite ends of vessel get close, a fixed-point suture is made superiorly and inferiorly. Each stitch shall pass through the vessel from inside to outside so as to prevent thrombosis caused by residual adventitia brought into the vessel. Two stitches are simultaneously ligated lateral to the vessel. Perform ligation gently and stably. Be cautious not to tear the wall. Then, make another stitch between the two fixed-point threads. Properly add a stitch in accordance with vascular

size. Generally, stitch length and edge distance is 0.5–1 mm respectively. For small vessels, they should be 0.3–0.5 mm. After ligation of each stitch, an assistant can gently lift the suture to facilitate suturing of next stitch. After the anterior wall is sutured, turn over vascular clamps at two ends. Then, suture the posterior wall using the method described above. During suturing, put the flat-end needle into the lumen. Wash the lumen with heparin solution. When the last stitch is sutured, re-check the lumen, and wash it gently to avoid blood clot residues. After the posterior wall is sutured, turn back the vascular clamps to restore normal position of the vessel. If a vessel is thick, perform two-fixed-point mattress suture to achieve more satisfactory eversion of intima.

7. Three-fixed-point continuous suture. The operating technique is roughly the same with the two-fixed-point method and the only difference is point selection. Make three equidistant fixed-point sutures along vascular circumference, and pull each suture to form an equilateral triangle. Firstly ligate the posterior wall and then ligate the fixed-point suture of anterior wall. Lift two fixed-point sutures. Use a non-traumatic needle and suture to continuously stitch anterior 1/3 of the vessel between fixed-point sutures. Each stitch should make the intima of both vascular ends aligned. Properly tighten the suture. Do not excessively tighten it, otherwise the lumen will be reduced. At the end, tie a knot of suture and fixed-point suture. Use the same method to suture 1/3 edge of the other side. Finally, turn over two vascular clamps to expose 1/3 edge of the posterior vascular wall. Similarly, perform continuous suture.

Post-anastomosis Management

1. Loosen vascular clamps. After anastomosis is completed, firstly loosen distal vascular clamps. If there is mild blood leakage at the anastomotic stoma, press with gauze for several minutes before the bleeding can be stopped. Add 1–2 stitches at the blood leakage position when necessary. However, it is necessary to try best to avoid such an event in order to prevent thrombosis. Anastomosis should be perfect as much as possible. Loosen proximal vascular clamps immediately after there is no blood leakage.
2. Management of artery spasm. Check pulsation of arteries above and below the anastomotic stoma and also the color, temperature and pulse of distal limb. In case of arterial spasm, apply gauze dampened with 2.5% papaverine solution. In case of poor blood supply to the damaged limb, block sympathetic ganglion or perivascular nerve with procaine solution.
3. Covering anastomotic stoma

   After vascular anastomosis is accomplished and bleeding is stopped, use healthy tissue, preferably adjacent muscle, to cover the anastomotic stoma. Do not expose the vessels, otherwise infection or scar embedding may occur. For war wounds or wounds with great risk of infection, skin is subject to fixed-point suture or is not sutured after vascular suture and muscle covering. Keep drainage. The wound will be sutured later or subject to skin grafting. If fracture exists near the suture position, use muscle to separate vessels from fracture ends so as to prevent porosis which will compress vessels.

18.3.2.3 End-to-Side Anastomosis

This method makes broken vascular ends at the donor site anastomosed with lateral-wall opening of recipient vessels. Its objective is to guarantee continuous blood supply from recipient vessels to the original blood donor site. It is suitable to use limb proximal blood vessels as main vessels, because a distal blood supply disorder will occur if they are cut off. End-to-side anastomosis must be done in case end-to-end anastomosis is not appropriate. If donor-site vessels and recipient vessels to be anastomosed have a great difference in diameter, end-to-side anastomosis can be used.

Vascular Lateral-Wall Opening

Firstly, make an opening in lateral wall of vessels. Separate and trim loose connective tissue on the superficial layer of vessels. At the planned position of opening, use a sharp blade to properly cut open vascular wall so that an appropriate amount of recipient vascular wall is cut off vertically. Since vascular wall retracts naturally along the longitudinal axis, an oval opening is formed on the lateral vascular wall. Use a 7-0 non-traumatic thread to penetrate through the vascular wall according to the longitudinal diameter to be cut open. After lifted slightly, the vascular wall is cut off to obtain an oval gap. This opening should be equal in diameter to or slightly larger than the vessel broken ends to be anastomosed with it. If the opening is smaller in diameter, post-operative stenosis of anastomotic stoma cannot be avoided. If end-to-side anastomosis is used because of a great difference in vascular diameter, the opening of lateral vascular wall shall be about 2 cm above the vascular ligature to prevent the intra-vascular formation of thrombus which will influence vascular patency.

Two-fixed-point end-to-side anastomosis. Trim broken ends of donor-site vessels in end-side anastomosis into a bevel. The angle between the bevel and longitudinal axis of lateral-wall-buttoned vessel should be 45°–60°. This angle should not be too small, otherwise blood flow in post-anastomosis vessels will be influenced. Then, make the tip pointed to the proximal end of recipient vessels. Suture the vessels using end-to-end method. Make two-fixed-point suture between the proximal and distal apexes of opening in recipient vessel wall. Then, suture the anterior or posterior wall of vessel.

18.4 Microsurgical Repair of Peripheral Vascular Injury

18.4.1 Pre-operative Preparation for Microsurgical Repair of Peripheral Vascular Defects

If hemorrhage is massive and condition of the patient is emergent after vascular injury, it is important to evaluate correctly and timely the relevant damage. Generally, it is not difficult to make a diagnosis based on blood ejection from the wound, ischemia of a limb, weakening or disappearance of arterial pulse, decrease in blood pressure, etc. Atypical symptoms also exist, such as closed or small wounds, a far distance from vascular body surface location zone, no history of shock, invisible ischemia of the distal limb. For patients with atypical symptoms, diagnosis is likely missed or misdiagnosis is likely made. When hematoma is formed due to arterial or venous rupture, blood clots may block the broken vascular ends so that bleeding from the broken vascular ends is reduced. In case of incomplete blockage by blood clots, a part of blood flow still passes through the vessels. In addition, collateral circulation exists in surrounding tissues. Therefore, distal ischemia of injured limb is not obvious. Arterial pulse can even be palpated. However, such blood circulation is not sufficient to maintain limb blood supply. In such a condition, long-term limb ischemia may cause muscular necrosis, compartment syndrome and other adverse consequences. It is necessary to ask the injured carefully about his/her medical history. Especially, in patients with open wound, blood pressure is low and blood ejection at the moment of being injured is an important sign. In patients with obvious local swelling, consider possibility of vascular injury. Doppler ultrasound is an easy and non-invasive examination to help diagnosis. Make examination carefully and closely observe changes in the patient's condition. Missed diagnosis of injury to the peripheral main vessel is dangerous, leading to secondary bleeding or endangered life. Long-term limb ischemia results in a high amputation rate.

Pre-operative preparations should be well made while possible shock is prevented. Prepare to perform surgery after the patient's blood pressure is stable. For large vessels like femoral artery, hemorrhage from broken ends is massive and shock can hardly be controlled. In this situation, surgical exploration should be done as soon as possible and surgeons cannot just wait for control of shock. In this way, bleeding can be stopped effectively during operation and shock will be relieved. Persistent shock may lead to multiple organ failure and death. After a definite diagnosis at an emergency department, the patient with vascular injury are not to be transferred to a ward of microsurgery department. Once pre-operative preparations are accomplished at the emergency department, the patient will be sent directly to an operating room to save time. Priority of vascular anastomosis depends on time of ischemia. If ischemia has existed for more than 6 h, arterial anastomosis shall be completed as soon as possible to establish arterial blood supply before other operations can be conducted. Otherwise, nervous and muscular tissue ischemia will last long enough to make the injury irreversible, and in some cases the patient will have to receive amputation. Therefore, for vascular injury, control of bleeding and establishment of arterial blood supply is the key treatment.

18.4.2 Repair Methods of Vascular Defects

18.4.2.1 Angiostomy

It is applied for vascular defects ≤2 cm. For operating methods please refer to Sect. 18.3.

18.4.2.2 Vascular Transplantation

Vascular transplantation is a surgical method commonly used when vascular defects exist and direct suture is infeasible. Embed the grafted vessel into the defective site. Suture one end. Then, cut off excessive vessels. Finally, stitch the other end. Grafted vessels can be an autogenous artery or vein, allogeneic artery or vein, or artificial blood vessel. Autogenous artery and vein grafting is the most frequently used in microsurgery for defective vessels.

Management Principles for Vascular Transplantation

In transplantation of free tissues, vascular denudation or displacement cannot be used to repair defects because the vascular pedicle of transplanted tissue is too short and there is a defect between the pedicle and recipient vessel. For defects following debridement of damaged vessels or resection of tumor-affected vessels, vascular denudation or displacement cannot be used.

Requirement and Selection of Donor-Site Vessels

Donor-site vessels must be normal. Their external diameter should be similar to that of recipient vessels, and the difference cannot be great. They should be long enough. Resection of donor-site vessels should not cause any blood circulation disorder at the donor site (ischemia or blood stasis).

Generally, arterial transplantation and reconstruction are used for artery defects. Venous transplantation and reconstruction are used for vein defects. However, in clinical practice, arteries are always deep and their quantity is small. Furthermore, removal of some arteries will lead to insufficient blood supply to some regions. On the contrary, as veins are located superficially and large in quantity, they are easy to find. Resection of one segment of vein will not induce backflow obstruction. Therefore, in microsurgery, autogenous vein graft is usually used for repair of venous and arterial defects.

Autogenous veins suitable for grafting include great and small saphenous veins, external jugular vein, cephalic vein, basilic vein, dorsalis pedis vein, dorsal metacarpal vein, and so on. Because great and small saphenous veins and external jugular veins have a too thick and large trunk, they are not suitable for repair of small vascular defects. Generally, branches of these veins are used. These venous branches are appropriate in external diameter and have a thin wall. Like superficial veins of upper limb, dorsalis pedis vein and dorsal metacarpal vein are commonly used as autogenous vein grafts.

Surgical Procedures

1. Measurement of vascular defect length. The length of vessel to be resected depends on lesion range, i.e., the length of vascular defect. However, for vascular defects caused by trauma, a vascular defect length should be longer than the actual defect length in measurement due to vascular retraction. Grafted vessels can be cut off according to the measured defect length. The excessive part will be cut off during suturing.
2. Resection of grafted vessels. Choose a proper vessel for grafting in accordance with the defect length and the external diameter of the recipient vessel. Usually, proper superficial veins near the surgery field is chosen for grafting. Sometimes, arterial transplantation is used. For example, in reimplantation of a severed finger, the digital artery of one side is grafted to repair the digital artery of the other side. After a grafted vessel is determined, separate and ligate it and cut off all its branches. Cut off a vein or artery of the same length with that of the recipient vessel defect. During cutting, 1–2 mm membrane beside the adventitia of broken vascular end shall be separated. In venous transplantation, use suture to mark the distal end of the vein.
3. Rinse and dilatation of grafted vessels. After a grafted vessel is cut off, insert its flat end into the lumen, and thoroughly wash away the blood inside the lumen with heparin saline to prevent blood coagulation. Vascular separation frequently leads to vasospasm. Before suturing, insert the tips of tweezers into the broken vascular ends for slight dilatation, thus to facilitate suturing.
4. Suture. Embed a grafted vessel between two broken ends of the defective vessel, and prepare for suturing. When an autogenous vein is used for repair of arterial defects, the grafted vein should be inverted so that its distal end is sutured with the proximal end of artery and its proximal end is sutured with the distal end of vein. If an autogenous vein is used for repair of venous defects, or an autogenous artery is used for repair of arterial or venous defects, inversion is not necessary. A proximal end is sutured with a proximal end, and a distal end is sutured with a distal end. Suture by end-to-end method. Suture the recipient vessel with one end of the grafted vessel. After suture is completed, hold the other end of grafted vessel with tweezers tips. Apply slight traction to make it aligned with the other end of defected vessel. If a grafted vessel is too long, cut off its excessive part before suture.
5. Convalescence serum. After anastomosis is accomplished, remove small vascular clamps from the distal end and proximal end successively to restore blood flow. Closely observe blood supply after operation. Use periodic Doppler ultrasonic examinations to check whether the reconstructed blood vessel is unobstructed. Once stenosis of anastomotic stoma or obstruction of distal vessel is detected, make correction promptly. Intensive pain and obvious swelling of limb as well as sensation and movement disorder with unexplainable fever and heart rate acceleration indicate high pressure of intermuscular septum. In such cases, incision and decompression of deep fascia should be performed immediately. After operation, routine application of antibiotics should be offered to prevent infection. Observe the wound every 24–48 h. In case of infection, early drainage should be done and necrotic tissue should be cleared away.

18.4.3 Precautions After Microsurgical Repair of Peripheral Vascular Injury

After an anastomosed vessel is unobstructed, especially an artery, carefully observe changes in blood supply to the distal limb. Red color, increased skin temperature and restored arterial pulse should be observed. If the distal end of limb is still painful, ischemic and free of arterial pulse, check whether the vessel is unobstructed and whether thrombosis exists. Make exploration timely. In one of our patients, thrombus was formed after arterial anastomosis, distal arterial pulse disappeared, there was no bleeding during needle puncture, and swelling of calf worsened. Exploration found femoral arterial thrombosis. After thrombus extraction, arterial pulse recovered. After ischemia reperfusion of limb, limb swelling and increase in fascial compartment pressure may occur and compartment syndrome is possible. If obvious limb swelling is detected, preventive incision and decompression should be done during or after surgery. In one of our studies, 21 patients had compartment syndrome. Although their limbs were preserved, nervous and muscular ischemia and degeneration existed and their limb function was poor. Pay attention to anticoagulant, anti-inflammatory and anti-spasm therapy. For patients with long-term limb ischemia, treatment in a hyperbaric oxygen chamber can be offered to restore aerobic metabolism of cells and to prevent degeneration and necrosis of cells.

18.5 Microsurgical Repair of Traumatic Aneurysm

18.5.1 Mechanisms of Aneurysm Formation

Aneurysm is a permanent abnormal dilation arising from local weakness on the arterial wall. Traumatic aneurysm refers to that caused by trauma. Since its wall is not complete and only composed of arterial intima or peripheral fibrous tissues, it is also called as false aneurysm. Among the aneurysms of limb, traumatic aneurysm is the most frequently seen. It may exist in all arteries of arms and legs, especially in femoral and popliteal arteries.

Traumatic lesions can be classified into direct violence or indirect violence injury. The former, such as penetrating injury due to a bullet or prick, may lead to rupture and breakage of arterial wall; the latter (e.g. explosion injury) always has a certain distance from the artery, but may cause severe arterial contusion and arterial wall avulsion due to high-speed and high-pressure wave transmission. Additionally, traumatic aneurysms may be induced after endarterectomy, arterial anastomosis and transplantation of artificial blood vessels.

In case of hemorrhage from the arterial wall with traumatic rupture, due to nearby thick soft tissues and small and winding wound tracts, blood discharge is difficult and the hematoma interlinked with artery is formed. 4–6 weeks later, fibrosis of outer-wall tissue of hematoma leads to formation of tumor wall. Most traumatic aneurysms belong to this type. Aneurysms may rupture and result in secondary infection and arterial embolism.

In patients with a definite history of trauma, local pulsatile mass appears after injury, frequently with swelling pain or jumping pain. If adjacent nerves are involved, the patient may have numbness and radiating pain. If infection is concurrent, there will be persistent intense pain. Distal limb may present with ischemic symptoms. By local examination, localized uplift can be seen along the arterial course. Swelling pulsatile mass can be palpated. Systolic thrill and murmurs exist on the surface. Compression blocks blood flow in the arterial trunk close to the mass. Therefore, the mass can be reduced. Pulse, thrill and murmurs decrease or disappear. Distal limb ischemia is manifested as pale skin, muscle atrophy, toe-end ulceration or necrosis, or weakening or disappearance of distal arterial pulse.

Generally, it is not difficult to make a diagnosis according to medical history and clinical manifestations. In case of difficulty in making a definite diagnosis, ultrasonic examination, diagnostic puncture and arteriography can be helpful. Because arteriography can determine the position, size, range and collateral circulation of an aneurysm, it can be applied as a routine pre-operative examination. Surgery is the only effective treatment for traumatic aneurysms.

18.5.2 Timing of Surgery

When rupture of traumatic aneurysm or detachment of intra-tumor thrombus leads to arterial embolism and thus endangers limb survival, surgery shall be performed emergently. If an aneurysm enlarges quickly, tends to rupture and severely compresses the peripheral nerves or has concurrent infection, surgery shall be done as soon as possible. Generally, a wound heals 1–2 months after injury. Surgery can be done after inflammation and edema in local and adjacent tissues disappear. Due to development of vascular transplantation, it is no longer necessary to wait 3–6 months for sufficient formation of collateral circulation before surgery can be performed.

18.5.3 Methods of Surgery

Decisions should be made according to the position, size and local anatomical condition of an aneurysm, infection, and collateral circulation. Following surgical methods are usually used.

1. Aneurysm resection and arterial end-to-end anastomosis. For larger main arteries of limbs, after resection of aneurysm, free the proximal and distal vessels and perform end-to-end anastomosis of two broken ends.
2. Aneurysm resection and vascular transplantation. If end-to-end anastomosis is infeasible due to a large aneurysm and a long post-resection vascular defect, autogenous veins or artificial vessel grafts can be used.
3. Aneurysm resection and proximal/distal arterial ligation. For aneurysms of a non-major artery, remove the tumor body and ligate the arteries of two broken ends.
4. Endovascular repair of aneurysm. Block blood flow of two ends of the tumor body, cut open the tumor wall, find arterial rupture and perform simple suture repair or patch repair.
5. Ligation of arteries of two aneurysm ends. Extra anatomic autologous venous bypass grafting and tumor cavity drainage can be conducted.

18.6 Microsurgical Repair of Traumatic Aneurysm

18.6.1 Pathogenic Mechanisms of Arteriovenous Fistula

Abnormal arteriovenous circulation due to injury is called traumatic arteriovenous fistula. It is mostly caused by a penetrating wound such as knife stab wound, gunshot wound and metal chip injury. It may also result from iatrogenic factors such as arterial/venous puncture. The injury also damages adjacent arteries and veins, resulting in direction circulation between artery and vein.

Traumatic arteriovenous fistula may occur immediately after injury or after organization and dissolution of hematoma between arterial and venous rupture sites. The former, called as acute arteriovenous fistula, is rare and mostly found during the chronic stage.

In the acute period, local pulsatile mass may appear, with thrills and murmurs. In the chronic period, these are mainly reactions induced by hemodynamic changes. Clinical manifestations vary due to differences in fistula orifice size, position and onset time. Since blood in a high-pressure artery directly flows into a low-pressure vein, thrill is obviously palpated at local fistula orifice and mechanical murmur is audible in auscultation. Due to venous hypertension, the limbs proximal and distal to fistula orifice may present with dilatation of superficial veins. Due to reduced arterial blood supply and venous blood flow congestion, the limb distal to fistula orifice may suffer nutritive changes such as skin smooth and thin skin, hyperpigmentation, ulceration or even finger or toe-end gangrene. Temperature of the skin around the lesion increases, and temperature of the distal skin decreases. Massive arterial blood directly flows into veins, so returned blood volume increases, leading to heart failure.

1. Measurement of venous pressure and venous blood oxygen content

   When the venous pressure of a diseased region increases, the venous blood oxygen content also increases.
2. Color Doppler Ultrasound

   Blood flows through an artery and fistula orifice into a vein. Blood flow volume of the artery proximal to fistula orifice increases, but the distal blood flow volume decreases. Doppler blood flow analysis indicates low resistance of artery and arterialization of veins.
3. Arteriography or digital subtraction angiography (DSA)

   The most accurate diagnostic method should accurately detect the position and size of fistula orifice and surrounding vascular lesions. Opening of rich collateral vessels is visible in the early-phase development of vein. The artery proximal to fistula orifice thickens and distorts. Development of distal artery reduces or even disappears.

In addition, for patients with a large fistula orifice and long duration, echocardiography provides data of their heart function. Diagnosis can be made if local pulsation, thrill and continuous vascular murmur appear after injury with concurrent superficial vein dilation, distal tissue ischemia or venous congestive change. For patients with a large fistula orifice and large shunt volume, after blockage of fistula orifice by compression, increased blood pressure and slowed heart rate may occur. These manifestations are called positive Branham signs and beneficial to diagnosis.

18.6.2 Timing of Surgery

1. It is appropriate to perform operation 3–6 months after fistula formation, when collateral circulation has been established sufficiently. However, for patients with early heart failure, operation should be considered in advance.
2. For arteriovenous fistula of main vessels, remove the fistula. Respectively suture fistula orifices in arterial and venous walls. Alternatively, suture fistula orifices in venous wall. Perform arterial end-to-end anastomosis or vascular transplantation.
3. Sometimes, it is feasible to perform recuperative repair as follows: cut open the venous cavity, suture fistula orifice in arterial wall, keep artery unobstructed, and do venous repair or ligation to prevent ischemia or necrosis of injured limb.
4. For arteriovenous fistula of non-major vessels which have rich collateral circulations, four-end ligation and fistula resection can be done. Alternatively, simply ligate the arteries proximal and distal to fistula to relieve symptoms.
5. For arteriovenous fistula in main vessels, embolization of fistula orifice can be done by interventional method if surgical therapy is difficult.
6. In case of symptoms of heart failure, firstly offer necessary treatment. Perform further therapy after improvement. If no therapeutic effect is achieved or the patient's condition is exacerbated, ligate the proximal vein to reduce heart burden. After cardiac and general conditions are improved, secondary operation can be done.
7. Other measures are the same with the pre-operative preparations for aneurysm.

18.6.3 Methods of Surgery

Once traumatic arteriovenous fistula is formed, surgical treatment is required so as to prevent systemic and local circulatory disturbance. There are two types of surgery: vascular reconstruction and vascular ligation.

18.6.3.1 Vascular Reconstruction

1. Fistula orifice repair. Cut open an artery or a vein. After the fistula orifice is repaired in the lumen, suture the artery or vein. Surgical procedure is easy. However, sutures left in the vascular lumen easily lead to thrombosis.
2. Fistula orifice resection and vascular reconstruction. After fistula orifice is removed, perform end-to-end anastomosis of the artery and vein respectively, or conduct vascular transplantation. Surgery is thorough, and the effect is good.

18.6.3.2 When Arteriovenous Fistula Cannot Be Excised, the Following Are Feasible

1. Arterial ligation. Ligate and cut off the arteries at both ends of a fistula orifice. Then, perform end-to-end anastomosis of the proximal and distal arteries, and interposition of autogenous saphenous vein or artificial blood vessel. Ligation of the main arteries proximal to fistula orifice may cause blood supply disorder at the distal limb or even ischemia and necrosis. This procedure can only be applied in case of pre-existing heart failure or endocarditis or poor tolerance to operation.
2. Four-end ligation. In case of chronic arteriovenous fistula, extensive surrounding collateral circulation and difficult arterial ligation, "four-end ligation" can be performed. Respectively ligate the input and output ends of artery and vein at positions closest to the fistula orifice. This method is indicated for arteriovenous fistula of branches below the elbow or knee.

18.6.4 Post-operative Management

1. Closely monitor pulse and blood pressure. Timely detect heart failure and offer treatment.
2. For patients who have cardiac damage before surgery, postoperative in-bed time should be increased according to their condition.
3. Reexamination generally 3 weeks after the surgery. Avoid excessive physical labor within 2–3 months.
4. Other managements are the same with those for aneurysm.
5. For patients who have cardiac damage, routine care for heart disease should be offered. Other measures are the same with aneurysm nursing. Blood circulation of limb is good. Heart failure disappears. Pay subsequent visits 3, 6 and 12 months after discharge. Examine blood circulation of the affected limb and of the state of heart.

18.7 Post-operative Complications of Peripheral Vascular Injury and Their Management

Main post-operative complications of peripheral vascular injury include secondary bleeding, vascular crisis, thrombosis, and etc. Judgment and management of secondary bleeding is the same with that of primary bleeding. For detailed information, please refer to related chapters.

18.7.1 Vascular Crisis

It refers to postoperative circulatory disturbance caused by arterial or venous obstruction after free tissue transplantation, limb reimplantation, finger reconstruction and vascular anastomosis. Vascular crisis is manifested as arterial crisis, including pale skin, worsened skin wrinkles, decreased finger temperature, lowered finger pulp expansive force, shrunken blood capillary, increased filling time and weakening or disappearance of pulse.

Vascular crisis after vascular repair is mostly arterial crisis and occurs in patients who only have one side of the digital artery anastomosed. Manifestations shortly after arterial blood flow are the following: fingers turn from red to pale, filling of finger-end and subungual blood capillaries disappears, finger pulp expansive force decreases, finger pulp shrinks, and the lateral incision of finger end has no blood discharge. Sometimes, dark violet blood oozes slowly because of venous return. The main cause of intra-operative vascular crisis is arterial spasm.

Arterial spasm is frequently caused by the patient's nervousness, stimulation by low room temperature, and pain due to disappearance of anesthetic action. To prevent arterial spasm, explain key surgical points to the patient and use sedatives before operation. Temperature in an operating room should be maintained from 22 to 25 °C. In winter, corresponding heat-preservation measures shall be taken to reduce exposure of the trunk and limbs. During long duration of reimplantation, indwelling catheterization should be offered before operation to eliminate the patient's restlessness resulting from urinary retention during operation. Local anesthetics should be supplemented in case of pain. For spastic vascular segments, external papaverine solution is applied and external local hot-wet compression with saline water is used. Usually, most vasospasms can be resolved after blood circulation to fingers is restored. If spasm is relieved but finger blood circulation is not improved after the above management, occurrence of arterial embolism should be suspected.

18.7.2 Thrombosis

1. Arterial embolism. It is frequently caused by incomplete vascular debridement or poor vascular suture. During operation, heat preservation, pain management and spasmolysis are often offered. If finger blood circulation is still not restored, arterial embolism is suspected. The operator separates and completely clears away extra-adventitia tissues and fiber bundles nearby the arterial anastomotic stoma. Then, the operator should unpick sutures, conduct debridement of two broken vascular ends, eliminate embolus of anastomotic stoma and cut off the embolic vascular segment. Lumens of two terminal vessels should be smooth and intima should be complete, free of cellulose and blood clot attachment. After irrigation by heparin saline, perform vascular anastomosis again to recover blood circulation.

Methods to take out embolus. The operator gently clamps the head of embolus with microsurgical forceps, slowly and carefully pulls outward, clamps the embolus with another pair of microsurgical forceps and pulls outward using the same method. After the embolus is taken out, the lumen is rinsed with heparin saline repeatedly. The lumen with damaged intima or accumulated cellulose should be removed and subject to microscopic examination. Only after the above procedures are completed can vessels be re-sutured. In case of vascular defects, repair can be done through vascular transplantation.

2. Venous Embolism. The main causes of intra-operative venous embolism include incomplete debridement of vessels, poor quality of vascular anastomosis and small quantity of repaired veins. Manifestations after venous embolism include the following: tissue expansive force increases, fingers turn cyanotic, blood capillaries change from fullness into disappearance quickly, and skin temperature decreases. At the moment of incision bleeding, dark violet blood firstly flows out and then red blood. Once venous embolism is confirmed during operation, promptly probe venous anastomotic stoma. Then, excise the embolic segment for anastomosis or vascular transplantation once again to establish venous return passage. Usually, venous return can only be guaranteed after repair of more than two veins. Vascular crisis easily occurs 1–7 days after operation, especially within 1–3 days. The nature, category and managements of vascular crisis are similar to the intra-operative ones. Short-term observation can be done after operation. If there is no improvement after pain management, heat preservation, spasmolysis and exploration should be performed timely to avoid delay. Surgical exploration method is similar to intra-operative one.

Bibliography

1. Yingze Z. Thinking on vascular injury in traumatic orthopedics clinical practices. Chin J Orthop Trauma. 2014;16(1):3–5.
2. Matuszewski Ł. Evaluation and management of pulseless pink/pale hand syndrome coexisting with supracondylar fractures of the humerus in children. Eur J Orthop Surg Traumatol. 2014;24(8):1401–6.
3. Langer V. Management of major limb injuries. ScientificWorldJournal. 2014;2014:640430.
4. Burnett HF, Parnell CL, Williams GD, Campbell GS. Peripheral arterial injuries: a reassessment. Ann Surg. 1976;183(6):701–9.
5. Wani ML, Ahangar AG, Ganie FA, Wani SN, Wani N-u-d. Vascular injuries: trends in management. Trauma Mon. 2012;17(2):266–9.

19 Microsurgical Repair of Bone Defects and Bone Nonunion

Chun Zhang

19.1 Etiology and Classification

Bone defects refer to the deletion of skeletal integrity. They can be partial volumetric ones or a certain length of complete structure. Their etiology depends on their types. The first type is pathological ones, caused by bone tumor or postoperative tumor-like lesion. A bone defect after resection of benign or tumor-like lesions is just a partial structural or volumetric one that needs to be treated by filling of bone grafts, while other bone tumors or lesions need to be treated by segmental bone resection. The second type is traumatic bone defects. Most of the traumatic ones are high-energy injury caused by something like an automobile accident or rolling and need emergency treatment. This type can be a partial bone defect or a long-segment defect of structural integrity. The third type is infectious bone defects. Most of the infectious ones are post-traumatic complications induced by post-traumatic infection. This type is clinically common and shows an increasing trend annually.

Due to different etiologies, bone defects vary greatly in severity. They can be a partial defect, a defect of structural integrity, or a long-segmental defect; they can be closed or open; they can be a single defect or a complex defect complicated with defects of adjacent composite tissue. The surgical plan should be designed according to the variety of bone defects.

According to the range and severity of traumatic bone defects, Orthopedics Trauma Association (OTA) classifies them into (Fig. 19.1): type I (those with a diameter <50%), type II (those with a diameter >50%), and type III (circular ones). Based on the classification, OTA also proposes corresponding treatment methods.

Clinical experience suggests that treatment of bone defects is far more complex and difficult than their diagnosis, especially in traumatic bone defects and infectious complex bone defects. Due to the particularity and discrepancy, each individual case should be treated using a targeted and specific treatment in accordance with the following principles and selection methods:

1. A pure and simple bone defect with a diameter <50% can be treated by filling autogenous or artificial bone.
2. A simple bone defect with a diameter >50% can be supported with a small segment or a large piece of iliums or filled with graft.
3. The bone defects at special parts, such as the navicular bone, proximal femur, astragalus, tibia, and the upper section of humerus, can be treated by adjacent alternative bone flaps with vascular pedicles as far as possible.
4. Bone defects of more than 6 cm in length are commonly treated by vascular anastomosis of the fibula and ilium.
5. As for complex bone defects concurrent with soft tissue defects can be treated by graft filling or structural long bone transplantation. The bone pieces (sections) grafted should be covered by flaps or musculocutaneous flaps simultaneously to rebuild the integrity of body structure after detect repair and wound closure. Furthermore, local blood circulation and anti-infection should be strengthened to promote healing of grafts.
6. In recent years, seriously infectious and complex long-segment bone defects are treated using Ilizarov bone transport and encouraging results have been achieved.

The controversy on definition of bone nonunion mainly involves the time limit of bone fracture healing. Bone nonunion includes nonunion and delayed union which are generally defined as a bone fracture which remains ununited 4 months and 6 months postoperation, respectively. American Food and Drug Administration (FDA) proposes 9 months as the standard for bone nonunion.

The causes of bone nonunion mainly include: (1) biological factors, such as destruction of blood supply; (2) mechanical factors, such as instability and excessive distraction of gap; (3) systemic factors, such as poor immune function,

C. Zhang (✉)
Department of Orthopedics, Zhejiang Tong De Hospital, Hangzhou, Zhejiang, China
e-mail: hzzhangchun@yeah.net

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_19

Fig. 19.1 Three types of bone defects . (**a**) Type I. (**b**) Type II. (**c**) Type III

diabetes, chronic insufficiency of liver or kidney, alcohol, smoking, poor nutrition, and cancer etc.

Bone nonunion is classified as follows: (1) Hypertrophic bone nonunion. Although the facture ends of this type are usually unstable, stressed callus changes develop due to the osteogenic activities. (2) Atrophic bone nonunion. Due to the poor blood supply on the fracture ends, osteogenic activities are poor. More seriously, absorption at the fracture ends can be induced. Meanwhile, the far and near ends of the fracture shows pen-tip-like changes and the bone section develops osteoporosis. (3) Infectious bone nonunion. The incidence of this particular type increases year by year. Obviously, with the development of modern society, injuries, as well as surgically fixed implants, have witnessed an increase. The clinical manifestations of infectious bone nonunion are also characteristic. The basic ones are bone growth defects on the fracture ends, bone absorption changes on the periphery of internal implants, and repeated acute or chronic inflammations on the limbs (such as red swelling hot pain of soft tissues, chromatosis, and stoma sinus of skin). Treatment of infectious bone nonunion is more complex and hard. The basic principles are as follows: remove internal fixation devices, such as intramedullary nails and steel plate; completely debride the inflammatory capsule, infectious bone, and free dead bone surrounding the internal fixation; completely eliminate the thickening and scarring soft tissues that have lost activity due to blood supply deficiency induced by inflammatory erosion. However, the feasibility and methods of conducting phase-I grafting and repairing on the remaining bone and soft tissue are controversial. Our way to conduct phase-I grafting for bone defects is building the skeletal stability using external fixators after complete debridement and repairing the soft tissue defects using muscle flaps or myocutaneous flaps. This way has achieved favorable results.

19.2 Classification of Bone Grafting

On the basis of types, anatomical characteristics, blood supply and transplantation compositions, bone grafts can be roughly classified as follows:

1. Autologous bone grafts. With the ilium as the donor site, this type is the most representative and commonly used up to now. Its advantages include quick ossification, freedom from immunological rejection, and definite effects. In clinical treatment, large iliac graft blocks (<6 cm) can be used for structural support or be processed into

matchstick-like pieces, grains, or paste to fill small-range defects or for bone nonunion. Through creeping substitution, new bone and host bone can fuse together. Its main disadvantages include new surgical trauma, remaining pain at the donor site, and limited graft availability.

2. Allogeneic bone. With the technical development in processing and storage of allogeneic bone, large bone defects can be rebuilt by particle and favorable materials. Allogeneic bone plays an important role especially in the salvage treatment of limb tumor.
3. Synthetic bone. Synthetic bone refers to bone graft materials that are chemically synthesized, mainly calcium phosphate salts. The materials commonly used in clinic include absorbable or non-absorbable hydroxyapatite, calcium sulfate, calcium phosphate, and composites of two of these materials. The artificial bone made of a single material is merely conductive while it is inactive in inducing osteogenesis. The composite artificial bone is combined with BMP to enhance the osteogenesis ability. The antibiotic-loaded artificial bone is produced by loading the antibiotics to treat osteomyelitis. All the three types above do not have blood supply.
4. Bone grafts with blood supply (live bone grafts). Although there have been dozens of donor sites for live bone grafts, only a few of these donor sites are widely used in clinic.

1. Bone grafts with muscle pedicle. This class is mainly used for bone grafting at specific parts. Bone flaps of quadratus femori and iliac bone flaps of tensor fasciae latae are majorly used for femoral neck nonunion, bone defect, and avascular necrosis of the femoral head; fibular flaps of long and short fibular muscle pedicles can be attached or embedded in the middle section of the tibia to treat long tibial defects (>6.0 cm).
2. Bone grafts with vascular pedicle. Different from the bone grafts with muscle pedicle, they have merely a very short rotation arc. However, the rotation arc is more flexible and can be rotated by 180° because the bone grafts with vascular pedicle own a longer vascular pedicle. The following are commonly used surgical methods: bone flaps on the axillary margin of scapula with thoracodorsal vascular pedicle are used to treat bone defects and nonunion of proximal humerus; clockwise or counterclockwise fibular flaps with fibular vascular pedicle are transpositioned to the proximal or distal tibia to treat tibial defects; radial flaps with recurrent vascular pedicle branches of the radial artery are applied to treat scaphoid nonunion; cubiod flaps with the external artery pedicle of the tarsal joint are used to treat astragals nonunion.
3. Bone grafts with vascular anastomosis. Their common donor sites include iliac crest, fibula, external margin of scapula, and ribs. This type is mainly used to treat long bone defects, especially applicable to repair and rebuild composite tissues. Compared with the grafts of autogenous bone, allergenic bone, and composite bone without blood supply, the most significant advantage of bone grafts with blood supply lies in that the blood supply and living cells of grafts are reserved so that the survival of grafts is unaffected by the soft tissue conditions at the donor sites. Moreover, the inter-bone healing is achieved by the growth of fresh fracture callus instead of creeping substitution. With stress increasing after transplantation, the adaptability and anti-infection ability are both strengthened. Therefore, bone grafts with vascular anastomosis are the optimal way to repair long complex bone defects.

19.3 Indications for Bone Grafting with Vascular Pedicle

Transposition of a bone flap with vascular pedicle is commonly used to treat bone defects and bone nonunion in microsurgery. According to the requirements for repairing donor sites, small bone flap blocks can be cut and grafted into bone nonunion sites or filled into bone defects and nonunion sites on some special body parts. Moreover, large bone flap blocks can be used for structural support of corresponding body parts. Since the bone flap bears a vascular pedicle, application of this type grafting is limited by the length of vascular pedicle. Therefore, the recipient area and the donor site can be only ipsilateral and adjacent. The following are common indications for bone grafting with vascular pedicle while their surgical methods are introduced in other sections.

1. The bone flaps on the axillary margin of scapula with thoracodorsal vascular pedicle are transpositioned to the proximal humerus to treat defects and nonunion of the proximal humerus.
2. The radial flaps with the recurrent radial styloid process pedicle and branches of radial artery are transpositioned to the navicular and semilunar bones to treat nonunion, defect, and osteonecrosis of navicular bone.
3. The periosteum flaps with deep iliac circumflex vascular pedicle are transplanted to the femoral neck, proximal femur, femoral head, proximal femoral neck to threat nonunion, defect, and necrosis of the femoral head and defect and nonunion of the proximal femur.
4. The iliac bone flaps with vascular pedicle of ascending branch of lateral femoral circumflex artery are transpositioned to the femoral neck, femoral head, and proximal femur to treat bone defects and nonunion at corresponding donor sites.
5. The vascular pedicled fibular flaps are transferred to the tibia to treat long-segmental defects of the tibia (>6 cm).

6. The cubiod flaps with external arterial pedicle on the tarsal joint are used to treat nonunion, defect, and necrosis of astragals.

19.4 Indications for Bone Grafting with Vascular Anastomosis

The bone grafting with vascular anastomosis is mostly suitable for long bone defects of long tubular bones in the four limbs. Especially, the complex bone defects accompanied by soft tissue defects can be repaired by transplantation of the osteo-myocutaneous flaps of vascular anastomosis. Up to now, this way has still been the primary treatment to repair and rebuild complex long bone defects.

The ilium grafting with vascular anastomosis has the following advantages: the length of ilium can be 15 cm long at maximum; compared with the fibula, since the ilium has more cancellous bone, larger vessels, a higher healing speed, and larger cross section, it is more suitable for the areas surrounding a joint; the ilium can be integrated into a composite tissue flap for osteogenesis. Its disadvantage is that the arc shape of the ilium is unsuitable for treatment of a bone defect with a diameter >10 cm. After resection of large bone flaps, complications, such as hematocele, infection, local depression, pain, anterior superior iliac spine fracture, lateral thigh numbness and abdominal wall hernia, can be induced by incorrect treatment on the donor sites.

The fibular grafting with vascular anastomosis has the following advantages: the fibula can be more than 20 cm long at maximum; the capitula fibula can be reserved to rebuild the distal radial and proximal humeral joint defects; the fibula bears higher mechanical strength and can be joined by the soleus and skin for composite tissue transplantation. Its disadvantages are as follows: a long fibula, especially a single fibula, tends to become thicker adaptively after transplantation; the shaping process is long; graft facture may be induced. When long fibula grafting is used for a femoral defect, the fibula should be cut off and folded while its vascular pedicle should be made into a "U" shape to increase the strength of the fibula. In addition, the fibula grafts need firm fixation. The fibula should be resected from the position that is 3~5 cm above the tibiofibular joint to prevent distal tibiofibular instability.

19.5 Preoperative Preparation and Postoperative Management of Bone Grafting

19.5.1 Preoperative Preparation

1. Evaluate systemic conditions. Carefully inquire the medical history. Conduct physical examination, laboratory examination, and imaging examination. Definitely assess the operational indications and tolerance. Make preoperative preparations. Determine whether or not there is accompanying hypertension, diabetes, or disease of an important organ, whether or not the diseases are under control or stable, and whether or not there is anemia or low protein status, and the severity of anemia or low protein status as well. As for traumatic patients, make clear the cause and mechanism of the injury. Have a clear idea of the operative protocols, such as treatment applied after the facture, operation time, operation mode, grafting necessity, grafting materials, fracture fixation methods, postoperative wound healing condition, wound infection condition, follow-up treatment, and injury evaluation.
2. As for local lesions (in a recipient zone), determine the sites of bone nonunion and defect (on backbone or metaphyseal end), the type and severity of bone defect and nonunion, and existence of osteomyelitis using X-ray primarily, using computed tomography (CT) or magnetic resonance imaging (MRI) if necessary.
3. Investigate the status of soft tissue of injured limbs, including normality and integrity of the soft tissue structure, existence of scars or fistula, exposure situation of the muscle, tendon, bone, and implants in the deep tissues, joint function, and superficial artery pulse condition of the limb. As for bone grafting with vascular anastomosis, it is important to determine the vascular condition of the injured limb using digital subtraction angiography (DSA) if necessary.
4. Preparation at the donor site for bone grafting: focus on observation of breakage, scar, inflammatory furuncle, and folliculitis that may hinder the incision on the superficial soft tissue at the bone flap donor site.

19.5.2 Intraoperative Preparation

1. Local cleaning and debridement of bone defect and nonunion: completely remove the hypertrophic scar tissue among the bone defects and nonunion and the periphery, and thoroughly remove the dead bone and devitalized bone until bleeding appears on the bone end.
2. As for bone defects of <6 cm, use traditional grafting methods.
3. As for bone defects of >6 cm, use bone grafting or transposition with a vascular pedicle.
4. In regard to the maintenance and reconstruction of bone stability, no matter what kind of grafting is used, keep effective stability of the bone ends and bone shaft, and fixate a long bone graft using an anatomical plate or a LCP locking bridging plate available. Reliable bone stability plays an active role in early rehabilitation training of limbs and joints, because it prevents muscle atrophy,

joint stiffness and phlebothrombosis, and promotes fracture healing.
5. Cover bone graft bed. Open bone grafting is not advised. It is recommended to avoid wound closure under tension. Any soft tissue defect, even if small, should be decisively covered with an adjacent flap or muscle flap to close the wound and prevent poor wound healing, infection, and adverse effects induced by excessive tension.
6. Put cigarette-type drains or drainage tubes into the cavity to prevent hematocele. Since there is much errhysis in the early cavity drainage after bone grafting, negative pressure drainage may increase bleeding.

19.5.3 Postoperative Preparation

1. Raise the affected limb slightly above the heart level, keep the wound clean and the drainage smooth.
2. Conduct routine "three anti–treatments" (anticoagulation, anti-inflammation, and anti-convulsion) and analgesic treatment effectively.
3. Two to three days after operation, remove the drainage gradually.
4. Conduct controllable training for active and passive limb movement.
5. Conduct regular follow-up and X-ray examination to monitor the graft healing.

19.6 Bone Shifting with Vascular Pedicle

19.6.1 Selection of Donor Site

Donor site selection is firstly based on the evaluation of characteristics of bone nonunion and defects. Typically, defect site, defect length, defect diameter, accompanying soft tissue defect, infection, limb force line, limb length, and function and mobility of adjacent joints should be evaluated. Meanwhile, as an important factor for selection of operation methods, the patient should be taken into consideration, include age, gender, systematic condition, occupation, and function recovery requirements etc. A comprehensive evaluation before operation can lead to reasonable selection of the donor site, reduced operation risk, increased success rate and patient's satisfaction.

Transposition of pedicled bone and periosteal flaps requires that a donor site should be selected at the surrounding area of a recipient zone. with the development of microsurgery and clinically applied anatomy, there have been a great deal of bone graft donor sites available on most parts of the limb bones. Transposition of pedicled bone flap has been increasingly applied due to its availability, limited surgical trauma, simple operation, reliable effect, and popularity. Currently, it has exceeded free transplantation with vascular anastomosis.

Although there have been dozens of alternative donor sites for bone flap grafting and transposition in human body, years of clinical practice have confirmed the following commonly used donor sites: peroneal artery-pedicled fibular flap transposition used for repair of tibial defect and union, iliac flap transposition with deep iliac circumflex artery pedicle used for repair of femoral neck bone nonunion, scapula flap transposition with thoracodorsal artery scapula pedicle branches used for repair of proximal humeral nonunion, radial flap of the recurrent radial styloid process pedicle branches of radial artery used for repair of the carpal scaphoid nonunion.

19.6.2 Clinically Applied Anatomy

19.6.2.1 Fibular Flaps with Fibular Artery Pedicle

The fibula is a non-main weight-bearing bone of calf. The fibular head on the upper end and the tibia constitute the tibiofibular joint, but it is not a constituent part of the knee joint. The lower end of the fibula is a part of the ankle joint. An adult fibula is about 34 cm long, with a quadrangle upper section and a triangular lower section. The 1/4 lower section is used to stabilize the ankle joint, while the upper 3/4 part is mainly used for attachment of muscle groups of lateral calf but not weight-bearing-oriented. Adults can provide a backbone of about 20 cm that is suitable for repairing bone defects of limbs, especially for a long bone defect accompanied with soft tissue defect.

Fibular blood supply is mainly sourced from the fibular artery, with 90% from the posterior tibial artery, 1% from the anterior tibial artery, 1% from the popliteal artery, and 8% from the fibular artery as a replacement of the posterior tibial artery. The start section of fibular artery is about 3.7 mm on average (1.5~6.0 mm) and about 1 cm from the fibula, accompanied with two veins with an outer diameter of about 4.5 mm (1.7~6.7 mm). From the start section, the fibular artery extends outwardly and downwardly. As it extends downwardly, it draws close to the fibula. It crosses the upper back of tibialis posterior and then develops downwardly along the spaces among the fibula, tibial posterior, and hallux longus. The terminal branches reach to the lateral malleolus, comprising an arterial network of the ankle. The fibular artery has five kinds of branches in the downstream.

1. Nutrient fibular artery: This kind is one in number on the majority of cases, with the start from the 14.2 mm below the fibular head (10.3~23.4 mm). From the start of fibular artery to the outer aperture of the nutrient foramen of fibular artery, the nutrient fibular artery is about 1.8 cm on

average. On the start end, the outer diameter is about 1.2 mm (0.4~2.2 mm) on average. After entering the marrow cavity of fibula, the nutrient fibular artery is divided into deep branches and descending branches, which are further branched to bone substance.

2. Arcuate artery: This type is 9 on average 9 (4~5). The outer diameter of the start end is 1.4 mm (0.4~1.8 mm) on average. From the fibular artery (the start), some of the arcuate arteries attach on the periosteal surface. Others develop into periosteal branches on the fibula surface through a short section of muscle fibers, which further encircles into the fibula from back to outside and front. Arcuate arteries contain rich anastomosis distributing on the adjacent periosteum and muscles. Their periosteal branches distribute on the backbone and comprise the periosteal vascular network to support the periosteum and bone stem.
3. Muscular branches: In addition to the muscular branches branching through arcuate arteries, the fibular artery also distribute direct muscle branches to the gastrocnemius, soleus, hallux longus, flexor digitorum longus and tibialis posterior etc. However, the branches to these muscles are greatly different in number. Approximately, 16 branches to the hallux longus are the most. About eight branches reach to the posterior tibial muscle, while the branches to other muscles are fewer and finer. Muscular branches distribute periosteal branches when drawing close to the bone surface, involved in the network composition of periosteal vessels.
4. Cutaneous branches and musculocutaneous branches: This type is 4–8 on average. These branches provide nutrients to the lateral crural skin via the gaps among calf muscles, especially the thick and constant three branches (with an outer diameter of 1.6 mm on average) 9~20 cm below the fibular head. The fibular artery supplies blood to a lateral crural flap in a range of up to 30 cm × 15 cm.
5. The malleolus anastomosis branches. (a) Perforating branches: These branches orientate from the 6 to 7 cm above the lateral malleolus and anastomoses with the branches passing through the flexor depth and the posterior tibial artery inwardly to the lateral malleolus and the lateral tarsal branches of dorsal artery. In addition, there are some smaller ones, eight at maximum, which pass through the interosseous membrane to the front of calf. (b) Communicating branches: This kind is soured from the 6~7 cm above the lateral malleolus and communicates with the posterior tibial artery through the flexor depth inwardly. The perforating branches, communicating branches, and the terminal branches of the ankle joint can be used in a reverse vascularized fibular flap and reverse lateral crural island flap clinically since they form a communicate network on the ankle join.

19.6.2.2 Ilium Flaps with Deep Iliac Circumflex Artery

Because of its hidden location, the iliac bone is endowed with the characteristics of cancellous bone and compact bone. Therefore, resection has little effect on the function of iliac bone. The iliac bone is mostly used as a donor bone for traditional autogenous bone graft. In addition, multiple and rich blood supply of the iliac bone provides a plurality of multiple blood vessels as the nutritional vessels in a pedicled and free iliac graft. In 1978, Taylor firstly and successfully treated two cases of traumatic tibia and soft tissue defect through transplantation of free iliac bone flaps pedicled on the superficial circumflex iliac vessels. In 1979, he further published clinical and experimental reports concerning the ilium flap transplantation using the deep circumflex iliac vessels of vascular anastomosis, demonstrating that this treatment was better than the former. In 1980, Huang Gongkang proposed the deep circumflex iliac vessel pedicled and non-flapped iliac bone grafting and discussed the relationship between the deep circumflex iliac vessel and the iliac blood supply in detail. Since then, clinical application of the iliac bone flap transplantation with vascular anastomosis or vascular pedicled iliac flap transposition have seen continuous innovation and development. Iliac bone flaps with a variety of vascular pedicles have their own characteristics and provide favorable and abundant choices for surgeons to make an optimal operation scheme.

59.5% of the deep iliac circumflex arteries are sourced from the external iliac artery and the remained 40.5% from the femoral artery. From the external iliac artery or the femoral artery, the deep iliac circumflex artery extends outward and obliquely along the deep surface of the lateral half above the inguinal ligament and then extends towards the medial anterior superior iliac spine to the upper edge of the iliac crest. On the basis of the trending, the deep iliac circumflex artery can be divided into three sections. The first segment is from the start to the medial anterior superior iliac spine (inguinal segment). The second segment is from the medial anterior superior iliac spine to the healing line of transversalis fascia and iliac fascia (interior iliac crest segment). The third segment is from the upper edge of the iliac crest to the end (posterior iliac crest segment). In the first segment, vessels are branched outwardly and ascendingly at the 13~24 mm from the start point. Ninety percent of the ascending branches are single while 4.3% of them are coupled. On the starting point, the ascending branches, which are 1.4 mm in diameter and 91 mm in length on average, develop upwardly along the mammary line between the internal oblique and transverse abdominis and anastomose with the branches of the inferior epigastric artery and arteriae lumbales. These branches can serve as the donors of abdominal muscle and skin. In the interior iliac crest segment, vessels are located on the depth surface of the iliacus and the point of 10 mm on the inside of anterior superior spine. Then they are divided into 3~9 arteries outwardly on the point of 20~25 mm far. These arteries then enter the 1/3 point on the front of the ilium via iliacus and periosteum, namely, in a range of 8~10 cm in the anterior ilium. When an iliac bone flap is resected, part of the iliacus in this segment, the ilium periosteum, and the ilium blocks in the artery blood supply range should be included.

On the starting point, the deep iliac circumflex artery is (2.82 ± 0.56) mm in outer diameter on average and the vascular pedicles are (5.06 ± 0.86) cm long on average. From the anterior superior iliac spine (2.8 ± 4.7) mm, the deep iliac circumflex artery is divided into 3–9 supplying the ilium and obliquus internus nutrient branches. The ilium bone flaps pedicled on the deep iliac circumflex artery and the ilium periosteal flaps employ the intersection point of the inguinal ligament and the femoral artery as their rotating shaft and the distance from the arterial pulse point below the inguinal ligament to the anterior superior iliac spine as their rotating distance.

19.6.2.3 Scapular Flaps with Thoracodorsal Artery Scapular Pedicle Branches

The scapula is an irregular triangular flat bone with three faces, three triangles, and three edges. The largest bone mass parts of the scapula are located on the lateral border and the spine scapula. Starting from the thoracodorsal artery, the scapula crosses the teres major downwardly and extends downwardly along the front edge of the depth face of latissimus dorsi. Along the extending trend, it constantly sends out coarse scapula branches, serratus anterior branches, and a number of smaller teres major and teres minor branches. The trunk scapula continuously develops downwardly along the depth surface of latissimus dorsi and is branched into medial and lateral branches. On the beginning point, the thoracodorsal artery is 2.7 mm in diameter on average, accompanied with two thicker veins mostly. The scapula branches are located on the 4.1 cm below the thoracodorsal artery starting point and sent out from the posterior medial wall of the thoracodorsal artery. On the beginning point, they are 1.5 mm in outer diameter on average and accompanied with two thicker veins. Scapula branches are classified into two types from the starting point, including the common stems of scapula branches and the serratus anterior branches with a length of 1.9 cm (0.8~3.2 cm) and an outside diameter of 2.1 mm (1~2.8 mm) (80%) and 1~2 single scapular branches accounting for 20%. For the latter, single scapula branches account for 87.5% and coupled scapula branches account for 12.5%. From the starting point, a scapula branch inclines internally by about 1~2 cm and then prolongs along the middle-to-low part of the axillary margin of scapula closely in the gap formed by the subscapularis muscle, the lateral margin of teres major, and serratus anterior muscle. Along the strike, scapula branches are branched into 4~9 musculoskeletal branches with an outer diameter of 0.3~0.8 mm. From the high to low, these branches enter the outside of the axillary margin of scapula via the sarcoplasm on the lower part of the starting point of teres minor muscle and the starting part of teres major muscle. There are also branches of scapular branches distributing from the anterolateral side of the musculus subscapularis to the anterolateral surface of the axillary margin.

19.6.2.4 Processus Styloideus Radii Bone Flaps with Recurrent Processus Styloideus Radii Vascular Branch Pedicle

The radial artery bypasses the lower end of styloid process from the front of the radius. Then it obliquely passes through the depth surfaces of the extensor hallucis longus tendon and the abductor pollicis longus tendon and reaches the nasopharyngeal fossa on the dorsal carpal side. On the point of (1.2 ± 0.3) cm below the styloid process, it sends out one thick dorsal carpal branch to the ulnar side. The proximal dorsal carpal branch of the radial artery sends branches, or, the main proximal radial artery directly sends out branches. These branches return to the tip of styloid process, called as recurrent processus styloideus radii vascular branches. Single recurrent processus styloideus radii vascular branches account for 76% while coupled recurrent processus styloideus radii vascular branches account for 24%. These branches are (1.2 ± 0.3) cm long on average. The start end is (0.4 ± 0.2) cm in outer diameter and 0~1.2 m far from the distal syloid process tip. According to starting types and branch number, recurrent processus styloideus radii vascular branches can be classified into four types. (a) Single type. A single recurrent styloid process branch is sent out by the radial artery, accounting for 65.8%. (b) Double branch type. Double recurrent styloid process branches are sent out by the radial artery stem, accounting for 15.8%; (c) Co-stem type. The co-stem recurrent styloid process branches and dorsal carpal branches. This type can be also regarded as sending out from the dorsal carpal branch to the styloid process, accounting for 13.2%. (d) Hybrid type. This type includes a single branch divided from the radial artery and the co-stem of the single branch with the dorsal carpal artery, accounting for 2.6%.

19.7 Bone Grafting with Vascular Anastomosis

19.7.1 Donor Site Selection

Donor site selection is relatively free in bone grafting with vascular anastomosis. When the main goal is to repair supporting function, it is suitable to select long bones, such as the rib and fibula, as a flap donor to take full advantage of the supporting feature of long bones. When bone healing is highly demanded, cancellous bone is appropriate as a donor site, such as the iliumn and scapula. In general, resection of a bone flap should follow the rules as follows: repair a functional zone using a nonfunctional zone, repair primary functional zone using a secondary functional zone, and repair non-main vessels firstly and main vessels next. If a simple and adjacent bone or periosteal transposition with vascular pedicle is available, bone grafting with vascular anastomosis is not selected. If a simple and adjacent bone or periosteal transposition with vascular pedicle is unavailable or adjacent flaps fail to satisfy phase I repair of the bone defects accompanied with massive soft tissue defects, a free flap or periosteal flap transplantation with vascular anastomosis can serve as an option.

Bone graft with vascular anastomosis is hard to be popularized due to its high surgical requirements and surgical risks. Clinically, this operation is mainly used to repair long segmental bone defects of more than 6 cm. The longest bone flap donor contains the fibula, ilium, and scapula etc. In general, an adult fibula and iliac bone can provide a bone flap of about 20 and 16 cm respectively, while the scapula is mainly applicable in repair of bone defects of below 6 cm.

19.7.2 Clinically Applied Anatomy

19.7.2.1 Applied Anatomy of Fibular Flaps (See Sect. 19.6)

19.7.2.2 Applied Anatomy of Iliac Flaps

The iliac flaps pedicled with deep iliac circumflex artery (see Sect. 19.6).

The iliac flaps pedicled with superficial circumflex iliac artery.

The superficial circumflex iliac artery has greatly different origins. Investigation by Miao Hua et al. (1981) of 201 superficial circumflex iliac arteries concludes that 75.1% of the superficial circumflex iliac arteries originate from the femoral artery, 12.9% from the deep iliac circumflex artery, 8.0% from the lateral femoral circumflex artery, 3.5% from the deep femoral artery, 0.5% from the medial femoral circumflex artery. On the origin, the outer diameter is 1.3 mm. From the main trunk, the superficial circumflex iliac arteries further branch into superficial branches (along the superficial surface of deep fascia) and deep branches (along the deep surface of deep fascia). After being branched from the main superficial iliac circumflex artery, the superficial branches go through the femoral fascia to the inferolateral side of inguinal ligament and then obliquely extend upward and outward. After crossing the anterior superior spine surface, they turn upwardly. The superficial branches mainly distribute in the skin near the lateral inguinal half and the forepart of iliac crest. The deep branches develop on the deep surface and along the lower part of inguinal ligament and end on the place near the anterior superior spine after passing through the deep fascia. They further divide before passing through the deep fascia. These branches distribute in the muscles near the anterior superior spine, as well as the periosteum and bone cortex of the anterior iliac crest. Superficial iliac circumflex arteries are mainly cutaneous ones with limited nutrient bone and periosteum. This type of arteries is suitable in repair of small bone defects accompanied with large skin defects.

19.7.2.3 Applied Anatomy of Scapular Flaps (See Sect. 19.6)

19.8 Microsurgical Repair of Humeral Nonunion

The causes for humeral nonunion are indicated as follows: (1) In an open comminuted humeral fracture induced by severe trauma, bone fragments are lost at the moment of injury. Through debridement, reduction and fixation, bone nonunion or bone defect is caused and often associated with soft tissue defects that are needed to be repaired. (2) In a closed comminuted humeral fracture, the periosteum is stripped and the blood supply on the fracture ends is seriously destructed. In this case, humeral nonunion may by induced by bone fracture nonunion after operation. In addition, humeral nonunion can also be iatrogenic due to incorrect surgical operation on a simple humeral fracture. (3) Infected bone nonunion results from infections after open or closed humeral fracture. After debridement, bone defects may develop. With social development, serious injury grows increasingly. Bone nonunion caused by serious injury also sees an annual increase. The complex condition and protracted course of humeral nonunion increase the difficulty of treatment.

In clinic, humeral nonunion is still commonly treated by traditional free bone graft. However, the “creeping substitution” process in a traditional method is mainly used to repair small bone defects. As for bone defects of above 6 cm, traditional non-blood supply bone graft calls for long healing time. Meanwhile, most of the bone grafts are absorbed in different degrees or fail to achieve complete substitution. Therefore, the treatment effect is not ideal. Moreover, since the body needs to be fixated for a long time, the joint function is greatly influenced. With development of microsurgical techniques, it is now possible to use various autologous tissues and vascular pedicled bone grafts to repair long segmental bone defects. Since a grafted bone flap owns its own blood supply, the healing way of vascular pedicled bone grafting is similar to the healing process of bone fracture. Therefore, the length of bone graft can be neglected. Moreover, owning to rich blood supply, the bone grafts show a high anti-infection ability and thus are more advantageous in treatment of infected nonunion. Their repair effect is obviously superior to that of the traditional method.

19.8.1 Preparation of Recipient Zone

The recipient zone of humeral nonunion calls for debridement firstly. The debridement includes resection of the fibrous callus tissue in the focus of bone nonunion, removal of the sclerotic bone until bone surface errhysis, and breaking through the medullary cavity. In addition, the tissues in the focus need routine pathologic examination and bacterial culture. When an internal fixator is still effective, the fixation is kept. When an internal fixator is ineffective, it should be substituted with a stronger one. In case of infection, the internal fixation should be removed and changed into external fixation. The cases treated by free flap grafting should be dissected to expose the deep brachial artery and its accompanying veins and cephalic veins after debridement to prepare for vascular anastomosis.

19.8.2 Dissociated Transposition of Fibular Flap with Vascular Anastomosis

The route takes the Henry on the posterior-lateral calf. The incision begins from the capitula fibula and develops along the oblique posterosuperior part of the biceps tendon for 5~6 cm. Then it extends downwardly along the lateral side of the fibula to a length needed. The lower section of the incision is slightly curved and tends backward laterally. This incision is equivalent to the gap between the fibular muscle and the soleus muscle, with its upper end as the trending direction of the common fibular nerve. After incision of the skin and fascia of calf, the common fibular nerve is firstly separated on the posterior-inferior edge of the biceps tendon, which is further dissociated to the inlet of peroneus longus to the distal end for protection. From the bottom to the top, the gaps among the peroneus longus, brevis muscle, and soleus are isolated in a hidden way and the soleus is pulled back. On the internal upper edge of the starting part of hallux longus, it is visible that the fibular artery and veins obliquely enter the deep surface of the hallux longus from the posterosuperior part.

The peroneus longus and brevis attaching on the outside of the fibula are separated through sharp dissection. The process is as follows. With the point where the fibular nutrient artery enters the fibula as the center, the fibula is cut using a wire saw by the required operation length on the proximal or distal osteotomy plane selected. If the bone segment includes the caput fibulae, the caput fibulae is disarticulated from the tibia joint while part of the surrounding soft tissues of the caput fibula are retained to sew up the caput fibula with the soft tissue in the recipient area in the reconstruction. In this way, the fibula can be pushed and rotated to expose the surrounding tissues of fibula, which is very good for further dissection of the fibula. By rotating the fibula backwardly along the long axis, the musculus extensor and interosseous membrane on the front of fibula can be separated sharply. As the anterolateral surface of the fibula is cut off, only a thin muscle sleeve of about 2~3 mm thick can be retained on the fibula. Successively, the fibula is rotated forwardly to clearly disclose the posterior tissue. Along the fibular artery and veins, part of the hallux longus and tibialis posterior are incised so that the fibula posterior can retain the muscle sleeves of approximately 0.5~1.0 cm thick with fibular artery and veins. Then the distal fibular vascular bundle is cut off firstly. Afterwards, the upper section of fibular vessels is further dissociated when the grafted fibular section is further dissociated. Other disassociation ranges follow the operation requirements in the recipient zone and can extend to the posterior tibial vascular branches. Now, the bone flaps are completely disassociated for use.

If the cutaneous branches of fibular artery are used to monitor a skin flap, they should be searched for and protected in the cutaneous flap range designed preoperatively when the fibula is incised. With the cutaneous artery as the center, we cut a piece of cutaneous flap in a size of about 5 cm × 3 cm to retain part of the soft tissues around the cutaneous artery. Before the pedicle is cut off, it should be ensured that the cutaneous flap and the fibula have normal blood supply. If there are soft tissue defects that need flap coverage in the recipient zone, the monitoring range of cutaneous flap can be expanded to the size needed.

We keep an appropriate length of vascular pedicle. The fibular artery and veins of this vascular pedicle are cut and ligated. Then the upper and lower ends of the humerus bone graft are inserted into the humeral marrow cavities on the proximal and distal ends of the lesion respectively so that the two ends of lesion can be propped by the fibula under certain strain to restore the original length of humerus. Using the longitudinal compression of the surrounding muscles and soft tissues, the grafted fibula can play an internal fixation role, facilitating the healing of grafted fibula. On the proximal and distal ends, the grafted fibula is fixated using 1~2 screws. Moreover, the fibular artery is anastomosed with the deep brachial artery. One fibular artery is anastomosed with the accompanying vein of deep brachial artery, and the other with the cephalic vein.

Complications include arteriovenous crisis, infection, internal fixation failure, bone resorption, nonunion or delayed union, bone fracture, and shoulder joint dysfunction.

19.8.3 Grafting with Vascular Scapula

On the lateral position, start the incision from the posterior axillary fold and extend it upwardly for 6~7 cm along the posterior edge of deltoid muscle. Then from the top of posterior axillary fold, it obliquely turns internally and downwardly to the 2~3 cm below the angulus inferior of scapula. After blunt separation of the teres major and the latissimus dorsi muscle, the upper edge of the latissimus dorsi muscle is incised for 3~5 cm longitudinally and downwardly on the angulus inferior of scapula. Meanwhile, the latissimus dorsi muscle is pushed outwardly. At this time, it is visible that the scapula branches sent from the thoracodorsal artery incline inwardly and draw close to the middle part of the axillary margin of the scapula downwardly in the operational view. Along the scapula branches, the incision is extended carefully to thoracodorsal artery to separate the scapula branches. After the circumflex scapular artery is ligated, the incision continues expanding upstream to the vessels under the scapula to increase the rotating arc of the scapula. From the angulus inferior of scapula to the scapula glenoid, a flap of 2 cm wide is resected along the lateral edge of scapula. Then the subscapularis muscle is cut off and the bone flap resection is completed.

The bone flap resected is transposed to the proximal anterior of humerus via the axillary subcutaneous tunnel to bridge bone nonunion or bone defect. The distal and proximal ends of the bone flap are inserted into the medullary cavities of humerus respectively and fixated using 1~2 screws.

19.8.3.1 A Typical Case

The typical case is a male patient. After operation for the right humerus fracture, his sinus repeatedly suppurated for 22 years. Preoperatively, the proximal anterior and lateral sinus of the right upper arm was visible (Fig. 19.2). X-ray (Fig. 19.3) and CT (Fig. 19.4) examinations suggested osteomyelitis on the right proximal humerus and sequestrum surrounded by massive inflammatory bone callus. After debridement, a free fibular graft was used to repair the bone defect surface (Fig. 19.5). Meanwhile, vancomycin-loaded artificial bone was implanted for infection control (Fig. 19.6). Half a year after operation, reexamination showed bone union of the fibular flap and humerus bone (Figs. 19.7 and 19.8) and favorable healing condition of the wound surface (Fig. 19.9).

Fig. 19.2 Chronic osteomyelitis of the right humerus and the sinus on the proximal anterior part of the right upper arm

19.9 Microsurgical Repair of Scaphoid Nonunion

The carpal scaphoid is the longest carpus. It is about 21~23 mm long and S-shaped. Its distal end is connected with the distal row carpus while its proximal end with the proximal row carpus through ligaments. when the capus back hits the ground in extension position in a fall, the ground shock force is conducted upward along the distal navicular bone and causes facture in the neck or wrist of scaphoid. The blood supply of scaphoid involves a dorsal group and a palmar group. The dorsal group is sourced from the distal side of dorsal crest and supplies blood to 70~80% of the proximal side of scaphoid. The palmar group enters the bone from the palmar node and supplies blood to 20~30% of the distal side of scaphoid. On the proximal, the scaphoid bone shows no vesicular access. In a fracture of the wrist of scaphoid, the retrograde blood supply is damaged. Therefore, proximal scaphoid nonunion or bone necrosis is a likely consequence. Clinical reports suggest that the nonunion rate of scaphoid

Fig. 19.3 Osteomyelitis lesions and sequestrum in the middle-to-upper section of humerus on the X-ray photo

Fig. 19.4 Sequestrum in the lesions clearly shown by CT

Fig. 19.5 Bone defects repaired by free fibular flap after complete debridement of the osteomyelitis lesions

Fig. 19.6 Anastomosis of the peroneal artery with the deep brachial artery; fixation of the two ends of fibular flap on the humerus using screws; implantation of vancomycin-loaded artificial bone for infection control

fractures lies between 5 and 50%. Clinically, scaphoid nonunion is treated by implantation of vascular pedicled radial bone flap. The implantation provides new blood supply to the scaphoid whose blood supply has been destroyed. Moreover, the periosteum of the bone flap can cover the fracture line to accelerate formation of bone bridge and bone union in turn. If necessary, the implantation can be assisted by resection of processus styloideus radii. The following part describes the two kinds of vascular pedicled bone flaps.

19.9.1 Radial Bone Flaps Pedicled with Recurrent Radial Artery Branch

An S-shaped incision is made by cutting the skin and subcutaneous tissue on the carpal dorsal radial side through the

Fig. 19.7 Bony union of fibular flap and tibia shown by X-ray photo half a year after operation

nasopharyngeal fossa. In this process, attention should be paid to protection of the superficial branch of radial nerve, radial artery, and cephalic vein. After the extensor retinaculum is cut open, the tendon of extensor pollicis longus, tendon of extensor pollicis longus brevis, and extensor tendon in thumb are retracted laterally. Then we search for the dorsal carpal branches and recurrent branches of the radial artery on the distal processus styloideus radii. Next, the ligament on the dorsal carpal radial side and the joint capsule are incised successively to expose the scaphoid nonunion. Using a miniature osteotome and curette, the fiber sclerotic bone and granulation tissue on the bone nonunion location are carefully removed to be fresh. Then the bone fracture is reduced to observe the bone defect size on the bone fracture end. On the point 1.5 cm away from the distal radius, a stripped flap in corresponding size is drilled using an osteotome. From the distal end to the proximal end, the vessels are carefully disassociated to the bone block position. In this process, the vascular network and periosteum on the bone flap surface

Fig. 19.8 X-ray photo of the donor site of fibular flap

Fig. 19.9 Healing of osteomyelitis half a year after operation

should be protected as much as possible. The vascular pedicles are then pulled toward the radial and ulnar sides respectively for osteotomy, respectively. The periosteum cut should be slightly larger than the radial flap to avoid injury to the vascular pedicle. Then tourniquet is then relaxed to observe bleeding condition of the radial flap. The bone block size is then trimmed to be appropriate for the bone defect on the bone fracture end. Then the radial flap with vascular pedicle is embedded into the position of scaphoid bone defect.

19.9.2 Radial Bone Flap Pedicled with Dorsal Branches of Arteria Interossea Volaris

Incision is started from the carpal dorsal median of the forearm longitudinally, with the distal end extending to the nasopharyngeal fossa and the proximal end extending to the 2/3 of the forearm. Then the subcutaneous tissue is cut and the flap is pulled over to both sides. The dorsal carpal ligament exposed is longitudinally incised. Then the extensor hallucis longus of the thumb, and the extensor digitorum communis and extensor digitorum communis of the forefinger are retracted laterally. On the distal end and carpal dorsal side, the dorsal branches of arteria interossea volaris longitudinally distribute on the proximal end of the radial end and carpal dorsal side, accompanied with small veins and the carpal dorsal artery network. With the dorsal artery branches as a shaft axis, the big and small fascia vascular pedicles in size of 1.2 cm × 1.5 cm are disassociated on the carpal dorsal side, with the proximal end on the distal end of radius and the distal end on the carpal dorsal vesicular network. On the dorsal carpal scaphoid, a bone groove in size of 1.5 cm × 0.6 cm × 0.6 cm is cut along the longitudinal axis. Then with the vascular pedicle as the axis, the radial periosteum is cut off in a range slightly larger than the bone incision range on the distal end of radius. On the proximal end, the dorsal blood vessel bundle is cut off. After the periosteum is pealed to the predicted bone incision line, the surrounding of the bone flap is incised using a small bone knife carefully to provide the bone flap with sufficient cancellous bone. The island-type bone flap with vascular disc membrane as pedicle is formed thereby. Then the vascular disc membrane is rotated by 90° and the radial flap is embedded into the bone groove of carpal scaphoid. Finally, the surrounding periosteum of bone flap is sutured with surrounding joint capsule.

The key to surgical treatment lies in reconstructing blood circulation and effectively removing the processus styloideus radii and the internal fixator of bone graft. When the periosteum is stripped in operation, the recurrent nasopharyngeal fossa vessels attached on the surface of the periosteum should be specially protected. During the resection of radial graft, the bone substance, the periosteum with recurrent vascular branches attached, and the muscular tissue attachments should be preserved intact so that the blood supply to the proximal end of the scaphoid can be effectively reconstructed when the graft is turned over by the radical bone flap with vascular pedicle. Fixation of bone grafts is also important. In operation, the bone graft blocks should be fixated using Kirschner wire. After operation, they should be externally fixated using tube-like plaster. Favorable fixation can provide a stable mechanical environment, which is conductive to the healing of bone fracture. In addition, the processus styloideus radii should be resected quite appropriately during operation. Excessive resection may cause instability of the carpal joint while insufficient resection may induce inter-collision of the bone blocks on the proximal end of the carpal scaphoid bone. Inter-collision increases the shearing force on bone fracture line and affects bone fracture union. Meanwhile, traumatic arthritis of the carpal joint, which is highly probable, triggers carpal pain and influences mobility of the joint.

After implantation, the radical flap is fixated using Herbert screws to treat scaphoid nonunion. The treatment effect is satisfying. In operational design, the flap with vascular pedicle is implanted into the bone fracture end to provide rich blood supply, thus effectively promoting bone fracture union. Meanwhile, since the pitch of the Herbert screw head is larger than that of the tail, the screw may exert pressure on the bone fracture end when it is completely sunk into the scaphoid. The biggest advantage of using hollow screws for fixation lies in that Kirschner wire can be used to guide location and the operation is relatively simple.

19.10 Microsurgical Repair of Nonunion of Femoral Neck Fracture

Femoral neck fracture is common mainly in old people. The incidence of femoral neck fracture accounted for 3.6% of all bone fractures and 53% of hip fractures. Since femoral neck fracture may be accompanied with hip joint dislocation, the blood supply in the femoral head is destructed, inducing femoral neck fracture nonunion, followed by avascular necrosis of the femoral head. The nonunion rate is reported from 7 to 15%.

19.10.1 Anatomical Basis of Femoral Neck Fracture Nonunion

The blood supply of the femoral neck has a special anatomic structure. The blood supply of the femoral head is mainly sourced from the internal and external femoral circumflex arteries, which constitute an arterial ring out of the joint capsule. From this arterial ring, these two arteries further divide and their branches pass through the joint capsule. On the intersection with the femoral neck, the arteries enter the femoral head. According to the blood supply position, the small arterial group is divided into a lateral energy artery group and an internal energy artery group. The lateral energy artery group of 2~6 branches is the most important for the femoral head, since it is responsible for the blood supply to 2/3–3/4 of the outer and upper parts of the femoral head. The internal energy artery group of 1–2 branches supplies blood for 1/4–1/2 of the internal and lower parts of the femoral head. The vessels in the small concaved initial belt merely provide blood supply to the concave part of the femoral head. The vessels around the femoral neck are vulnerable to femoral neck fracture, and displacement in particular. Angiography confirms that, in case of displaced femoral neck fracture, the retinacular artery, as well as the internal and lateral circumflex femoral arteries, will be destroyed. Chalmers who used injection technique to study the blood supply of femoral head found that the femoral head maintained merely 16% of the blood supply after femoral neck fracture. Sugamoto utilized a laser Doppler device to measure hemodynamic variations of the femoral head after femoral neck fracture and found that the cases of femoral neck fracture with displacement presented less blood flow in the femoral head. Xu Shaoting pointed out that the femoral head ischemia should be revascularized to support the femoral head through the growth of the cervical vessels in the head end after femoral neck fracture. Although the vessels in the femoral head are not the terminal branches, the substitution process is very slow due to the insufficient vascular anastomosis. Avascular necrosis of the femoral head is observed in 85% of the femoral neck fractures. Through restoration of blood supply by vascular reconstruction, the femoral head is resurrected. However, some of the ischemic necrosis always fails to be recovered, especially the lateral-superior ischemic necrosis of the femoral head supported by upper supporting vessels. The dead bone of trabecular facture may induce collapse of the femoral head. At the same time, femoral neck fracture only has the blood supply on the distal end. On the proximal end, the blood supply can only be reconstructed through restoration and the ischemic necrosis of new vessels. The bone fracture on the proximal end is thereby influenced. Moreover, since facture happens in the joint capsule, there is fibrinolysis in the joint capsule liquid to prevent formation of blood blocks, cytomorphosis, and invasion of vessels into the femoral head. The fracture union is thereby influenced, resulting in nonunion of femoral neck fracture and even femoral head necrosis.

To provide more compensatory blood supply to the femoral head and neck in case of femoral neck fracture nonunion, bone flap grafting with muscular pedicle or vascular pedicle can be used.

19.10.2 Ilium Flap Transplantation

19.10.2.1 Ilium Flap with Tensor Fasciae Latae Pedicle

The patient is on supine position. The incision starts form the anterior hip joint. The longitudinal incision is cut along the first half of crista iliaca toward the anterior superior spine direction, extending for 8~10 cm toward the distal end along the femur. On the deep fascia layer, the incision is pulled laterally to expose the anterior superior spine, crista iliaca, tensor fasciae latae, and sartorius etc. On the interior of anterior superior spine, the anterolateral femoral cutaneous nerve is dissected and protected by rubber strip pulling. Then the two lateral margins of tensor fasciae latae are isolated bluntly to the crista iliaca attachment. At the position of 2 cm from the anterior superior spine, the iliac strips in size of 6 cm × 1.5 cm × 1 cm with outer table instead of inner table are cut using an osteotome backwardly. Then the tensor fasciae latae bearing iliac strips are separated for 10 cm to the distal end. Be careful to avoid the stripping of and injury to the tensor fasciae latae attachment before entering the muscular nutrient vessels. At this time, the errhysis on the wound face of the bone strip is seen. Then the musculoskeletal flap is wrapped using saline gauze for use. To expose the femoral neck and the internal fixation of bone fracture, the sartorius is pulled over, and the rectus femor is cut off from the starting point. The incision is then pulled laterally to expose the capsule of hip joint. Along the direction of femoral neck, the joint capsule is cut open to disclose the femoral neck and bone fracture. The scar fibrous tissue or bone sclerosis in the gaps of bone fracture, if exists, should be removed. In direct vision, the bone fracture is restored. Then three holes are drilled on the 1 cm in a triangle shape below the slope of greater trochanter by space of 1.5~2 cm. Along the three holes, three compressive hollow screws are driven into the femoral head for fixation via the femoral neck and fracture surface. On the anterior femoral head, a bone groove, 5 cm in length, 1.5 cm in width and 1 cm in depth, is drilled along the long axis. Then it is and further dug for 1 cm to get a femoral head cave. The iliac flap of tensor fasciae latae pedicle is rotated for 45° to make the outer table of bone turn outwardly. Then one end is inserted into the femoral head cave while the other end is embedded into the bone groove. The bone blocks are flipped using a bone hammer to be fast. The outer end of bone block is further fixated using one cancellous screw. After rinsing the incision, the starting point of rectus femoris is sutured by layers.

19.10.2.2 Illium with Deep Iliac Circumflex Artery

The deep iliac circumflex artery is sourced from near the junction of external iliac artery and femoral artery. It includes an abdominal wall muscle branch and a crista iliaca branch. The crista iliaca branch has coarse outer diameter and locates on the (1.8 ± 0.4) mm on the anterior superior iliac spine. From the interior-posterior side of anterior superior spine, this artery extends toward the exterior-posterior along the interior-posterior side of crista iliaca and is branched into the muscle-periosteum branches, supplying nutrients for the illium, and the bony branches, passing through the illum, which are located in the obliquus externus abdominis and the obliquus internus abdominis respectively. On the deep transversalis fascia flexor, it is visible that the deep iliac circumflex artery inclines outwardly and upwardly. In the anterior superior spine, the artery is perpendicular to the lateral femoral cutaneous nerve. The vascular pedicle is about 5~7 cm in length, which is an important anatomic symbol. At this position, it is suitable to disassociate the vascular bundles form the near end to the far end. Then the outer and inner table of ilium is peeled to window the marginal periosteum. Then an electric saw is employed to reserve the iliac flap in an appropriate size of 4 cm × 2 cm~4 cm × 2.5 cm on the cartilage edge of crista iliaca. Meanwhile, the appearance of crista iliaca is kept. The iliac bone flap should be bleeding and the vascular bundle should present arterial pulses. The characteristics of iliac bone flap are constant anatomy, being easy to find, and coarse vessels. The implantation plays an active role in reconstruction of the femoral head and neck.

The patient is in a supine pose intraoperatively. The injured hip is elevated using a sandbag pad. A modified S-P incision is employed. Firstly, the deep iliac circumflex vessels are dissected. After the crista iliaca branches are found from far to near, the abdominal wall muscle branches are cut off and ligated. Then the internal iliac periosteum is incised and peeled downwardly to expose the internal illiac table range. In the same way, the outer table is exposed. Using a saw, the island-shaped bone flap pedicled with deep iliac circumflex artery is formed by resection from outside to inside. The hip joint exposed is cut by cross. Part of the anterior synovial membrane is resected to expose the femoral neck and femoral head. In direct vision, the fracture ends are restored. From the upper, lower, and posterior sides (a triangular shape), three double-end compression screw nails are inserted respectively. On the bone fracture part, a bone groove of 2.0 cm in width and 1.5 cm in depth is opened beneath the head. The bone flap reserved is introduced into the bone groove via the deep surface of the iliopsoas. On the distal end, the flap is fixated using one absorbable screw. Then the joint capsule and bone flap are sutured together with a drainage tube placed in 24–48 h later, the tube is extracted. On the crista iliaca, three layers of muscle are sutured using coarse thread to prevent abdominal hernia. The incisions are sutured by layers. In the postoperative treatment, routine vasodilator drugs are used to prevent vasospasm. When the injured limb is capable of abducting in a neutral position, sitting is allowed. X-ray photoes should be reviewed monthly. Three months later, non-weight-bearing hip and knee joint function exercise are permitted. Six months later, non-weight-bearing walk assisted by crutches are permitted according to the fracture healing condition.

19.10.2.3 Pedicled Iliac Bone with Ascending Branch of Lateral Femoral Circumflex Artery

The ascending vascular branch of lateral femoral circumflex artery consists of one artery and two accompanying veins. It has a constant position and is easy to be dissected. Its start point is 7.33~9.11 cm away from the anterior superior spine. Its sufficient length ensures that the pedicled bone flap can be implanted into the femoral head without tension. Moreover, since the bone flap donor site is near the recipient zone, the transposition is convenient. The turn and twist of pedicle can be avoided thereby. Moreover, as the vessel is 2.22~3.50 mm in outer diameter on the start point, the bone flap has abundant blood supply, leading to a low incidence rate of vascular embolization.

Epidural anesthesia and modified Smith-Peterson incision are employed. The patient takes a supine position, with the hip on the injured side padded up by 30°. While the incision is made, attention should be paid to protection of the lateral femoral cutaneous nerve. Reveal the start point of the ascending branch of lateral circumflex femoral artery. Along the major blood vessel of the ascending branch of lateral circumflex femoral artery, the broad fascia tensor, and the fascia of the tensor, the incision is traced upwardly and reversely to the iliac muscle porta. The iliac outer table is not peeled. The inner table is stripped beneath the periosteum. Then we take the iliac block in size of about 2 cm × 1 cm × 4 cm on the lateral half layer from the broad fascia tensor and the anterior superior spine. Remove the pedicled iliac flap intact. The pedicled iliac flap obtained is wrapped using saline gauze for use. Treatment of the femoral neck nonunion and the bone flap grafting method are described as the above.

19.10.2.4 A Typical Case

The patient is a male of 25 years old. He suffered from bone union for three years after femoral neck facture. Preoperative X-ray (Fig. 19.10) and CT (Fig. 19.11) showed cystic degeneration of the subchondral bone in the weight-bearing zone on the anterior and superior femoral head, suggesting necrotic bone sclerosis (Fig. 19.12). Intraoperatively, a groove was made from the femoral neck to the femoral head

Fig. 19.10 The bone nonunion 3 years after operation for femoral neck fracture and the crescent sign of femoral head

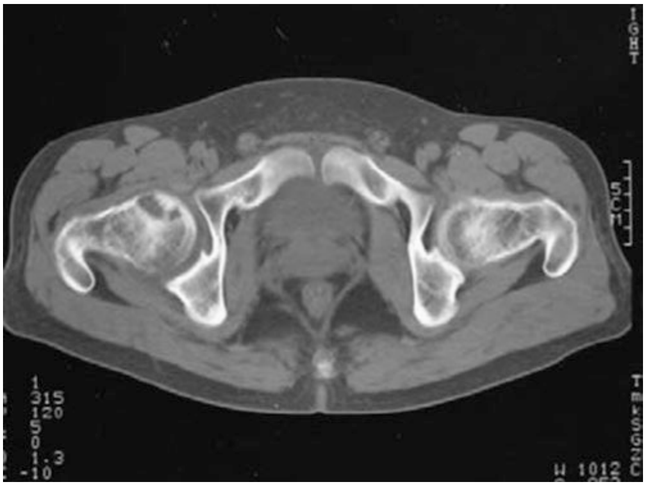


Fig. 19.11 The cystic degeneration of subchondral bone in the weight-bearing zone on the anterior and superior femoral head on the CT scan

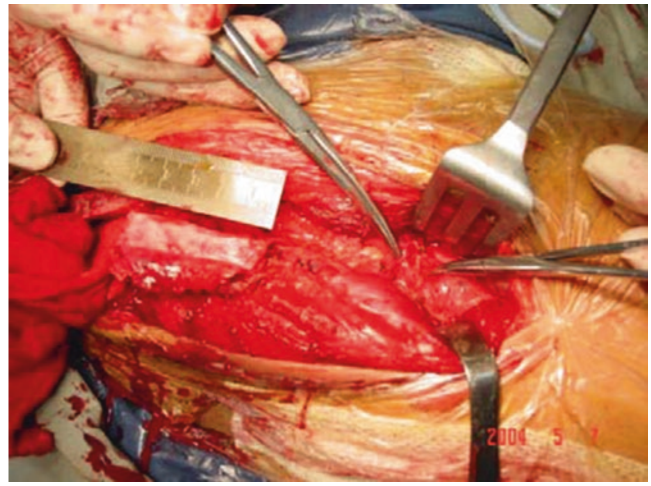


Fig. 19.13 Resection of the iliac bone flap of tensor fasciae latae

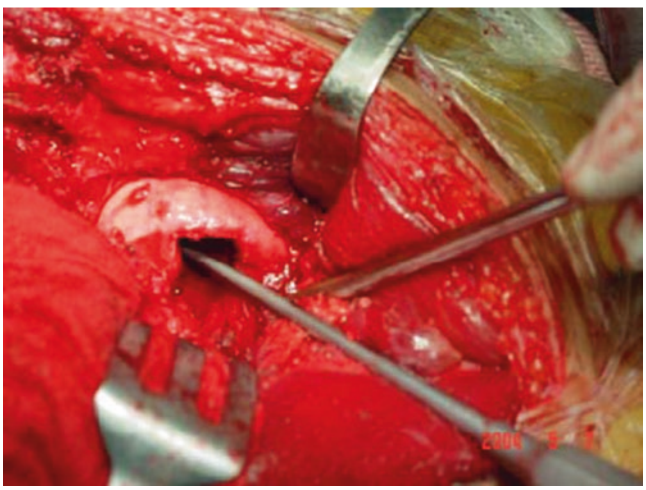


Fig. 19.12 The groove from the femoral neck to the femoral head for removal of necrotic hardening bone

Fig. 19.14 The bony union of the iliac flap in the examination half a year after operation

to remove the necrotic hardening bone. In addition, an iliac bone flap pedicled with tensor sciae latae (Fig. 19.13) was used to repair the bone defect. Half a year (Fig. 19.14) and 4 years (Fig. 19.15) after operation, examinations showed that his femoral head was in good shape and no obvious osteoarthritis was observed. Moreover, his hip function was restored favorably (Fig. 19.16).

19.10.3 Fibular Flap Transplantation

The operation is divided into two groups. The resection method of fibular flap is described in Sect. 19.8 of Chap. 19. The fibular flap with fibular vessels is about 5 cm in length. Incision is made from the anterior hip joint to expose the ascending branches of the lateral femoral circumflex artery. Meanwhile, attention should be paid to

Fig 19.15 The favorable femoral head morphology on X-ray 4 years after operation

Fig. 19.16 Good function of the injured hip

protection of these branches. The treatment method of femoral neck nonunion is described as the above. After the facture ends are fixated, a groove is opened toward the femoral head on the front of the femoral neck. After the periosteum on one side of the fibular flap is stripped appropriately for about 1 cm, the fibular flap is inserted into the femoral head. Note that the vascular pedicle side should lie ahead to avoid influence of entrapment on the blood supply to the fibular flap. The fibular flap is fixated using one cancellous screw or absorbable screw. The fibular artery is anastomosed with the ascending branch of the lateral circumflex femoral artery. After the drainage tube is placed in, the incision is sutured by layers.

19.11 Microsurgical Repair of Tibial Fracture Nonunion

Tibial defect and nonunion are severe complications after tibial trauma. Their treatment is difficult, especially when they are complicated with local soft tissue bone paste scar, ulcer, fistula, even soft tissue defect, and exposure of bone or internal fixator. The condition of the soft tissue around a tibial defect or tibial nonunion plays an important role in an ideal and effective treatment. It can be imagined that how outcomes of a bone grafting will be if soft tissue coverage is not fine and blood supply structure is not normal. Therefore, the tibial nonunion accompanied with local soft tissue defects should be treated using microsurgical techniques. In such a treatment, the tibial nonunion or defect is firstly repaired and reconstructed using grafting. Then a bone and myocutaneous flap with rich blood supply is used to cover the wound surface. Repair of soft tissue is the most effective method for this kind of complex condition in phase I, and sometimes, is the only alternative method.

19.11.1 Etiological Factors

1. High energy injury is the most common and primary cause, especially for open comminuted fractures whose incidence increases significantly in a positive correlation with high energy injury.
2. Infection. Infective factors include local infection after injury, operation and long treatment, limited osteomyelitis, and escape or removal of dead bone.
3. Improper operation time. Emergency treatment after trauma or early operation aggravates the injury to soft tissue, leading to poor wound healing and significant swelling of the soft tissue after tibial fracture. Especially when blisters appear on the lateral pretibial skin, bone exposure and delayed healing are almost inevitable due to the poor healing condition after reduction and internal fixation.
4. Improper operative incision. An incision that is parallel to the tibial surface on the pretibial inside is simple and easy to treat. However, if an incision is sutured under tension, wound dehiscence and nonunion are hard to be avoided.
5. Improper internal fixator, especially a steel plate used in an emergency or subemergency condition.
6. Too wide operation exposure range and rough operation.

Our clinical experience reveals that poor local soft tissue condition or soft tissue coverage deletion in tibial trauma is closely correlated to bone nonunion or bone defect at a corresponding position. In many cases, because of poor wound healing, wound dehiscence, exudation, secondary infection, long treatment, defect area expansion and bone exposure, limited traumatic osteomyelitis is also inevitable once the medullary cavity is opened, no matter the upper or lower end of the tibia or the middle-to-lower end of the tibial stem is involved.

It should be realized that, in a tibial and fibular fracture caused by high energy injury, the calf, especially the pretibial soft tissue (also the first to bear the brunt), is also injured by the high energy infringement. It is the same in understanding and treatment of tibial defect and nonunion accompanied with local soft tissue defect. In evaluation and treatment of the fracture, the injury situation of soft tissue should be acknowledged and assessed before a reasonable treatment plan can be formulated and a minimally invasive treatment can be conducted to minimize or avoid “iatrogenic” invasion.

19.11.2 Clinical Characteristics

1. The patients are mostly young adults and males are more than females.
2. Tibial nonunion and defect mostly follow a comminuted tibia fracture, accompanied with local bone defect on the upper and lower ends of the tibia. Long bone defects (greater than 6.0 cm) are few.

3. In tibial nonunion and defect, local soft tissue has unstable bone paste scar, wound center exudation, and sinus formation.
4. The patients with tibial nonunion and soft tissue defect always suffer from wound surface infection, bone exposure, and exposure and invalidation of implants (plate, intramedullary needle).
5. The course is long and joint function is limited, especially in the patient with lesions on the upper and lower ends of the tibia.
6. The wound bacteria are grouped, complex and strongly drug-resistant. The drug sensitivity results reveal that only a few cases are sensitive to the third generation cephalosporins and vancomycin etc. Our study shows the following sequence of drug-resistance by the bacterial culture: *Bauman's composite calcium acetate acinetobacter, Pseudomonas aeruginosa bacillus, Staphylococcus aureus, Staphylococcus epidermidis,* and *Escherichia coli* according to the occurrence probability. Some patients show mixed florae. With a prolonged treatment course, florae also change. The cases of *Staphylococcus aureus* infection are most difficult to treat.
7. Operation is difficult and highly risky.

19.11.3 Design of Treatment Plan

The treatment of tibial defect and nonunion accompanied with soft tissue defect and nonunion is still a great clinical challenge in orthopedics. An ideal treatment is believed as follows: (1) Conduct sufficient and effective bone graft after removal of bone lesions. (2) Applying as simple and effective skeletal fixation as possible. (3) Repair the skin defect and close the wound using favorable soft tissue coverage in Phase I operation and the treatment course is shortened. (4) Early limb and joint rehabilitation exercise is allowed. (5) Good soft tissue conditions are created for functional reconstruction or replacement of the knee and ankle joint in a later phase.

The following questions concern three critical aspects.

1. After local debridement of bone lesions, which kind of bone grafting is suitable? Is phase I bone grafting, phase II bone grafting, or open bone grafting? If phase I bone grafting is selected, what kind of bone grafts should be used? Is autogenous bone, artificial bone, or antibiotic impregnated bone? Our approach is as follows: (1) Before operation, the wound surface is cultured in nonbacterial condition. If the disease course is short, the pulp cavity is slightly infected after lesion debridement, and financial status of the patients is not good, autologous iliac bone grafting is preferable. However, the wound surface should be filled or covered with a musculocutaneous flap or cutaneous flap. (2) Antibiotics carrier artificial bone (the Calcium sulfate cement with vancomycin produced by American Wright Company) is used in the following conditions: there is still bacterial growth after culture on the wound surface; a large amount of inflammatory granulation tissue or pus is observed intraoperatively on the bone lesion position; medullary cavity infection is wide and bone graft mass exceeds 10 g; the patient is infected by *Staphylococcus aureus* and *Bauman's composite Acinetobacter calcoaceticus*. (3) As for a long bone defect exceeding 6 cm, a free fibular flap or ipsilateral vascularized fibular flap can be used to attach the bone graft or a free iliac bone flap with deep iliac circumflex vessels can also be applied.
2. Maintenance or reconstruction of bone stability. Should the original fixation be retained or removed? This depends mainly on the effectiveness of the internal fixation. Our approach is as follows: if a steel plate is loosely fixated or external fixation is added or applied as a substitute after debridement of bone lesions, the external fixation is employed after removal of the intramedullary nails in patients with a long duration of intramedullary nail fixation. Priority is given to three-dimensional fixators. Lack of effective skeletal stability will significantly affect bone healing. Therefore, maintenance or reconstruction of skeletal stability is extremely important and cannot be ignored. At the same time, effective skeletal stability plays a positive role in enhancing local bone blood circulation, preventing limb muscle atrophy and joint stiffness, and promoting bone healing through early postoperative rehabilitation for limbs and joints.
3. Coverage of the wound surface of soft tissue defect. This aspect is as important as, or even more important than, bone grafting. It is impossible for a bone-exposed wound without favorable soft tissue coverage or closure to achieve good results. In a sense, soft tissue coverage and closure of wound surface after grafting is the key to a successful operation. Therefore, after lesion debridement and graft repair and reconstruction, a musculocutaneous flap or myocutaneous flap is an irreplaceable and effective way to repair soft tissue defects, achieving effective coverage and closure of the wound. In the proximal tibia, the adjacent cutaneous flaps available for coverage of a soft tissue defect wound after grafting include head muscle flap of medial gastrocnemius + full-thickness skin grafting, myocutaneous head muscle flap of medial gastrocnemius, head muscle flap of lateral gastrocnemius + full-thickness skin grafting, and head muscle flap of lateral gastrocnemius and musculi soleus + full-thick-

ness skin grafting. The myocutaneous flaps and methods for coverage and closure of the soft tissue defect wound surface on the middle section and middle-to-low section of the tibial bone include adjacent fascia pedicle flap, distal pedicled fibular artery perforator vascular (muscular) flap, posterior tibial artery perforator vascular (muscular) flap, and distal pedicled sural neurocutaneous vascular (muscular) flap. In repair of a massive soft tissue defect, we can also use femoral anterolateral myocutaneous flap and thoraco-umbilical flap of vascular anastomosis in a few cases and head myocutaneous flap of cross-leg medial gastrocnemius for individual cases.

In summary, treatment of tibial nonunion and defect accompanied with soft tissue defect is a complex and delicate process. Due to the particularity of coverage and closure of each wound surface, it is difficult to design a universal operation method. Instead, the operation should be flexibly planned and conducted according to each actual situation, each specific patient and experience of specific surgeons.

19.11.3.1 Typical Case 1

This case is a male patient who suffered from 2 years' bone exposure and wound nonunion after internal fixation of fracture of the right upper tibia caused in an accident. His bone defect was 50% smaller than the cross-section diameter (Figs. 19.17, 19.18, and 19.19). After debridement, a head myocutaneous flap of gastrocnemius medial was designed to cover the wound (Fig. 19.20). The wound cavity of bone defect was filled with vancomycin artificial bone + autologous iliac bone (Fig. 19.21). The wound healed primarily (Fig. 19.22). Three year later, examination showed good bone healing (Fig. 19.23).

19.11.3.2 Typical Case 2

This case is a male patient who suffered from protracted sinus tract nonunion two years after an operation for open fracture of the right tibia and fibula (Figs. 19.24 and 19.25).

Fig. 19.17 The preoperative necrosis and yellowing tibial fragments in the wound

Fig. 19.18 Preoperative X-ray film showing a bone defect range 50% smaller than the cross-section diameter

Fig. 19.19 The residual wound cavity of bone defect after lesion debridement

Fig. 19.20 The wound coverage by a head myocutaneous flap of gastrocnemius medial

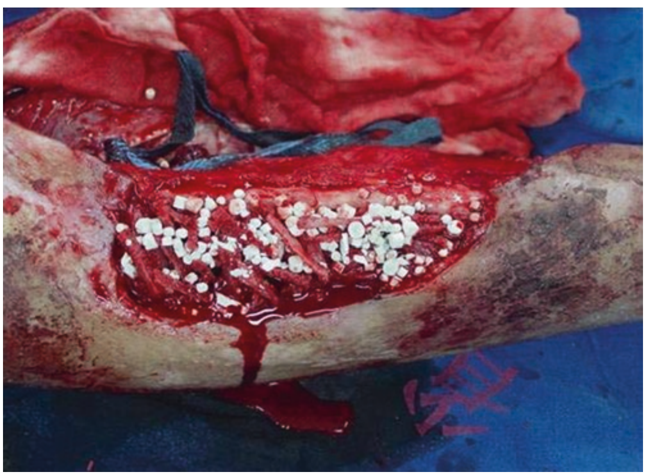


Fig. 19.21 The wound cavity of bone defect was grafted with antibiotic loaded artificial bone and autologous iliac bone

Fig. 19.22 The postoperative phase I closure of the wound

Fig. 19.23 The union of artificial bone grafted and iliac bone 3 years after operation

Fig. 19.24 The sinus tract on the wound before operation

Fig. 19.25 The X-ray film before operation

Fig. 19.26 The free fibular flap with a monitoring skin island

After debridement, a free fibula flap (with a monitoring skin island) was transplanted to repair bone defects (Figs. 19.26 and 19.27). The bone flap stability was established using external fixation. Six months after operation, the fibular flap with tibial bone healed (Figs. 19.28 and 19.29).

Fig. 19.27 Postoperative appearance

Fig. 19.28 The appearance half a year after operation

Fig. 19.29 The union of fibular flap with tibia half a year after operation

Bibliography

1. Fishero BA, Kohli N, Das A, Christophel JJ, Cui Q. Current concepts of bone tissue engineering for craniofacial bone defect repair. Craniomaxillofac Trauma Reconstr. 2015;8(1):23–30. https://doi.org/10.1055/s-0034-1393724. Epub 2014 Nov 18. Review. PubMed PMID: 25709750; PubMed Central PMCID: PMC4329034.
2. Konofaos P, Kashyap A, Ver Halen J. Biomedical approaches to improve bone healing in distraction osteogenesis: a current update and review. Biomed Tech (Berl). 2014;59(3):177–83. https://doi.org/10.1515/bmt-2013-0096. Review. PubMed PMID: 24399674.
3. Mankovecky MR, Prissel MA, Roukis TS. Incidence of nonunion of first metatarsal-phalangeal joint arthrodesis with autogenous iliac crest bone graft after failed Keller-Brandes arthroplasty: a systematic review. J Foot Ankle Surg. 2013;52(1):53–5. https://doi.org/10.1053/j.jfas.2012.06.001. Epub 2012 Oct 12. Review. PubMed PMID: 23063206.
4. Doi K, Hattori Y. Vascularized bone graft from the supracondylar region of the femur. Microsurgery. 2009;29(5):379–84. https://doi.org/10.1002/micr.20671. Review. PubMed PMID: 19530087.
5. Musharafieh R, Osmani O, Musharafieh U, Saghieh S, Atiyeh B. Efficacy of microsurgical free-tissue transfer in chronic osteomyelitis of the leg and foot: review of 22 cases. J Reconstr Microsurg. 1999;15(4):239–44. Review. PubMed PMID: 10363546.
6. Rockett MS, De Yoe B, Gentile SC, Zygmunt K. Nonunion of a Hawkin's group II talar neck fracture without avascular necrosis. J Foot Ankle Surg. 1998;37(2):156–61; discussion 174. Review. PubMed PMID: 9571464.
7. Szendröi M, Vizkelety T. [Results with endoprostheses and bone transplantation in surgery for bone tumors]. Orv Hetil. 1992;133(34):2141–6. Review. Hungarian. PubMed PMID: 1508538.
8. Louer CR, Garcia RM, Earle SA, Hollenbeck ST, Erdmann D, Levin LS. Free flap reconstruction of the knee: an outcome study of 34 cases. Ann Plast Surg. 2015;74(1):57–63.
9. Niikura T, Lee SY, Sakai Y, Nishida K, Kuroda R, Kurosaka M. Outcome of fixation for nonunion of extremities. J Orthop Surg (Hong Kong). 2014;22(3):309–12.
10. Demiralp B, Ege T, Kose O, Yurttas Y, Basbozkurt M. Reconstruction of intercalary bone defects following bone tumor resection with segmental bone transport using an Ilizarov circular external fixator. J Orthop Sci. 2014;19(6):1004–11.
11. Lakhani A, Singh D, Singh R. Outcome of rail fixator system in reconstructing bone gap. Indian J Orthop. 2014;48(6):612–6.
12. Badekas T, Takvorian M, Souras N. Treatment principles for osteochondral lesions in foot and ankle. Int Orthop. 2013;37(9):1697–706. https://doi.org/10.1007/s00264-013-2076-1. Epub 2013 Aug 28. Review. PubMed PMID: 23982639; PubMed Central PMCID: PMC3764304.
13. Fitzgibbons TC, Hawks MA, McMullen ST, Inda DJ. Bone grafting in surgery about the foot and ankle: indications and techniques. J Am Acad Orthop Surg. 2011;19(2):112–20. Review. PubMed PMID: 21292934.
14. Schieker M, Heiss C, Mutschler W. [Bone substitutes]. Unfallchirurg. 2008;111(8):613–9; quiz 620. https://doi.org/10.1007/s00113-008-1489-6. Review. German. PubMed PMID: 18704540.
15. Boyer MI, Bowen CV. Microvascular transplantation of epiphyseal plates: studies utilizing allograft donor material. Orthop Clin North Am. 2007;38(1):103–8, vii. Review. PubMed PMID: 17145299.
16. Khan SN, Cammisa FP Jr, Sandhu HS, Diwan AD, Girardi FP, Lane JM. The biology of bone grafting. J Am Acad Orthop Surg. 2005;13(1):77–86. Review. PubMed PMID: 15712985.
17. Lucarelli E, Donati D, Cenacchi A, Fornasari PM. Bone reconstruction of large defects using bone marrow derived autologous stem cells. Transfus Apher Sci. 2004;30(2):169–74. Review. PubMed PMID: 15062758.
18. Gamradt SC, Lieberman JR. Bone graft for revision hip arthroplasty: biology and future applications. Clin Orthop Relat Res. 2003;417:183–94. Review. PubMed PMID: 14646716.
19. Szpalski M, Gunzburg R. Applications of calcium phosphate-based cancellous bone void fillers in trauma surgery. Orthopedics. 2002;25(5 Suppl):s601–9. Review. PubMed PMID: 12038849.
20. Bauer TW, Muschler GF. Bone graft materials. An overview of the basic science. Clin Orthop Relat Res. 2000;371:10–27. Review. PubMed PMID: 10693546.
21. Lane JM, Tomin E, Bostrom MP. Biosynthetic bone grafting. Clin Orthop Relat Res. 1999;(367 Suppl):S107–17. Review. PubMed PMID: 10546640.
22. Stevenson S. Enhancement of fracture healing with autogenous and allogeneic bone grafts. Clin Orthop Relat Res. 1998;(355 Suppl):S239–46. Review. PubMed PMID: 9917643.
23. Jones DB Jr, Rhee PC, Bishop AT, Shin AY. Free vascularized medial femoral condyle autograft for challenging upper extremity nonunions. Hand Clin. 2012;28(4):493–501. https://doi.org/10.1016/j.hcl.2012.08.005. Review. Erratum in: Hand Clin. 2013;29(2):xi. Bishop, Alan T [corrected to Bishop, Allen T]. PubMed PMID: 23101599.
24. Beris AE, Lykissas MG, Korompilias AV, Vekris MD, Mitsionis GI, Malizos KN, Soucacos PN. Vascularized fibula transfer for lower limb reconstruction. Microsurgery. 2011;31(3):205–11. https://doi.org/10.1002/micr.20841. Epub 2011 Feb 25. Review. PubMed PMID: 21360586.

25. Hierner R, Täger G, Nast-Kolb D. [Vascularized bone transfer]. Unfallchirurg. 2009;112(4):405–16; quiz 417–8. https://doi.org/10.1007/s00113-009-1613-2. Review. German. PubMed PMID: 19347381.
26. Doi K, Hattori Y. The use of free vascularized corticoperiosteal grafts from the femur in the treatment of scaphoid non-union. Orthop Clin North Am. 2007;38(1):87–94, vi–vii. Review. PubMed PMID: 17145297.
27. Kneser U, Schaefer DJ, Polykandriotis E, Horch RE. Tissue engineering of bone: the reconstructive surgeon's point of view. J Cell Mol Med. 2006;10(1):7–19. Review. PubMed PMID: 16563218; PubMed Central PMCID:PMC3933098.
28. Malizos KN, Zalavras CG, Soucacos PN, Beris AE, Urbaniak JR. Free vascularized fibular grafts for reconstruction of skeletal defects. J Am Acad Orthop Surg. 2004;12(5):360–9. Review. PubMed PMID: 15469230.
29. Shin AY, Bishop AT. Vascular anatomy of the distal radius: implications for vascularized bone grafts. Clin Orthop Relat Res. 2001;(383):60–73. Review. PubMed PMID: 11210970.
30. Perry CR. Bone repair techniques, bone graft, and bone graft substitutes. Clin Orthop Relat Res. 1999;(360):71–86. Review. PubMed PMID: 10101312.
31. Eisenschenk A, Lautenbach M, Rohlmann A. [Free vascularized bone transplantation in the extremities]. Orthopade. 1998;27(7):491–500. Review. German. PubMed PMID: 9728360.
32. Payatakes A, Sotereanos DG. Pedicled vascularized bone grafts for scaphoid and lunate reconstruction. J Am Acad Orthop Surg. 2009;17(12):744–55. Review. Erratum in: J Am Acad Orthop Surg. 2010;18(4):31A. PubMed PMID: 19948699.
33. Zhang GL, Zhang M. [Therapeutic progress of avascular osteonecrosis of the femoral head using a fibular graft by vascular anastomosis]. Zhongguo Gu Shang. 2009;22(1):76–8. Review. Chinese. PubMed PMID: 19203057.
34. Terada S, Sato M, Sevy A, Vacanti JP. Tissue engineering in the twenty-first century. Yonsei Med J. 2000;41(6):685–91. Review. PubMed PMID: 11204820.
35. Cariou JL. [The peroneal or fibular free flaps. Surgical anatomy, operative procedures and indications]. Ann Chir Plast Esthet. 2000;45(3):219–71. Review. French. PubMed PMID: 10929455.
36. Brunelli F, Mathoulin C, Saffar P. [Description of a vascularized bone graft taken from the head of the 2nd metacarpal bone]. Ann Chir Main Memb Super. 1992;11(1):40–5. Review. French. PubMed PMID: 1375492.
37. Schoofs M, Bovet JL, Amarante J, Baudet J. [Late revascularization for partial amputation of the thumb]. Ann Chir Main. 1983;2(4):362–4. Review. French. PubMed PMID: 9382653.
38. Franzin FJ, Gotfryd AO, Neto NJ, Poletto PR, Milani C, Mattar T, Rodrigues LM. Radiographic and functional evaluation of the iliac bone graft in the treatment of adolescent idiopathic scoliosis. J Pediatr Orthop B. 2014;23(4):307–11. https://doi.org/10.1097/BPB.0000000000000037. PubMed PMID: 24755849.
39. Friedrich MJ, Gravius S, Schmolders J, Wimmer MD, Wirtz DC. [Biological acetabular defect reconstruction in revision hip arthroplasty using impaction bone grafting and an acetabular reconstruction ring]. Oper Orthop Traumatol. 2014;26(2):126–40. https://doi.org/10.1007/s00064-013-0270-3. Epub 2014 Apr 3. German. PubMed PMID: 24691908.
40. Hinterwimmer S, Mehl J. [Combination of ACL-replacement and high tibial osteotomy]. Oper Orthop Traumatol. 2014;26(1):43–55. https://doi.org/10.1007/s00064-013-0269-9. Epub 2014 Feb 9. German. PubMed PMID: 24553688.
41. Berkowitz MJ, Clare MP, Walling AK, Sanders R. Salvage of failed total ankle arthroplasty with fusion using structural allograft and internal fixation. Foot Ankle Int. 2011;32(5):S493–502. https://doi.org/10.3113/FAI.2011.0493. PubMed PMID: 21733457.
42. Frey P, Müller M, Munzinger U. [Closing-wedge high tibial osteotomy with a modified Weber technique]. Oper Orthop Traumatol. 2008;20(1):75–88. https://doi.org/10.1007/s00064-008-1230-1. German. PubMed PMID: 18338121.
43. Eingartner C, Volkmann R, Ochs U, Egetemeyr D, Weise K. Intramedullary stabilization of periprosthetic fractures of the femur taking special account of bone defects. Oper Orthop Traumatol. 2006;18(4):341–63. English, German. PubMed PMID: 17103132.
44. Shelbourne KD, Patel DV. Rehabilitation after autogenous bone-patellar tendon-bone ACL reconstruction. Instr Course Lect. 1996;45:263–73. PubMed PMID: 8727745.
45. Hidalgo DA. Fibula free flap mandibular reconstruction. Clin Plast Surg. 1994;21(1):25–35. Review. PubMed PMID: 8112010.
46. Jones DB Jr, Rhee PC, Shin AY. Vascularized bone grafts for scaphoid nonunions. J Hand Surg Am. 2012;37(5):1090–4. https://doi.org/10.1016/j.jhsa.2012.03.001. Epub 2012 Apr 5. Review. PubMed PMID: 22483177.
47. Harvey EJ, Berger RA, Osterman AL, Fernandez DL, Weiss AP. Bone-tissue-bone repairs for scapholunate dissociation. J Hand Surg Am. 2007;32(2):256–64. Review. PubMed PMID: 17275604.
48. Shin AY, Dekutoski MB. The role of vascularized bone grafts in spine surgery. Orthop Clin North Am. 2007;38(1):61–72, vi. Review. PubMed PMID: 17145295.
49. Hierner R, Stock W, Wood MB, Schweiberer L. [Vascularized fibula transfer. A review]. Unfallchirurg. 1992;95(3):152–9. Review. German. PubMed PMID:1553568.
50. Kakar S, Duymaz A, Steinmann S, Shin AY, Moran SL. Vascularized medial femoral condyle corticoperiosteal flaps for the treatment of recalcitrant humeral nonunions. Microsurgery. 2011;31(2):85–92. https://doi.org/10.1002/micr.20843. Epub 2011 Jan 25. PubMed PMID: 21268108.
51. Coles CP, Barei DP, Nork SE, Taitsman LA, Hanel DP, Bradford Henley M. The olecranon osteotomy: a six-year experience in the treatment of intraarticular fractures of the distal humerus. J Orthop Trauma. 2006;20(3):164–71. PubMed PMID: 16648697.
52. Gill DR, Torchia ME. The spiral compression plate for proximal humeral shaft nonunion: a case report and description of a new technique. J Orthop Trauma. 1999;13(2):141–4. PubMed PMID: 10052791.
53. McKee MD, Miranda MA, Riemer BL, Blasier RB, Redmond BJ, Sims SH, Waddell JP, Jupiter JB. Management of humeral nonunion after the failure of locking intramedullary nails. J Orthop Trauma. 1996;10(7):492–9. PubMed PMID: 8892150.
54. Cadet ER, Yin B, Schulz B, Ahmad CS, Rosenwasser MP. Proximal humerus and humeral shaft nonunions. J Am Acad Orthop Surg. 2013;21(9):538–47. https://doi.org/10.5435/JAAOS-21-09-538. Review. Erratum in: J Am Acad Orthop Surg. 2013;21(11):21a. PubMed PMID: 23996985.
55. Butt U, Charalambous CP. Complications associated with open coracoid transfer procedures for shoulder instability. J Shoulder Elb Surg. 2012;21(8):1110–9. https://doi.org/10.1016/j.jse.2012.02.008. Epub 2012 May 18. Review. PubMed PMID: 22608928.
56. King AR, Moran SL, Steinmann SP. Humeral nonunion. Hand Clin. 2007;23(4):449–56, vi. Review. PubMed PMID: 18054672.
57. del Piñal F, Innocenti M. Evolving concepts in the management of the bone gap in the upper limb. Long and small defects. J Plast Reconstr Aesthet Surg. 2007;60(7):776–92. Epub 2007 Apr 23. Review. PubMed PMID: 17452133.
58. Hausman M, Panozzo A. Treatment of distal humerus fractures in the elderly. Clin Orthop Relat Res. 2004;425:55–63. Review. PubMed PMID: 15292788.
59. Volgas DA, Stannard JP, Alonso JE. Nonunions of the humerus. Clin Orthop Relat Res. 2004;(419):46–50. Review. PubMed PMID: 15021130.

60. Sayegh ET, Strauch RJ. Graft choice in the management of unstable scaphoid nonunion: a systematic review. J Hand Surg Am. 2014;39(8):1500–6.e7. https://doi.org/10.1016/j.jhsa.2014.05.009. Epub 2014 Jul 3. Review. PubMed PMID: 24997785.
61. Al-Jabri T, Mannan A, Giannoudis P. The use of the free vascularised bone graft for nonunion of the scaphoid: a systematic review. J Orthop Surg Res. 2014;9:21. https://doi.org/10.1186/1749-799X-9-21. Review. PubMed PMID: 24690301; PubMed Central PMCID: PMC3976175.
62. Yao J, Read B, Hentz VR. The fragmented proximal pole scaphoid nonunion treated with rib autograft: case series and review of the literature. J Hand Surg Am. 2013;38(11):2188–92. https://doi.org/10.1016/j.jhsa.2013.08.093. Epub 2013 Sep 19. Review. PubMed PMID: 24055132.
63. Moon ES, Dy CJ, Derman P, Vance MC, Carlson MG. Management of nonunion following surgical management of scaphoid fractures: current concepts. J Am Acad Orthop Surg. 2013;21(9):548–57. https://doi.org/10.5435/JAAOS-21-09-548. Review. PubMed PMID: 23996986.
64. Buijze GA, Ochtman L, Ring D. Management of scaphoid nonunion. J Hand Surg Am. 2012;37(5):1095–100; quiz 1101. https://doi.org/10.1016/j.jhsa.2012.03.002. Review. PubMed PMID: 22541157.
65. Pal CP, Kumar B, Dinkar KS, Singh P, Kumar H, Goyal RK. Fixation with cancellous screws and fibular strut grafts for neglected femoral neck fractures. J Orthop Surg (Hong Kong). 2014;22(2):181–5. PubMed PMID: 25163951.
66. Bansal P, Singhal V, Lal H, Mittal D, Arya RK. A convenient way to do valgus osteotomy for neglected fracture neck of femur. Kathmandu Univ Med J (KUMJ). 2013;11(42):147–51. PubMed PMID: 24096223.
67. Yu XB, Zhao DW, Zhong SZ, Liu BY, Wang BJ, Liu YP, Zhang Y, Cui DP, Fu DP, Xie H. Prospective and comparative analysis of internal fixation of femoral neck fractures with or without vascularized iliac graft in young adults. Orthopedics. 2013;36(2):e132–8. https://doi.org/10.3928/01477447-20130122-12. PubMed PMID: 23379828.
68. Shen JZ, Yao JF, Lin DS, Lian KJ, Ding ZQ, Lin B, Guo ZM, Zhang MH, Li Q, Li L, Qi P. Hollow-bone-graft dynamic hip screw can fix and promote bone union after femoral neck fracture: an experimental research. Int J Med Sci. 2012;9(10):916–22. https://doi.org/10.7150/ijms.4567. Epub 2012 Nov 22. PubMed PMID: 23236261; PubMed Central PMCID: PMC3520017.
69. Xie X, Zhang C, Jin D, Chen S, Gao Y. Free vascularised fibular graft for neglected femoral neck fractures in young adults. Hip Int. 2012;22(3):319–23. https://doi.org/10.5301/HIP.2012.9247. PubMed PMID: 22740274.
70. Sen RK, Tripathy SK, Goyal T, Aggarwal S, Tahasildar N, Singh D, Singh AK. Osteosynthesis of femoral-neck nonunion with angle blade plate and autogenous fibular graft. Int Orthop. 2012;36(4):827–32. https://doi.org/10.1007/s00264-011-1344-1. Epub 2011 Sep 1. PubMed PMID: 21881882; PubMed Central PMCID: PMC3311820.
71. Tripathy SK, Goyal T, Sen RK. Revision internal fixation and nonvascular fibular graft for femoral neck nonunion. J Trauma. 2011;71(1):270–1; author reply 271–2. https://doi.org/10.1097/TA.0b013e3182217a7f. PubMed PMID: 21818050.
72. Zhenyu P, Aixi Y, Guo-Rong Y, Shaobo Z, Kai D. Treatment of serious femoral neck fractures with the transposition of vascularized greater trochanter bone flap in young adults. J Reconstr Microsurg. 2011;27(5):303–8. https://doi.org/10.1055/s-0031-1278709. Epub 2011 May 18. PubMed PMID: 21594807.
73. Elgafy H, Ebraheim NA, Bach HG. Revision internal fixation and nonvascular fibular graft for femoral neck nonunion. J Trauma. 2011;70(1):169–73. https://doi.org/10.1097/TA.0b013e3181e5108b. PubMed PMID: 20693917.
74. Jun X, Chang-Qing Z, Kai-Gang Z, Hong-Shuai L, Jia-Gen S. Modified free vascularized fibular grafting for the treatment of femoral neck nonunion. J Orthop Trauma. 2010;24(4):230–5. https://doi.org/10.1097/BOT.0b013e3181be3ec3. PubMed PMID: 20335756.
75. Roshan A, Ram S. Early return to function in young adults with neglected femoral neck fractures. Clin Orthop Relat Res. 2006;447:152–7. PubMed PMID: 16505718.
76. Varshney MK, Trikha V. Intertrochanteric osteotomy using a dynamic hip screw for femoral neck nonunion. J Orthop Trauma. 2005;19(10):751; author reply 751. PubMed PMID: 16314727.
77. Lash NJ, Feller JA, Batty LM, Wasiak J, Richmond AK. Bone grafts and bone substitutes for opening-wedge osteotomies of the knee: a systematic review. Arthroscopy. 2015;31(4):720–30. https://doi.org/10.1016/j.arthro.2014.09.011. Epub 2015 Jan 14. Review. PubMed PMID: 25595695.
78. Le Nail LR, Stanovici J, Fournier J, Splingard M, Domenech J, Rosset P. Percutaneous grafting with bone marrow autologous concentrate for open tibia fractures: analysis of forty three cases and literature review. Int Orthop. 2014;38(9):1845–53. https://doi.org/10.1007/s00264-014-2342-x. Epub 2014 Apr 13. Review. PubMed PMID: 24728310.
79. Donnenwerth MP, Roukis TS. Tibio-talo-calcaneal arthrodesis with retrograde compression intramedullary nail fixation for salvage of failed total ankle replacement: a systematic review. Clin Podiatr Med Surg. 2013;30(2):199–206. https://doi.org/10.1016/j.cpm.2012.10.007. Epub 2012 Nov 26. Review. PubMed PMID: 23465809.
80. Hak DJ. Management of aseptic tibial nonunion. J Am Acad Orthop Surg. 2011;19(9):563–73. Review. PubMed PMID: 21885702.
81. Tarkin IS, Siska PA, Zelle BA. Soft tissue and biomechanical challenges encountered with the management of distal tibia nonunions. Orthop Clin North Am. 2010;41(1):119–26; table of contents. https://doi.org/10.1016/j.ocl.2009.07.009. Review. PubMed PMID: 19931060.
82. Goulet JA, Templeman D. Delayed union and nonunion of tibial shaft fractures. Instr Course Lect. 1997;46:281–91. Review. PubMed PMID: 9143973.
83. Evrard J. [Role of tibial-fibular grafting in the treatment of infected pseudarthrosis of the tibia]. Rev Chir Orthop Reparatrice Appar Mot. 1992;78(6):389–98. Review. French. PubMed PMID: 1304638.
84. Meister K, Segal D, Whitelaw GP. The role of bone grafting in the treatment of delayed unions and nonunions of the tibia. Orthop Rev. 1990;19(3):260–71. Review. PubMed PMID: 2184392.
85. Ward WG, Goldner RD, Nunley JA. Reconstruction of tibial bone defects in tibial nonunion. Microsurgery. 1990;11(1):63–73. Review. PubMed PMID: 2182966.
86. Csongradi JJ, Maloney WJ. Ununited lower limb fractures. West J Med. 1989;150(6):675–80. Review. PubMed PMID: 2665320; PubMed Central PMCID: PMC1026705.
87. Miao H, Yin ZY, Huang GK. Blood supply of the anterior part of the iliac crest. Anat J. 1981;4:376–381, 449.

20 Microsurgical Repair of Ischemic Necrosis of Bone

Benjie Wang, Yupeng Liu, Yao Zhang, Xiaobing Yu, Weimin Fu, Daping Cui, Fengde Tian, Xiuzhi Zhang, and Dewei Zhao

20.1 Introduction

Benjie Wang and Dewei Zhao

20.1.1 Etiology of Osteonecrosis

According to the 1993 definition of osteonecrosis by the Association Research Circulation Osseous (ARCO), bone is a type of mineralized tissue, and any disease that causes necrosis of bone tissue is called osteonecrosis. Common features include bone tissue degeneration, necrosis, and collapse caused by temporary or permanent loss of bone blood supply. Pathological changes often involve joints, leading to the collapse of the articular facet and resulting in disability. Osteonecrosis can occur in various body parts. Femoral head necrosis can be classified as traumatic or idiopathic. The author investigated necrosis of the femoral head in 30,080 normal people (>15 years old) from nine provinces and autonomous regions in China. The incidence of femoral head necrosis was 0.726% (1.02% in men and 0.51% in women). The results show non-traumatic osteonecrosis is a public health issue in China.

As mentioned above, osteonecrosis can be classified as traumatic osteonecrosis or non-traumatic osteonecrosis (i.e., idiopathic osteonecrosis).

1. Traumatic ischemic osteonecrosis: The pathogenesis of traumatic ischemic osteonecrosis is well understood. Impaired integrity of the arteries supplying bone tissue or the compression and obstruction of blood vessels, etc. due to trauma results in ischemic osteonecrosis. Examples include secondary ischemic osteonecrosis after a femoral neck fracture, dislocation of the hip, carpal scaphoid fracture, and lunate dislocation.
2. Non-traumatic ischemic osteonecrosis: Non-traumatic (i.e., idiopathic) ischemic osteonecrosis is associated with several diseases and drugs. However, its pathogenesis is not as well characterized as that of traumatic ischemic osteonecrosis. Osteonecrosis caused by diseases or drugs is difficult to comprehensively explain and is confounded by the effects of accumulated physiological and mechanical factors on osteonecrotic pathology. Therefore, the term "non-traumatic ischemic osteonecrosis" is inappropriate. At present, the common term in the literature is "idiopathic ischemic osteonecrosis." Causes include all factors except severe trauma. Common causative diseases include collagen disorders (e.g., rheumatoid arthritis), blood system diseases (e.g., sickle cell anemia, thalassemia, and Gaucher disease), urinary system diseases (e.g., nephrotic syndrome and chronic kidney insufficiency), endocrine system diseases (e.g., hypercortisolism, hypothyroidism, and myxoedema), nutrition and metabolic diseases (e.g., diabetes and gout), diseases caused by physical and chemical factors (e.g., radiation sickness, Caisson disease, heat damage, carbon tetrachloride poisoning, and fluorine poisoning), and hormone treatments (e.g., long-term administration of several glucocorticoids).

20.1.2 Pathological Changes of Osteonecrosis

The histopathologic changes of osteonecrosis can be divided into two phases: the bone tissue necrotic and bone repair phases.

1. Bone tissue necrotic phase

   This phase is characterized by bone cell necrosis. Bone cell pyknosis and hypochromatosis can be observed initially. Thereafter, bone marrow solidifies, dissolves,

B. Wang · Y. Liu · Y. Zhang · X. Yu · W. Fu · D. Cui · F. Tian
X. Zhang · D. Zhao (✉)
Department of Orthopedics, Zhongshan Hospital Affiliated to Dalian University, Liaoning, China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_20

liquefies, and shrinks. Bone cells exhibit degenerative necrosis and disappear from the lacunae in the early stage of necrosis. However, the structure of the trabecular bone is unaltered. The bone marrow exhibits necrosis of hematopoietic cells, clear cell outlines, and nuclear pyknosis. Eosinophilic granules, sinus congestion, interstitial hemorrhage, and edema can also manifest. Bone cells necrose further, followed by focal necrosis of the trabecular bone, bone absorption, and expansion of the lacunae. Some experts only consider cases to be trabecular bone necrosis if the necrosis of bone cells in lacunae is at least 75%.

2. Bone repair phase

   This phase includes revascularization and osteoanagenesis. After bone death, hyperemia in the blood sinuses, fibroblast emergence, poor bone marrow regeneration, and vacuole lacuna formation can be observed. In this phase, new blood vessels and fibrous tissue grow into the necrotic area and form granulation tissue that is rich in blood vessels and fibers. Osteoclasts appear at one side of the necrotic trabecular bone. The necrotic trabecular bone is then absorbed and replaced by granulation tissue; this change is most common in the remaining bone and areas adjacent to the necrotic area. Next, osteoblasts appear on the other side, and new bone begins to form. Hyperplastic granulation tissue extends from normal bone tissue to the necrotic bone and removes dead bone together with osteoclasts. The granulation tissues gradually transform into collagen fibers. Part of the necrotic trabecular bone is surrounded by different amounts of new bone tissues, which gradually absorb and replace the necrotic trabecular bone. This process is called "creeping substitution." The repair expands from the outside of the necrotic area to the inside as observed on microscopy. The necrotic trabecular bone is filled by proliferative mesenchymal cells, new capillaries, and different amounts of collagen fibers. The mesenchymal cells in the necrotic area can differentiate into osteoblasts and form new bone. The necrotic bone is absorbed gradually and replaced by new bone, completing the creeping substitution. During creeping substitution, angiogenesis occurs, the granulation tissues become fibrous tissues, and the new bone gradually matures. In general, the necrosis is not obvious, but if the necrotic area is obvious, especially where necrotic articular cartilage is replaced by fibrous tissue or fibrocartilage, loads cannot be borne, resulting in deformity. The newly repaired bone tissue is believed to collapse because of pressure. Greater repair ability is associated with larger scope and higher collapse rates. Collapse often occurs at the junction between necrotic and normal bone. Radiographic imaging reveals obvious bone fracture and collapse.

20.1.3 Diagnosis of Osteonecrosis

Osteonecrosis can develop in any part of the human body, particularly in the weight-bearing bones and large joints. Femoral head necrosis is the most common form of osteonecrosis. The diagnosis of osteonecrosis is mainly based on the history of chronic diseases, symptoms, physical examination, imaging tests, etc.

1. Disease history: the presence of high risk factors for osteonecrosis (basic diseases, trauma, etc.)
2. Symptoms: pain, limited joint motion, joint swelling, interlocking, and snapping
3. Signs: joint deformity, tenderness, sensitivity to percussion, and limited passive activities
4. Special examination: Allis signs, Thomas signs, Trendelenburg signs, Ober signs, Patrick signs, etc.
5. Imaging tests: imaging tests are the major means of diagnosing osteonecrosis. They play a crucial role in the diagnosis and differential diagnosis of osteonecrosis, determination and staging of disease condition, choice of treatment, and prognosis. Common examinations include radiography, CT, intraosseous pressure measurement, MRI, angiography, radioisotope scanning, and stroboscopic photography.

20.1.4 Treatment Principles of Osteonecrosis

There are various treatments for ischemic osteonecrosis. When formulating a scheme for osteonecrosis, different parts and conditions (i.e., staging, volume of necrosis, joint function as well as patient age, occupation, compliance with preserved joint treatment, etc.) should be considered comprehensively.

1. Non-operative therapy

   Patients presenting with early-stage osteonecrosis can be administered conservative therapy including plaster fixation, load limitation, traction, medication, and physical therapy.

2. Surgical therapy

   Different surgical modes can be selected according to the specific circumstances of osteonecrosis, such as the different parts, staging, and joint function. For early/intermediate-stage osteonecrosis, younger patients can be administered surgical treatments such as bone grafts and vascularized bone flap transplants to repair the bone tissue, rebuild, or restore bone blood flow. In late osteonecrosis, the lesion is wider and the joint is involved, causing serious joint deformation and collapse and osteoarthritis (e.g., femoral head necrosis and late necrosis of the scaphoid bone). Artificial joint replacement and joint fusion can be considered on the basis of the parts experiencing osteonecrosis and other specific conditions.

20.2 Microsurgical Repair of Aseptic Scaphoid Osteonecrosis

Yupeng Liu and Dewei Zhao

When the scaphoid fractures, proximal bone fragments will necrose, because the scaphoid blood supply mainly comes from the distal part and the proximal blood supply is poor. Scaphoid fractures, which are the most common fracture of the wrist, can be classified into four types: waist, proximal, distal, and tubercle fractures. A scaphoid fracture commonly exhibits illegible fracture lines with little or no callus on radiographs. Approximately 70% of scaphoid fractures occur at the waist. In some cases of scaphoid acute fractures, the radiograph may not show an obvious fracture. However, the fracture line will become clear after 2 weeks because of bone resorption at the fracture site. Scaphoid fracture is more common in people younger than 30 years (85% are male) but is rare in children. Fractures on the right side account for 70% of cases. Because of the specificity of its blood supply, scaphoid fractures may be difficult to heal and are often associated with avascular necrosis and cystic change. The prognosis is generally poor when a scaphoid fracture is accompanied by other wrist fractures or dislocations. On the other hand, tubercle fractures, a type of extra-articular fracture (the incidence of which is 10–15%), is rarely the cause of osteonecrosis because of its better blood supply.

20.2.1 Anatomy and Pathology

The blood supply of the scaphoid bone mainly comes from the radial artery. There are 2–4 small arteries that branch from the radial artery in the anatomical snuffbox, extending from the outside to the inside through the radial carpal ligament dorsal and through the distal portion of the scaphoid waist dorsal ridge and tubercle poles into the scaphoid bone; these arteries provide 70–80% of the blood supply to the scaphoid. In addition, the dorsal carpal branch network enters the bone. Approximately one-third of the proximal scaphoid blood supply comes from the scaphoid waist. As scaphoid fractures are a type of intra-articular fracture, the nonunion rate is high (~14–39%). The bone fracture line can be classified as the transverse (i.e., stable), or oblique or vertical (i.e., unstable) form. When the scaphoid waist fractures, the proximal bone block will have poor blood supply, facilitating necrosis. The necrosis rate of unstable fractures is as high as 20–30%.

The incidence of proximal scaphoid fractures is ~20%, because the proximal fracture fragment is small with poor blood supply, increasing the likelihood of avascular necrosis. The overall rate of scaphoid bone necrosis after a scaphoid fracture is 15%. If the scaphoid-lunate is fractured or dislocated, the scaphoid fracture nonunion rate and necrosis rate are much higher. For instance, in fractures of the proximal scaphoid bone and magnum, the triangular bone is dislocated and the scaphoid bone necrosis rate is approximately 55%. Scaphoid necrosis can gradually cause osteoarthritis.

The pathology of scaphoid bone necrosis mainly manifests as surface cartilage cell necrosis. Sometimes cystic degeneration occurs or unsmooth bone tissue surfaces form, which hinder joint movement.

20.2.2 Clinical Manifestation and Imaging Examination

If the patient has a history of trauma such as trans-scaphoid and perilunate fracture or dislocation, the scaphoid area aches, especially during labor or activity. After radial deviation, wrist activity is limited with mild local swelling. There is tenderness in the anatomical snuff box. The wrist aches upon tapping of the fist on the distal end of the second and third metacarpus. Wrist flexion and extension function is also limited. Wrist dorsal protrusion can be observed when trans-scaphoid perilunate fracture or dislocation is present.

Radiographic imaging shows changes 1 month or even a few months after symptoms appear, such as increased bone density, joint space narrowing, surrounding carpal bone osteoporosis, cystic absorption, and cyst formation. After a few years, bone mineral density can return to normal, but the bone shape remains irregular and cysts persist; it is mainly observed as a cystic and lucent density. Congenital double scaphoid is rare and often needs to be identified from old scaphoid fractures. A radiograph of congenital double scaphoid shows a clear, regular, and smooth boundary between two bones. No dense necrosis or irregular edge is observed. ECT can show density of nuclides in the necrotic area early, and MRI can detect focal necrosis early.

20.2.3 Treatments

Avascular scaphoid necrosis is closely associated with trauma. Fractures in the middle and proximal parts of the scaphoid bone easily lead to nonunion and avascular scaphoid necrosis near the fracture. This is because of the characteristics of the blood supply to the scaphoid bone. Scaphoid dislocation commonly leads to a high rate of scaphoid necrosis. Traditional treatments include bone grafting, radial styloidectomy, and proximal row carpectomy. Microsurgical treatment is currently widely used, with reportedly superior curative effects. These methods are similar to the treatment of ischemic lunate necrosis, because the two bones are adjacent and transplantation of bone or periosteal flap with vascular pedicle is feasible.

For early-stage scaphoid bone necrosis, patients commonly require long-term immobilization. The wrist is kept in mild ulnar deviation for >3 months. In addition, treatments such as bone formation promotion, blood circulation activation, and stasis removal can be expedient. Otherwise, surgery can be performed. In patients with fracture nonunion, the dead bone is removed to prevent excision of the entire scaphoid bone. An artificial prosthesis subsequently replaces the bone in combination with radial styloidectomy to relieve pain and reduce traumatic arthritis. Dorsal feeding vessels of the radial artery or bone grafts with vascular pedicles can also be used for transplantation. Radiocarpal fusion should be performed in cases of serious traumatic arthritis associated with destruction of the capitate articular facetis. For patients engaged in light manual work, the curative effect of proximal row carpectomy may be sufficient.

At present, microsurgical techniques for scaphoid fracture nonunion and avascular necrosis achieve satisfactory treatment effects. Microsurgical treatment for avascular scaphoid necrosis primarily uses vessels and fascia between the radial arteries, veins, and radial styloid process as the pedicle. The bone block above the radial styloid process with blood vessels is excised and implanted into the scaphoid groove. As the bone block has blood vessels, a new blood supply is established in the necrotic bone, improving blood circulation. For the larger feeding area of the implanted bone block to the necrotic bone, the blood circulation in the necrotic bone is also improved, which will promote fracture union. Furthermore, implantation of the bone block also exhibits certain fixed function, which can maintain the stability of necrotic bone and aid its union.

1. Transplantation of the radial bone block with vascular and fascial pedicle for the treatment of scaphoid necrosis

   For microdissection of the blood circulation of bone and fascia, during bone grafting, the flap with a fascia pedicle of a certain thickness and width can provide the graft with a rich blood supply and venous circuits. This places the creeping substitution of traditional bone transplantation into direct union. This does not increase operation difficulty, and can accelerate fracture union. The stress of the radial styloid process to the scaphoid fracture site is one of the most important factors of osteonecrosis; it is also an important factor contributing to late-stage complications such as wrist pain, dysfunction, and traumatic arthritis. Incision of the radial styloid process is not only advantageous for bone union, but can also reduce the incidence of late-stage complications and sequelae. Thus, the curative effect of this method has been confirmed. However, this treatment alone is often insufficient. Combining two surgical methods to transplant the radial styloid process flap with the radial recurrent branch as a vessel pedicle drastically improves outcomes. This combination technique uses vessels and fascia between the radial arteries, veins, and radial styloid process as a pedicle. As mentioned above, the bone block above the radial styloid process with the blood supply vessel is excised and implanted into the scaphoid groove; because the bone block carries blood vessels, a new blood supply will be established in the scaphoid bone, improving blood circulation in the focal zone. The periosteum of the implanted bone block is larger than the bone block. The process of periosteal osteogenesis will lead to expedient reconstruction of the necrosed bone.

   (a) Applied anatomy

   The radial artery rounds the lower styloid process via the facies anterior radius and passes through the tendon of the extensor pollicis longus and abductor pollicis longus to the dorsal anatomical snuff box. It possesses a wider dorsal carpal branch to the ulnar side 1.2 ± 0.3 cm below the styloid process. The dorsal carpal branch of the radial artery branches off toward the proximal side, which returns to the top of the styloid process. Otherwise, a branch of the proximal radial artery returns to the top of the styloid process, namely the radial recurrent artery. Single- and double-branch recurrent arteries account for 76% and 24% of cases, respectively. The mean length of the radial recurrent artery is 1.2 ± 0.3 cm with a diameter of 0.4 ± 0.2 cm at the starting point. The starting point is 0–1.2 cm from the distal panel of the styloid process. According to the origination type and amount of radial recurrent branches, four types can be distinguished:

   Single-branch type: only one branch arises from the radial artery, which returns to the styloid process (65.8% of cases).

   Double-branch type: two branches arise from the radial artery, which returns to the styloid process (15.8% of cases).

   Common trunk type: the recurrent branch and dorsal carpal branch share the same trunk, which can also be considered the branch arising from the dorsal branch to the styloid process (13.2% of cases).

   Hybrid type: one branch arises from the radial artery trunk, while another branch shares a common trunk with the dorsal carpal artery (2.6% of cases).

   (b) Surgical methods

   A longitudinal incision or S-shaped incision is made in the lateral wrist through the long axis of the anatomical snuff box (Fig. 20.1).

Fig. 20.1 Operative incision

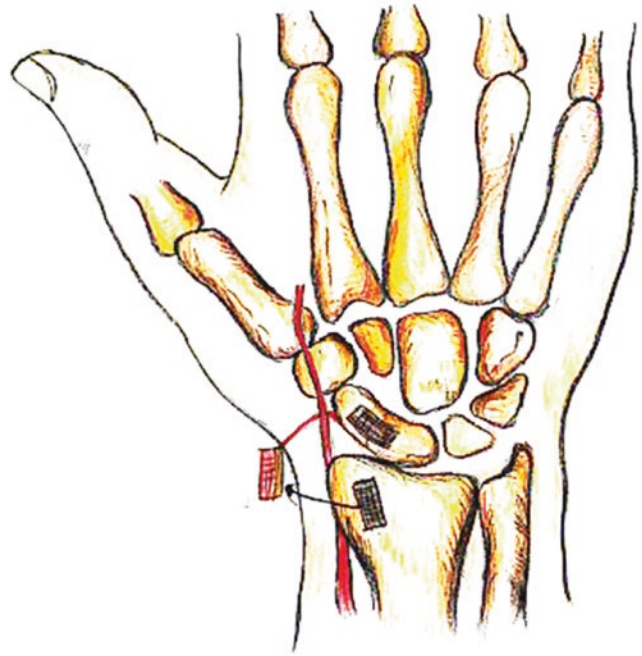


Fig. 20.2 Transplantation of the radial bone block with vascular and fascial pedicle

2. Incision of the bone (i.e., periosteal) flap: After skin incision, the superficial branch of the radial nerve and cephalic vein is pulled aside. Approximately 1.2 cm from the distal radius, the radial artery is found between the tendons of the extensor pollicis longus and extensor pollicis brevis. The plane of the styloid process is searched for along the ulnar side of the proximal radius. The radial artery produces a dorsal carpal branch from its ulnar side as well as a radial recurrent branch from its dorsal side. The radial recurrent branch sometimes begins at a high position. The starting point is located underneath the tendon of the extensor pollicis longus and extensor pollicis brevis. With the recurrent branch as the pedicle, the bone flap of the radial styloid process (0.8 × 1.2 cm) is excised. The periosteal flap (0.8 × 1.2 cm) can be excised in the dorsal lateral styloid process between the tendon of the extensor pollicis longus and extensor pollicis brevis, where the periosteum is not covered by tendon (Fig. 20.2).
3. Transplantation of the bone (i.e., periosteal) flap: The wrist joint capsule is incised to expose the scaphoid bone. The wrist ulnaris flexion is manipulated to fully expose the scaphoid bone. A bone chisel is used to remove necrosed bone in the scaphoid. Then, a bone groove 1.0 × 0.5 × 0.5 cm is chiseled in the dorsal scaphoid along the longitudinal axis of the scaphoid. The bone flap is embedded and fixed with a Kirschner wire. The periosteal flap can be rolled into a strip with the germinal layer outside, and implanted in the scaphoid. Then, the root of the periosteal flap is sutured with the carpal ligament. The joint capsule is sutured, and the dorsal lateral carpal ligament, subcutaneous tissue, and skin are repaired. A plaster cast is used to fix the forearm in a functional position. The sutures should be removed 2 weeks postoperatively. Finally, a tubular cast is used for immobilization until bone union is complete.
4. Transplantation of the periosteal flap with the dorsal carpal branch of the anterior interosseous artery as the pedicle for the treatment of scaphoid necrosis: The periosteal (i.e., bone) flap with the lateral terminal branch of the dorsal carpal branch or the radial osteo-cutaneous branch of the anterior interosseous artery as a pedicle can be excised from the distal dorsal radius. The blood supply is from the dorsal carpal branch of the radial artery, which is reliable. The pedicle is long and can easily be translocated. The periosteal flap supplied by the lateral terminal branch of the dorsal carpal branch or radial osteo-cutaneous branch of the anterior interosseous artery is primarily used for treating scaphoid fracture, bone nonunion, and avascular necrosis of the scaphoid and lunate.

(a) Applied anatomy

The dorsal carpal branch of the anterior interosseous artery is the distal terminal branch of this artery; it passes through interosseous membrane on the top margin of the pronator quadratus to the distal dorsal forearm, with medial and lateral branches anastomosed with the dorsal carpal branch of the ulnar and radial arteries. The anatomical position is constant, which is the anatomical basis of the reverse transplantation periosteal flap. The dorsal carpal branch gives off the radial and ulnar cutaneous branches; their descending branches arise from the periosteal branches, which are distributed to the distal dorsal radius and ulna.

(b) Surgical methods

A longitudinal incision of approximately 10.0 cm is made in the midline of the dorsal wrist. The skin and subcutaneous tissue are cut to expose the dorsal carpal ligament. The dorsal carpal ligament is incised longitudinally, and the tendon of the extensor pollicis longus and extensor digitorum are pulled out to expose the wrist and lower end of the radius. The dorsal carpal branch of the anterior interosseous artery is associated with the dorsal carpal vessel net. Fasciae (3 cm) are used to separate the dorsal carpal branch of the anterior interosseous artery. To increase the length of the vessel pedicle, some of the dorsal carpal vessel net can be retained. With this as a pedicle, an ulnar or radial periosteal flap measuring 1.2 × 0.6 × 0.6 cm is taken. The dorsal carpal branch in the proximal periosteal flap is ligatured. The periosteal flap is transferred from the distal area to the scaphoid groove. A Kirschner wire is used for fixation, while the edge of the periosteal flap and surrounding soft tissue are sutured (Fig. 20.3).

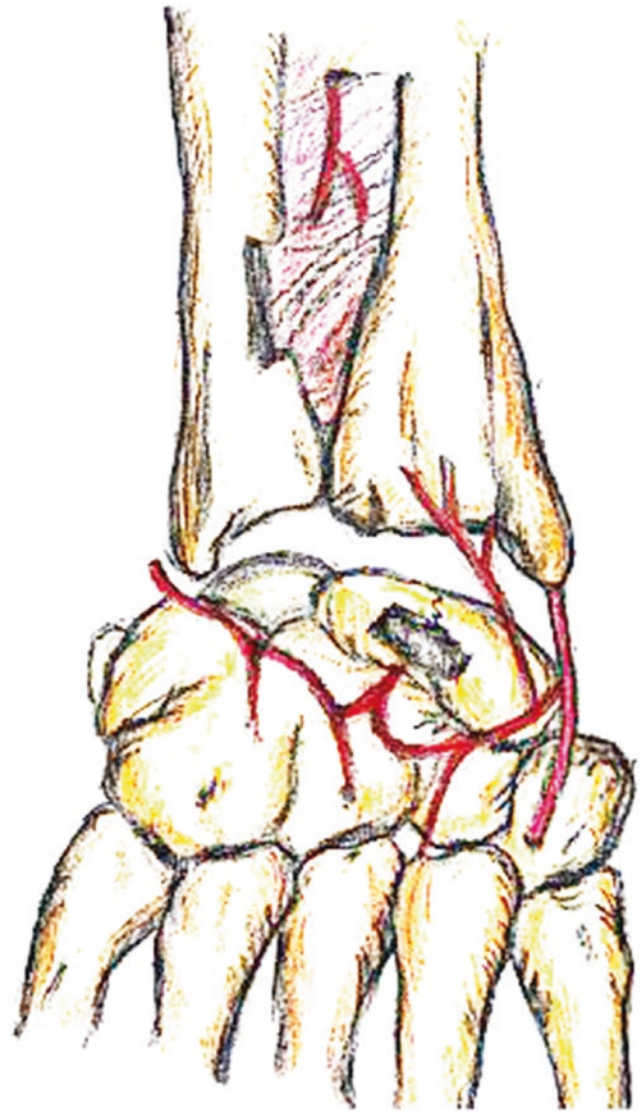


Fig. 20.3 Transplantation of the periosteal flap with the dorsal carpal branch of the anterior interosseous artery as the pedicle

5. Transplantation of the bone flap from the distal radius with the pronator quadratus as a pedicle for the treatment of scaphoid necrosis

(a) Applied anatomy

The pronator quadratus is a square-shaped muscle on the distal third of the forearm. It is attached by the radial, ulnar, and interosseous membranes of the forearm. Its fibers run perpendicular to the direction of the arm. It starts from the distal quarter of the ulna and ends in the distal quarter of the radius. Its blood supply primarily comes from the anterior interosseous artery.

(b) Surgical methods

An S-shaped incision is made in the palmar carpal side. The pronator quadrates beneath the flexor digitorum profundus are exposed. The distal radial bone flap (1.0 × 0.5 × 0.5 cm) is taken from the pronator quadrates with blood supply from the anterior interosseous artery. The transverse carpal ligament is removed to expose the scaphoid. A bone chisel is used to remove necrosed bone in the scaphoid. Then, a bone groove measuring ~0.5 × 0.5 cm is chiseled on the palm side of the scaphoid. Spongy bone is transferred from the bone donor area to the bone defect area. The bone flap is embedded in the scaphoid groove in the antegrade transplantation. Two Kirschner wires are used to fix the bone flap. A plaster cast is used to fix the wrist, while the Kirschner wires are retained for 6 weeks (Figs. 20.4 and 20.5).

6. Radial styloid process resection and bone grafting

(a) Applied anatomy

The scaphoid is the largest bone among the proximal carpal bones and has a slightly convex and smooth articular surface at the proximal end, which is associated with the radius. When the wrist leans to the radial side, the radial styloid process contacts the lateral middle part of the scaphoid. Radial or ulnar deviation of wrist after scaphoid fracture can reach the scaphoid through the middle joint of the wrist. It

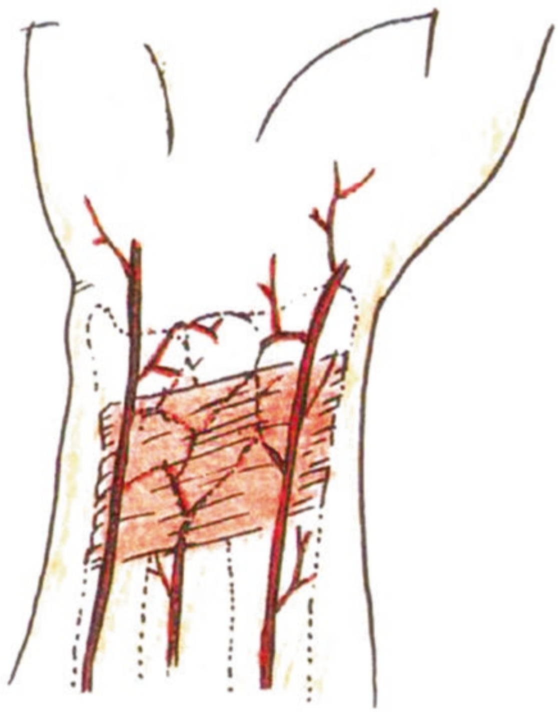


Fig. 20.4 Blood supply of the pronator quadrates

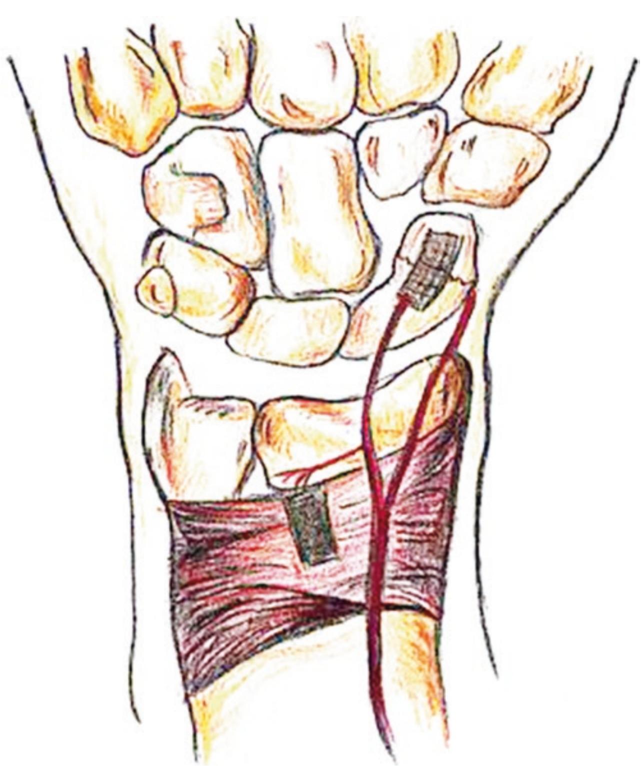
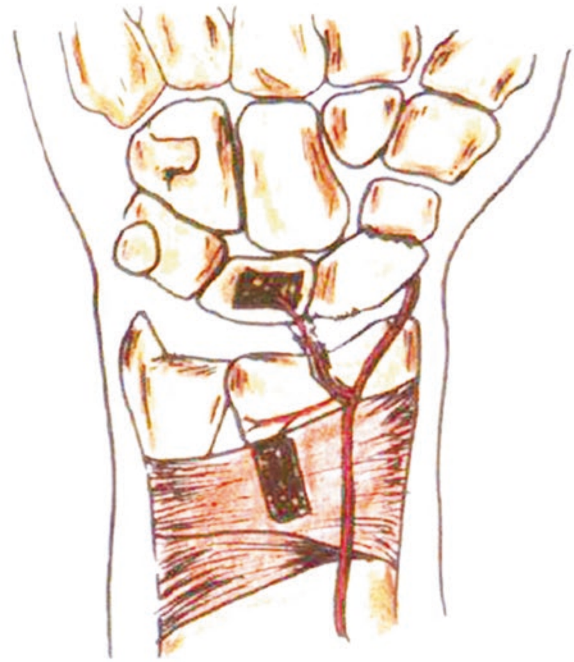


Fig. 20.5 Transplantation of the distal radial bone graft with the pronator quadratus as the pedicle

passes the fracture line, which is detrimental to fracture union and necrosis at the proximal fracture area. For unstable scaphoid fractures near the waist, poor



blood supply and compression of the radial styloid process often lead to bone nonunion. In order to prevent scaphoid necrosis or nonunion, resection of the radial styloid process combined with grafting can be performed.

(b) Surgical methods
- Incision: The incision starts from the endpoint of the abductor pollicis longus tendon in the palmar radial wrist to the endpoint of the radial flexor tendon, leaning toward the ulnar side. Then, the incision is extended along the radial flexor tendon to the proximal end. The total incision is ~4 cm. Skin and superficial fasciae are carefully incised to avoid damaging the radial artery.
- Exposure of the radial styloid process and scaphoid: The radial artery and vein are separated and pulled to the ulnar side to avoid damage. The tendons of the abductor pollicis longus and extensor pollicis brevis are pulled to the dorsal wrist. The radial artery and radial flexor tendon are pulled to the ulnar side. The periosteum and wrist joint capsule of the radial styloid process are incised. An osteotome is used to gradually strip the periosteum of the radial styloid process to confirm the scaphoid fracture line.
- Incision of the radial styloid process and grafting: The radial styloid process is resected ~0.2 cm from the proximal fracture line of the scaphoid. A free bone block is taken from the bone donor area and implanted at the scaphoid fracture area based

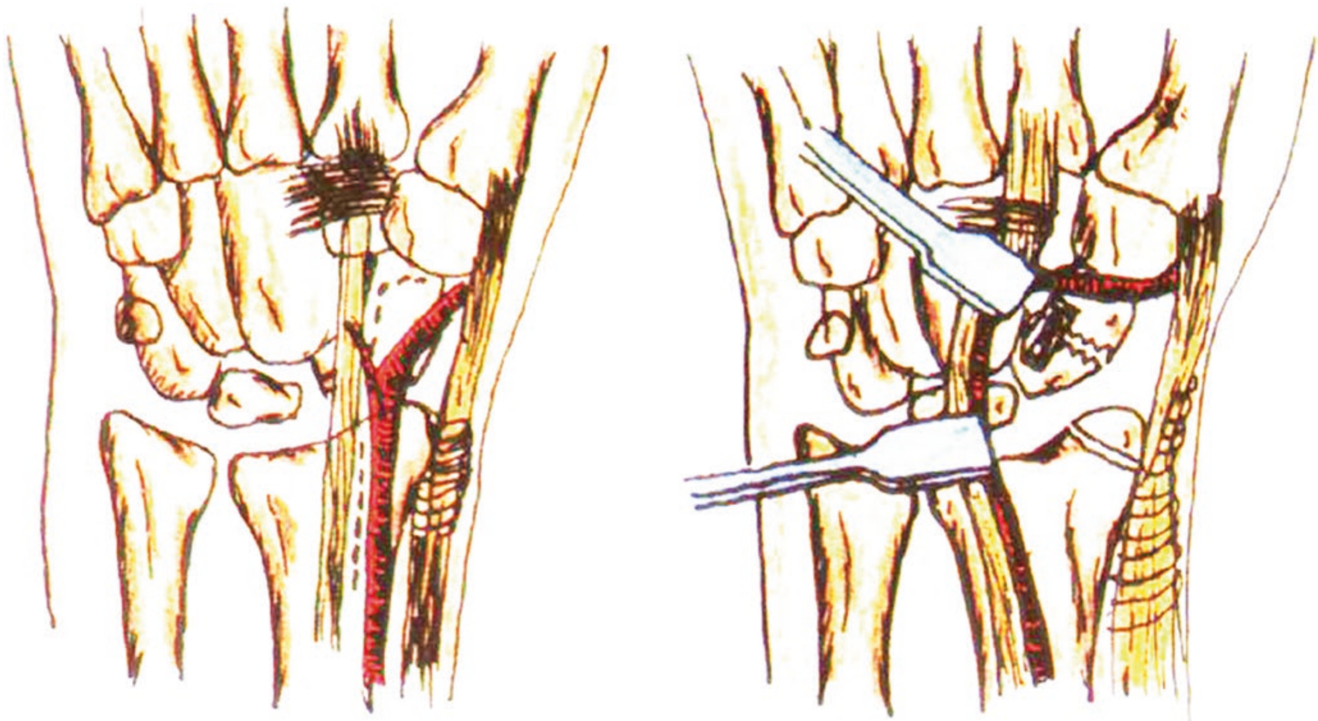


Fig. 20.6 Radial styloid process resection and bone grafting

on the conventional grafting method. The incision is subsequently sutured (Fig. 20.6).

(c) Postoperative treatment: A plaster cast is used to fix the forearm for 3 months. Radiographs are performed monthly; external fixation is used until the bone graft heals.

7. Wrist fusion

   Long-term scaphoid necrosis may lead to extensive osteoarthritis in the wrist, severe joint dysfunction, or stubborn joint pain, which severely affect patient quality of life. If non-surgical treatment is ineffective and surgical methods for retaining joint movement are inappropriate, wrist fusion is an appropriate solution. Common surgical procedures include the Abbott, Smith-Petersen, and Gill methods.

   Other surgical procedures for avascular scaphoid necrosis are reported in the literature; the specific surgical methods are not discussed here.

20.3 Microsurgical Repair of Lunate Aseptic Necrosis

Yao Zhang and Dewei Zhao

Lunate aseptic necrosis is a type of wrist pain of unknown etiology. It frequently occurs in the wrists of habitual male laborers 15–40 years old. Lunate aseptic necrosis was first discovered by Peste in 1843. In 1910, Kienbock described its clinical symptoms and signs in detail; therefore, lunate aseptic necrosis is also known as Kienbock disease.

20.3.1 Lunate Anatomy

1. Gross anatomy of the lunate bone

   The lunate bone is situated in the center of the proximal row of the carpal bones and is semi-lunar or crescent-shaped. It articulates with the adjacent bones to form five articular surfaces, with ligament attachment only in the palmar and dorsal sides. The lunate bone is also the center of the wrist, namely the center of the capitate–lunate–radius chain. It is prone to distortion and crushing injury (Fig. 20.7).

2. Blood supply of the lunate bone

   The lunate bone receives poor blood supply. Blood only comes from small vessels at the attachment of the dorsal and palmar ligaments, which form a network in the bone to nourish the lunate bone and extend to the inferior zone of the articular cartilage. Lunate blood supply modes can be classified as follows: (a) single vessel, in which the entire lunate bone is supported by the dorsal or palmar feeding vessels (~25% of cases); (b) multiple groups of vessels without anastomosis, in which the lunate bone is supported by groups of dorsal and palmar feeding vessels but do not anastomose in the center of the lunate bone (~8% of cases),

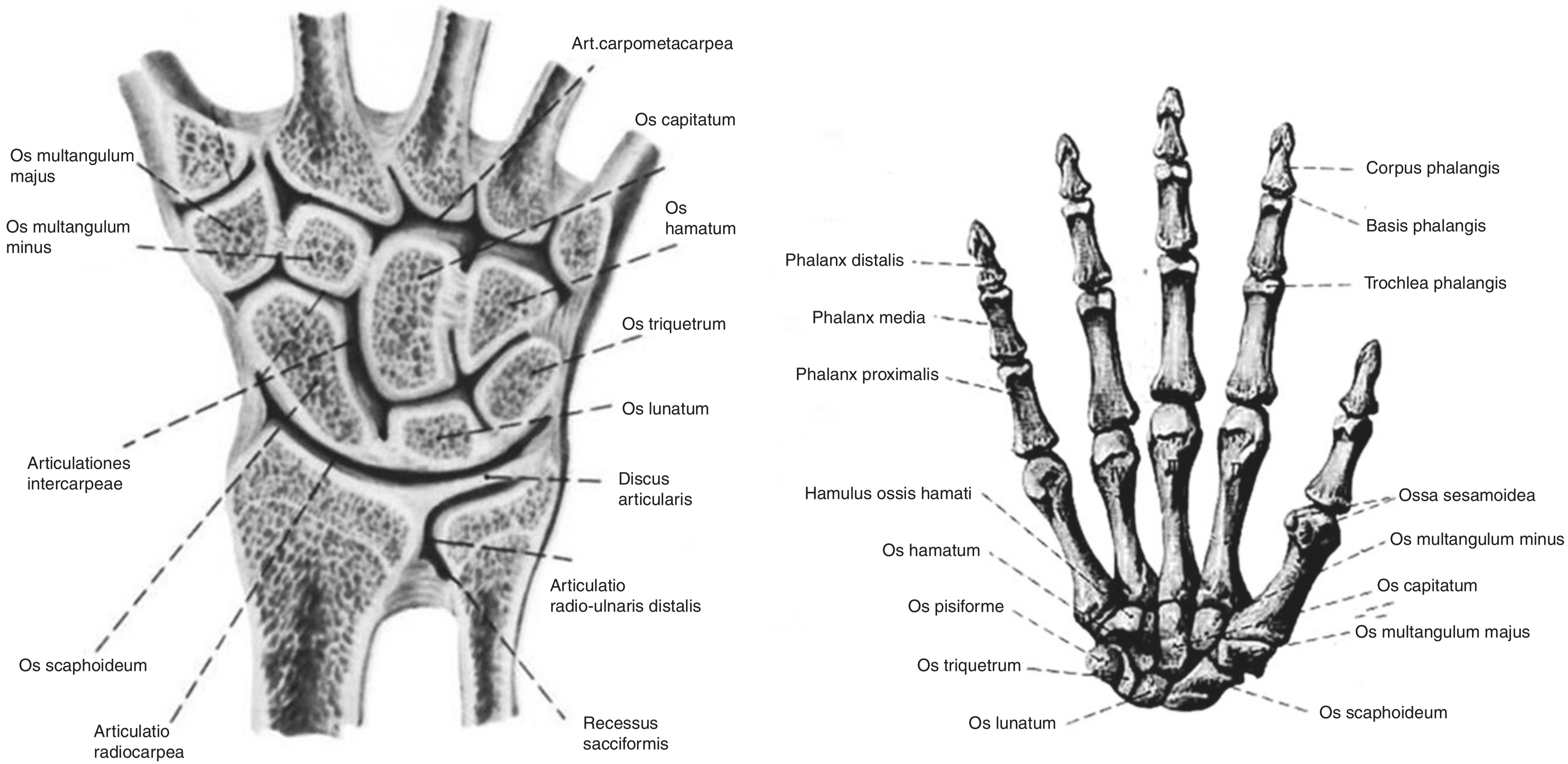


Fig. 20.7 Lunate bone anatomy

or (c) multiple groups of vessels with anastomosis, in which the lunate bone is supported by groups of vessels, which anastomose in the bone (~67% of cases).

3. Characteristics of the lunate trabecular bone

   The lunate trabecular bone is oriented from the distal to the proximal side, which is consistent with the stress transfer in the lunate bone. The trabecular area is largest in the center, followed by the dorsal side, and smallest in the palmar side. The quantity of trabecular bone can indirectly reflect the load-bearing capacity of each part of the lunate. Owing to its poor resistance to tension, the palmar lunate bone is prone to fracture, interruption of the trabecular bone, and microvascular injury inside the bone when the load increases.

20.3.2 Pathogenesis and Etiology of Lunate Necrosis

1. Pathogenesis
   (a) The theory of external causes refers to the process in which repeated micro-damage of the wrist leads to injury of the lunate attachment ligament and rupture of feeding blood vessels, resulting in lunate aseptic necrosis. For a lunate bone supported by a single trunk vessel, once the attached ligament injures, lunate bone fractures will lead to injury of the feeding artery. If there is thrombosis, it is prone to partial or whole ischemic osteonecrosis.
   (b) In the theory of internal causes, blood vessels in the palmar lunate with the largest number and widest diameter form the main blood supply system of the lunate. In the center of the lunate, vessels from the dorsal and palmar sides cross into the network. There are fewer vessels in the dorsal lunate, so its blood supply is poorest among the palmar and central part. The palmar trabecular bone is poorly resistant to tension, so trauma can easily lead to interruption of the trabecular bone and microvascular injury inside bones, resulting in ischemic lunate necrosis.
   (c) Hulten proposed the theory of negative ulnar variation in 1928. He claimed that negative ulnar variation causes a relative concentration of the load on the lunate; the increased stress, fracture, and microvascular injury consequently cause lunate aseptic necrosis. In patients with lunate necrosis, the radiolunate angle and capitate-lunate angle are significantly increased, showing a tendency to palmar flexion. This palmar flexion can make the palmar lunate bone the center of stress conduction, where the load increases. Moreover, the palm lunate has poor resistance to tension and ruptures easily, resulting in damage to the palmar feeding vessels and lunate aseptic necrosis.
2. Etiology

   Lunate aseptic necrosis may be caused by several factors. The most common situations are as follows: (a) people with repeated micro-damage of the wrist, such as carpenters, porters, blacksmiths, etc.; (b) people with serious trauma of the wrist, including lunate fractures, various lunate dislocation, and dislocation of the wrist (Fig. 20.8); (c) heavy manual workers 20–40 years old; and (d) people

Fig. 20.8 Radiographic signs of lunate dislocation

with negative ulnar variations or a smaller angle of ulnar deviation on the articular surface of the distal radius. Pathogenic factors such as negative ulnar variance can increase the load of the lunate and damage the capillary. In addition, if these lunates are supported by a single vessel or exhibit bacterial embolism and vasculitis, then the occurrence of acute fractures, repeated micro-damage, or increased stress may lead to a block in venous return, followed by insufficient arterial blood supply and nutrition disorders, culminating in lunate aseptic necrosis.

20.3.3 Clinical Manifestations and Imaging Examination

As lunate necrosis progresses slowly and the early symptoms are atypical, with only mild pain in the wrist and tenderness in the dorsal lunate bone, it is easily overlooked in clinical practice. With disease progression, the wrist swells with increasing pain and carpal dysfunction appears. Late clinical symptoms and signs of the disease are typical, including swelling in the dorsal lunate area, wrist pain, and wrist joint dysfunction. There is local tenderness in the dorsal lunate area. Percussion on the second and third metacarpal bones can induce wrist pain, and grip strength is weaker than that of a healthy hand. The third metacarpal bone can even be observed ectopically to the proximal side. Axial percussion pain on the third metacarpal bone should be used as a unique clinical sign for early diagnosis.

20.3.3.1 Imaging Findings and Radiographic Classification

1. Radiographic signs and classification

   Lichtman classification is the most common, which classifies lunate necrosis into four stages:
   - Stage I: the lunate retains its normal structure, but there may be linear fracture or compression fractures;
   - Stage II: the lunate retains its normal contour, but there are changes in bone mineral density along with osteonecrosis and osteosclerosis;
   - Stage III: there is lunate collapse and fragmentation in addition to collapse of the wrist; Stages IIIA and IIIB are not accompanied and accompanied by flexion deformity of the scaphoid, respectively.
   - Stage IV: there is lunate osteosclerosis, and the whole wrist shows degenerative changes (Figs. 20.9, 20.10, 20.11, and 20.12).
2. MRI results
   - Stage I: local or diffuse low signal intensity of the necrotic areas can be observed on T1-weighted images; no abnormalities are apparent on T2-weighted images;
   - Stage II: low signal intensity for lunate osteosclerosis can be observed on T1-weighted images; high signal intensity is apparent on T2-weighted images;
   - Stage III: the lunate collapses and flattens. Its gap with surrounding bone joints widens, and the capital bone shifts to the proximal side. Subluxation of navicular bone is often observed;
   - Stage IV: chiefly characterized by diffuse osteonecrosis signal, severe lunate collapse or even fragmentation, accompanied by degeneration characteristics of the entire wrist.

Early symptoms of lunate necrosis are atypical, and the clinical diagnostic rate is poor. More attention should be paid to the examination of the percussion pain of the third metacarpal bone. In the middle and late stages, patients experience pain and swelling in the wrist and wrist joint dysfunction. Physical examination for tenderness of the lunate area can reveal percussion pain in the second and third metacarpal bones and weaker grip strength of the diseased than the healthy hand. The diagnosis of lunate aseptic necrosis can generally be made when combined with an imaging examination.

20.3.4 Treatments

20.3.4.1 Conservative Treatment

Conservative treatments for lunate aseptic necrosis include local plaster fixation, physical therapy, and improvement of microcirculation; the aim is to reduce pressure on the lunate and promote angiogenesis and new bone formation. Conservative treatment is generally suitable for patients in

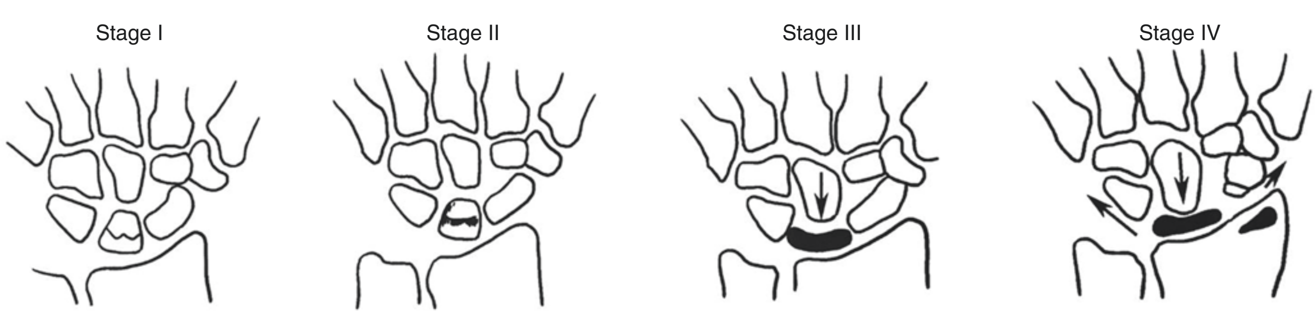


Fig. 20.9 Lichtman's classification of lunate aseptic necrosis

Fig. 20.10 Stage II

Fig. 20.11 Stage III

stages I and II. The patients are fixed with plaster casts for 4–6 months. They are reexamined monthly with radiographs of the wrist joint to determine whether the disease has progressed.

20.3.4.2 Surgical Treatments

1. Simple lunate excision

   Simple lunate excision only removes the necrotic lunate and eliminates the primary lesion so as to relieve pain in the wrist joints. Most authors believe the capital bone will shift down after lunate excision, consequently exhibiting carpal collapse and wrist arthritis. However, in recent years, some authors have proposed the opposite view that the therapeutic effect of simple lunate excision can be comparable to radial shortening and scaphoid–trapezium–trapezoid fusion. Therefore, we should reconsider the therapeutic effects of simple excision on lunate aseptic necrosis.

Fig. 20.12 Stage IV

2. Lunate excision and replacement

   Lunate excision and replacement refers to the treatment where the lunate is replaced by a silicone lunate, pisiform bone, tendon, or fascia after excision. This treatment is suitable for patients with stage III and IV lunate osteonecrosis.
3. Scaphoid–trapezium–trapezoid fusion

   In scaphoid–trapezium–trapezoid fusion, which was first developed by Watson et al. in 1985, the distal scaphoid is fused with the trapezium and trapezoid to reduce the load on the lunate by conducting the load through the scaphoid, trapezium, and trapezoid. This surgical method can relieve pain in the wrist and increase grip strength.
4. Proximal row carpectomy

   Proximal row carpectomy removes the entire proximal row of carpal bones including the scaphoid, necrotic lunate, and triangular bone. Therefore, a new joint is reformed between the proximal articular surface of the distal row of carpal bones and the radial articular surface.
5. Transplantation of a pisiform bone graft with the deep palmar branch of the ulnar artery as a vascular pedicle

   An S-shaped incision is made in the wrist and forearm palm. Then, dissection is performed along the trunk of the ulnar artery distally to seek the feeding vessels of the pisiform bone, which originate from the deep palmar branch of ulnar artery. The abductor digiti minimi attached to the pisiform bone and its surrounding ligaments are excised, while the attachment of the flexor carpi ulnaris is retained. The pisiform bone with its ulnar feeding vessels is dissected from the radial side. The lunate is removed completely in the middle of the palmar wrist. The articular surface of the pisiform bone with the vascular pedicle is connected to the articular surface of the capitate bone, which fills the gap due to lunate resection. A crossed Kirschner fixation for pisiform bone is performed with two Kirschner wires which are inserted separately from the triangular bone at the ulnar side and scaphoid at the radial side. The wrist joints are fixed by a plaster slab postoperatively, and the Kirschner wires should be retained for 6 weeks. (Figs. 20.13 and 20.14)

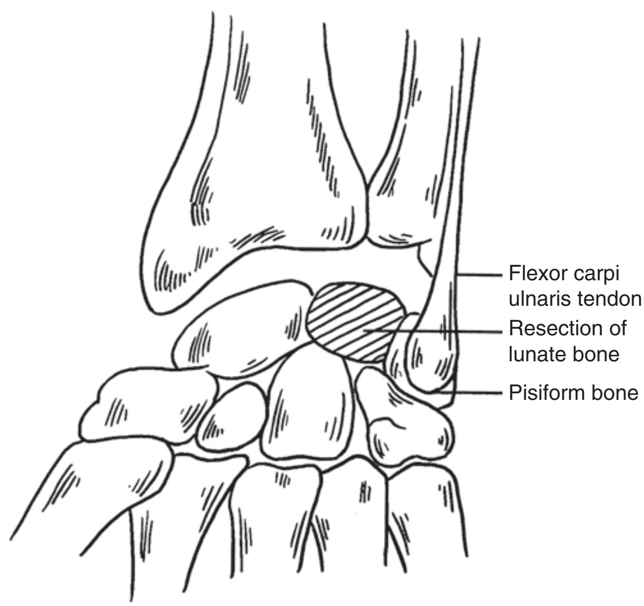


Fig. 20.13 Lunate excision and replacement

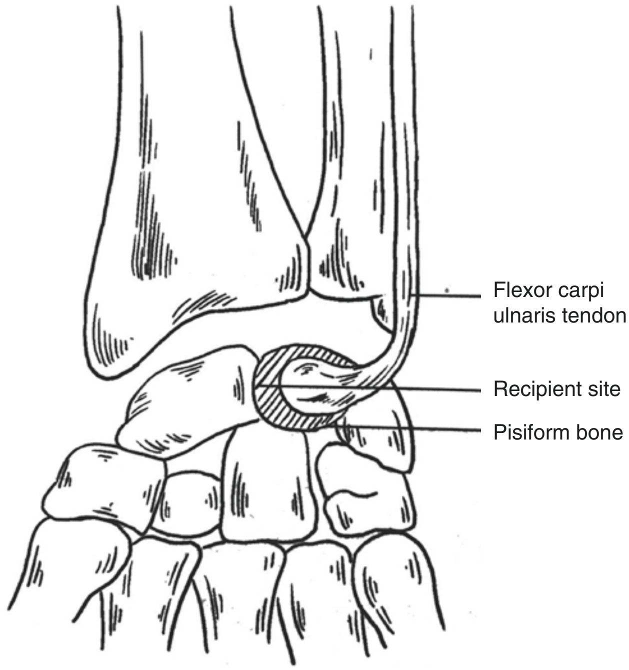


Fig. 20.14 Transplantation of pisiform bone graft with vascular pedicle

6. Transplantation of the radial bone graft with the dorsal carpal branch as the vascular pedicle

   A longitudinal S-shaped incision is made in the middle of the dorsal wrist. The dorsal carpal branches of radial artery are found in the first and second extensor retinaculum and protected. Then, the dorsal carpal branches with a surrounding tissue pedicle of 0.5 cm are dissociated. A bone flap (6.0 × 10.0 cm) is excised at the dorsal radial side (with a goose saw) where the vessels enter the distal radius. In the same incision, the dorsal carpal ligament and joint capsule are incised to expose the lunate bone and remove necrosis. The radial flap with the vessel pedicle is transferred to the defective bony area of the lunate. After suturing and fixing the soft tissue on the bone flap surface with the surrounding tissues, the bone flap should be cross-fixed on the lunate with two Kirschner wires. The wrist joints are fixed by plaster slab postoperatively, and Kirschner wires should be retained for 8 weeks (Figs. 20.15 and 20.16).
7. Transplantation of the radial bone graft with the palmar radial branch as a vascular pedicle

   An S-shaped incision is made in the palmar wrist to expose the radial vessel bundle. The palmar branches that originate from the radial artery can be seen on ulnar side. A bone flap with a vascular pedicle measuring 5 × 0.5 × 1.0 cm is taken by a small osteotome at the distal palmar radius 0.5 cm from the edge of the

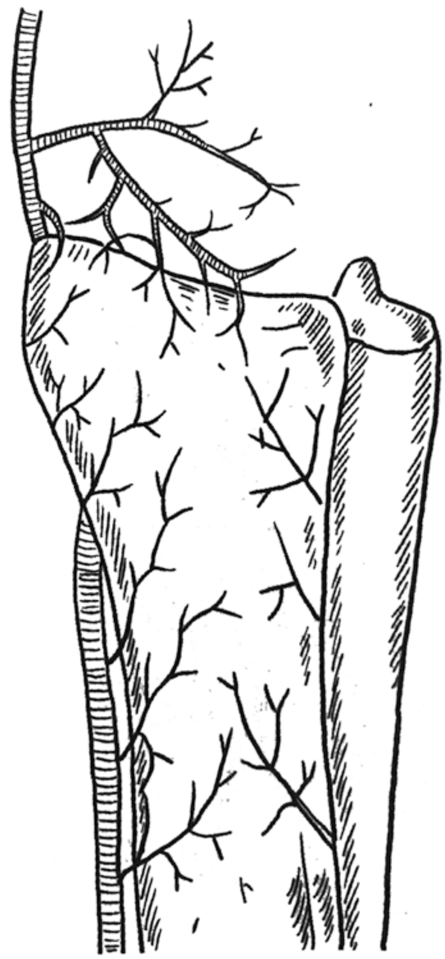


Fig. 20.15 Dorsal carpal branches of the radial artery

   articular surface. Then, the transverse carpal ligament is incised, and the lunate is exposed. A bone window of ~0.5 × 0.5 cm is chiseled at the palmar lunate, and the lesion is removed. Cancellous bone taken from the donor area is implanted in the defective area. The bone flap is transposed and inserted into the lunate groove. The bone flap should be cross fixed with two Kirschner wires. The wrist joints are fixed with a plaster slab postoperatively, and the Kirschner wires should be retained for 6 weeks.
8. Transplantation of the distal radial bone graft with the pronator quadratus as a pedicle

   An S-shaped incision is made in the palmar wrist to expose the pronator quadratus, which is in the deep flexor digitorum profundus muscle. A bone flap measuring 1.0 × 0.5 × 0.5 cm is taken at the distal radial pronator quadratus, which is supported by the anterior interosseous membrane artery. A bone window measuring ~0.5 × 0.5 cm is chiseled at the palmar lunate, and

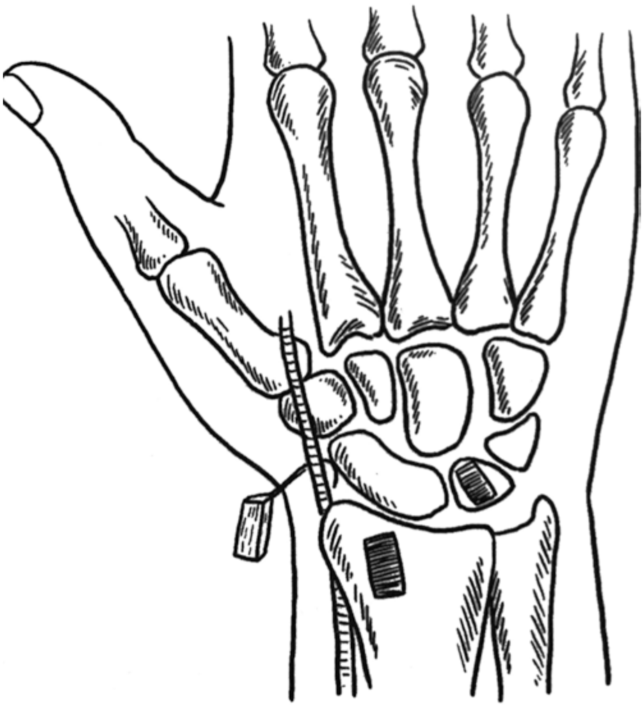


Fig. 20.16 Transplantation of the radial bone graft with the dorsal carpal branch as a vascular pedicle

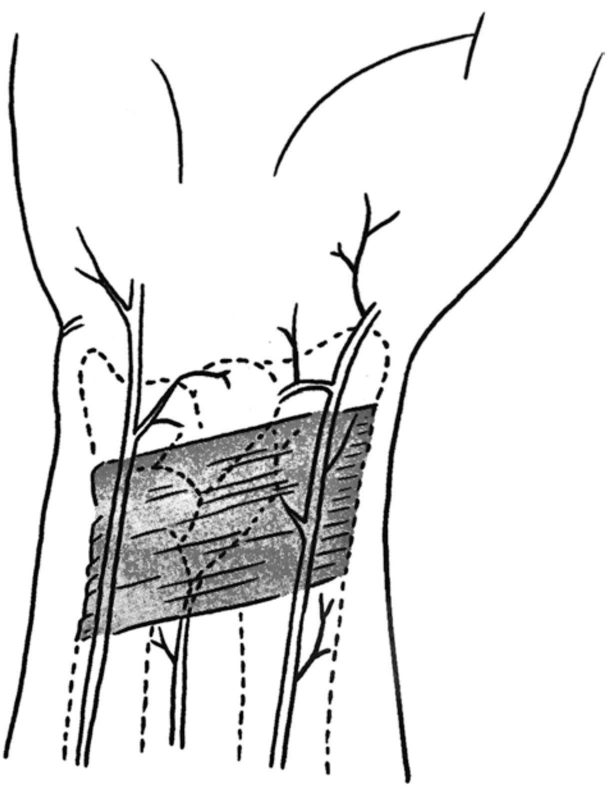


Fig. 20.17 Blood supply of the pronator quadrates

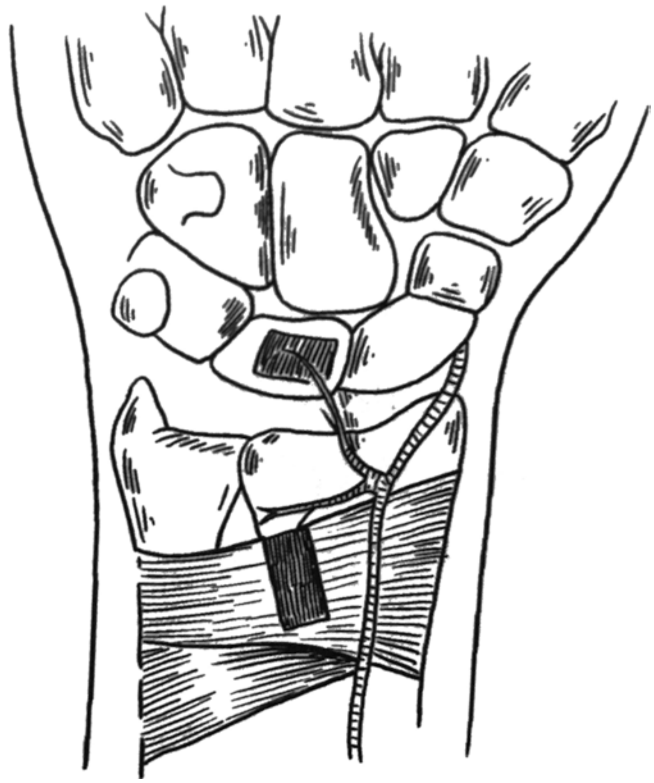


Fig. 20.18 Transplantation of the distal radial bone graft with the pronator quadratus as a pedicle

the lesion is removed. Cancellous bone taken from the donor area is implanted to the defect area. The bone flap is transposed and inserted into the lunate groove. The bone flap should be cross-fixed with two Kirschner wires. The wrist joints are fixed with a plaster slab postoperatively, and the Kirschner wires should be kept for 6 weeks (Figs. 20.17 and 20.18).

9. Radial shortening

   Radial shortening was developed by Almquist et al. on the basis of the theory of negative ulnar variance proposed by Hulten. This method shortens the radius by 2 mm, 7 cm from the distal radial articular surface and fixes the bones with a compression plate. The procedure can alleviate wrist pain and delay the occurrence of osteoarthritis and wrist collapse.

10. Ulnar lengthening

    Ulnar lengthening was first reported by Persson et al. in 1950 and is suitable for young patients with negative ulna variance at an early stage. Ulnar lengthening extends the ulna by 2 mm without affecting the ulnar deviation of the wrist. This procedure can alleviate wrist pain and improve grip strength. However, the surgery may cause complications such as ulna nonunion or ulnar–carpal impingement syndrome.

20.4 Microsurgical Repair of Ischemic Necrosis of the Humeral Head

Xiaobing Yu and Dewei Zhao

Ischemic necrosis of the humeral head is a type of shoulder pain of unknown etiology, whose most common cause is impaired blood supply to the humeral head due to trauma, including proximal humeral fractures, humeral neck fracture, and shoulder joint dislocation. Trauma accounts for 15–30% of ischemic necrosis of the humeral head. In addition, nontraumatic ischemic necrosis of the humeral head is commonly associated with corticosteroids, alcoholism, autoimmune disease, etc.

20.4.1 Anatomy of the Humeral Head

1. Bony structure of the proximal humerus

   The proximal humerus consists of the humeral head, anatomical neck, greater tubercle, and lesser tubercle. The humeral head, which has a nearly hemispherical form, articulates with the glenoid cavity of the scapula. The narrow groove around the humeral head is called the anatomical neck, which supports the attachment of the joint capsule. The greater tubercle is situated lateral to the proximal humerus, shifting down to the crest of the greater tubercle. Meanwhile, the lesser tubercle is anterior to the proximal humerus, shifting down to the crest of the lesser tubercle. The longitudinal groove between the greater and lesser tubercles, called the intertubercular groove, lodges the long tendon of the biceps brachii muscle; its respective boundaries are the crests of the greater and lesser tubercles, which are the attachments of the pectoralis major muscle and teres major tendons, respectively. The bottom of the groove is attached to the latissimus dorsi. The thinner part below the greater and lesser tubercles is called the surgical neck, which is the junction of the compact and spongy bone; it is susceptible to facture. On the coronal plane, a collodiaphyseal angle from ~130 to 135° can be observed between the humeral head and shaft. On the cross-section, the humeral head bends back and crosses the transverse axis of the elbow joint, forming a caster angle from ~20 to 30°.
2. Origin, direction, and distribution of the anterior humeral circumflex artery

   The anterior humeral circumflex artery originates from the axillary artery. In some cases, it shares the same trunk as the posterior humeral circumflex artery, while in other cases, it branches from the deep humeral artery. The main trunk runs beneath the coracobrachialis and short head of the biceps brachii muscle, rounds the surgical neck, and produces a branch that ascends to the humeral head and shoulder joint. Then, the trunk runs beneath the long tendon of the biceps brachii muscle and produces descending marginal branches when crossing the superior edge of the attachment point of the pectoralis major muscle. The branches are the lateral descending branch and the medial descending branch, which pass near the periosteum along the medial or lateral terminal tendon of the pectoralis major muscle. The medial descending branch is involved in the vessel network of the anterior periosteum of the middle humerus. The lateral descending branch runs along the lateral terminal tendon of the pectoralis major muscle and disperses to the area of the proximal lateral humerus that is covered by the anterior deltoid muscle. The distance from the starting point of this descending branch on the anterior humeral circumflex artery to the highest point of the greater tubercle is 4.1 cm, and the outer diameter of the branch is 1.2 mm. The total length of the descending branch is 6.0 cm, and the area of the osteoperiosteal flap is ~7.0 × 2.0 cm (Fig. 20.19).
3. Origin, direction, and distribution of the posterior humeral circumflex artery

   The posterior humeral circumflex artery is the second largest branch of the axillary artery. In 48.1% of cases, the posterior humeral circumflex artery shares the axillary trunk with the subscapular artery or anterior humeral circumflex artery. Meanwhile, 32.5% originate from the axillary artery, with an outer diameter of 2.4 mm and a vertical distance from the top of the greater tubercle of 6.4 cm. Clinging to the surgical neck and axillary nerve, it goes beneath the deltoid through the quadrilateral fora-

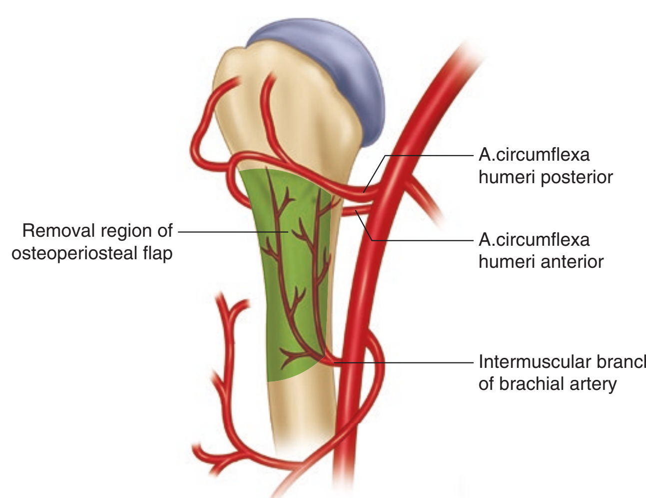


Fig. 20.19 Distribution of the anterior humeral circumflex artery and osteoperiosteal flap design (anterior view)

men and produces the deltoid branch and greater tubercle periosteal branch at the outlet of the quadrilateral foramen. The diameter of the muscle branch is 1.9 mm. The trunk is terminally anatomized with the anterior humeral circumflex artery. The trunk of the posterior humeral circumflex artery has a total length of 8.2 cm. It produces a greater tubercle periosteum branch at the outlet of the quadrilateral foramen 5.5 cm to the top of the greater tubercle, which runs along the facies lateralis of the greater tubercle. The greater tubercle periosteal branch is further divided into 4–5 lateral branches that are distributed in the lateral periosteum of the great tubercle, with an outer diameter of the starting point of 1.1 mm and a periosteal flap area measuring 3.0 × 5.0 cm. The medial margin of the osteoperiosteal flap is the lateral margin of the supraspinatus, infraspinatus, and the endpoint of the teres minor muscle. Its lateral margin extends to the lateral wall of the intertubercular groove; the upper margin extends to the plane of the top point of the greater tuberosity, and the lower margin is at the level of the humeral surgical neck (Fig. 20.20).

4. Scapular branch of the thoracodorsal artery

   The scapular branch is 4.1 ± 1.1 cm beneath the starting point of the thoracodorsal artery and exits the posterior internal wall. Among the scapular branches, ~80% share the thoracodorsal artery common trunk with the serratus anterior muscle, while 20% originate from the thoracodorsal artery. The scapular branch tends inward and nears the axillary margin of the scapula. It steers to the front of the axillary margin of the scapula 2 cm from the inferior angle of the scapula. The infraspinous branch of the suprascapular artery enters the infraspinous fossa over the superior transverse scapular ligament and divides into several branches. Its trunk rounding the supraspinatus incisure to infraspinous fossa is known as the infraspinous branch. Originating from the supraspinatus incisure, the infraspinous branch extends medially and transversely for 3.5 ± 0.2 cm and simultaneously produces 4–6 periosteal branches. An anastomoticus with an outer diameter of 1.1 ± 0.4 mm is directed beneath the infraspinous branch 0.5–1.0 cm to the supraspinatus incisures. It extends downward along the axillary margin of scapula and forms the reticular anastomosis with the posterior humeral circumflex artery and circumflex artery of the scapula. The trunk of the infraspinous branch is ~2.5 cm from the inferior margin of the scapular and has an initial diameter of 1.8 ± 0.3 mm.

5. Acromial branch of the thoracoacromial artery

   The thoracoacromial artery, which has an initial outer diameter of 2.7 ± 0.5 mm, passes the clavipectoral fascia through the superior border of the smaller pectoral muscle, dividing into the clavicular, acromial, and deltoid branches. The acromial branch extends outward beneath the deltoid muscle. Its trunk reaches the acromioclavicular joint after 5.1 ± 0.4 cm. Then, it rounds the anterior lateral margin of the acromion and sends periosteal branches into the acromial artery net. The outer diameter of the acromial branch is 1.5 ± 0.2 mm. The deltoid branch extends from the thoracoacromial artery, passes through the deltopectoral groove, and is distributed in the anterior part of the deltoid muscle. The deltoid muscle has an outer diameter of 1.9 ± 0.2 mm, with a length from origin to the point inlet of 4.8 ± 0.5 cm.

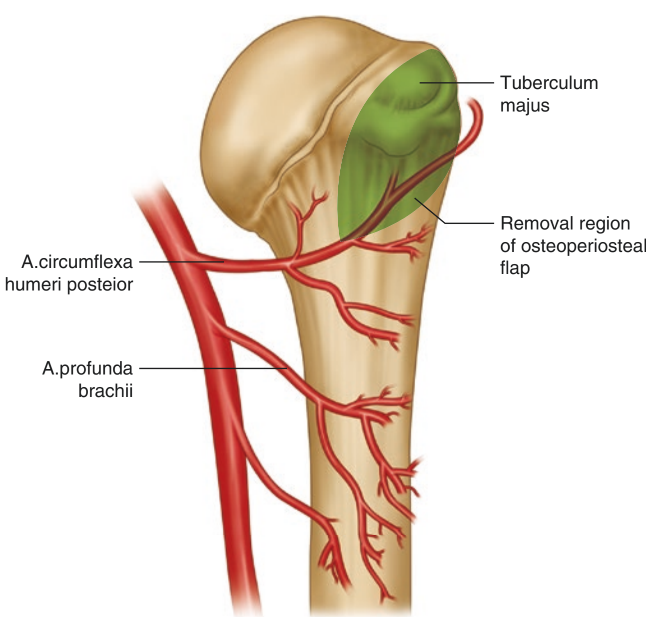


Fig. 20.20 Distribution of the anterior humeral circumflex artery and osteoperiosteal flap design (posterior view)

20.4.2 Pathological Changes of Humeral Head Necrosis and Imaging Examinations

When the feeding artery of the humeral head is injured, the blood supply is blocked, and chondrocytes in the articular surface are degenerated and necrosed. The bone cells subsequently exhibit nuclear degeneration, necrosis, and separation from the head. Some bone cells exhibit cystic degeneration. Bone tissue appears uneven on the surface and affects joint motion. During stage I, no lesion is observed on radiographs, necrotic lesions can be detected on MRI, and bone necrosis is evident on histopathological examination. During stage II, radiographs show sclerotic bone in the upper third of the humeral head, which is round. Histopathological examination shows bone cell necrosis, bone repair, and angle plasticity. During stage III, subchondral fracture occurs and the humeral head is

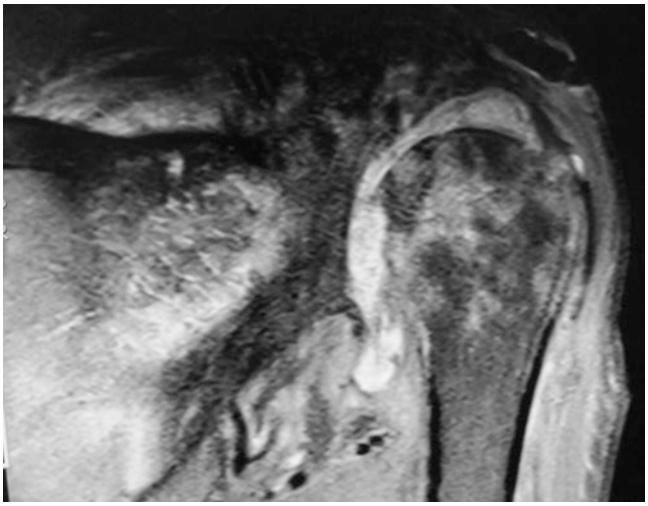


Fig. 20.21 MRI signs of stage III humeral head ischemic necrosis

not round. A radiograph shows a crescent sign for subchondral fracture. Lesions are commonly observed around the arm extorsion, i.e., the chondroid flap is lifted because of subchondral sclerosis, and the cartilage surface is compressed, although there is no observable collapse. During stage IV, collapse and necrosis of the femoral head are apparent and are sometimes accompanied by exfoliated necrotic bone. The glenohumeral joint surface grows incompatible and can cause local degeneration. During stage V, the necrotic area of the humeral head collapses further. Glenohumeral arthritis, sclerosis, and cystic change are observed, and the humeral head is damaged further. Phases I and II can be reversed by treatments, while phases III, IV and V cannot (Fig. 20.21).

20.4.3 Clinical Manifestations

Shoulder pain is the main symptom during the early stages. Nocturnal pain, limitations of shoulder joint activity, necrosis, or separation of the humeral head occur during disease progression. Examination of shoulder activity may produce clacking sounds but is not necessarily accompanied by pain. Local tenderness and limitation of activity are signs during the late stage. Pain is often insidious. As the shoulder glenoid is not the weight-bearing joint, the pain is not as sharp as pain in the lower-limb joints.

20.4.4 Treatments

In recent years, microscopic repair such as vascularized bone transplantation and osteoperiosteal flap transplantation has become an important treatment method for humeral head necrosis.

20.4.4.1 Microsurgical Repair Surgery

1. Transplantation of the humeral osteoperiosteal flap from the lateral descending branch of the anterior humeral circumflex artery

   The patient is placed in the supine position with a flat pillow under the affected shoulder and the corresponding arm and hand on the chest. A 7-shaped incision is made at the anterior shoulder joint. The skin, subcutaneous tissue, and deep fascia are incised to identify the cephalic vein. The anterior deltoid is pulled out to reveal the long head of the bicep tendon passing through the trunk of the anterior humeral circumflex artery and its lateral descending branch. This branch extends downward near the lateral surface of the humerus at the terminal tendon of the pectoralis major muscle. A strip of the osteoperiosteal flap can be excised as needed. With the germinal layer of the osteoperiosteal flap outside, an absorbable suture is used to sew the flap into the cigarette-shaped spare. The upper limb is rotated externally. Then, the subscapularis tendon and joint capsule are incised longitudinally to expose the anterior humeral head and clean the joint cavity. A bone hole is chiseled from the anterior middle of the anatomical neck to remove the dead bone and granulation tissue of the humeral head. If the humeral head collapses, a special impactor is used to impact it so as to maximally restore it. A small amount of cancellous bone from the greater tubercle is used for filling, and the osteoperiosteal flap with pedicle is implanted in the bone hole, which is fixed with the surrounding soft tissue by using sutures to prevent slippage.

2. Transplantation of the humeral osteoperiosteal flap with the lateral descending branch of the posterior humeral circumflex artery as the vascular pedicle

   The patient is placed in a supine position with the head toward the contralateral side and the affected shoulder abducted and slightly flexed. A sand pillow is placed under the affected shoulder. Otherwise, the patient can be placed in a lateral position with the upper limb on a support device. The posterior approach is adopted. The incision starts from the acromioclavicular joint, goes back over the acromion to the scapular spine, then bends outward and downward, and ends ~4.0 cm above the post-axillary plica. The skin, subcutaneous tissue, and deep fascia are subsequently incised to identify the posterior margin of the deltoid. This is separated until 1.0 cm below the starting point where it is excised and dissected until the acromioclavicular joint. The supraspinatus, infraspinatus, and teres minor muscles are exposed. The posterior humeral circumflex artery and axillary nerve trunk with its branches can be found in the outlet of the quadrilateral foramen below the teres minor muscle. The axillary nerve is carefully dissected, while the greater tuberosity periosteal branch and deltoid branch of posterior humeral circumflex artery should be properly protected. Behind the lateral surface of the greater tubercle, an osteoperiosteal flap measuring 3.0 × 5.0 cm is excised with the direction of the greater tubercle periosteal branch as the longitudinal axis. With the germinal layer of the osteoperiosteal flap on the outside, an absorbable suture is used to sew the flap into the cigarette-shaped spare. The deltoid branch and extending branch of the posterior circumflex artery should be carefully ligatured during the operation. It is cut off at the endpoint of the infraspinatus and teres minor muscle. The joint capsule is incised longitudinally to expose the posterior humeral head. A bone hole is chiseled from the lateral middle part of the anatomical neck to the middle of the humeral head central. The rest of the operation is the same.

3. Transplantation of the bone flap of the axillary margin scapula with the scapula branch of the thoracodorsal artery as the vascular pedicle

   The patient is placed in the lateral position with the upper limb on a support device. The incision is made from the top of the post-axillary plica and extends 6–7 cm upward along the posterior margin of the deltoid. It subsequently turns to the medial and inferior side of the post-axillary plica and ends 2–3 cm below the inferior angle of the scapula. The teres major and latissimus dorsi muscles are separated bluntly. Then, a longitudinal incision 3–5 cm long is made from the superior margin of the latissimus dorsi to the inferior angle of the scapula. The latissimus dorsi muscle is pulled open. At this time, the operation file shows the scapula branch that originates from the thoracodorsal artery leaning medially and downward along the axillary margin of the scapula. The scapular branch is carefully separated and extends to the thoracodorsal artery. After ligation of the scapular vessel, it can be returned to the subscapular vessel to increase the rotating arc.

4. Transplantation of the bone flap of the lateral scapular branch with the acromial branch of the thoracoacromial artery as the vascular pedicle

   The patient is placed in the lateral position with the upper limb on the chest. The proximal humerus is repaired. An inverse U-shaped incision is made in the shoulder joint. If the lesion is in the lower part of the head, a Y-shaped incision can be made. With the acromioclavicular joint as the center, an arc incision that extends longitudinally downward from the middle is made. The acromioclavicular joint and acromion are exposed to seek the acromial network formed by the acromial branch of the thoracoacromial artery above the acromion. The separation is along the acromial branch centripetal to the origin. The disposition of the bone flap carried by the acromial branch only reaches the humeral head. If the bone flap is supported by retrograde blood of the deltoid branch, the vascular pedicle can be up to 10 cm. Bone flap transplantation can repair the humeral head.

5. Transplantation of the bone flap of the pedicled scapular with the infraspinous branch of the suprascapular artery as the vascular pedicle

   The patient is laid in a lateral position with the upper limb on the support device. The incision is made inward from the acromial end along the spine of the scapula and then extended along the spine margin of the scapula downward. In the lower margin of the scapular, the start and end points of the deltoid and trapezius are cut off. The supraspinatus is excised along the lower margin and spinal margin of the scapula. The infraspinatus is pulled open to the spinoglenoid notch. The infraspinous trunk is exposed ~2.5 cm below the scapular spine. The trapezius muscle is separated from the superior margin of the spine of the scapula. The supraspinatus muscle is then pushed to expose the scapular supraspinous fossa and obtain the bone flap. When using this type of bone flap disposition to repair the humeral head, only part of the scapular spine needs to be obtained. The medial half is better because it may retain sufficient blood supply and is conducive to local transplantation. If anastomoses can be used for reverse blood supply, a longer rotating arc will be obtained to repair the humeral head.

20.4.4.2 Other Treatments

Symptomatic treatment at an early stage or core decompression can relieve pain. When free bodies join the interlocking joint, shoulder arthroscopy can be used for cleaning. However, the methods described above are temporary solutions, and curative effects are difficult to assess. If the disease is at a late stage with joint deformity and osteoarthritis such that microscopic bone flap transplantation will not aid repair, prosthetic replacements can be utilized.

20.5 Microsurgical Repairation for Avascular Necrosis of the Femoral Head

Weimin Fu and Dewei Zhao

Avascular necrosis of the femoral head (avascular necrosis, AVN) is one of the most refractory disease in the orthopedic, non-traumatic AVN has a high incidence in young and middle-aged patients, if they delay treatment who will develop to osteoarthritis a few years later, finally, they need to treat by the hip replacement. Considering the age and activity of these patients, they may face the hip replacement for many times in future. So reserving femoral head and delaying the time of hip replacement as soon as possible is definitely important. It’s a consensus that the cause of AVN is blood flow defects, so the main treatment is to recover the blood supply of femoral head. In clinical, The most common ways of reserving femoral head are bone graft with vascular pedicle and free vascularized fibular graft.

20.5.1 Anatomy

1. Femoral head anatomical structure: femoral head is circular spherical accounted for about two thirds of the ball, towards the direction of anterior superior, the acetabular surface of the joint, the concave at the top of the later, called concave of the femoral head, and the round ligament attach to this sites. Except femoral head fovea all femoral head covered by hyaline cartilage, with different degree of thickness, divided into pressure area and non pressure zone contact with the acetabular cartilage or not. Femoral head of the bone trabecular system is from the inner cortex of the femoral neck to a fan-shaped distribution, covering in cartilage of the femoral head lateral have much higher pressure, and the medial part of the compression force is relatively lower. The effect of pressure determines the structure of the cancellous bone, which is not only related to loading, but also to the action time. The femoral neck is the connecting part between the femoral head and the shaft of femur. The presence of the neck stem angle increases the movement range of the lower limb and is more suitable for loading. It was in the range of 110°–140°. Femoral front rake is 12°–15°.
2. Blood supply to the femoral head and neck: Femoral head and neck blood circulation mainly from the medial circumflex femoral artery, lateral circumflex femoral artery and obturator artery and their four branches of superior retinacular artery, inferior retinacular artery, anterior retinacular artery and round ligament artery of vascular plexus.

The femoral head ligament artery, mostly branch from the obturator artery is not the main nutrient femoral head blood vessels. Some viewpoint is that accounts for about 5% of the blood supply of the femoral head.

Retinacular arteries: The extracapsular arterial ring located at the base of the femoral neck anastomosis by medial circumflex femoral artery, lateral circumflex femoral artery and inferior gluteal artery. This ring gives off superior retinacular artery, inferior retinacular artery and anterior retinacular artery. Superior retinacular artery and inferior retinacular artery are generally considered to be the main source of blood supply of the femoral head. Distribute at the lateral and medial part of the femoral neck. The anterior retinacular artery is small, not constant, and its branches of the femoral head are less.

The femoral nutrient artery anastomose with retinacular artery to facilitate blood flow to the femoral head but only a few parts.

20.5.2 Etiology

Avascular necrosis etiology can be divided into traumatic and non-traumatic. Femoral head fractures, femoral neck fractures, intertrochanteric fractures and hip dislocation are common factors in traumatic avascular necrosis, and non traumatic etiology is mainly glucocorticoids and alcohol induced osteonecrosis of the femoral head. Also the hip joint abnormalities, decompression sickness, colored villous nodular synovitis, blood disease etc. can all cause avascular necrosis. At present, the research on the pathological mechanism of the avascular necrosis of the femoral head is mature on glucocorticoids and alcohol induced osteonecrosis. Although many theories for the avascular necrosis of the femoral head, have been put forward but many parts are still unclear.

20.5.3 Clinical Manifestation and Imaging Examination

AVN develops slowly and has a long course, possibly for a long time patients had no obvious clinical symptoms. The common symptom is hip discomfort or pain after walking, and the pain can be relieved by rest, in addition, the patients often appear lumbosacral or hip pain, which often cause clinically misdiagnosis as lumbar disc prolapse, synovitis. With the limp and the pain aggravate, hip function is limited gradually, at last, the hip become stiffness and disability.

X ray is the basic method for AVN, it generally contains A-P position and rana position. According to the X-ray manifestations, Ficat makes the AVN for five stages.

CT scan can get the high-resolution and precise axial tomographic image of the femoral head, which can get more accurate diagnosis. With a wide clinical applications of magnetic resonance, the early diagnosis of AVN has been greatly improved. Combined with typical morphological findings and clinical observations, MRI has been the main way for the early diagnosis of AVN. In 1993, the Association Research Circulation Osseous (ARCO) Committee proposed the definition and terminology of AVN, and make stage based on MRI (Table 20.1).

Table 20.1 Scheme of ARCO classification system

Stage	Radiological findings	Subclassification
0	Positive: histology negative/normal: Radiograph/CT/MRI/scintigraphy	–
I	Positive: MRI and/or bone scintigraphy negative/normal: radiograph/ CT	+′(a)
II	Radiograph: sclerotic, cystic or osteoporotic changes of femoral head	+′(a)
III	Radiograph: subchondral fracture (“crescent sign”)	+′ (a)
IV	Radiograph: flattening of femoral head	++′(b)
V	Radiograph: flattening of femoral head and osteoarthrotic changes: decreased joint space and acetabular changes	++′ (b)
VI	Complete joint destruction	–

(a) Location of femoral head necrosis: (1) medial third, (2) median third, (3) lateral third. Size of femoral head necrosis: (A) <15%, (B) 15–30%, (C)>30%

(b) Intrusion degree of femoral head contour: (A) <2 mm, (B) 2–4 mm, (C) >4 mm

20.5.4 Microsurgical Treatment of Avascular Necrosis of the Femoral Head

20.5.4.1 Treatment with Smith-Petersen Approach for Avascular Necrosis of the Femoral Head

Deep circumflex iliac artery or iliac (membranous) flap of the lateral branch of the lateral femoral vessel transplanting operation applied anatomy

1. Deep circumflex iliac artery: From the femoral artery or external iliac artery. The highest in the initial position of the inguinal ligament is 1.3 cm, and the lowest is 2.4 cm. The external diameter of the deep circumflex iliac artery was 2.8 mm. The blood vessel is on the outside of the inguinal ligament, and is on the side of the front. And then, along the front of the crista iliaca, to the iliac crest. During the trip, a number of branches (2–7) are emitted to the adjacent muscles. 4–10 branch form the crista iliaca segment in the trip, the bone from the medial and upper edge of the iliac crest to the iliac crest is a nutrient artery in the anterior iliac crest, the outer diameter of the iliac crest blood vessels was (0.5 + 0.1 mm) the deep circumflex iliac artery length (13.6 ± 1.2 mm). The deep circumflex iliac artery Anastomosis with Iliac branch of iliac artery in the backward, If need to cut the bone flap, can be separated from the vascular pedicle (Figs. 20.22 and 20.23).
2. Lateral cirumflex femoral artery

   Accounted for 95% origin from the profunda femoral artery, Only 5% directly from the femoral artery. According to the origin and the branch of the lateral cirumflex femoral artery, four types of cases can be distinguished: Type 1 (80%): the lateral cirumflex femoral artery from the profunda femoral artery, separated ascending branch、transverse branch and descending branch; Type II (5%): the femoral artery origin form the lateral cirumflex femoral artery, separated ascending branch、transverse branch and descending branch; Type III (5%): ascending branch of femoral artery, lateral cirumflex femoral artery separated transverse branch and descending branch, origin from the profunda femoral artery; Type IV (10%):the lateral cirumflex femoral artery separated ascending branch and transverse branch issued from the femoral artery, descending branch issued from the profunda femoral artery. The main length of the lateral cirumflex femoral artery was 11.9 + 2.7 mm. Starting place outside diameter 4.9 + 1.3 mm.
3. Lateral cirumflex femoral artery ascending branch

   The external diameter of the ascending branch of the lateral cirumflex femoral vessel was 3.5 + 0.9 mm, the ascending branch of the trunk is performed by the deep side of the rectus muscle, enter the door after the separation of the tensor fascia lata myocutaneous iliac crest branch, gluteal muscle branch and tensor fasciae latae branch. Iliac crest branch along the fascia lata medial to walking on, the anterior superior iliac spine is divided into 3~2 branches, and the anterior superior iliac crest is entered into the iliac crest. Ascending branch length of 8.5 + 3.0 cm, The fresh specimens of visible ink perfusion of the anterolateral iliac crest 8 cm*4 cm periosteum and bone ink dye (Figs. 20.24 and 20.25)

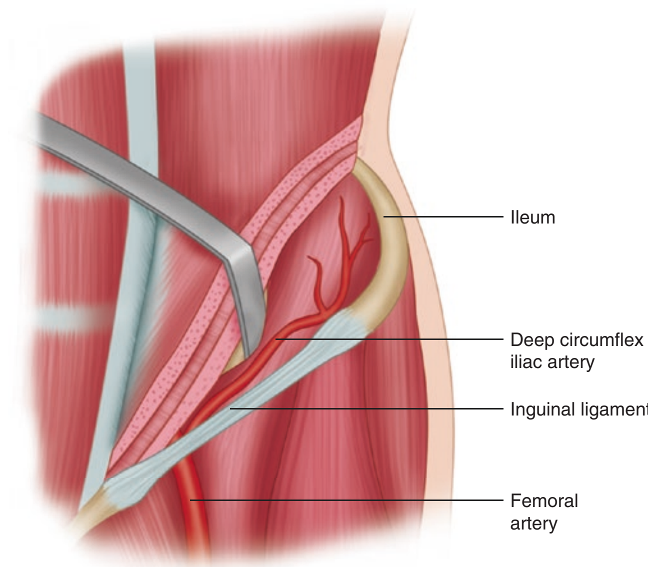


Fig. 20.22 The deep circumflex iliac artery

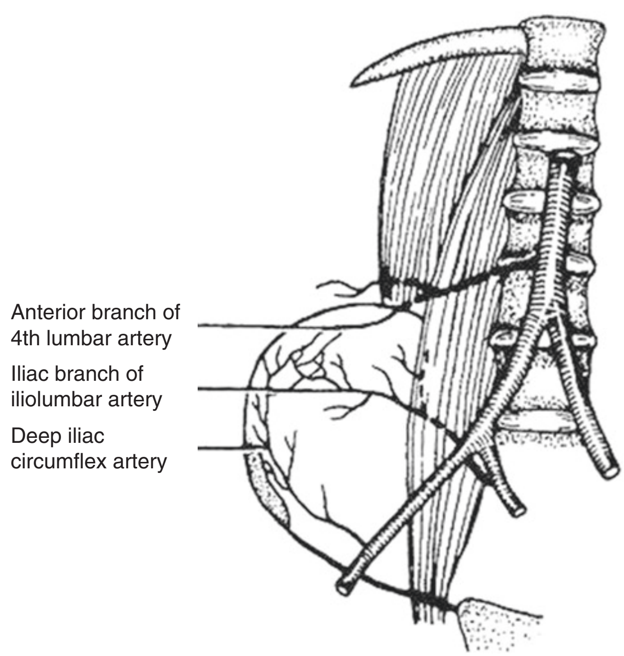


Fig. 20.23 The deep circumflex iliac artery. (1) Femoral artery. (2) The walk of the deep circumflex iliac artery. (3) Ilium

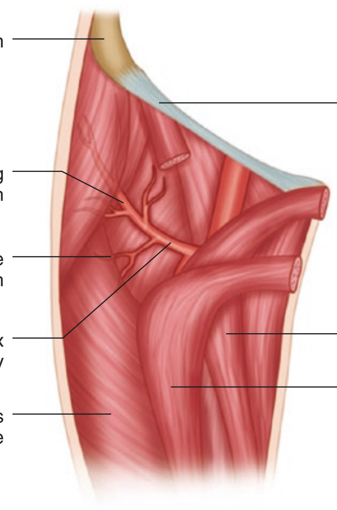


Fig.20.24 A sketch of the lateral ascending branch and the transverse branch of the rotating unit

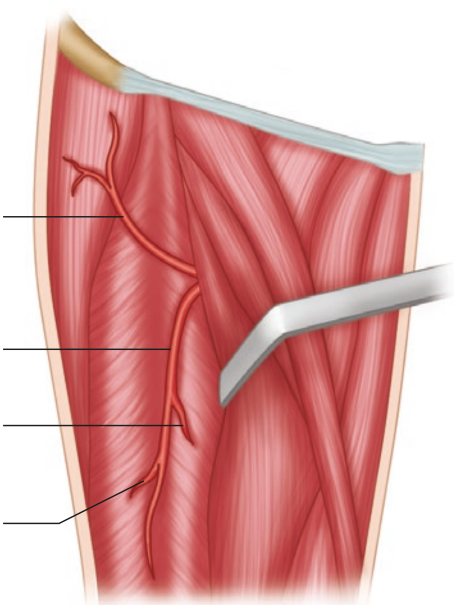


Fig. 20.25 The lateral branch of the descending branch of the lateral femoral vessels

20.5.5 Surgical Method

1. Surgical method for selecting the deep circumflex iliac artery: Along the incision to open anterior iliac crest in External oblique, musculi obliquus internus abdominis, temporarily cut off the inguinal ligament, anatomy of the cord or the ligament of the uterus, cut open transverse fascia can see the deep blood vessels, when the blood vessel is separated from the blood, the ascending branch and the muscular blood vessel are also raised, about 0.5 cm in the lateral ilium. 4 cm × 5 cm bone flap was performed in the center of blood vessel. A little bone tissue can be cut from 4 cm*5 cm periosteum, taking care the treatment of residual blood vessel after, ectropion periosteum, suture 3 needle with thread, as axis With blood vessel pedicle (vascular pedicle length 7–8 cm), take a tunnel along with the iliac muscle, fill in the window of the femoral head (Figs. 20.26 and 20.27).
2. Surgical method for the selection of the lateral cirumflex femoral artery ascending branch: Cut skin, subcutaneous tissue and fascia, Protection of the lateral cutaneous nerve, cutting off the anterior superior iliac spine and lower spine, initial of rectus femoris muscle(some of the operation method does not cut off the muscle) lateral femoral artery can be seen through the fascia. The anterior portion of the anterior superior iliac spine is cut by the cutting of the anterior portion of the suture and the rectus,

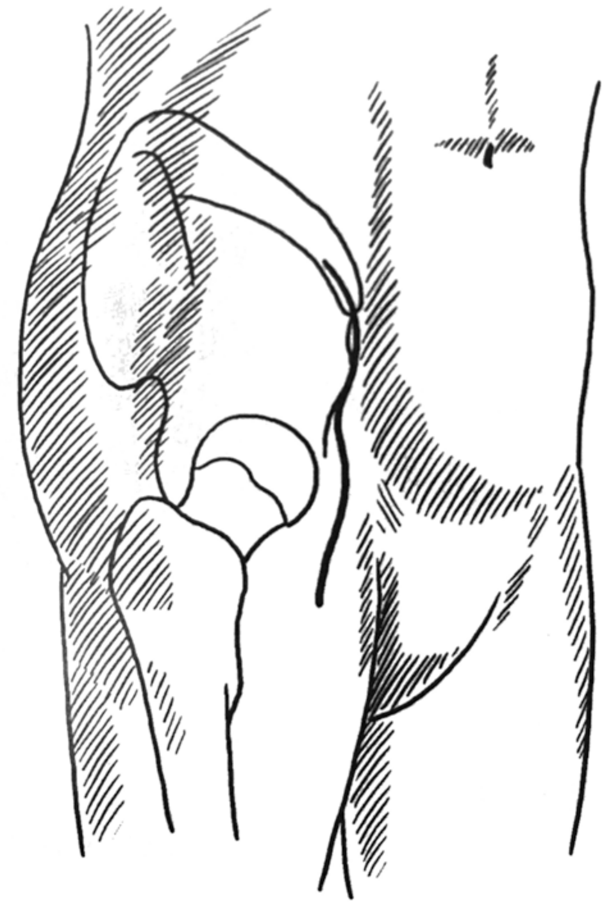


Fig. 20.26 Incision

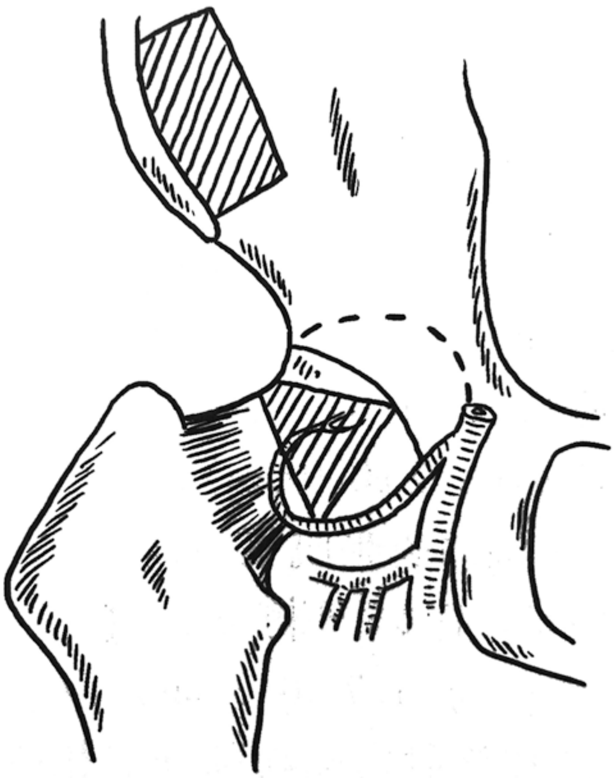


Fig. 20.27 Implanted in the head and neck window with the deep circumflex iliac artery vessel pedicle bone (membrane) flap

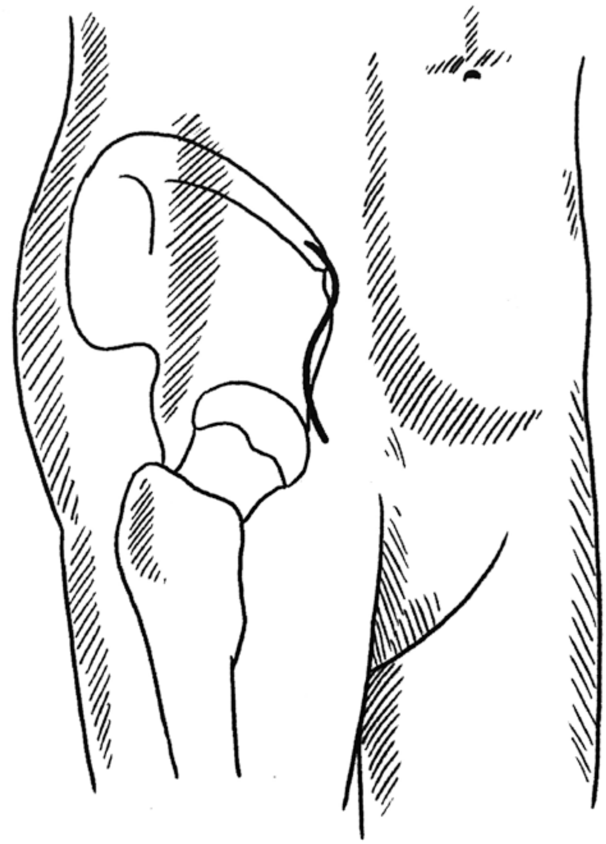


Fig. 20.28 Incision

the tensor fascia lata pulled outward, lateral femoral vessels ascending branch of the lateral femoral artery (Figs. 20.28 and 20.29), along the direction from the crista iliaca until initial of the tensor fasciae muscle(iliac crest branch is relatively thin, can be used together with the middle of the hip in the muscle). Cut the Iliac bone flap in the lateral of the anterior superior iliac spine about 3 cm*4 cm, desirable 3 cm*4 cm as if cutting the periosteum flap, to bring a little cortical bone, to avoid to injured the vascular net on the periost flap, the periosteum is turned out to be 2~1 needle into a mushroom. Transfer it to the femoral head and open the window and fill in the femoral head.

20.5.5.1 Transplantation of Greater Trochanter Bone Flap in the Transverse Branch of Lateral Femoral Circumflex Vessel

Applied Anatomy

Transverse branch of the lateral femoral circumflex vessel: the transverse branch exists at the lateral (2.3 ± 1.4 cm) from the origin of lateral circumflex femoral artery. The external diameter of vessel at the origin of transverse

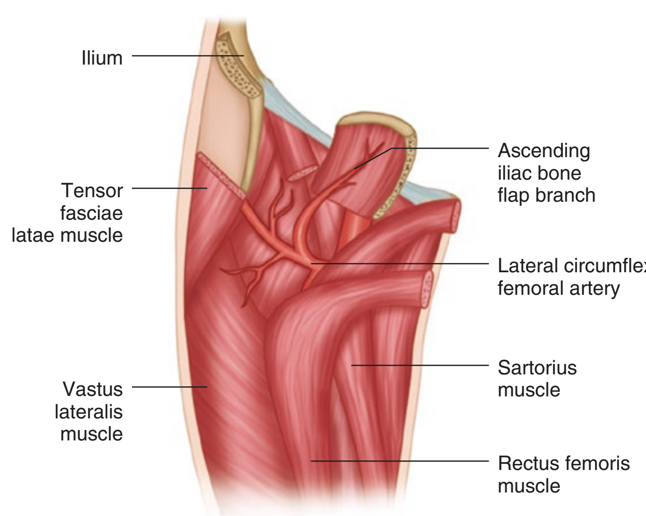


Fig 20.29 Cutting the iliac bone(membrane)flap in the lateral circumflex femoral blood vessel ascending branch

branch is 3.2 ± 0.9 mm. The artery goes outwards along the deep surface of rectus femoris, and develops the anterior branch and lateral branch of greater trochanter at the outward, downward deep surface and lateral border of the muscular porta of tensor fasciae latae. In general, there will be 2–3 branches with the external diameters of 1.7 ± 0.3 mm at the origin. The trunk of the transverse branch coincides with the medial circumflex femoral arterial branch after downward direction of greater trochanter. The transverse branch length of lateral femoral circumflex artery is 6.5 ± 1.2 cm and generally accompanied by two veins. The vascular pedicle length from the ascending branch (or descending branch) of lateral femoral circumflex artery to transverse branch is 7.8 ± 1.2 cm. It is observed after injecting ink into the vessel of the transverse branch that the range this vessel provides for the anterolateral side of greater trochanter is 3.5 cm × 2.0 cm × 4.0 cm (please refer to Figs 20.30 and 20.31).

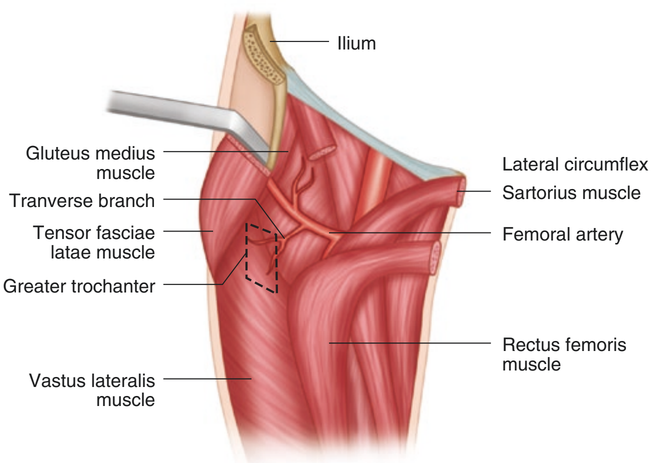


Fig. 20.30 The exposed lateral femoral circumflex vessels

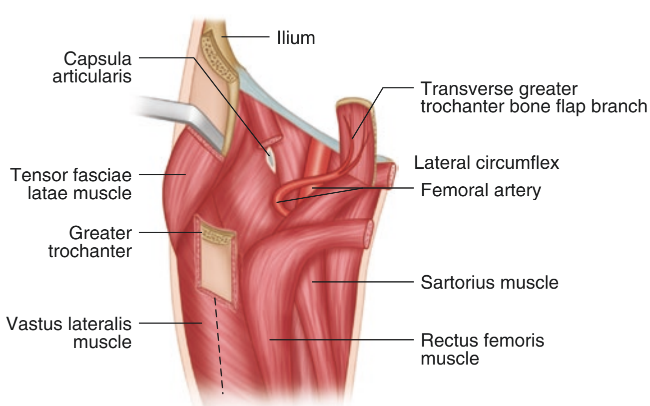


Fig. 20.31 The cut greater trochanter bone flap of lateral femoral circumflex vessels

Surgical Method

To protect the partial muscles attached to the greater trochanter branch, the lateral femoral circumflex artery is separated from fascia; the transverse branch is found at 1.5–3 cm upwards from the origin of this vessel and separated outwards from internal muscular porta of tensor fascia latae; and the muscle at 1–2 cm downwards from the origin of vastus lateralis muscle is cut to expose the vessel of the transverse branch and dissociate the vascular pedicle. Subsequently, the vascularized periosteal flap of 2 cm × 1.5 cm × 2 cm to 3 cm × 2 cm × 4 cm is cut at the anterolateral side of greater trochanter, transferred to the fenestration place of femoral head and neck and implanted in the femoral head (please refer to Figs 20.32 and 20.33).

20.5.5.2 The Periosteum Graft with the Periosteum Branch of the Descending Terminal of Lateral Circumflex Femoral Artery

Clinical Anatomy

1. The origin and diameter of the periosteum branch of the descending terminal artery of lateral circumflex femoral artery: The descending branch is one vessel which belongs to lateral circumflex femoral artery. The periosteum branch originates from the descending vessel distancing the origin point of descending vessel 4.0 ± 1.1 cm. The diameter is

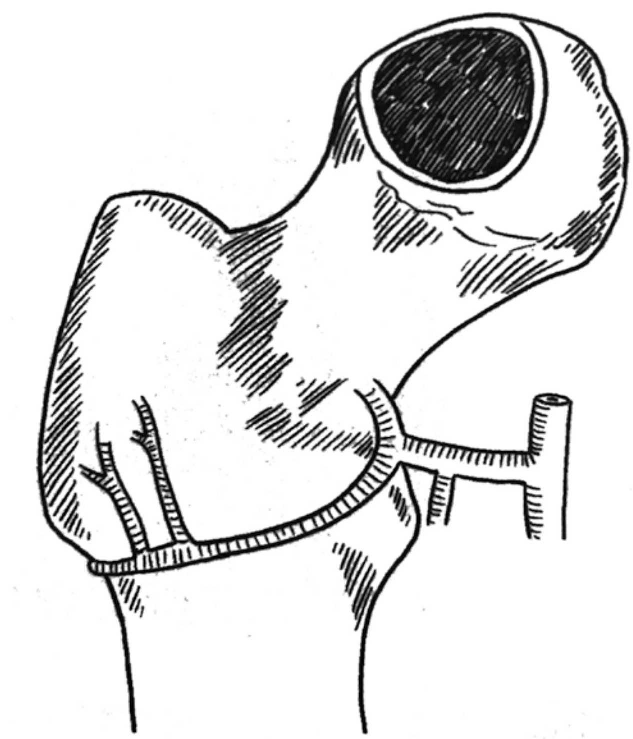


Fig. 20.32 1/3 upward femoral head of is necrotic

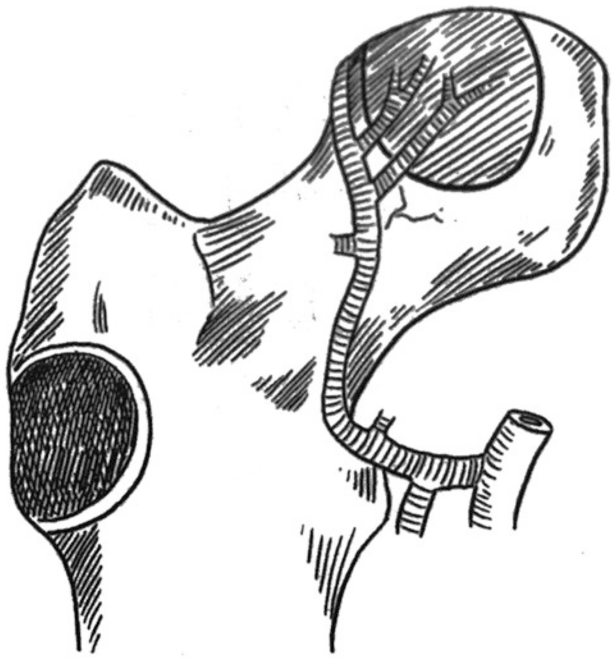


Fig. 20.33 The necrotic zone is cut and the vascular pedicled greater trochanter bone flap is transplanted

1.2 ± 0.5 mm, the length is about 7.1 ± 1.8 cm. The periosteum branch descends deep between vastus medialis muscle and vastus intermedius or passes vastus intermedius to anteromedia periosteum in middle-upper part femur.

2. The distribution of the periosteum branch of the descending terminal artery of lateral circumflex femoral artery: The descending branch of lateral circumflex femoral artery descents deep to the medial side of vastus lateralis muscle below rectus femoris. The length of this part is 12.6 ± 2.4 cm. The vessel descends deep to the rectus femoris, penetrates the vastus lateralis muscle and connects with the superior and inferior lateral genicular arteries near the knee. The total length from the descending branch to the periosteum branch is measured 11.1 ± 2.9 cm. The staining area of periosteum branch was measured 5 cm × 9 cm via perfused ink (Fig. 20.34).

Surgery Technique

Make downward extend skin incision, dissect the descending branch of lateral circumflex femoral artery, separate the arteries towards out-down. Find the periosteum branch from 3 to 6 cm place away the origin point (Fig. 20.35). After separate the periosteum branch, ligate the descending branch of lateral circumflex femoral artery, and harvest the graft with the periosteum branch vessel of the descending terminal artery of lateral circumflex femoral artery. Transfer the graft to the bone window at the femoral head-neck junction (Fig. 20.36).

Fig. 20.34 The distribution of the periosteum branch of the descending terminal artery of lateral circumflex femoral artery

20.5.5.3 Indications of Selection for Different Techniques of the Anterior Approach to the Hip

1. When the surface of articular cartilage still smooth in ONFH, or with buckling without broken, the best treatment for ONFH is the iliac graft with the ascending branch of the lateral femoral circumflex artery transplantation. Because the station of ascending branch of the lateral femoral circumflex artery is shallower, harvest it easier. If the patient has been undergone by the iliac graft with the ascending branch, the greater trochanter grafting with transverse branch, the iliac graft with the deep circumflex iliac vessel or the graft with the periosteum branch vessel of the descending terminal artery of lateral circumflex femoral artery should be chosen too.
2. When one third or one second area of superior part of femoral head is necrosis bone with the surface of articular cartilage buckling or broken, the necrosis bone need to be removed totally. Vascularized greater trochanter graft

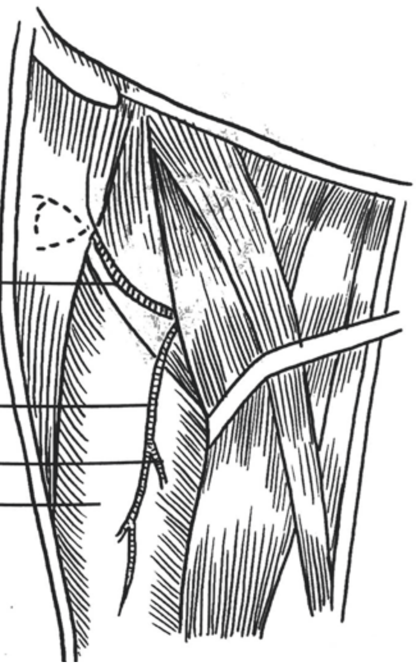


Fig. 20.35 Exposing the periosteum branch of descending branch of lateral circumflex femoral artery

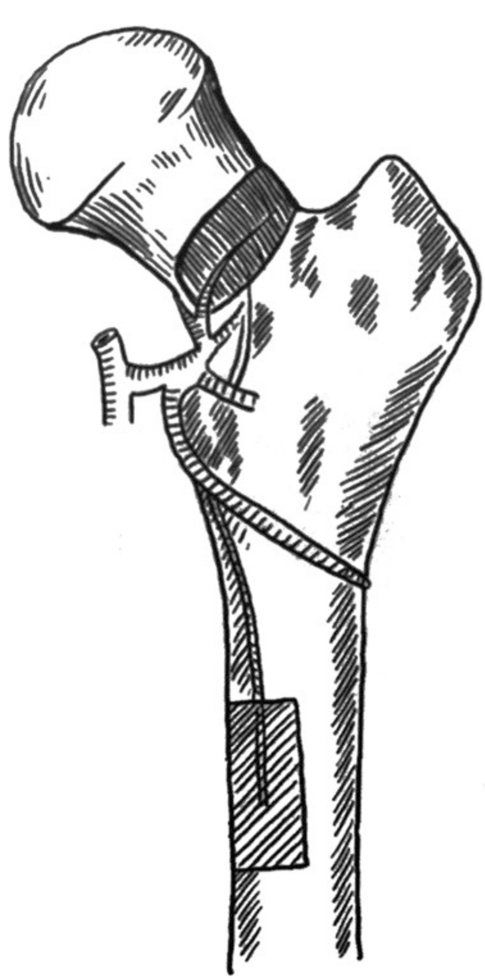


Fig. 20.36 Implantation the graft with periosteum branch vessel of the descending terminal artery of lateral circumflex femoral artery

perfused by branches of the LFCVs as an alternative method for osteonecrosis should be chosen. This technique should restore the normal biomechanical relationship between femoral head and acetabula. There is a trendency for cartilage metaplasia via the friction effect making dense connective tissue becoming cartilage.

3. If the range of necrosis develops all of the femoral head, it isn't enough to treat ONFH by simply using the greater trochanter grafting with transverse branch. It should be preferred combined use of the iliac graft with the ascending branch of the lateral femoral circumflex artery. Because of one stem with two vessels, to harvest graft easier and damage less.
4. If femoral head or part of femoral neck defect, the treatment of combining with the iliac graft with the ascending branch of LFCVs, the greater trochanter grafting with transverse branch of LFCVs, the iliac graft with the deep circumflex iliac vessel and the graft with the periosteum branch vessel of the descending terminal artery of LFCVs should be an alternative method.

20.5.5.4 Treatment of Avascular Necrosis of the Femoral Head in the Lateral Hip Approach

Dewei Zhao treatment of avascular necrosis of the femoral head using the lateral approach of the hip, the lateral approach of hip joint operation, enter from the tensor fascia and the gluteus medius muscle gap, this approach does not need to damage the muscle and soft tissue of the hip joint, in the postoperative hip joint, the adhesion of the hip joint and the muscle strength of the knee joint caused by the reduction of the incidence of the flexion of the hip joint. To avoid the pull of the femoral vein in the anterior approach, reduction of postoperative deep venous thrombosis. This operation approach for front fascia lata, in the muscle, the ascending branch of the lateral branch of the lateral femoral vessel, upward separation can be cut to take up the ilium spine ilium crest (membrane) flap. Dissect the transverse branch of lateral femoral circumflex artery in the outer edge of the tensor fascia lata, can be cut to take the greater trochanteric bone flap. Lateral femoral circumflex artery ascending branch of middle gluteal muscle branch through deep fascia lata, At the trailing edge into gluteus medius muscle and then divided into two branches, there is a branch down to walk, stop at

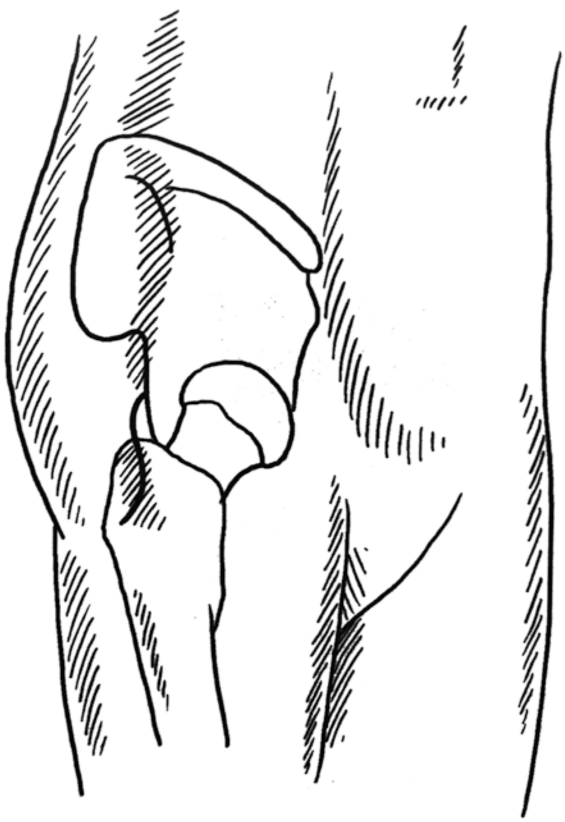


Fig. 20.37 Lateral hip approach, surface incision location

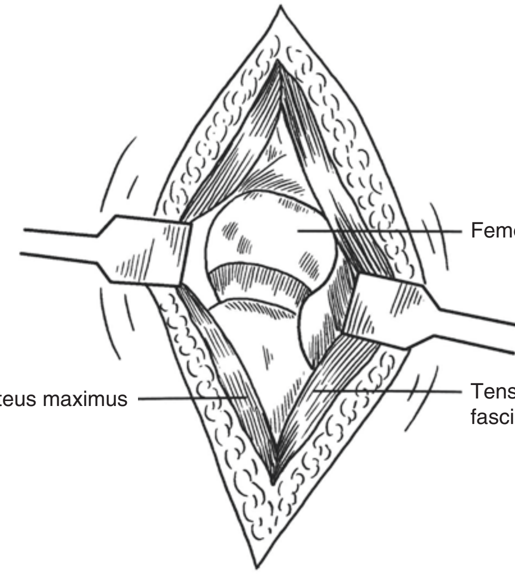


Fig. 20.38 Lateral hip approach, exposure of femoral head after dissection

the top of the greater trochanteric bone flap and the outside. Can be used to dissect and separation of the operation, cut off from the large bone flap of the large bone flap in the ascending branch of the lateral femoral vessel (Figs. 20.37, 20.38, and 20.39)

20.5.5.5 Transfer of Ilium (Membrane) Flap with the Ascending Branch of the Lateral Femoral Circumflex Artery

Surgical Technique

A double "S"-curved, 12-cm-long incision was generated along the line connecting the anterosuperior ilium spine and the posterior patella, and the proximal end of the incision traveled along the ilium crest 5 cm beyond the anterosuperior ilium spine (Fig. 20.40). Incision skin and subcutaneous tissue, In the gluteus medius, tensor fascia lata gap separation.

The interval between the mesoglutaeus and tensor fasciae lata muscle was located and split in the direction of the skin incision. Cut off part of the muscle in the posterior fascia lata, the musculus tensor fasciae latae was stretched outward to expose the ascending branch of the circumflexa femoris lateralis. Separation was performed toward the ilium crest to the starting point of the musculus tensor fasciae latae; the thinner

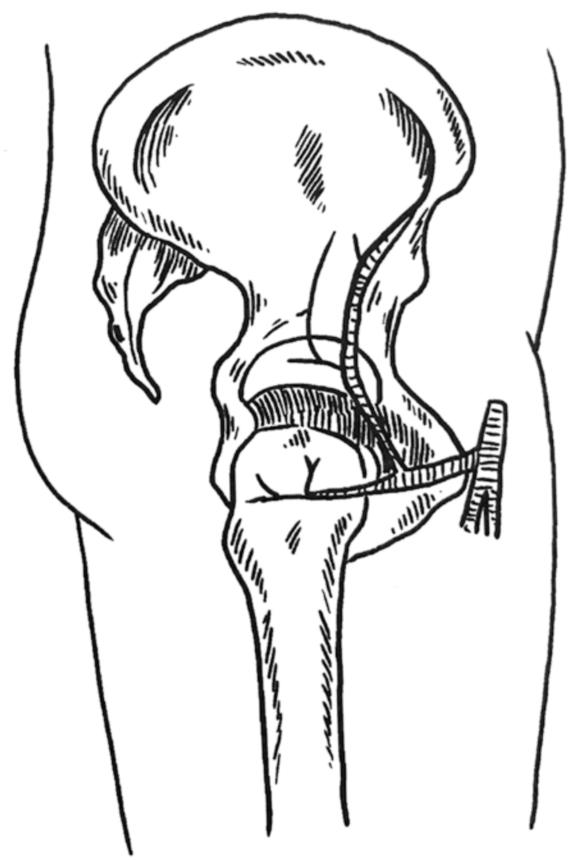


Fig. 20.39 Lateral hip approach, ascending branch of extrafemoral circumflex artery

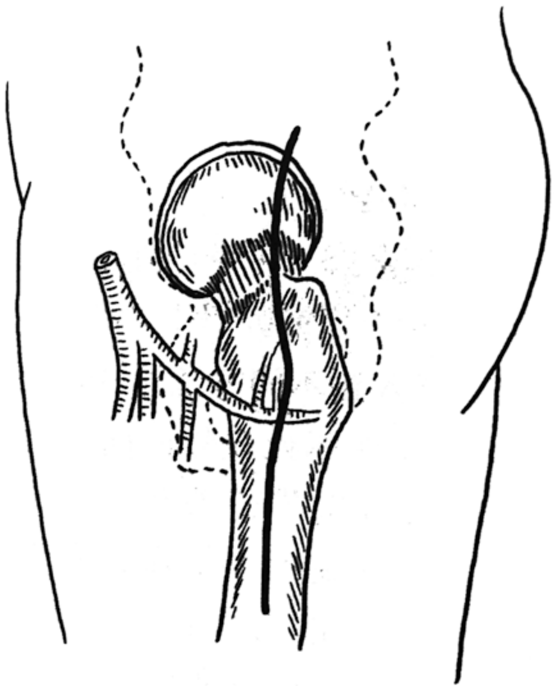


Fig. 20.40 Incision

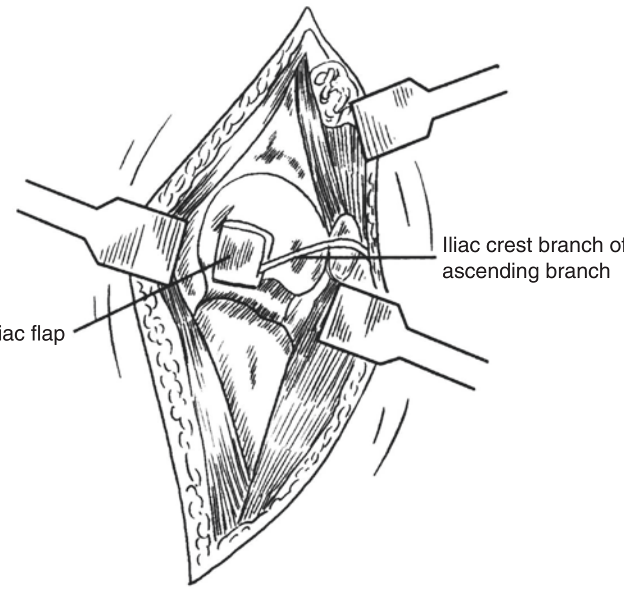


Fig. 20.41 Will be raised to the iliac bone flap in the head and neck window

branch of the ilium crest was brought together by a branch of gluteal muscle. An ilium graft was then taken from the lateral anterosuperior ilium spine, which was approximately 3 cm long and 4 cm wide, the pedicled bone block was saved in saline-wrapped gauze for later use. The hip joint was approached in the interval between the sartorius and the tensor fasciae lata superficially and between the gluteus medius and the rectus femoris underneath. The capsule was incised in a "+" shape to expose the femoral head and neck. Excision of synovial tissue inflammatory hyperplasia, osteophyma excision of the femoral head, femoral head rounded. A bone window approximately 2 cm × 2 cm was made at the femoral head-neck junction using anosteotome. A high-speed abrasive drill was used to remove the dead bone and curette a cavity in the femoral head until bleeding could be seen. The cancellous bone chips harvested from the ilium crest were placed in the excavated region of the femoral head and impacted to elevate the collapsed segment of the femoral head. The vascularized ilium bone graft was then inserted and impacted obliquely into this area (Fig. 20.41), without fixation, close the upper end of the joint capsule, and close the wound by layer.

20.5.5.6 The Liters of Lateral Femoral Circumflex Vessels with Gluteus Medius in the Greater Trochanter Bone Flap Transfer Operation

Applied Anatomy

The initial diameter in liters of lateral femoral circumflex vessels were 3.5 ± 0.9 mm, the trunk of liters run to the outside among the deep of rectus femoris. Then divided into iliac crest branch, gluteus medius branch and tensor fasciae latae branch behind the tensor fasciae latae (Fig. 20.42 and 20.43).

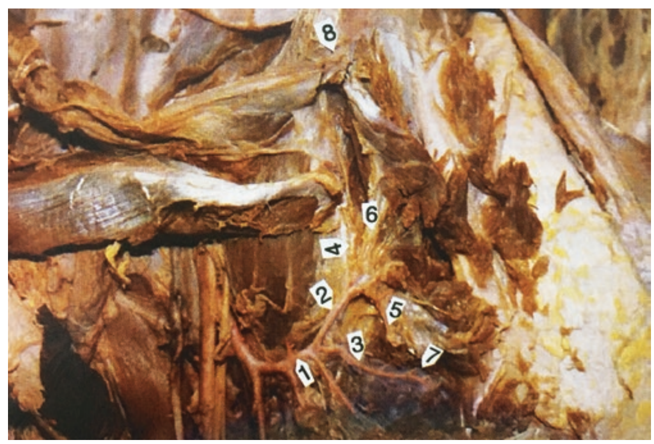


Fig. 20.42 Lining of the liters of lateral femoral circumflex vessels with gluteus medius. 1: lateral femoral circumflex vessels; 2, 6, 8: ascending branch of lateral femoral circumflex vessels; 3, 4, 5, 7: other branches of vessels

Surgical Method

Take hip lateral incisions, which come from spina illaca anterior superior 2 cm. Extend to the tip of greater trochanter, into a pair of "S" shape incision, about 12 cm (Fig 20.44). Cut open the skin and subcutaneous fascia, separating tensor fasciae latae and gluteus medius, and then cut off tensor fasciae latae trailing edge from the iliac crest, finding the liters of lateral femoral circumflex vessels, separating retrogradely to ensure the length of vascular pedicle until the inside tensor fasciae latae. Ligation the iliac crest branch, expose the gluteus medius branch, then extended distal down along the anterior boundary

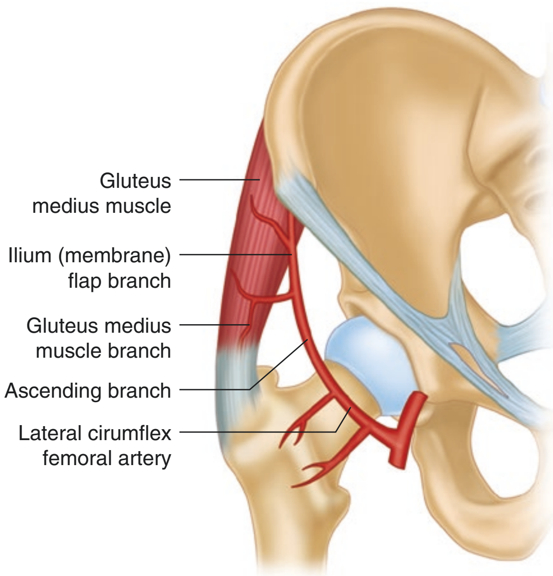


Fig. 20.43 Schematic diagram about lining of the liters of lateral femoral circumflex vessels with gluteus medius

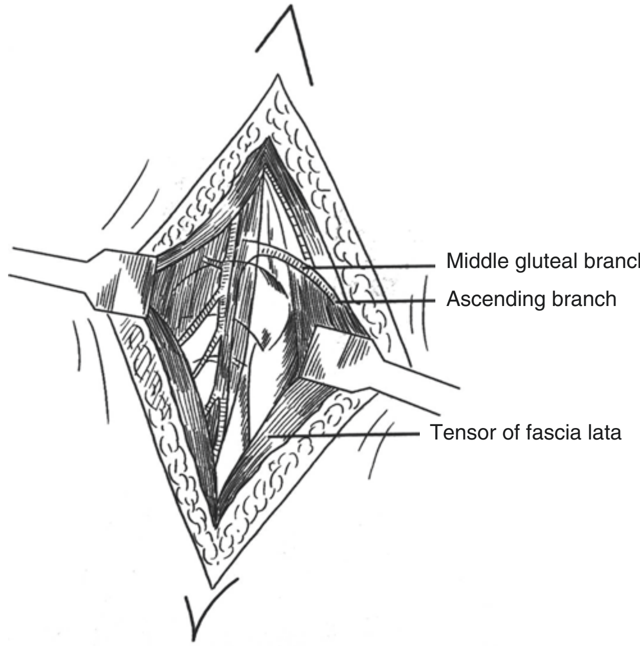


Fig. 20.45 Exposing the liters of lateral femoral circumflex vessels with gluteus medius

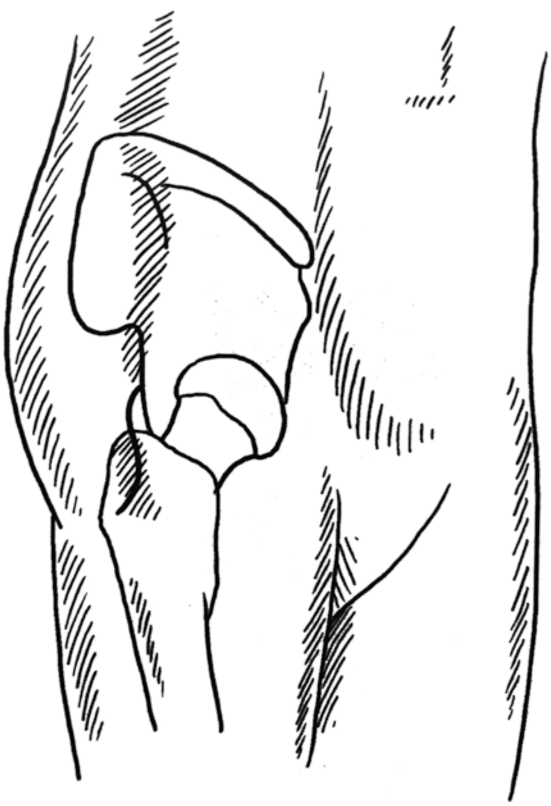


Fig. 20.44 Incision

of the trochanter. Muscle sleeve were protected among exposing the gluteus medius branch. Take great trochanter bone flap about 1.5 × 2.5 × 1.5 cm, The joint capsule was exposed by splitting the rectus femoris. A bone window of approximately 2 cm × 2 cm at the femoral head-neck junction was created by an osteotome. The necrotic bone was removed using grinding drill until cartilage was observed. The excavated area was filled by impacting the bone chips. Optimal force ramming to hold up the femoral head. Filling the vascularized bone graft into bone window at the femoral head-neck junction without fixed. Stitching tensor fasciae latae and joint capsule, close the incision steply (Fig. 20.45 and 20.46).

20.5.5.7 The Transfer Operation of Lateral Femoral Circumflex Vessels with Cross the Greater Trochanter Bone Flap

Surgical method. For the center with the greater trochanter "S" shape incision, proximal arc around the greater trochanter leading edge, incision both ends up and down to a total of about 12.0 cm. Skin incision, and the deep fascia, subcutaneous tissue in the outer level of the greater trochanter tensor fasciae latae and the vastus lateralis muscle forward under the separation between the starting point in the vastus lateralis muscle 1–2 cm incision under the muscle, free from cross vascular and proximally separation prolong vascular pedicle (Fig. 20.47), in order to protect the greater trochanter branch can take part of the muscle. In the greater trochanter anterolateral, cut with vascular pedicle periosteal flap of 2.0 cm × 3.0 cm, and taking part in the greater trochanter bone flap the chisel from cancellous skeletal body. Set aside. In the anterolateral femoral neck bone Windows open 2.0 cm × 2.0 cm, the necrotic bone drill clearance lesion at high speed and granulation tissue, cartilage, until the cancellous fill in skeletal bones, optimum compaction. Transfer the

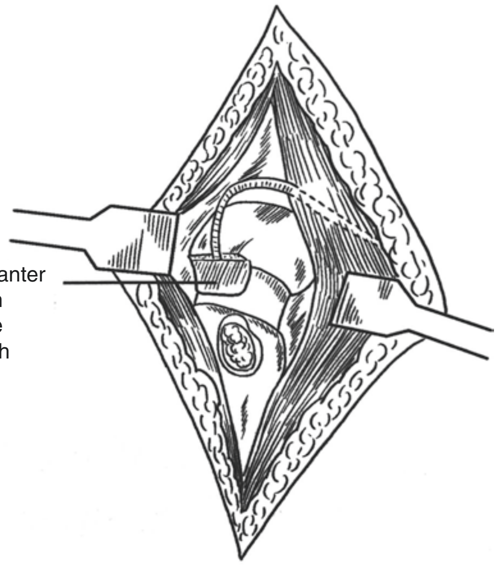


Fig. 20.46 Schematic diagram about filling the vascularized bone graft in to bone window

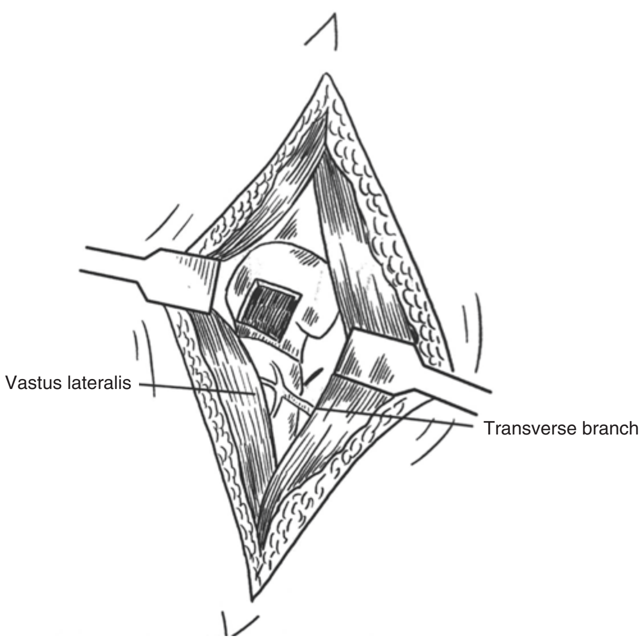


Fig. 20.47 Incision

greater trochanter bone flap with vessel pedicle in the head and neck into that open a window, the flushing incision, layered suture (Fig. 20.48).

20.5.5.8 Treatment with Posterior Approach for Avascular Necrosis of the Femoral Head

The greater trochanter bone flap transposition with deep branch of medial femoral circumflex artery (CHEN Zhen-guang)

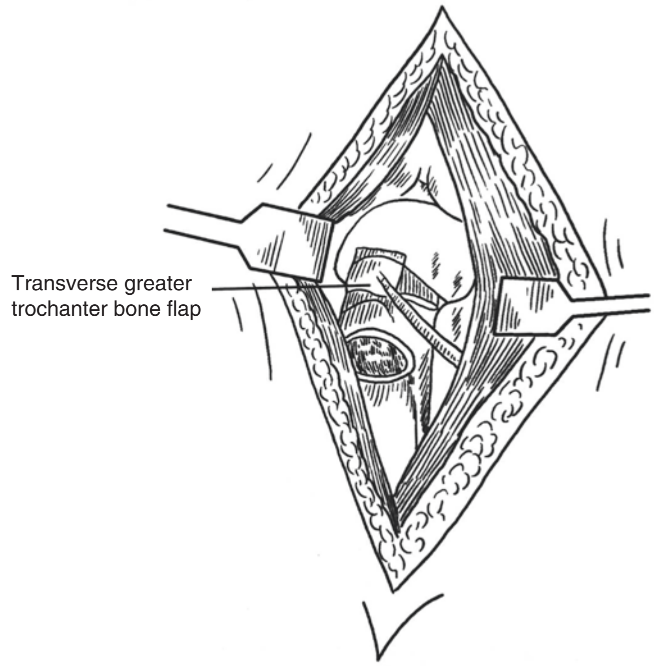


Fig. 20.48 Separate vascular pedicle, graft the bone flap

Applied Anatomy

Deep branch of medial femoral artery via between short adductor muscle and obturator muscle to the behind of the hip, followed by the shares between obturator muscle and quadratus femoris on the back of the line out through the base of the neck of femur, the end steal on the gemellus and the dark side of the obturator within the tendon, along the branch supply adjacent muscles, femoral neck and trochanter behind rear. The mean outer diameter of deep branch of medial femoral artery root is 1.7 mm. Fat average outer diameter of the rotor supporting the front 1.2 mm. The length from the root to the starting-point of the greater trochanter branch is about 4.0 cm, follow the direction of the intertrochanteric ridge. Two accompanying veins stand by deep branch of the medial femoral artery, the average outer diameter is 2.3 and 2.4 mm.

The trochanter originated from the deep femoral artery branch account for 65%, the average outer diameter is 0.7 mm. The starting-point locates below the upper of the quadratus femoris about 6.2 mm, the average distance to the intertrochanteric crest is about 7.9 mm. It extends through between the quadratus femoris and inferior gemellus mostly, cross the intertrochanteric crest, located in the rear of the greater trochanter as a sector. The inferior gluteal artery through via the front of the ischiadic nerve, then steal on the connective tissue between the quadratus femoris and inferior gemellus, where about 30% of the medial femoral neck to the base of the femoral artery into the deep branch artery loop. The great support is send from the arterial loop, and its

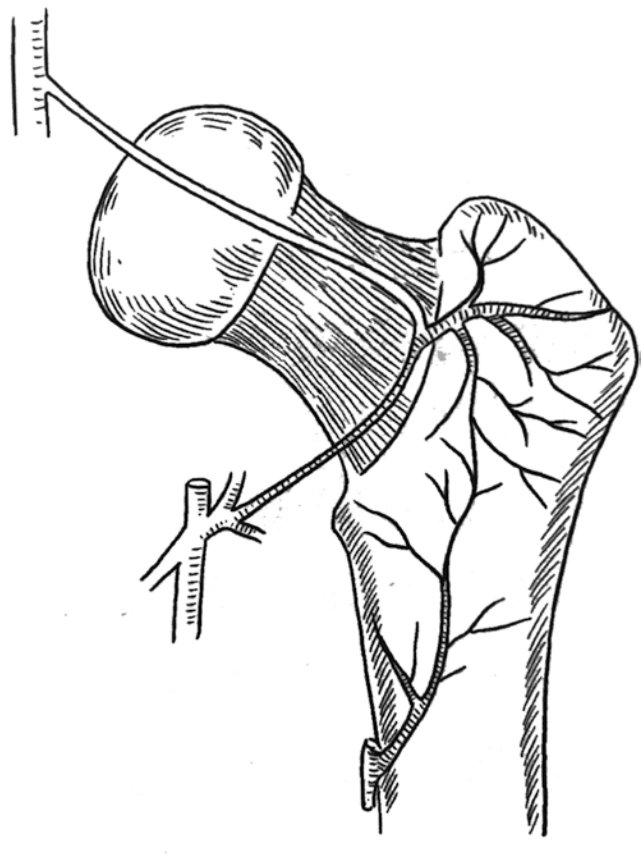


Fig. 20.49 Deep branch of medial femoral vascular anastomosis with inferior gluteal vascular

external diameter、walk line position and distribution area is similar to the greater trochanter which send out the deep branch of medial femoral artery. Another 5% of the greater trochanter is extended by the anastomosis branch of inferior gluteal artery directly (Fig. 20.49).

Surgical Method

The cut starts from the outside and below of the spina iliaca posterior superior, about 3 cm, cross the direction of the gluteus maximus fiber to the front of the top of the greater trochanter, then extends down to about 5 cm. Cut the skin, subcutaneous tissue and fascia cavity, dissect the gluteus maximus fiber bluntly, dissect the gluteus maximus vertical from the starting point of the tractus iliotibialis, and cut off part of the gluteus maximus arrived only in the femur. Pull open the gluteus maximus to both sides, see clearly the ischiadic nerve and the ramus anastomoticus of inferior gluteal artery which cross the face of it to avoid damage it. Pronation limb, reveal the femoral neck and trochanter rear organization fully, then we can see clearly the greater trochanter branch locates after the greater trochanter, which like bird claws, cut open the quadratus femoris from its starting point of greater trochanter, follow the deep branch of medial femoral artery to the direction cross the intertrochanteric crest. At the same time, we should make it clear that if there is inferior gluteal artery ramus anastomoticus between quadratus femoris and inferior gemellus that could make up artery loop with deep branch of medial femoral artery. If it exists, we choose the one who compose the main artery as the blood pedicle, or remains both. Protect the inferior gluteal artery ramus anastomoticus clearly when cut off the quadratus femoris inferior gemellus and the gemellus. Take a long strip of bone chisel, according to requirements, intertrochanteric crest as the inner side, up to the cusp of the greater trochanter, down to the edge of the small rotor, the length usually about 4–5 cm, width 2 cm, and thickness 1.5 cm. The length of bone flap is about 2 cm, but we could enlarge the range of periosteum as a bone-periosteal flap. We should be remove the hyperplastic synovial membraner tissue of necrosis of necrosis femoral head first, or repair the osteophyte. Then make a groove along vertical axis of the neck of femur, dig up the sequestrum and the granulation tissue of cystic degeneration. To the collapse articular surface, renew its restoration with a especial round head impacter. Implant the bone flap after filling caput femoris residual cavity with cancellous bone from greater trochanter. Bone head should be in-depth 1.5–2.0 cm. It is usually stable because the groove is deep, If it is necessary, we could reinforce its stability by implanting microxea with cortex from greater trochanter in the gap between the bone flap and bone groove.

20.5.5.9 Transplantation of Greater Trochanter Bone Flap with the Inferior Gluteal Vascular Anastomosis

Applied Anatomy

Gluteal artery anastomosis issue point is the lower edge of the piriformis, cross outward through the surface or deep face lines of the sciatic nerve, sneak in the connective tissues which between the quadratus femoris and musculus gemellus inferior to the base of the femoral neck, the possibility of anastomosis of its trunk and deep femoral artery branch is 78%, however, the end of the fraction of small branch anastomose the deep branch of the deep branch or reticular anastomosis is 22%, consistent with every hair in front constitute a small branch from trunk segment direct distribution at the top rear of the greater trochanter.

Surgical Methods

The former incision was choosed that in order to cut the skin, subcutaneous tissue, blunt dissection of the gluteus maximus fibers, longitudinal incision in the gluteus maximus attachment of the iliotibial band, gluteus maximus to both sides of the retractor to expose the sciatic nerve and cross the surface of the inferior gluteal artery anastomosis, free from foreign anastomosis down roots, separate stocks side muscle and muscle under the margin gap to close between the rotor crest, TDC shares square cut muscle, revealing the deep medial femoral artery Supporting its large rotor support, to protect the integrity of the anastomosis with the deep branch of the anastomosis, ligation anastomosis medial femoral artery proximal end and a distal branch of the deep branch of the trunk. Cut off part of the vastus lateralis muscle at the start, to the bottom, and a large branch to the vertical axis of the rotor, the rotor after the large, external cut an oval bone, fascia retains its fibrous tissue surface. Inverted T-shaped incision joint capsule, prolapse of the femoral head, removal of diseased bone tissue, or bone lesions first part chiseled lines emerge after cleaning. Trim flap, shift in the femoral stump to two 2 mm Kirschner wire through the bone fixation, pintail remain to be pulling the skin. After that, chiseled acetabular rim osteophytes, within mortar should also be trimmed by injustice. Inclusion of the femoral head, joint activities have been tested well, sewn part of the joint capsule.

20.5.5.10 With Muscle Pedicle Bone Flap Transfer Operation

1. The tensor fascia lata pedicled iliac bone flap transfer operation
   (a) Applied anatomy

   Tensor fascia lata in hip and thigh, living in sewing sartorius and the gluteus medius muscle, fascia originated from the anterior superior iliac spine and the iliac crest lateral lip of the front, full muscle package between the two layers of the fascia lata, thick thin, and gradually move to the iliotibial band, iliotibial tract down dead on the lateral condyle of the tibia and the muscle length 16.1 cm. Ascending branch of lateral femoral circumflex artery is the tensor fascia lata mainly nutrient vessels, the rise of the main branch of the rectus femoris muscle deep surface outward, and to the tensor fascia lata muscle and separate the iliac crest branch, gluteus medius muscle branch and tensor fascia lata branch. The iliac crest branch along the inside of the line, the iliac spine on the front of the 3~2, the length of the 8.5 + 3.0 cm (Fig. 20.50).

   (b) Surgical method

   Smith-Peterson incision of the hip in the front of the hip. Incision of skin and subcutaneous tissue, the incision of the tensor fascia lata front and lateral femoral cutaneous nerve protection and separation of the tensor fascia lata, rectus femoris gap, exposing the rectus femoris the deep surface of the lateral femoral circumflex artery, separation to the tensor fascia lata muscle door, pay attention to must not be damaged. In the anterior superior iliac spine cut to the iliac bone plate bone flap cm × 2.0 × 1.5 cm. The bone flap distally open, free muscle pedicle, about 6.0CM, vascular ligation of section of muscle, saline gauze wrapped spare and surgical procedures of sartorius pedicled iliac bone flap with (Fig. 20.51)

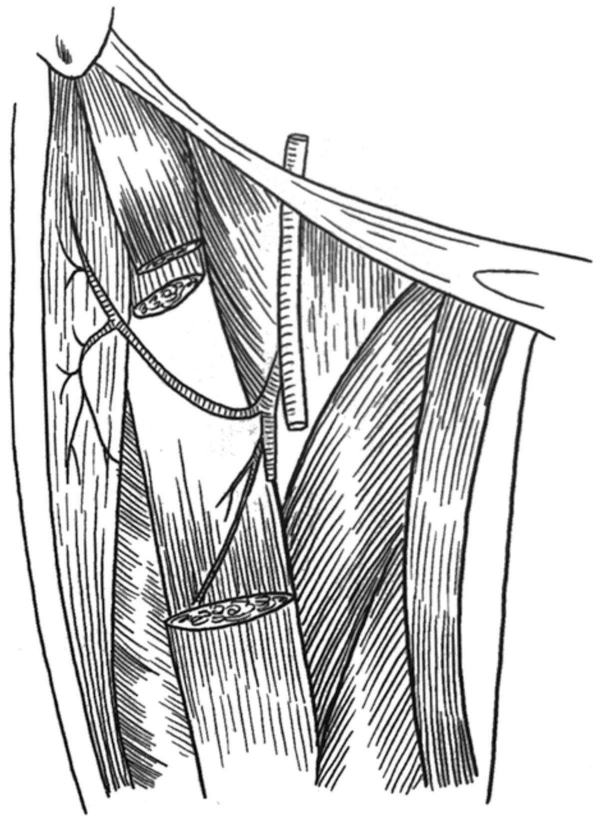


Fig 20.50 Vascular distribution of tensor fasicia lata

2. Transplantation of muscle pedicle greater trochanter flap at quadratus femoris
   (a) Applied anatomy

   Quadratus femoris starts from the lateral surface of ischial tuberosity, and its muscle bundle obliquely goes backwards. The part that the small muscle bundle winds the inferior border of ischium to the external border of ischium is called horizontal part. Later, it extends upwards to intertrochanteric crest and the bone surface of the external side, which is called the ascending part. The inferior border of quadratus femoris insertion is at the superior border of lesser trochanter. The quadratus femoris insertion parts take up 99% of muscles. Most upper parts are muscles while the lower 1/3 is tendon which occupies only 1%. The blood supply of quadratus femoris is mainly from the branches of inferior gluteal artery, deep branch of medial circumflex femoral artery and the first ascending branch of deep femoral artery. It has anastomotic branch in vessels of quadratus femoris insertion. The quadratus femoris is mainly supplied by muscular

Fig 20.51 The tensor fascia lata pedicled iliac bone flap transfer operation

artery distribution separated by multiple vessels. They can form fine anastomosis at the muscular surface and sarcoplasm and be distributed to vessels of greater trochanter zones and muscles. The quadratus femoris terminates at greater trochanter with muscles. The vessels of fascia at greater trochanter are from above vessels and extensively coincide with the vessels of periosteum at greater trochanter. Therefore, by cutting greater trochanter flap of quadratus femoris including the blood supply range of greater trochanter, flap with muscle pedicle and vascular pedicle can be formed with rich blood supply (please refer to Fig. 20.52).

(b) Surgical method

The posterolateral incision of hip joint starts from 5 to 6 cm outwards of spina iliaca posterior superior, tilts to the top anterior border of greater trochanter, goes further along the femoral shaft and terminates at 8–10 cm of tuberosity. Cut the skin and subcutaneous tissues, and separate them by making them go along the muscle fibers at the superior border of gluteus maximus. Subsequently, cut the posterior border of tensor fascia latae to expose the gluteus maximus insertion, cut partial gluteus maximus insertion, and lead gluteus maximus inwards. In this way, the external rotary muscle group of hip joint can be exposed. It is important to pay attention to protecting ischiadic nerves and internal rotary hip joints, cutting the intertrochanteric points of the piriformis, external obturator bone muscle and the superior and inferior gemellus and separating and exposing the back part of joint. Separate the loose connective tissues surrounding the

Fig. 20.52 Vascular distribution of quadratus femoris

quadratus femoris; cut a rectangle flap of 3.0 cm × 2.5 cm × 1.5 cm with osteotome at the border of femoral head; turn over proximad; and bind with saline solution and gauze. Open the hip joint capsule in “T” shape or “十” shape; cut the hyperplastic synovial membrane; dislocate the hip joint and cut the hyperplastic osteophytes at femoral head margins. Fenestration is operated at head and neck junction to eliminate the necrosis bones and granulation tissues in femoral head, implant iliac cancellous bone consolidatedly, implant muscle pedicle greater trochantejoint capsuler bone flap of quadratus femoris at the cancellous bone of fenestration, sews joint capsule and cut off the lateral border of muscles (Fig. 20.53).

20.5.5.11 Free Vascularized Fibula Grafting for the Treatment of Osteonecrosis of the Femoral Head

The Applied Anatomy of Fibula

The fibula is one of the two tubular bones in the calf. The fibula does not carry any significant load (weight) of the body. Its upper extremity is called caput fibula, placed below the level of the knee joint, and excluded from the formation of this joint. It’s lower extremity projects below the tibia, and forms the lateral part of the ankle joint called lateral malleolus.

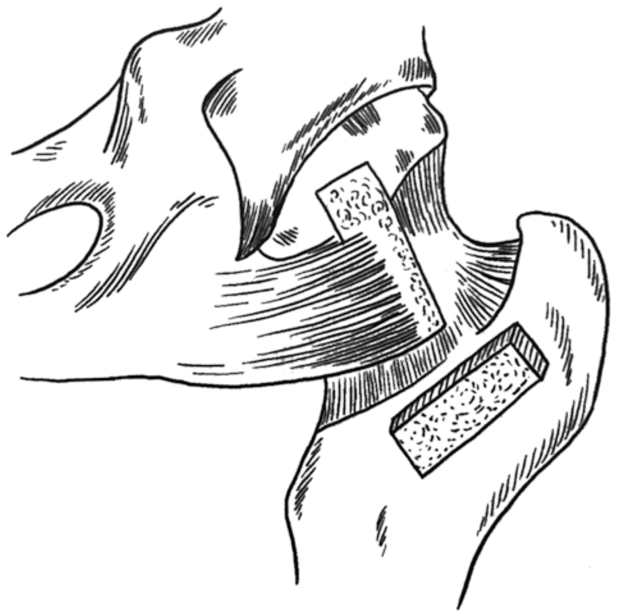


Fig. 20.53 Transplantation of muscle pedicle greater trochanter flap at quadratus femoris

There are four edges and four surfaces on the bone, which provides attachment points for the muscles. Extensor digitorum longus and fibularis tertius origin from anterior side of fibula. Soleus muscle and flexor hallucis longus muscle attach to the posterior side of fibula. Tibialis posterior muscle attach to the medial side of fibula. Fibularis longus and fibularis brevis origin from lateral side of fibula. Distal 1/4 of fibular is essential to the stability and function of ankle joint, so that this distal quarter must keep in place and not be transplanted during longer fibula transplantation. If fibula transplantation involved fibula capitulum, the tendon of biceps femoris muscle and lateral collateral ligament should be fixed to the outside of the tibial condyle or nearby dense connective tissue during the operation. Common peroneal nerve inclines along the lateral border of popliteal fossa and goes distally and laterally into the muscle gap between gastrocnemius muscle and the biceps femoris muscle. It is located in the subcutaneous layer just behind the fibula capitulum, and then winding forward along the fibula neck going into a narrow bone gap between the origin point of the peroneal muscle and fibula.

The blood supply of fibular comes from three sources: epiphyseal blood vessels, nourish blood vessels and periosteal vessels. The proximal head and the epiphysis are supplied by a branch of the anterior tibial artery. One or two branches are origin from the initial 2–3 cm of the pretibial artery supporting the nutrition of fibula capitulum. According to this anatomical features, proximal fibula capitulum pedicled with anterior tibial vessels was clinical used. The shaft is supplied in its middle third by a large nutrient vessel and segmental muscle periosteal vessels. The former supply medial half or two thirds of the cortex, the latter for the rest of the bone cortex, but both are the branches of the fibular artery, therefore fibular artery is a major source of blood supply.

In anatomy, the fibular artery (also known as the peroneal artery) is the biggest branch of the posterior tibial artery. The fibular artery arises from the posterior tibial about 2.5 cm to the initial, just 2–3 cm below the popliteus. The fibular artery is accompanied by two small veins (venae comitantes) known as fibular veins with a mean diameter of 4.5 mm. The mean diameter of peroneal artery at the initial point is 3.7 mm. They goes distally and laterally, across the upper back of tibialis posterior muscle, then traveling under the deep surface of the flexor hallucis longus along the backside of the fibula, the terminal branch to the lateral part of the calcaneus. During this trip, the fibular artery is located in a enclosed pipeline made by the fibula (anterolateral side), posterior tibial muscle (front and medial side) and flexor hallucis longus (posterior side). In general, the fibular artery provides 1–3 nutrient arteries through a oblique nutrient artery hole into the fibula. Nutrient hole located in the medial bone crest or posterior. Within marrow cavity, nutrient artery is divided into an ascending branch. and a relatively bulky descending branch. The anatomical characteristics determine the fibula with its vascular graft of the best middle-centered. According to this anatomical features, harvesting the vascularized fibula graf in the middle third area is the best choice.

Surgical Technique (Urbaniak)

Free Vascularised Fibular Grafting

1. The skin incision: A straight lateral 15-cm longitudinal incision is made coincident with the natural sulcus between the lateral and posterior compartments of the leg. The incision is begun 10 cm distal to the fibular head and ends 10 cm proximal to the lateral malleolus. For maintaining the stability of the ankle joint, at least distal 1/4 of the fibula must be retained. The first line along the incision skin incision, as muscle membrane surface, and then move forward, after appropriate free skin (Fig. 20.54).
2. Fibular show: Confirm the clearance between the fibula peroneal muscle and triceps, incision of the superficial fascia, blunt dissection to the fibula. Tissue cut close to the fibular cut fibula myocutaneous fibular attachment, and the peroneal muscle pulled to the front, fibular periosteum and the muscle attachment points (marble) technique was left on the fibula, so from near and far, until the distal incision can expose the lateral aspect of the fibula. In the operation, the attention should be paid not to damage the superficial nerve, the nerve is located in the deep side of the lower leg, and it can avoid the injury. In the proximal part of the incision exposure fibula, should pay attention to avoid damaging the peroneal nerve, the nerve

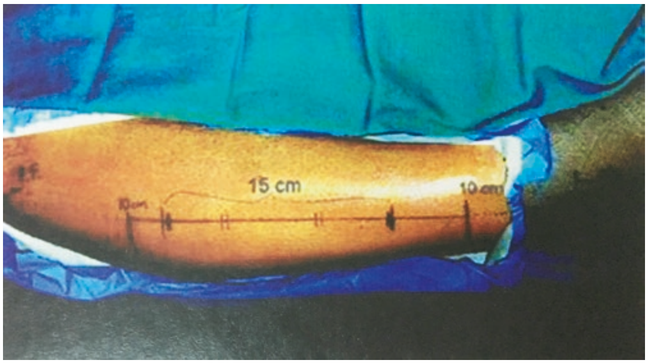


Fig. 20.54 A 15-cm incision is made on the lateral aspect of the leg between the lateral and posterior compartments. The incision is begun 10 cm distal to the fibular head and ends 10 cm proximal to the tip of the lateral malleolus

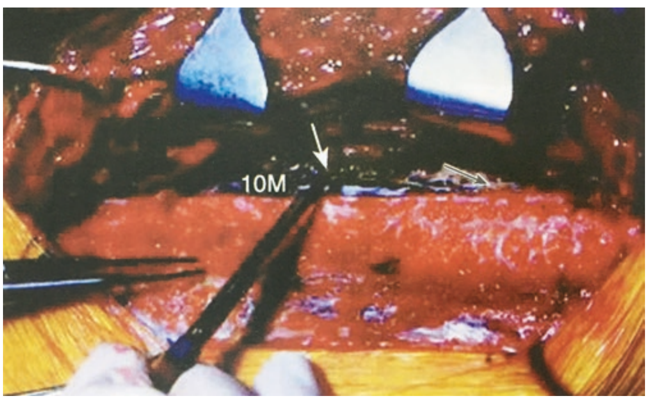


Fig. 20.55 The interosseous membrane is divided with a specially designed right-angle Beaver blade(white arrow). The close proximity of the deep peroneal nerve and anterior tibial artery can be seen in this photograph

in posterior to the fibular head around the neck of the fibula to the fibular ahead, at the time of surgery careful not to excessive exposure of the proximal fibula.

3. Free peroneal vessels: from proximal began near fibula cut extensor digitorum longus and extensor hallucis longus in fibula attachment, exposing the interosseous membrane. Close to the bone and the adhesion of the film to the fibula. The attachment of the posterior tibial muscle to the fibula was cut under direct vision. From far and near, dissected, until posterior tibial artery and peroneal vessels. The connective tissue between the proximal and distal ends of the blood vessel and the nerve bundle of the posterior tibial vessels. Then from far to near, cut off the flexor pollicis longus (Fig. 20.55).
4. Take the fibula: before the cut proximal vessels, tourniquet released, carefully check the fibular medullary cavity and muscle cuff blood oozing, determine the free fibula with good blood supply. Finally, near the posterior tibial artery, the peroneal artery and ligation were two veins, remove the fibula, close the wound of donor fibula.

Hip Surgery

The surgical area of the two groups of doctors at the same time to prepare the side of the hip joint and ipsilateral small leg. Patients in the lateral decubitus position, the aseptic towel, thigh using sterile tourniquet. The anterolateral approach road, along the fascia lata and the gluteus medius muscle gap exposed outer side of the proximal femur was carefully separated from the confirmation circumflex femoral lateral artery and vein and isolated from the ascending branch, as the blood vessels in the recipient area for anastomosis. The lateral femoral muscle is attached to the distal part of the femur and the proximal femur is exposed.

In the C arm X ray fluoroscopy along the femoral neck into the guide to femoral head necrosis area center. Attention to avoid penetrating the joint surface. The use of different diameter hollow drill from reaming until diameter of bone tunnel 16–21 mm. Tunnel from the lateral cortex of the femur, to the proximal end of the femoral head of the articular surface of about 3–5 mm. The necrosis of the femoral head can be removed while the bone tunnel is made by using a hollow drill. To the bone tunnel injection water soluble contrast agent, with C-arm X-ray machine get the contrast agent in the femoral neck bone tunnel on the positive side morphology and position were observed osteonecrosis has been cleaned. Position, the use of special pressure device in thighbone tuberosity obtaining cancellous bone loose bone send marrow tunnel within the bone grafting, combined with the use of type C arm X-ray machine and contrast examination and bone graft, bone graft must be sufficient.

The fibula with the same side length of about 13 cm with the fibula, as long as the retention of the blood vessel. At least the 10 cm of the posterior distal end of the fibula was made to ensure the stability of the ankle and knee joint. Pruning fibula to the appropriate length, distal fibula with periosteum stripping about 3–4 mm proximally, 3-0 absorbable suture the distal fibular periosteum and circular vascular bundle is fixed on the fibula, which can prevent the fibula when implanted into the bone tunnel occurred periosteum and blood vessels and fibula stripping. The fibula needs to be placed under the femoral head cartilage bone, which has a loose bone around the bone. The diameter of the bone tunnel must be greater than the diameter of the fibula 1–2 mm to prevent the pressure of the vessel, the blood flow of the fibula. A gap is obtained between the muscle of the middle and the lateral of the lateral femoral muscle and to facilitate the non tension suture of the blood vessel of the blood vessel and the lateral femoral artery. The 0.62 mm of the needle is fixed to the proximal femur. The 9-0 or 8-0 of the non injured nylon line of the microscope was used to make the ends of the blood vessel and the lateral blood vessel of the blood vessel. The cut, placed in the drainage tube, the area and the donor area are closed. In order to prevent the vascular compression of the anastomosis, the femoral intermediate and

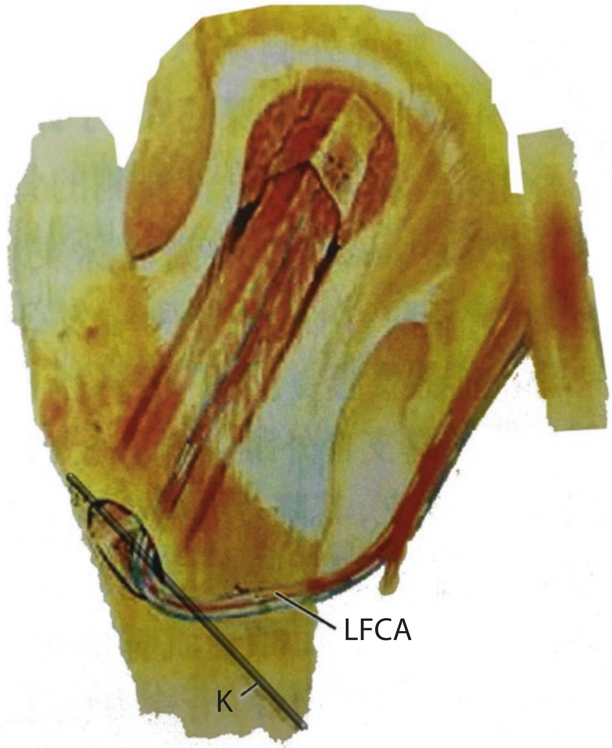


Fig. 20.56 A drawing of the final graft placement. Note the Kirschner wire placed through three cortices to secure the fibula within the femoral core

the lateral femoral muscle can not be stopped. After fixing support with short leg plaster (Fig. 20.56).

The method of cutting and taking the blood vessel pedicle and the hip operation has been improved by Changqing Zhang. Due to the improvement of the hip operation method, the free fibula and blood vessel pedicle are short, so that the fibula free can be completed only about 20 min. A small incision was designed, which was about 8–10 cm. By the tensor fascia lata and sewing sartorius gap revealed straight head of rectus femoris muscle, after cutting and turning straight head of rectus femoris muscle can be completed circumflex femoral lateral vascular bundle exposed to. This cut is significantly smaller than the lateral incision of Urbaniak, the separation of small muscles, the operation of light and the exposure of blood vessels is easy.

20.6 Microsurgical Treatment of Ischemic and Avascular Necrosis of the Talus

Daping Cui and Dewei Zhao

Avascular necrosis of the talus is a difficult problem for surgical treatment because of the anatomical position of the talus and its fragile blood supply. Avascular necrosis of the talus is primarily divided into three categories: (1) idiopathic ischemic necrosis caused by nontraumatic and medical factors, which has a low incidence (~10% of talus necrosis); (2) necrosis induced by drugs such hormones for the treatment of other diseases (~15%); (3) traumatic avascular necrosis of the talus due to fracture of the talar body and neck (~75%).

20.6.1 Anatomic and Blood Supply Features of the Talus

The talus is anatomically susceptible to trauma, because ~60% of its surface is cartilage. There are seven articular surfaces of the talus. The top surface, where the talar neck is the only part outside the joint, bridges the joint of the talus in the rear and front surface; this is the most vulnerable part of the talus. The talar neck is short in the middle and deviates from the interior part, which is inconsistent in the horizontal and sagittal planes. It deviates from the medial talar neck by ~10–44° (mean 24°), and in the sagittal plane the talar neck is offset 5–50° (mean 24°). In addition, the ligament between the calcaneus, talus, and talar neck ligament plays an important role in the stability of the talar neck and distal fracture fragments. If these ligaments are torn, dorsal subluxation and varus occur, and the rear of the talocalcaneal ligament is often the last support structure preventing prolapse.

The talar bone blood supply primarily comes from the anterior and posterior tibial and peroneal arteries, which collectively constitute the bone blood supply ring around talar neck and bone sinus. The tarsal sinus artery from the anterior tibial artery and peroneal artery branches are vital arteries for the stability and reduction of talar neck and body fracture. The tarsal artery from the posterior tibial artery, the deep surface of the medial malleolus in the triangular ligament distinguished under the deltoid branch, is an important vascular talar body for reducing talar neck or body fracture. Attention should be paid to the protection of the triangular support. Different parts of the talar blood supply are differently distributed from the bones with rich blood supply, chiefly by the anterior tibial artery supply; the middle and proximal bone internal circulation of the talus are mainly constituted by the tarsal sinus blood vessel and a triangle support supply; the anterolateral and posterior tubercles of the talar body provide scarce blood supply.

20.6.2 Etiology and Clinical Manifestation

Talar neck fracture accounts for 50% of talus fractures, while 90% of traumatic avascular necroses of the talus are due to talar neck fracture. The mechanism of talar neck injury is mainly dorsiflexion of the foot, which results in tibio-talar neck impact. If this force is sufficiently powerful, it can tear the talus intermediate and dorsal comminution, talocalcaneal ligament, talus, and talus articular capsule. Ankle supination with shock to the medial malleolus and talar neck can cause distance subluxation of the talar body; this occurs because the medial malleolus medial heel forces blood tube prolapse, talar neck middle crushing, and talar neck fracture. The Virginia College of Medicine describes the Hawkins types as follows: type I, no complications with subluxation and without displacement of the vertical talar neck fracture; type II, showing a shift combined with subtalar subluxation block and mild dorsal talar neck fracture; type III, injury including the talar neck of the talar shaft and subtalar subluxation such as malunion and increased talus osteonecrosis and secondary osteoarthritis; type IV, talonavicular joint dislocation with type II or III damage with a late-stage talus fracture and higher probability of necrosis.

20.6.3 Microsurgical Treatment of Avascular Necrosis of the Talus

Early avascular necrosis of the talus can be treated conservatively with treatments such as oral pain medication, braces, plaster fixation, and limited weight bearing. If 3 months of treatment is insufficient, surgical treatment such as a core decompression operation for pre-collapse with minor trauma can relieve postoperative pain. However, microsurgical treatment such as vascular pedicled bone flap transfer with vascular bundle implantation is more effective. For patients in the collapse stage with ankle joint osteoarthritis, tibiotalar fusion or tibiocalcaneal arthrodesis with talar resection can be considered; however, these have substantial technical requirements and require long operation times. Postoperative external fixation is required for an average of 7 months.

1. Medial cuneiform bone flap transplantation with a vascular pedicle

(a) Applied anatomy

The medial cuneiform bone blood supply is primarily supported by branches of the medial anterior malleolus artery and medial tarsal vessels. The medial anterior malleolus artery branches from the anterior tibial and dorsal arteries in 56.7% and 43.3% of cases, respectively (Fig. 20.57a). The main trunk inclines forward toward the tendon of the tibialis anterior medial line to the medial cuneiform bone margin in 70% of cases. The trunk at the rear foot navicular tuberosity attaches inside the arterial branches, forming the island, in 30% of cases (Fig. 20.57b). The artery to the medial cuneiform bone dorsal side of the anterior medial malleolus produces 2–6 branches; the diameters of the periosteal branches are ~0.20–0.8 mm, and are distributed to the rear inner side of the medial cuneiform bone tendon. The medial tarsal artery from the internal dorsalis pedis artery, whose main trunk is close to the anterior lateral tendon of the tibialis and reaches the medial margin of the bone is apparent in 70% of cases. The main trunk with the medial anterior malleolus artery forming an island anastomotic arch is present in 30% of cases. The medial artery of the medial cuneiform bone produces 2–9 branches 0.2–0.9 mm diameter, which are distributed in the anterior part of the medial cuneiform bone. The medial tarsal artery, superficial branch of the medial plantar artery, and medial anterior malleolus artery collectively form the surface arterial network of the bone.

(b) Operation method

An anteromedial incision of the malleolus beginning from above the medial malleolus and proceeding along the anterior tibial muscle tendon to the tarsometatarsal joint is made to expose the medial cuneiform bone. The skin and subcutaneous tissue are opened, the anterior tibial tendon and hallux longus

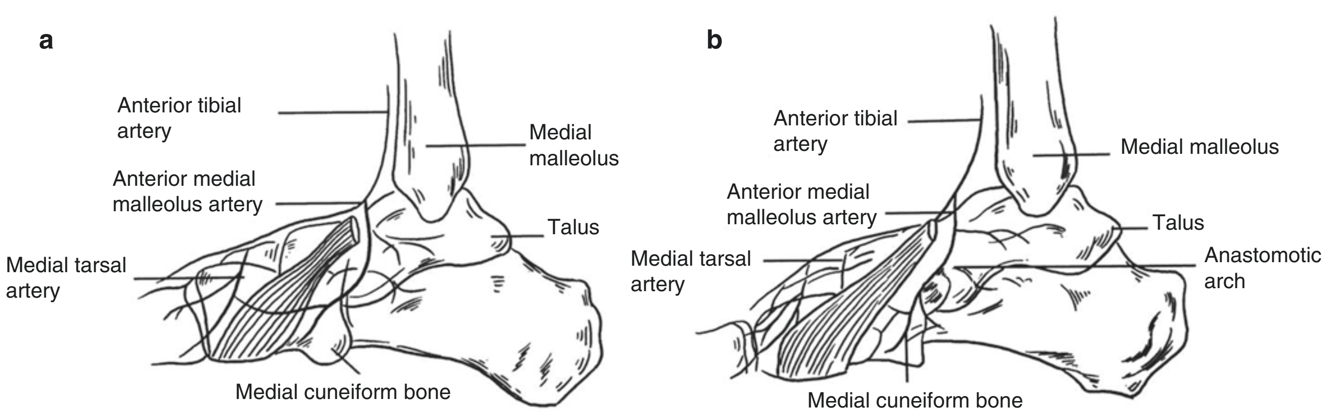


Fig. 20.57 The blood supply of medial cuneiform bone

muscle tendon are pulled aside, and the arterial trunk in the medial margin of the tendons of the tibialis anterior muscle are located. If the medial tarsal artery is desired as the pedicle, the dorsalis pedis artery should be revealed first to locate the medial tarsal artery in the anterior tibial muscle tendon lateral equivalent of the talonavicular joint. Then, the boundary of the medial cuneiform is determined using a bone chisel, and a vascularized cuneiform bone flap measuring 1.5 × 1.5 cm pedicled with vessels is excised after separation of the vascular bundle from distal to proximal to the root. The ankle joint capsule is accessed, and the weight-bearing plane of the joint and window of the talus below are opened to remove the dead bone. The anterior tibial tendon is pulled medially, and the bone flap pedicled with vessels is moved to open the window of the talus from inside the tendon, without external fixation. Finally, the cuneiform bone is bound with bone wax, and hemostasis and postoperative pressure bandages are applied.

(c) Postoperative treatment

Postoperative care includes a short leg plaster fixation for 6–8 weeks, without any weight on the affected limb for 3 months postoperatively accompanied by monthly follow-up radiographic examination.

2. Transplantation of the cuboid bone with a vascular pedicle flap

(a) Applied anatomy

The dorsal cuboid bone blood supply is from the lateral tarsal artery, which begins from the dorsolateral artery of the foot. The starting point is more commonly found at the talonavicular joint surface (~1.5 cm) and less commonly at the articular surface. The scaphoid of the foot artery has an inclined lateral surface deep enough to pass through the short extensor brevis and toe, close to the fifth metatarsal dorsal side of the cuboid. The artery across the dorsal cuboid portions on both sides of the artery produces 5–12 branches 0.2–1.0 mm in diameter that extend to the dorsal cuboid and enter the bone (Fig. 20.58a).

(b) Surgical methods

The ankle anterolateral incision is made from the outer lateral ankle, obliquely downward, over the talus anterolateral to the cuboid bone area, and extending along the fourth metatarsal. The skin and subcutaneous tissue are cut, the hallux extensor hallucis longus and extensor digitorum longus are pulled aside, and the starting point of the talonavicular joint lateral tarsal artery along the dorsal artery of the foot is identified. In front of the calcaneus, the extensor digitorum brevis is cut off, the lateral tarsal artery branch of the cuboid bone surface is exposed, the boundary of the cuboid bone is identified along with the lateral tarsal artery in the dorsal cuboid, whose axis is parallel to the calcaneocuboid joint line, and a bone flap measuring 2.0 × 1.0 × 0.5 cm is cut. The bone flap is lifted with the vascular pedicle, and the vascular bundle is separated to the starting place from distal to proximal. The ankle joint capsule is opened, the talar neck body on the outside window is identified, the talus is cleared within the dead bone, and the bone flap is embedded in the window. Finally, the cuboid bone is bound with the available extensor digitorum brevis (Fig. 20.58b).

(c) Postoperative treatment (same as previous)

3. Vascularized calcaneus bone flap transplantation

(a) Applied anatomy

The lateral calcaneal artery is the terminal branch of the peroneal artery between the Achilles tendon and lateral malleolus, penetrating the deep fascia from the surface to the calcaneal tuberosity of the fifth metatarsal. It produces the periosteal

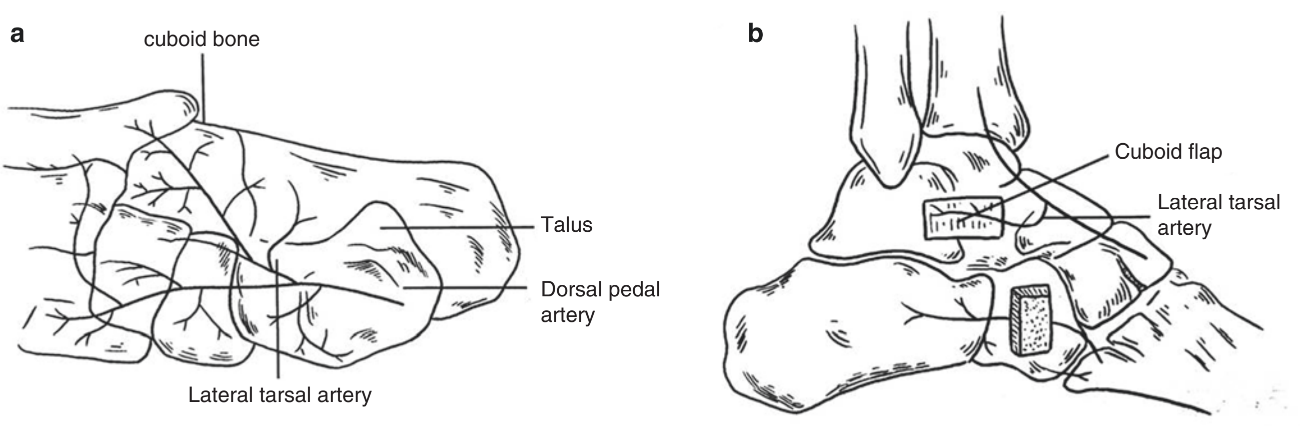


Fig. 20.58 Transplantation of the cuboid bone with a vascular pedicle flap. (**a**) The blood supply of cuboid bone. (**b**) Cuboid bone flap transplantation

branch of the lateral calcaneus, with 5–10 branches whose outer diameter is ~0.2–1.0 mm. The lateral tarsal artery begins from the artery exterior and passes through the dorsal cuboid to the lateral calcaneal, with 2–3 branches whose diameters are ~0.7–1.0 mm. The perforating branch of the peroneal artery descending from the tip of the lateral malleolus is 5.8 cm above the pierced interosseous membrane of leg (i.e., perforator). The descending branch is in the lower fascia, along the lateral descending anterior lateral malleolar from the ankle sulcus and lateral anterior malleolar artery anastomosis. The anastomotic arteries of the extensor digitorum brevis along the front surface and the peroneal tendon to the anterolateral foot coincide with the lateral tarsal artery and produce 1–3 periosteal branches that extend to the anterior lateral calcaneal body. The lateral anterior malleolar artery begins from the lateral side of the foot dorsal artery, extending to the extensor digitorum longus tendon, third fibular deep surface, and descending branch of the peroneal artery perforator, producing periosteal branches to the calcaneus anterolateral (Fig. 20.59).

(b) Operation method

- Vascular pedicled bone flap transplantation of the lateral calcaneus

  An anterolateral incision is made on the ankle, extending distally to the base of the fourth metatarsal bone. The skin and subcutaneous tissue are subsequently cut. In the dorsal artery of the foot lateral, the lateral tarsal artery with its calcaneal periosteum branch as the pedicle is identified, and subsequently excise a 1.5 × 1.0 × 1.0-cm bone flap. Next, the proximal bone flap is set, and the vascular pedicle is separated to the roots and embedded into the window to transpose the talus.

- Vascularized calcaneus posterolateral bone flap transplantation

  A lateral incision is made on the ankle, extending distally to the base of the fifth metatarsal bone; subcutaneously, the lateral calcaneal artery with its axis is located, and the distal vascular pedicle bone is ligated. Then, a posterolateral bone flap measuring 2.0 × 1.5 × 1.0 cm is cut. The proximal bone flap is then isolated along the vascular pedicle, and the bone flap is transported and embedded into the window of the talus.

(c) Postoperative treatment (same as previous)

4. Vascular pedicle flap transplantation of the navicular bone of the foot

   (a) Applied anatomy

   The anatomy is similar to that of the medial anterior malleolus and medial tarsal arteries (Fig. 20.60).

   (b) Operation method

   A medial anterior malleolus incision is made 3.0 cm above the medial malleolus along the long extensor of the toe and tendon of the tibialis anterior to the distal extension (8.0 cm in length). The skin and subcutaneous tissue are cut, and the anterior tibial tendon is pulled aside, exposing the dorsal artery of the foot and its branch of the medial anterior malleolus artery; the navicular bone border is then distinguished. In order to use the medial anterior malleolus artery as a pedicle in the dorsal scaphoid of the foot, a bone flap measuring 1.0 × 1.0 × 0.5 cm is cut and raised along with its vascular pedicle to obtain proximal separation to the roots. Finally, the bone flap is embedded in the window of the talus.

   (c) Postoperative treatment (same as previous)

5. Vascular bundle implantation

   (a) Applied anatomy

   The dorsalis pedis artery was renamed the anterior tibial artery and extends to the extensor support edge, which passes through the extensor pollicis brevis, issues the first dorsal metatarsal artery to the first metatarsal clearance, and branches to hallux toe dorsal side of the second toe and medial margin of the back edge.

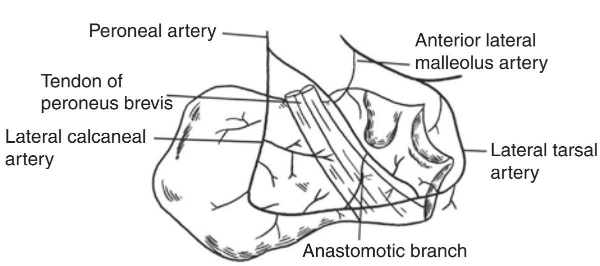


Fig. 20.59 The blood supply of calcaneus bone

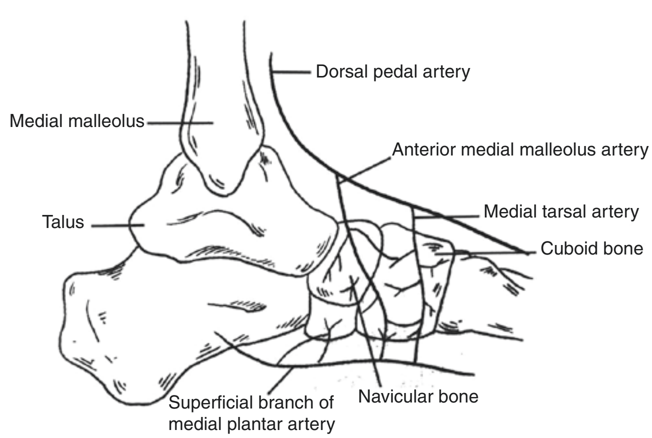


Fig. 20.60 The blood supply of navicular bone

(b) Operation method

An anterior ankle arc-incision ~7.0 cm is made. The skin, subcutaneous tissue, and extensor retinaculum are cut. Then, the dorsal vessel and deep peroneal nerve are pulled medially, exposing the ankle bursa. In the talus lateral to the talus center, a hole ~3 mm in diameter is drilled. Then, the first dorsal metatarsal artery is located along an incision of the inner edge of the dorsal artery of the foot and freed, and a vascular pedicle ~4–6 cm long is obtained. Next, distally pedicled vessels are cut and ligated in order to allowing embedding in the bone cave. Finally, the fasciae and talus of the vascular peripheral articular capsule are sutured.

(c) Postoperative treatment (same as previous)

20.6.4 Prophylaxis for Talar Necrosis

In order to avoid further talar necrosis, an appropriate surgical approach and operation time must be selected.

1. Choice of surgical approach

   The talar body position is difficult to expose. The joint capsule and ligament tissue are often an important pathway for talar body blood circulation. Therefore, the surgical approach directly influences the curative effects. Wang Yan states that surgeons should consider the following: (1) perform a CT scan of the talar body parallel to the subtalar joint surface and perpendicular to the subtalar joint surface to determine the position and degree of comminution of the main fracture block in order to facilitate the selection of a direct and effective incision; (2) the incision should minimize damage to the surrounding ligament and joint capsule, particularly avoiding the triangular ligament rear incision to protect the blood supply; (3) the anatomical characteristics of the talus should grasp the "irregular" bone.

2. Choice of surgical timing

   There are no independent feeding vessels to the talus that pass through the ligament and joint capsule as part of the blood supply of the talus. Talar neck fracture, dislocation, and surgical trauma can damage the blood supply of the talus, which is easily complicated by local skin necrosis. Chen Hongwei states the operative treatment of talar neck fractures should be determined on the basis of the time of injury and general condition of the patient. For patients with ankle joint dislocation and reduction failure, an emergency operation should be performed, body conditions permitting. Fulkerson reports that talar neck fracture with early closed reduction does not reduce the incidence of avascular necrosis of the talus. For patients with avascular necrosis of the talus, it is recommended to immediately transplant the vascular pedicle bone flap or cartilage. Otherwise, delayed reconstruction and arthrodesis is a suitable choice.

In summary, necrosis of the talus has become a serious issue owing to its increased incidence. Novel transplantation and minimal invasive techniques, etc. must be developed continuously. From the perspective of prevention and comprehensive research, better surgical treatments, achieving better results in the treatment of ischemic necrosis of talus are anticipated.

20.7 Microsurgical Repair of Avascular Necrosis of the Navicular Bone

Fengde Tian and Dewei Zhao

Spontaneous osteonecrosis of the tarsal navicular bone in adults, termed Müller-Weiss syndrome, differs from the well-recognized osteochondrosis of the tarsal navicular bone that occurs in children, termed Köhler disease. Multiple factors such as impaired blood supply to the tarsal navicular bone result in abnormal ossification (i.e., chondrification and ossification) or osteocyte death in cartilage.

Blockage of blood supply caused by arterial formation delays ossification of the tarsal navicular bone, and trauma can interrupt it, resulting in Müller-Weiss disease. Osteonecrosis of the navicular bone may also lead to flatfoot, which is also known as Müller-Weiss syndrome. The development of flatfoot may result in pain and weakness of the entire lower extremity, walking difficulty, and other clinical symptoms. Secondary to a mismatched talus joint after osteonecrosis of the navicular bone, the tarsal navicular bone is exposed to pressure after collapse of the arch. Gradually increasing pressure within the bone marrow is accompanied by impaired blood supply. Pathological examination shows scattered necrotic lesions caused by bone infarction, loosened bone tissue, bone cysts, nuclear depigmentation, osteocyte death in cartilage, and bone tissue necrosis associated with advanced collapse.

Köhler disease is a rare bone disorder of the foot in children that may result from stress-related compression at a critical time during growth. It is characterized by limping due to pain and swelling in the foot. It most commonly occurs in children 4–10 years old and affects males three times more frequently than females. Typically, only one foot is affected; only one-third of patients are bilaterally afflicted. Children appear to grow out of the disorder, and the affected bones regain their size, density, and structure within a year; however, in some patients, symptoms may last as long as 2 years. Irregular ossification is also found in the normal tarsal navicular bone. Diagnosis should be combined with clinical symptoms. The disease leaves no or little permanent disability.

20.7.1 Gross Anatomy of the Tarsal Navicular Bone

The navicular bone is located medially in the midfoot between the talus posterior and anterior of the three cuneiform bones (see the following image). It forms the uppermost portion of the medial longitudinal arch of the foot and acts as a keystone of the arch. It is a boat-shaped bone that sits between the talar head and the three cuneiform bones. The navicular bone has six surfaces. The posterior navicular surface is oval, concave, broader laterally than medially, and articulates with the rounded head of the talus. The medial navicular surface slopes posteriorly, ending in a rounded prominent tuberosity. The anterior navicular surface is convex from side to side and is subdivided by two ridges into three facets for articulation with the three cuneiform bones. The lateral surface is rough and irregular for the attachment of ligaments and occasionally presents a small facet for articulation with the cuboid bone. The navicular bone is located in the highest point of the medial longitudinal arch, which is the center of gravity. Therefore, the navicular bone is thought to be pinched or impinged between the bones to the front and back, resulting in its compression. The navicular is the last tarsal bone to ossify in children. This bone may be compressed between the already ossified talus and the cuneiforms when the child grows heavier. Compression involves the vessels in the central spongy bone, leading to ischemia, which subsequently causes clinical symptoms.

The blood supply of the navicular bone comes from two arteries: the medial plantar and dorsalis pedis arteries. A branch from the dorsalis pedis artery crosses the dorsal surface of the navicular and produces 3–5 branches. Some small branches come from the medial plantar artery to supply the plantar surface. These blood vessels create a dense network around the bone and come from the perichondrium toward the center of the cartilage. Less commonly, a single dorsal or plantar artery is found in anatomic specimens. The blood supply can be easily damaged by trauma, causing ischemic necrosis, which is difficult to repair (Fig. 20.61).

20.7.2 Treatment

20.7.2.1 Conservative Treatment

Köhler disease is self-limiting and resolves in childhood, generally without requiring surgical treatment. Conservative treatment involves resting the affected foot, taking analgesics, and avoiding pressure on the foot. In acute cases, the patient is often fitted with a cast that stops below the knee; the cast is worn for 7–8 weeks, keeping the foot at 15° strephenopodia and 20° plantar flexion to alleviate the pull stress from the posterior tibialis muscle. After the cast is removed, some patients are prescribed arch supports for ~6 months. Moreover, moderate exercise and physical therapy are often beneficial. The prognosis of children with this disease is very good. Although it may persist for some time, most cases are resolved within 2 years of initial diagnosis.

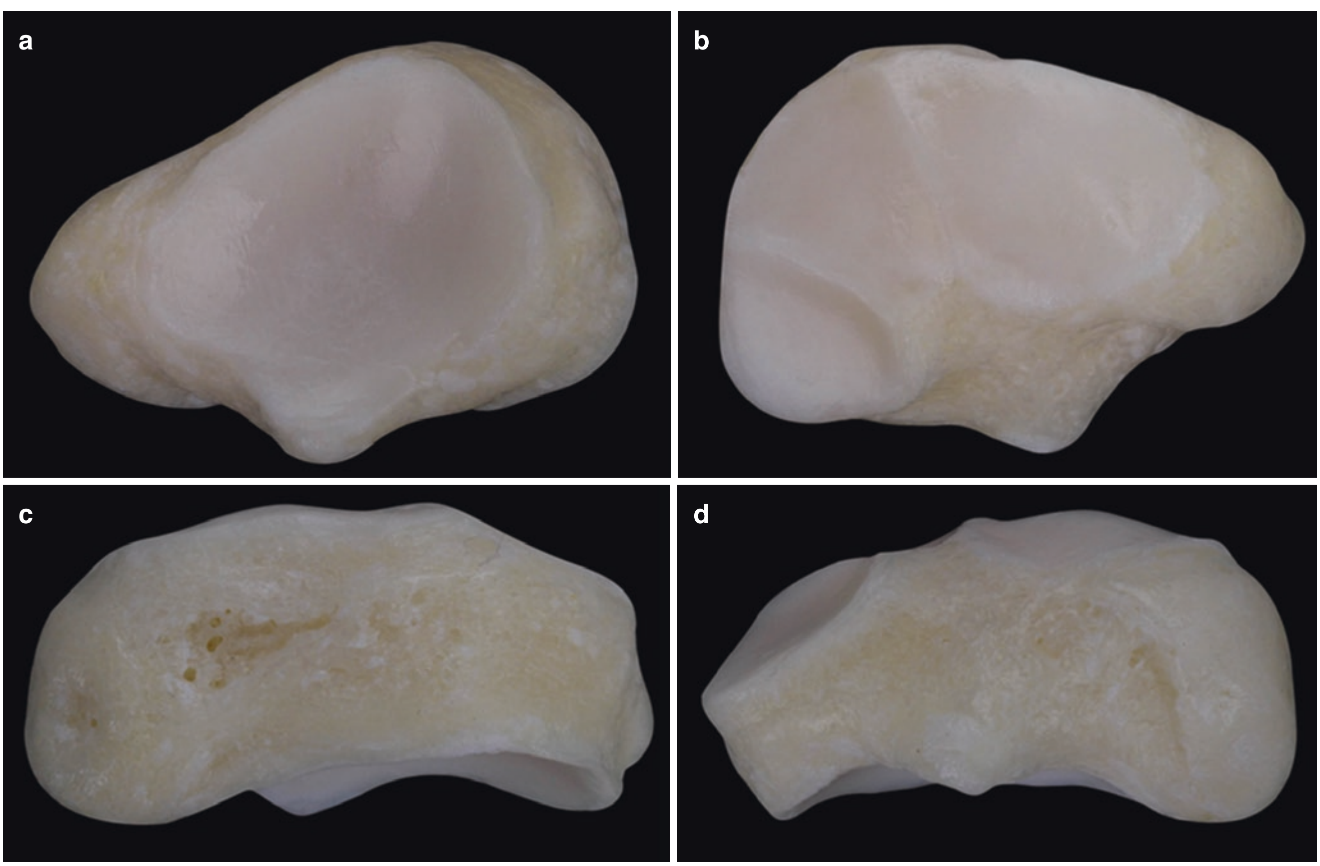


Fig. 20.61 The anatomy of tarsal navicular bone. (**a**) Proximal articular surface; (**b**) distal articular surface; (**c**) dorsal side; (**d**) plantar side

20.7.2.2 Surgical Treatment

Children with Köhler disease may return to normal after 2–3 years of conservative treatment. However, most experience difficulty adhering to long-term braking or wearable supports. The disease may progress, leading to ischemic bone tissue necrosis, which subsequently leads to arch collapse, flat feet, and forefoot supination deformity; at this point, conservative treatment fails to relieve the symptoms, and surgical treatment should be proposed. The surgical technique aims to alleviate pain and maintain normal paratalar joint function.

1. Triple arthrodesis

   Spontaneous osteonecrosis of the tarsal navicular bone in adults, termed Müller-Weiss disease, does not represent persistence of Kohler's disease, which commonly resolves in childhood. The treatment of Müller-Weiss disease should be based on its etiology and clinical staging. For the early stage with non-severe clinical symptoms, conservative treatment is appropriate, although the long-term curative effects are not ideal. Triple arthrodesis was performed in our patients with triple osteoarthritis, who complained of severe pain and loss of function. Patients should be informed of the possibility of postoperative hindfoot stiffness.
2. Microsurgery

   Chronic midfoot pain over the dorsomedial aspect of the foot can be resolved after complete removal of the necrotic bone from the tarsal navicular, followed by a vascularized autologous bone grafting into the defective area. According to the vascular supply present, two adjacent bone flaps can be used to rebuild the necrotic tarsal navicular bone, including the anteromedial cuneiform bone flap pedicled with the medial malleolus artery and the anterolateral cuboid bone flap pedicled with the lateral tarsal artery (Fig. 20.62). A medial approach is available to repair adjacent talus bone lesions with a vascularized bone flap pedicled with the medial malleolar artery. This bone flap is not only used along the line to the first metatarsal, but can also be shifted up to repair distal tibial lesions. An anterolateral approach is available to repair tarsal navicular bone lesions using a vascularized cuboid bone flap pedicled with the lateral tarsal artery. The lateral tarsal artery is a branch from the dorsalis pedis artery that crosses the dorsal surface of the navicular and produces branches to supply the navicular and cuboid bones; this artery offers constant and sufficient blood supply to the cuboid bone, which is a good option for the bone flap. The above two types of operative methods can effectively decompress the necrotic bone. Pain over the dorsomedial aspect of the foot can be resolved after complete removal of the necrotic bone from the tarsal navicular, followed by vascularized autologous bone grafting into the defective area. A bone graft can provide adequate blood supply and cellular components to the necrotic tarsal navicular. The anatomical location of the bone flap and artery is superficial. The operation is relatively simple and sufficiently safe to be used as an effective treatment for tarsal navicular necrosis.

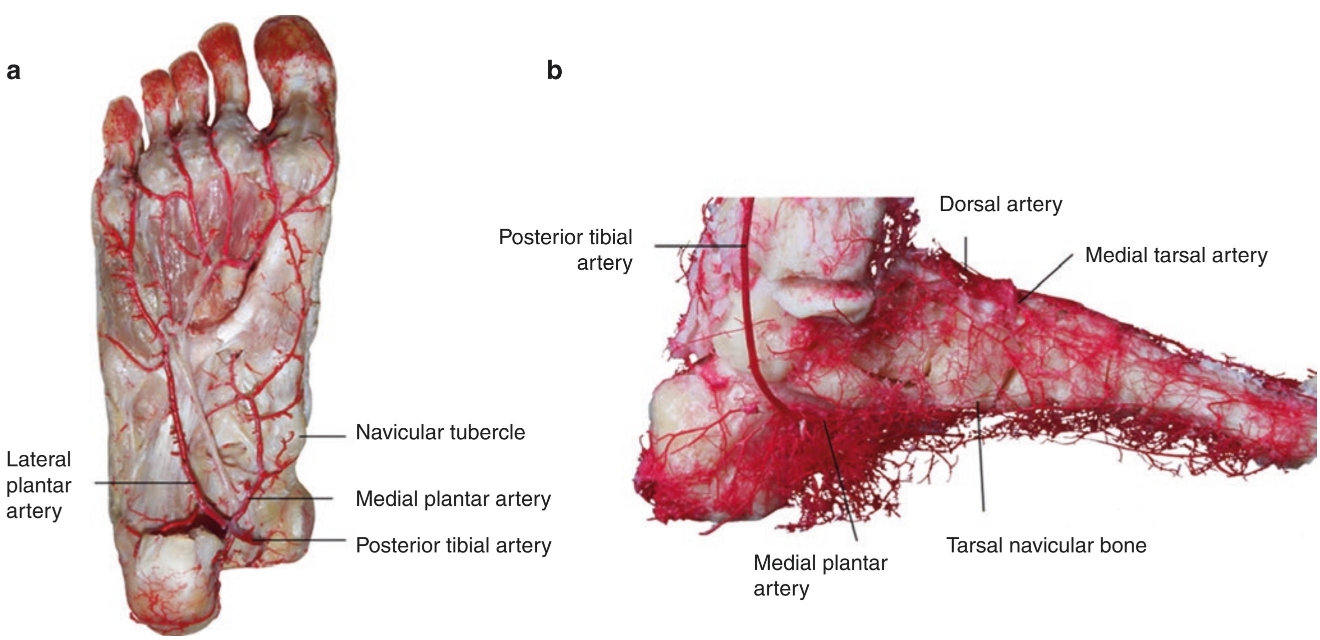


Fig. 20.62 Vascular distribution of tarsal navicular bone. (**a**) Plantar side; (**b**) medial side

Transplantation of the Vascularized Cuneiform Bone (i.e., Periosteum) Flap

An anteromedial ankle incision is performed, starting from the top of the medial malleolus, extending along the anterior tibial tendon to the tarsometatarsal joint in order to fully reveal the medial cuneiform bone.

1. Surgical procedures

    The skin and subcutaneous tissue are cut, and the anterior tibial and hallucis longus tendons are pulled to the side. The anterior tibial artery is identified at the medial edge of the anterior tibial tendon. If the medial tarsal artery is the target pedicle, the dorsalis pedis artery should be exposed lateral to the anterior tibial tendon at the point equivalent to the talonavicular joint. The medial cuneiform bone boundary is distinguished, and a medial cuneiform bone (i.e., periosteum) flap measuring 1.5 × 1.5 cm is excised with the vascular pedicle (i.e., the anterior tibial or medial tarsal artery); the flap is removed, and the vascular bundles are isolated to their roots. The tarsal navicular is revealed, a bone window is opened at the back, and the center necrotic tissue is cleaned with a small spatula. Next, some cancellous bone is excavated from the first cuneiform bone for implantation in the cavity of the tarsal navicular. The vascularized bone flap is subsequently embedded into the defective area through the bone window of the tarsal navicular. The bone flap does not generally need to be fixed. The cuneiform is coated with bone wax to stop bleeding. The incision is then sutured and dressed routinely.

2. Postoperative treatment

    Postoperatively, the patient is often fitted with a short plaster cast that stops below the knee. The cast is commonly worn for 6–8 weeks. Avoid weight-bearing for 3 months. Follow-up radiographs should be taken monthly (Fig. 20.63).

Transplantation of the Vascularized Cuboid Bone Flap

1. Surgical procedures

    The skin and subcutaneous tissue are cut, the anterior tibial and hallucis longus tendons are pulled to the side, and the anterior tibial artery is located at the medial edge of the anterior tibial tendon. If the medial tarsal artery is the target pedicle, the dorsalis pedis artery should be exposed lateral to the anterior tibial tendon at the point equivalent to the talonavicular joint. The medial cuneiform bone boundary is distinguished, a medial cuneiform bone (i.e., periosteum) flap measuring 1.5 × 1.5 cm is excised with the vascular pedicle (i.e., the anterior tibial or medial tarsal artery); the flap is removed, and the vascular bundles are isolated to their its roots. The tarsal navicular is revealed, a bone window is opened at the back, and the center necrotic tissue is cleaned with a small spatula. Some cancellous bone is subsequently excavated from the first cuneiform bone for implantation in the cavity of the tarsal navicular. The vascularized bone flap is then embedded into the defective area through the bone window of the tarsal navicular. The bone flap does not generally need to be fixed. The cuneiform is coated with bone wax to stop bleeding. The incision is then sutured and dressed routinely. An anterolateral ankle incision is made from the anterolateral side of the ankle joint over the anterolateral talar body to the cuboid bone area, extending along the fourth metatarsal. The skin and subcutaneous tissue are cut, the hallux longus and extensor digitorum longus are pulled to the side along the lateral side of the dorsalis pedis artery, and the starting point of the lateral tarsal artery at the level of the talonavicular joint is located. In front of the calcaneus, the extensor digitorum brevis is cut, the lateral tarsal artery branch is revealed at the cuboid bone surface, and the border cuboid bone is distinguished. According to the axis of lateral tar-

Fig 20.63 Transplantation of vascularised cuboid bone flap

sal artery, parallel to the calcaneocuboid joint line, a cuboid bone flap measuring 2.0 × 1.0 × 0.5 cm is excised with the vascular pedicle; the flap is removed, and vascular bundles are isolated to their roots. The tarsal navicular is revealed, a bone window is opened at the back, and the center necrotic tissue is cleaned with a small spatula. Then, the vascularized cuboid bone flap is embedded in the defective area through the bone window of the tarsal navicular. The cuboid bone wound is subsequently packed with the extensor digitorum brevis. Finally, the incision should be sutured and dressed routinely.

2. Postoperative treatment

   Postoperatively, the patient is often fitted with a short plaster cast that stops below the knee. The cast is commonly worn for 6–8 weeks. Weight bearing is avoided for 3 months. Follow-up radiographs should be performed monthly.

20.8 Microsurgical Treatment of Ischemic Necrosis of the Second Metatarsal

Xiuzhi Zhang and Dewei Zhao

Freiberg disease is also known as metatarsal aseptic necrosis or metatarsal osteochondrosis. The disease occurs more commonly in women aged 10–20 who stand for long periods of time, such as nurses, hotel staff, and textile workers. It commonly invades the distal second metatarsal head and unilateral part, and occasionally the third and fourth metatarsal; in 10% of cases, it occurs in the bilateral part. The common pathological changes include metatarsal flattening and collapse, retrograde degeneration of the metatarsophalangeal joints, and finally metatarsophalangeal joint arthrosis. Its key clinical symptoms are metatarsophalangeal joint swelling, pain, and restricted activity (Fig. 20.64). The clinical progress of Freiberg disease is slow and easily overlooked. If it reaches a late stage, the patient will require surgical treatment.

Fig. 20.64 Second metatarsal necrosis

20.8.1 Pathogenesis

Freiberg disease is considered to arise from several of the following factors:

Cumulative strain: The second metatarsal is the longest. Its proximal end is surrounded by three cuneiform bones, and its low mobility causes a tendency towards stress accumulation. Therefore, the second metatarsal is under excessive pressure, resulting in bone compression, intramedullary pressure increase, and blood clots; this finally results in necrosis. Women have a higher incidence of this disease because of weaker foot muscles, lower arches, and lower and more relaxed horizontal bows. They also often wear high-heeled shoes. These factors bring about excessive pressure on the second metatarsal.

Anatomical pathology factors: Freiberg disease commonly occurs in adolescents. The ossification center of the metatarsal begins to appear from 2 to 6 years of age and fuses from 17 to 19 years of age. Prior to this, the epiphysis is not closed, with the epiphyseal arterial blood supply only from the joint capsule and ligaments. The vasculature that enters the metatarsal epiphysis via the ligament is occluded by trauma and compressive strain, which cause the epiphyseal avascular to necrose. Freiberg disease occurs in adolescents whose events are large and epiphysis is not closed.

Impact of glucocorticoids: The link between long-term or high-dosage corticosteroid use and Freiberg disease is controversial. Long-term corticosteroid use can cause arteritis, which leads to a loss of blood supply to the subchondral bone and necrosis.

20.8.2 Clinical Situation and Diagnosis

The signs and symptoms of Freiberg disease are swelling and pain at the affected metatarsophalangeal joint. Walking, running, and jumping are limited. The symptom is most severe when walking on uneven ground. It is apparently painful when the patient walks down stairs and less painful when at rest. The thick and rugged metatarsal can be felt on the dorsal metatarsophalangeal joint. When the bone is under pressure, the patient feels pain, particularly on the plantar side. Pressing longitudinally or tapping the corresponding toe causes metatarsophalangeal joint pain. The mobility and dorsiflexion of the joint are limited. A sound can occasionally be heard when moving the bone. The patient may have joint stiffness and other symptoms at the late stage of Freiberg disease.

20.8.3 Staging

Smillie classifies of Freiberg disease on the basis of the typical metatarsal necrosis lesions, including ischemia, necrosis, articular fractures collapse, absorption, and remodeling.

- First stage: The blood supply of the metaphysis is impaired, the metaphysis fractures, the surrounding spongy bone begins to harden, and there are no apparent external manifestations.
- Second stage: The hardened spongy bone at the metatarsal center is absorbed, causing the dorsal cartilage to collapse on the plantar side. The contour of the metatarsophalangeal joint changes.
- Third stage: As the bone is further absorbed, the cartilage continues to collapse on the plantar side. However, the plantar side of the cartilage is still relatively intact.
- Fourth stage: Throughout the metatarsal collapse, part of the articular cartilage begins to fall and finally forms a loose body.
- Fifth stage: The metatarsal experiences arthritis, the bones flatten, and deformity forms.

20.8.4 Microsurgical Treatment of Freiberg Disease

The treatment of Freiberg disease varies according to clinical stage. During the early stage of Freiberg disease, the main conservative treatment is to avoid weight bearing by reducing local pressures. However, with a lack of awareness of the disease, the disease is often discovered and diagnosed in middle to advanced stages, which require surgery.

Current surgical methods include local drilling decompression, metatarsal head debridement and bone grafting, metatarsal head osteotomy, prosthetic replacement for metatarsophalangeal joint, a combination of metatarsophalangeal joint forming, digitorum longus tendon lengthening surgery, etc. To improve patient quality of life, several factors must be considered in order to minimize the impact of treatment on the active function of the foot, reduce surgical trauma, retain the load capacity of the metatarsals, and maintain and repair necrotic bone. Therefore, microsurgical repair has been applied to treat Freiberg disease.

20.8.4.1 Retrograde Transposition of Metatarsal Flaps with Vascular Pedicle

Applied Anatomy

1. First metatarsal dorsal artery

   The first metatarsal dorsal artery, found in the first metatarsal gap, produces several symmetrical periosteal branches that are distributed in the inner and outer sides of the first and second metatarsals. When the first metatarsal dorsal artery is 1.6 cm from the web space edge, it separates the two dorsal arteries and supplies the Martin–Gruber anastomosis to the plantar, which anastomoses the first metatarsal artery. The first metatarsal dorsal artery lies unevenly in the gap of the first metatarsal. According to Jinbao Wu, it can be divided into three types: types I, II, and III are the shallow, deep, and thin or absent type, respectively.

2. Second metatarsal dorsal artery

   The second metatarsal dorsal artery, found in the second metatarsal gap, produces several symmetrical periosteal branches that are distributed in the inner and outer sides of the second and third metatarsals. When the second metatarsal dorsal artery is 1.6 cm from the web space edge, it separates the two dorsal arteries and supplies the Martin-Gruber anastomosis to the plantar, which anastomoses the second metatarsal artery. The second metatarsal dorsal artery lies shallowly in the gap of second metatarsal. It is situated on the surface or the shadow of the interosseous muscle in 86.7% and 13.3% of cases, respectively.

Procurement and Displacement of the Bone Flap

1. Incision

   The patient is placed in the supine position. An S-shaped incision with the second metatarsal as the vertical axis is made, starting at the second tarsometatarsal joint and ending at the distal second metatarsophalangeal joint; it can reveal the gap between the first and second metatarsals as well as the second metatarsal.

2. Revealing the vascular pedicle

   The skin is cut while protecting the dorsal nerves. The first dorsal metatarsal artery is located on the interosseous muscle surface and shadow of the first metatarsal gap. If the blood vessel is of type I, it can be used; if it is of type II or III, the second dorsal metatarsal artery can be used.

3. Bone flap procurement

   The proximal and dorsal outer surface of the first metatarsal or the soft tissue of the proximal and dorsal inner surface of the second metatarsal is cut to the shallow side of the periosteal surface. The two parts are then divided: one part consists of the internal and external branches of the deep peroneal nerve's terminal branches, and the other consists of the first and second dorsal metatarsal vascular bundles. Next, a bone flap measuring 1.0 × 0.5 × 0.5 cm is intercepted with a small swing saw. The periosteal germinative layer is paced outwards, and the periosteal flap is made into a spare wand using absorbable sutures. The proximal end of the first or second dorsal metatarsal artery is subsequently cut and ligatured. The bone or periosteal flap is separated to the distal end, so the vascular pedicle can be successfully transposed in the osteotomy; however, it should not exceed the Martin-Gruber anastomosis point ~2 cm from the first or second web space edge.

4. Bone flap displacement

   The second metatarsal head is revealed, all of the cartilage fragments in the joint cavity are removed, the proliferated synovial is cut, the osteophyte is chiseled, the metatarsal head is dressed and polished with a bone file. A groove hole ~0.5 cm deep is drilled at the proximal enlargement tuberosity at the back of the second metatarsal head; the groove hole should be 0.5 cm wide, 0.5 cm deep, and 1 cm long. The dead bone and granulation tissue in the head are removed. If necessary, a small amount of cancellous bone from the proximal end of the metatarsal can be applied to fill the head. The bone or periosteal flap is implanted into the cave to suture the periosteum and soft tissue. If the cartilage surface of the metatarsal head has been damaged, the dorsal fascia of the adjacent pedicle bone can be used to encircle it after trimming. The bone is fixed with a plaster footrest for 8 weeks (Fig. 20.65).

20.8.4.2 Vascular Bundle Implantation

Free Anatomy of the First Dorsal Metatarsal Arteriovenous Bundle

The starting point of the first dorsal metatarsal arteriovenous is present in the dorsal arteriovenous bundle. The first dorsal metatarsal arteriovenous is dissected to the first and second dorsal branches along this point to the distal. The method of cutting the first dorsal metatarsal arteriovenous bundle is subsequently selected on the basis of the position and range of the metatarsal head necrosis:

1. The first dorsal metatarsal arteriovenous is cut at the starting point of the instep arteriovenous, forming retrograde vascular bundles.
2. The first dorsal metatarsal arteriovenous bundle and first or second dorsalis medialis are freed. A sufficient length is obtained for use as vascular bundles.
3. A piece measuring 2 × 1.5 cm is cut from the first metatarsal head and neck periosteum from the branch of the first dorsal metatarsal arteriovenous bundle; this will form the first venae metatarsales dorsales as a vascular pedicle for the periosteal flap.

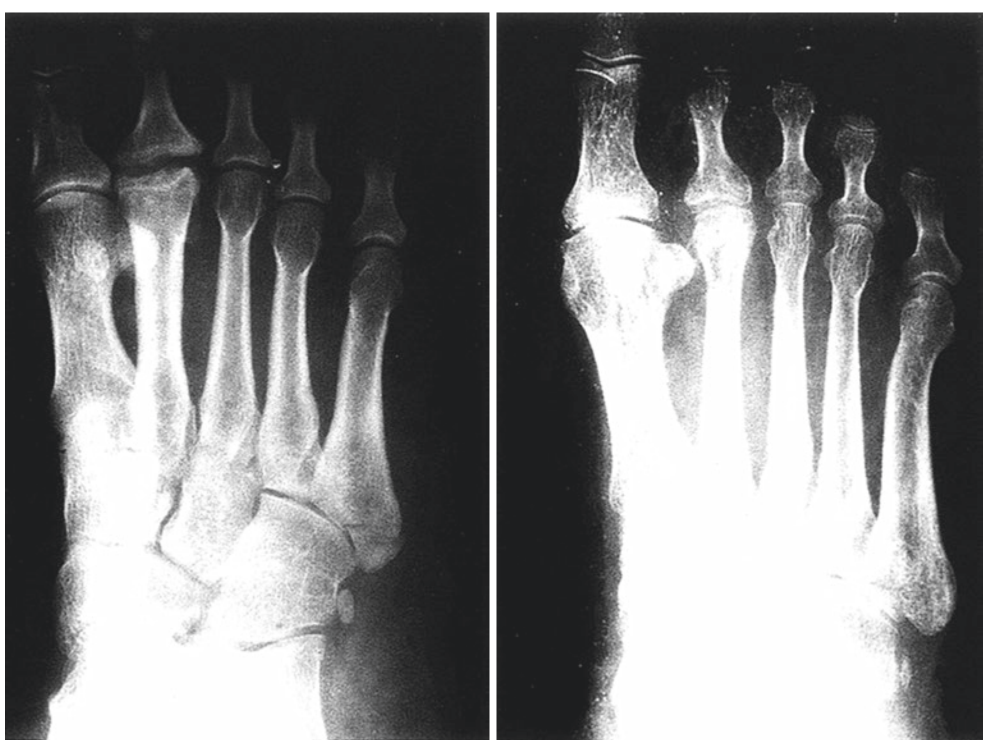


Fig. 20.65 Transplanted vascular pedicle of the first dorsal metatarsal and first metatarsal flap to repair the second metatarsal head necrosis. Left: Preoperative radiograph, right: Postoperative radiograph

Metatarsal Head Preparation

The metatarsophalangeal joint is cut, free bone fragments in the joint are cleared, and 4–6 holes 0.8 mm in diameter are bored on the metatarsal head with a Kirschner wire. Holes on the tibial end of the metatarsal head are drilled. The sequestra and sclerotic bones are scraped to loosen the bone holes. For example, the periosteum transplantation requires bone slots with an appropriate size. Patients with severely fragmented metatarsal heads require periosteum embedment.

Vascular Bundle Implantation

The free first dorsal metatarsal arteriovenous bundle or periosteal flap is implanted into the bone and a suture is made. The bone is fixed with a plaster footrest for 4–6 weeks. Treatments to prevent spasms and blood clotting should be adopted for 3–5 days. The patient can walk with their heel after removing the stitches and can walk with weight on the front foot.

20.8.5 Outlook

Bone marrow stem cells have multi-lineage differentiation potential. They can differentiate into osteoblasts, vascular endothelial cells, and other cells under the influence of the microcirculation environment, stress, and blood supply conditions in vivo. Therefore, they are an important material for constructing tissue engineered bone. Today, autologous marrow stem cell transplantation is a prominent topic in the field of osteonecrosis treatment. Autologous marrow stem cell transplantation safely and effectively repairs damaged bone tissue and improves blood supply system. Furthermore, there are no ethical problems or exclusive problems. Several issues require further study regarding bone marrow stem cell transplantation in the treatment of osteonecrosis. However, the use of bone marrow stem cell transplantation in the treatment of osteonecrosis is promising. Stem cell transplantation is expected to become a novel and effective means of treating Freiberg disease in the near future.

Microsurgery of Bone Disease and Bone Tumor

21

Jing Li, Lei Shi, Chun Zhang, Jianli Wang, and Guangjun Liu

21.1 Microsurgery for Osteopathy and Bone Tumor

Jing Li and Lei Shi

21.1.1 Part 1: Overview

Tumorous bone removal or resection is the most common method to treat osteopathy and bone tumor. However, a large bone defect after lesion removal brings about a challenge of reconstruction for surgeons. Introduction of artificial metal prosthesis is a great progress in reconstruction of large bone defects. With advantages of simple operation, immediate stability after surgery, reliable functional rehabilitation, few complications at the early stage, prosthesis reconstruction becomes an important reconstructive method of limb salvage for osteopathy and malignant bone tumor. But in recent years, its clinical application takes on a declining trend. A major reason is that the number of failed artificial prosthesis reconstruction increases remarkably due to long-term complications (such as loosening, infection, fracture, etc) (The survival rate of prosthesis in 10 years is about 63%). Thus, biological reconstruction gradually becomes the mainstream management for segmental bone defects caused by osteopathy or bone tumor.

Biological reconstruction includes autogenous bone and allogeneic bone transplantation. Its outcomes are somehow opposite to those of prosthesis construction. It is more complicated in surgical procedures and leads to more early-stage complications, but 3–5 years later, almost no complication will occur. So its effects are more lasting.

Common features of all biological reconstructions are integration, adaption, regeneration and replacement of bone structure with the patient's own potentials. The condition of receptor bed (including circulation and soft tissue coverage) is crucial throughout all the processes. So, two aspects should be considered for biological reconstruction: (1) the soft tissue condition of the recipient area after tumor resection, and (2) the age of the patients (better regeneration ability in young patients).

Vascularized bone grafting is an important method to biologically reconstruct segmental bone defects after tumor resection in micro-orthopedics. It includes transplantation of vascularized ilium, fibula, rib, scapula, etc. Each of the donors has its own indications, advantages and disadvantages. For reconstruction of common bone defects after tutor resection, vascularized fibular grafting is the most frequently used.

21.1.2 Part 2: Application of Vascularized Fibula in Reconstruction of Bone Tumor and Limb Salvage

21.1.2.1 Overview

In 1884, Hahn completed the first case of vascularized fibular grafting for tibial pseudarthrosis. In 1911, Walter reported free nonvascularized fibular grafting. In 1973, Ueba completed the first reconstruction of bone defects after neurofibrosarcoma with free vascularized fibula, but he reported it in literature 9 years later [1]. Consequently, Taylor is regarded as the first surgeon who described free vascularied fibular grafting technique and applied it in bone defect reconstruction [2]. Vascularized fibular flap grafting is an important method to rebuild a segmental bone defect longer than 6 cm. Since Yoshimura [3] introduced free fibular composite tissue flap transplanted with a monitoring skin island in 1983, this technique has been gradually applied in reconstruction of

J. Li (✉) · L. Shi
Department of Orthopaedics, Xijing Hospital, Air Force Medical University, Xi'an, P. R. China

C. Zhang (✉)
Department of Orthopedics, Zhejiang Tong De Hospital, Hangzhou, Zhejiang, China

J. Wang (✉) · G. Liu
Department of Orthopaedics, PLA 89th Hospital, Weifang, China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_21

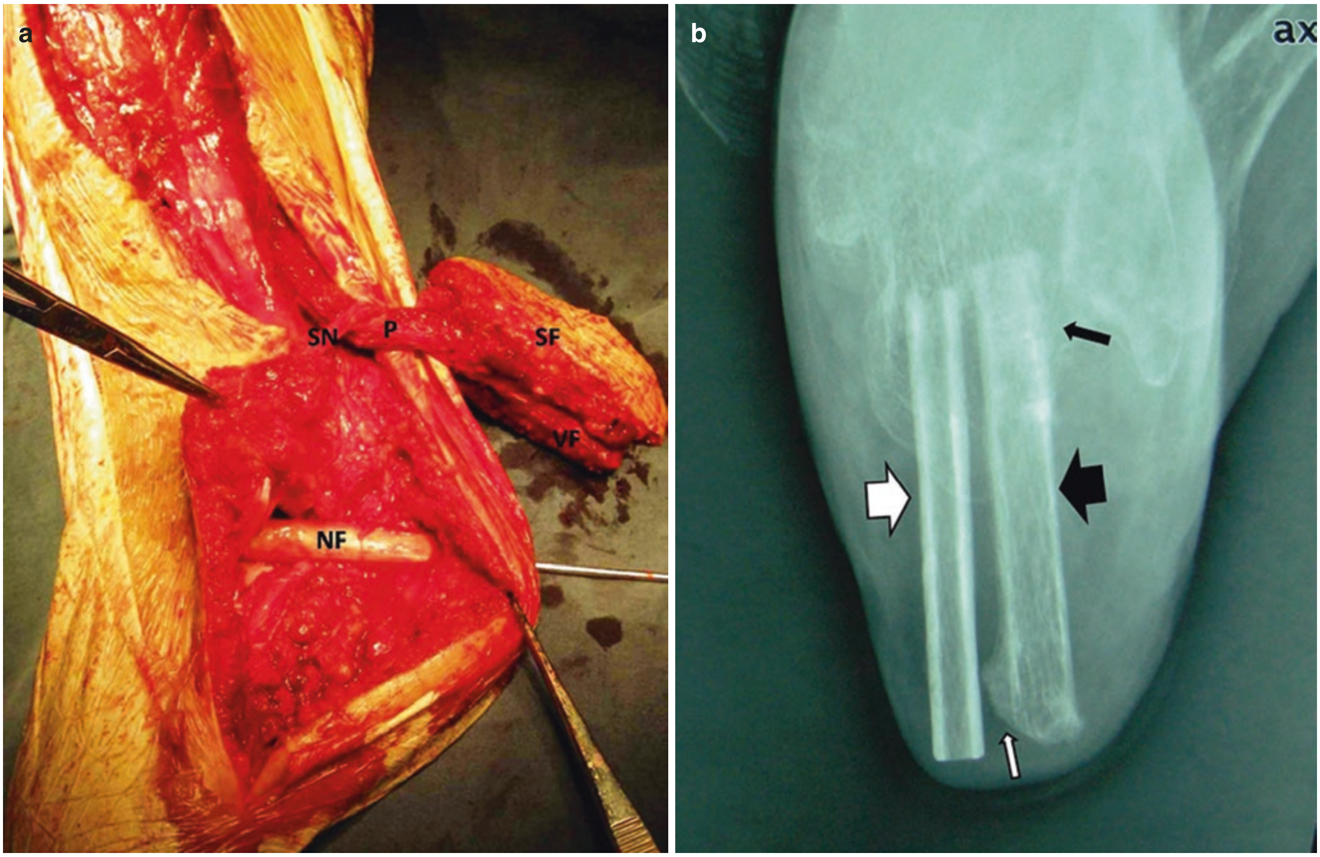


Fig. 21.1 (**a**) Fibular flap transfer: the no vascularized fibula (NF) has been fixed with Kirschner's pin; the vascularized fibular skin flap is prepared for retrograde transfer and is arranged in parallel with the former to reconstruct the calcaneus. *P* vascular pedicle, *SN* sural nerve, *SF* skin flap, *VF* vascular bone flap. (**b**) One year after operation, X-ray films shows the response of different segments of the same fibula to stress stimulation: the vascularized fibula (black thick arrow) is significantly thicker than the non-vascularized fibula (white thick arrow). The proximal vascularized fibula fuses well with the talus junction (black thin arrow); the stress callus forms at the loading end (white thin arrow), and there is no bone remodeling at the corresponding non-vascularized fibula

segmental bone defects caused by malignant bone tumor resection and developed into different types of operation. There are two advantages in using vascularized fibula to reconstruct massive bone defects after bone tumor resection.

1. Autogenous bone transplantation

   After reconstruction by vascularized fibular grafting, blood circulation of bone can be immediately recovered while the creeping substitution process [4] in avascularized bone graft and rejection [5] in allogeneic bone graft are avoided. The healing process of grafted bone and stump bone in the recipient area is almost identical with that of a common fracture. The healing (union) rate of vascularized fibula and recipient bone at 2–12 months after the surgery is 71–100%. Even if healing is delayed or unsuccessful, proper treatment can raise the healing rate up to as high as 90–100%.

2. Biological remodeling capacity

   As vascularized fibular grafting retains circulation in endosteum and periosteum, the biological behavior is equivalent to that of normal living bone, showing remodeling capacity [6]. It can react against stress stimulation and become thickened [7] (Fig. 21.1). Because the circulation of growth cartilage plate is reserved in epiphysis transplantation, it provides not only a remodelable articular surface but also potential of longitudinal growth in growing children [8]. It is of great significance for limb length maintenance and arthrosis remodeling of malignant tumor limb salvage surgery in children.

21.1.2.2 Anatomic Basis for Fibular Tissue Flap Transplantation

1. Anatomy of fibular diaphysis blood supply [9]

   Fibular diaphysis blood supply mainly derives from the fibular nutrient artery and fibular arcuate artery. Most fibular arteries are branches of the tibiofibular diaphysis, with a few originating from popliteal vessels, posterior tibial arteries or anterior tibial arteries, with two accompanying veins. It originates from the posterior tibial tibiofibular diaphysis about 6.6 cm below the fibular head mucro, expands from interior upwards to exterior downwards within soleus, tibialis posterior and flexor hallucis longus, and finally ends up at heel lateral arteries. The fibular vessel bundle is in the pipe enclosed by the fibula (anterolateral), tibialis posterior (anterior and interior) and flexor hallucis longus (posterior). There is generally one nutrient artery, sometimes 2–3. It often goes from the middle fibula into the fibular marrow cavity, and falls into upper and lower sub-arteries (this is why clinical fibular diaphysis grafting often selects middle 1/3 of the diaphysis), within 1/2 to 2/3 of the nutrient cortex. Arcuate artery is a segmental fibular annular blood vessel surrounded by the peroneal artery. It surrounds the fibula in an arch shape and grows in muscles and feeds periosteum and 1/3 of the exterior cortex. The amount of arcuate artery varies, and the average number is 9. In the middle diaphysis, it grows horizontally, and in the lower diaphysis, it grows spirally. In the interior, it is 1 cm from the fibula; in the anterolateral, it is only 0.3 cm from the fibula.

The peroneal artery has some septal cutaneous branches and muscular cutaneous branches to feed skin on the fibular surface in the lateral crus. Septal cutaneous branches grow in posterior intermuscular septum. While muscular cutaneous branches first go through flexor hallucis longus, tibialis posterior or soleus, and then enter crus posterior intermuscular septum. All the cutaneous branches go into the intervals between fibular muscle and soleus. The number of cutaneous branches is 3–6, and they distribute segmentally on the fibular diaphysis. In free fibular flap transplantation with the accompany of these cutaneous branches, cutaneous fibular flap can be taken and used for bone and soft tissue repair (Fig. 21.2).

Some branches below the peroneal artery intersect with the posterior tibial artery. In the vicinity of tibiofibula interosseous membrane margin, some branches penetrate to the front of interosseous membrane, and have anastomoses with lateral malleolar branches of anterior tibial artery and tarsal branches of dorsalis pedis artery. They have anastomoses with branches of the posterior tibial artery and the ultimate lateral malleolar branches and calcaneus branches. These anastomoses structures are the anatomic basis for reconstruction of the calcaneus and distal tibia by reversed fibular flap transposition.

2. Anatomy of fibular epiphysis growth plate blood supply

Before the closure of fibular epiphyseal plate, the blood supply to fibular epiphysis and diaphysis comes from different feeding arteries. Study on the blood supply to fibular epiphysis initiated from the 1980s [10]. With the growth plate as boundary, the blood supply near the fibula can be divided into two parts. Peroneal artery can feed cells near the fibula, hypertrophic zone and calcification zone of the growth plate. The blood supply can cause calcification and death of cells in the hypertrophic zone. If the blood supply is damaged, cells in the hypertrophic zone are not to die, leading to fast growth of the epiphysis lengthways. Blood supply near the epiphysis and growth plate (cells in germinal and proliferative zones) originates from two sources: one is the lateral inferior genicular artery (LIGA). It independently originates from popliteal vessels, and is divided into anterior and posterior branches to feed the epiphysis. The anterior branches are thinner, and the posterior branches are thicker. The other is the fibular neck artery (FNA) (mostly originating from interosseous membrane posterior branches of anterior tibial artery and a few from popliteal vessel) generated from the anterior tibial artery when it passes interosseous membrane as well as anterior tibial recurrent artery (ATRA) after it passes interosseous membrane. Simultaneous damage to the two blood supply systems will make the epiphysis stop growing. The anastomosis among LIGA, FNA and ATRA determines that any separate blood supply of one vessel can make proximal epiphysis survive, and realize the purpose of fibular epiphysis transplantation (Fig. 21.3).

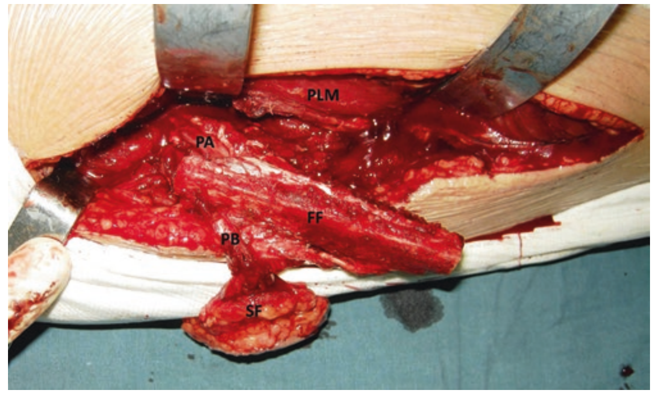


Fig. 21.2 After the fibular skin flap is completely free, the tourniquet is loosened before the pedicle is cut, which proves that the muscle sleeve, medullary cavity and the skin flap are bleeding well. *PLM* peroneal long muscle, *PA* peroneal artery, *PB* cutaneous branch of peroneal artery, *FF* fibular vascular bone flap, *SF* peroneal vascular skin flap

Clinical epiphysis grafting often needs accompany of the diaphysis in a certain length. The blood supply modes of fibular proximal grafting have two alternatives: one is the anastomosis of two sets of blood vessels (LIGA supplies blood for epiphysis and proximal growth plate, and peroneal artery supplies blood for distal growth plate and diaphysis) [11–13]. The anatomy study by Taylor & Bonnel shows that the blood supply to fibular epiphysis and proximal diaphyses can be ensured by feeding circulation of

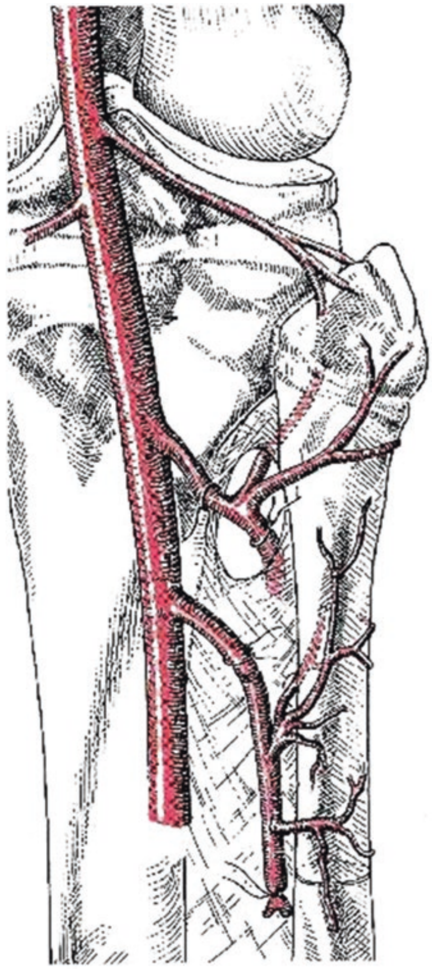


Fig. 21.3 Schematic diagram of blood supply of fibular head

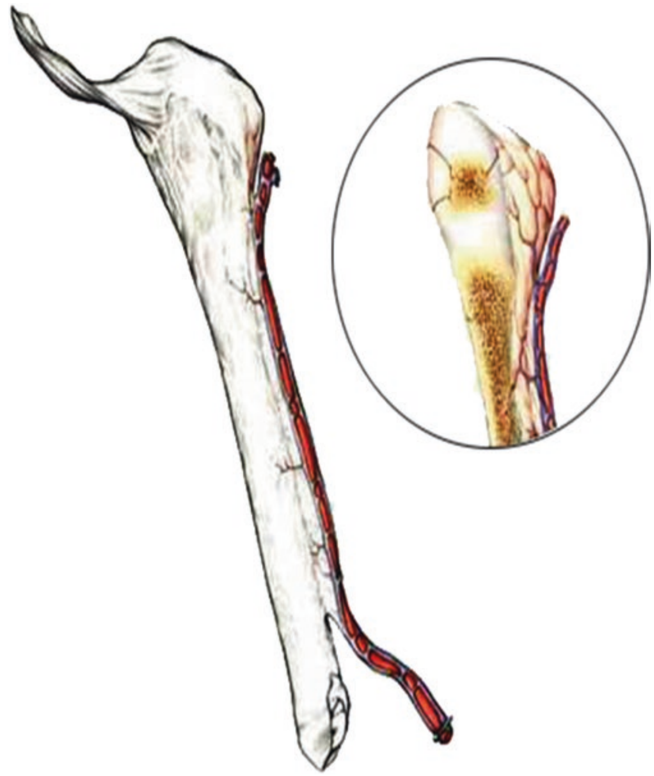


Fig. 21.4 Diagram of fibular epiphysis with retrograde blood supply from distal anterior tibial artery

epiphysis plate with anterior tibiofibular recurrent artery epiphysis branches and feeding circulation of proximal 1/2 to 2/3 fibular diaphysis with muscle periosteum branches (Fig. 21.4) [14]. The research by Restrepo shows that anterior tibial artery, through AON (a branch of anterior tibial artery before it goes through interosseous membrane, 80% occurrence), can anastomose with peroneal artery and genicular descending lateral artery. So singular anastomosis with anterior tibial vessel can supply blood for transplantation of fibular proximal epiphysis and diaphysis.

21.1.2.3 Clinical Application

1. Indications

   Free fibular grafting is often used in reconstruction of large segmental defects of long bone [15], especially intercalary reconstruction [16]. It may also used for arthrodesis of shoulder, knee and ankle [17].

   Fibular grafting includes singular fibular transplantation and barrel folded transplantation. Singular fibular reconstruction is mainly applied for the defects of long bone whose caliber is similar to that of the fibula, such as radius and ulna, metatarsus, middle-lower humerus, middle tibia, etc. It can also be used in femur reconstruction for children who have great remodeling potential. Barrel folded reconstruction is mainly used for the femur and tibia which have greatly different calibers from that of the fibula and bear great load stress [18].
2. Resection and fixation of proximal free fibular flap
   (a) Incision: It starts at the front of fibular head, and goes along the anterior fibula margin toward 5 cm above the distal ankle joint.
   (b) Make the incision till the deep fascia. Dissect backwards in the deep fascia, and upturn the deep fascia flap backwards to the posterior margin of peroneus longus and brevis muscles. Pull the peroneus longus and brevis muscles forwards, and carefully search the vascular cutaneous branches between the soleus and the fibula. Adjust flap position in accordance with the positions of cutaneous branches.
   (c) Peroneus longus and brevis muscles are dissected sharply from the fibula, and 3 mm muscle sleeve is reserved to protect the arcuate artery. Upturn peroneus longus and brevis muscles forwards to reveal anterior tibiofibular interval. Incise extensor hallucis longus and extensor digitorum longus from fibular surface to expose tibiofibular interosseous membrane.
   (d) Incise the fibula from preconcerted osteotomy surface periosteum, truncate it and turn it outwards. Incise interosseous membrane to enter posterior tibiofibular interval. Start the incision 1 cm from the

distal osteotomy surface, cut extensor hallucis longus open to reveal peroneal vessels and ligate it. Incise flap posterior margin to the lower deep fascia. Protect the continuity between cutaneous branches and crus lateral flap, and avoid unnecessary pulling.

(e) Incise along peroneal vessels cephalad to truncate fibular enthesis muscles (mainly extensor hallucis longus) and cut open tibial peroneal vessels, and protect arcuate artery emanated from peroneal vessels. Carefully ligate cutaneous branches anastomosis between fibular vessel and posterior tibial vessel. Dissociate fibular vessel to the starting point of tibiofibular diaphysis.

(f) Release tourniquet and observe the bleeding at the medullary cavity of free fibular broken end and muscle cuff. Cut off peroneal vessel in the junction of peroneal vessel and tibiofibular diaphysis to complete the bone flap harvest.

(g) Key points to the surgery
- Conduct radiography or ultrasound test before surgery to confirm the existence of fibular vessels.
- Conduct ultrasound test before surgery to find cutaneous branches, which helps skin flap design.
- Inclusion of nutrient vessels of middle fibular diaphysis in the resection scope is essential for fibular blood supply.
- Operate gently to maximize the reservation of arcuate muscle-periosteum vessels.
- Carefully ligate anastomosis between fibular vessel and posterior tibial vessel to avoid post-operative hematoma.

(h) Fixation method

The fixation methods for fibular grafting are various. The basic principle is to maximize the stability of the recipient area without affecting fibular circulation. Tools like external fixator, intramedullary needle, and bridge-type locking plate can be used. A typical case is the reconstruction of forearm bone and soft tissue defects with free fibular flap (Fig. 21.5).

(i) Circulation reconstruction

Generally, fibular vessels include one vein and two arteries; if possible all the vessels should be sutured. In case of poor vascular condition in the recipient area, satisfactory venous return can be realized by singular suture of a thick fibular vein.

3. Complications and prevention

(a) Bone nonunion

The occurrence of bone ununion is about 10–29% when vascularized fibular grafting is used for reconstruction of segmental bone defects [19]. The occurrence of bone ununion for lower limb reconstruction is 14–31%, higher than that for upper limb reconstruction (9–26%). This might have something to do with circulation reconstruction reliability, fixation method, grafted bone, etc. [20]. Compared with extramedullary fixation, the occurrence of bone ununion for intramedullary fixation is higher. Presumably this is related to blood supply and distribution of cortical bone. One week after the surgery, ECT can largely reflect the survival status of a grafted bone. The occurrence of bone ununion for non-perfused fibula is much higher than that for perfused fibula. First-stage grafting of cancellous bone can

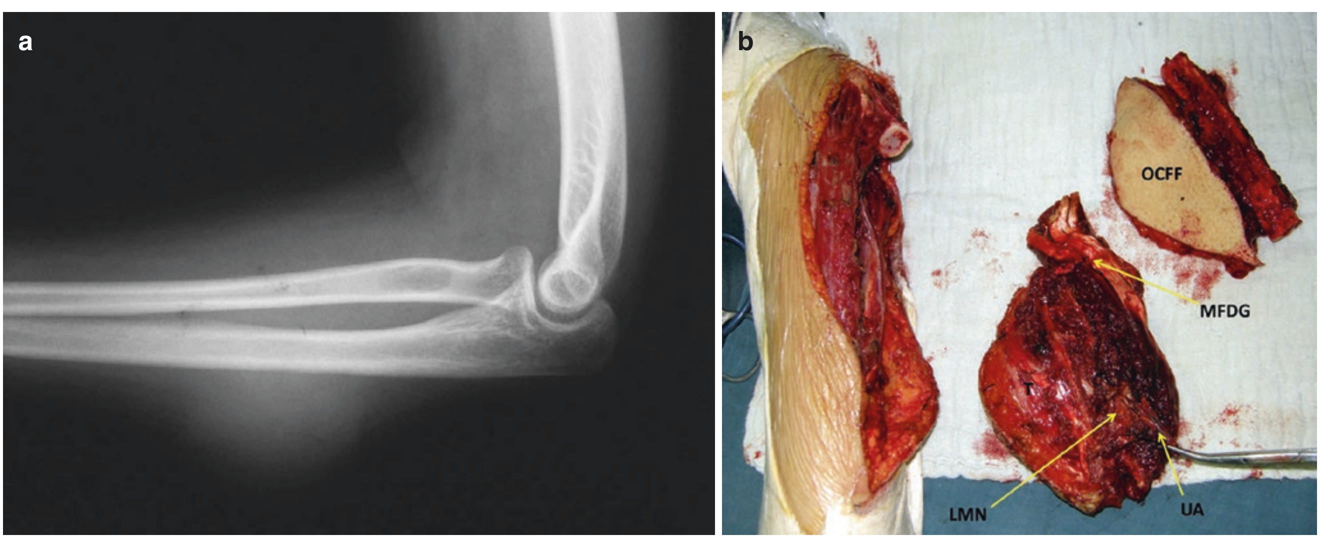


Fig. 21.5 (**a**) Lateral radiograph of forearm rhabdomyosarcoma shows soft tissue shadow of the tumor. The ulna and ulnar vessels were invaded by tumors in this case. (**b**) The tumors are removed and the fibular flaps matching the size of the defect are cut. *T* tumor, *UA* ulnar artery, *OCFF* fibular flap. (**c**) Fibula skin flap for repairing ulna and ulnar soft tissue and vascular defects. The two ends of peroneal vessels were anastomosed with the two ends of ulnar vessels (flow through technique). After the fibula is stuck into the ulna defect, it is fixed with a plate. Attention should be paid to the less screw on the fibula to avoid its influence on the bone circulation. *FF* the bone flaps of fibula flaps, *U* ulna, *SF* skin flaps, *VA* vascular anastomosis. (**d**) 8 weeks after surgery, distal junction (blue arrow) heals; proximal junction (yellow arrow) achieves clinical healing. (**e**) Appearance and function 8 weeks after operation

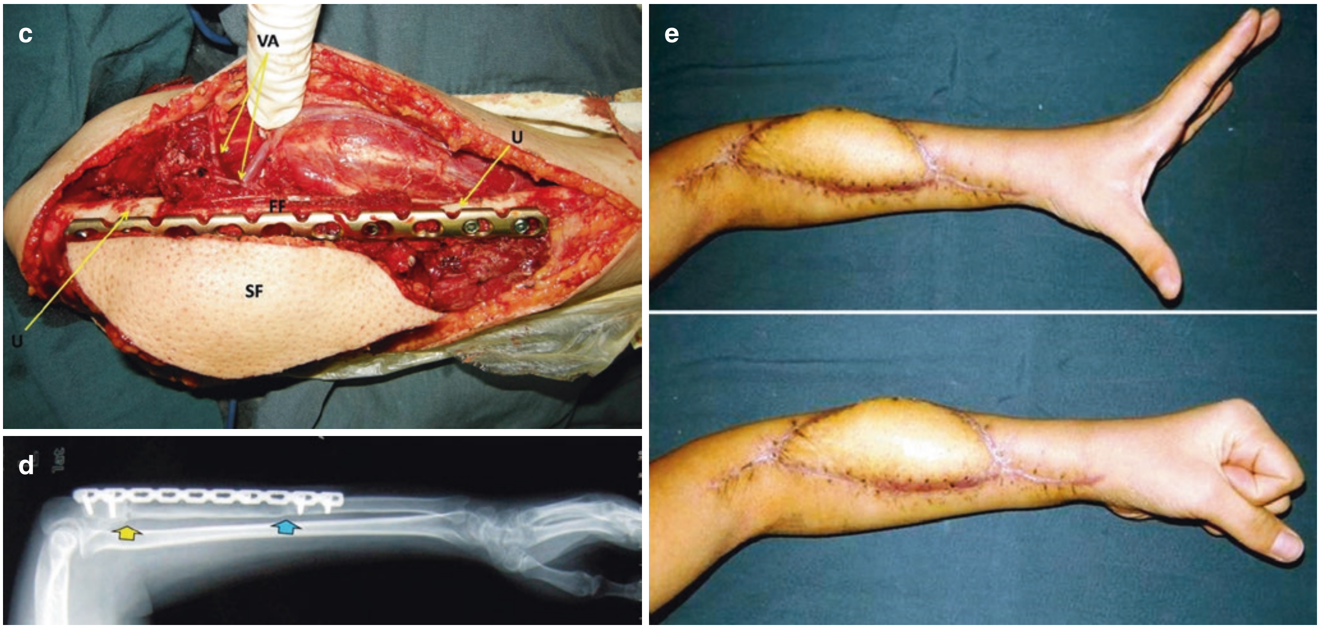


Fig. 21.5 (continued)

reduce the occurrence of bone ununion [21]. So, please pay attention to the following four aspects:

- Strict and rigorous operation to ensure reliable circulation after fibular grafting [22].
- The fixation should maximally avoid interference with circulation of the grafted bone and achieve early stability as soon as possible.
- Junction should be carefully treated. Since intercalary or scalariform junction can enlarge the contact between grafted fibula and recipient area, it is good for bone healing. For cases with a risk of delayed healing, we can consider using autologous cancellous bone grafting in the junction.
- In cases where early circulation reconstruction fails, make sure to lengthen external fixation time and strengthen the reliability of external fixation.

(b) Stress fracture

Due to factors like caliber difference, post-operation remodeling, etc, fracture is a common complication of fibula grafting. When the fibula is used for humerus reconstruction, the incidence of fracture is about 12–50%. When the fibula is used for reconstruction of radius & ulna and metatarsus (caliber similar to the fibular one), the incidence of fracture is quite low. When the fibula is used for lower limb reconstruction, the incidence is remarkably higher than that for upper limb, up to 60–100% as reported. Although most fractures can be cured through conservative treatment, some cases still need revision surgery. Fixation method is also a factor associated with stress fracture after operation. The incidence of fracture for intramedullary fixation is lower than that for extramedullary fixation. After extramedullary fixation is removed, stress fracture is likely to occur at the screw position. To prevent stress fracture, we should:

- Choose a proper fixation method. We recommend locking-plate cross-fibula fixation to enhance fixation capability and not to influence fibular blood circulation and biomechanical performance.
- Choose a proper indication. Singular fibular reconstruction is mainly applied to reconstruct radius & ulna as well as children's humerus. For femur and tibia reconstruction, we recommend barrel folded reconstruction or composite reconstruction (composite allogeneic bone or osteogenesis-based autologous inactivated tumor bone).
- Regular check. If signs of stress microfracture are found, immediately enhance the stability (e.g. add external fixation) to decrease stress load.
- Internal fixation should not be removed or removed too early. If it is necessary to be removed, proper protection should be provided.

(c) Infection

Most clinical researches show no association between infection and reconstruction sites. The Mayo clinic center showed that the infection rate of upper limb was higher than that of lower limb in a case series, presumably due to poor soft tissue coverage after tumor resection. So, the reconstructed site should be covered by a tissue flap transplanted to reduce the infection that might be caused by poor soft tissue coverage after tumor resection.

4. Bone ununion and fracture after large allogeneic bone surgery

Chang and Weber first applied vascularized fibula in revision surgery for bone ununion between host bone and allogeneic bone. They reported that 5 of the 6 patients were cured by the primary operation and the remaining one was also cured by vascularized fibular grafting twice [23]. Bae applied fibular grafting in the revision surgery of allogeneic bone fracture and ununion. Of the 8 patients treated, they cured 7 [24]. Friedrich used vascularized fibular grafting to treat complications following massive allogeneic bone surgery (bone ununion between parasitifer-allogeneic bone, allogeneic bone fracture and infection) in 33 cases. All the fractures and ununions were healed in an average time of 7.7 months [25]. So, vascularized fibular grafting can be used as a remedial surgery for unsuccessful allogeneic bone grafting.

5. Foot limb salvage

Foot sarcoma is rare. Of all the sarcomas, its incidence is less than 2%. Metastatic tumor and marrow tumor are also rare. The most common primary malignant foot tumors are osteosarcoma, Ewings sarcoma and synovial sarcoma. Subgenual amputation is a main treatment for primary malignant foot tumors. However, according to the clinical practice in the recent decade, if we can acquire safe surgical resection margin and loaded reconstruction can satisfy physiological needs, limb salvage surgery can achieve ideal control of the tumor and foot function in some selective cases [26]. A typical case is reconstruction of rear foot defects by distal vascularized fibular flap [27] (Fig. 21.6).

(a) Malignant foot tumor and limb salvage surgery
- Surgical margin
- There are many complex joints in foot which are closely connected. Cortical bone in the middle-rear foot is thin and full of nervus vascularises. Malignant foot tumor is apt to penetrate bone cortex to become exterior mesooecium tumor. Soft tissue synovial sarcoma of the foot has an implicit onset, often involving multiple joints through synovium. Preoperative MRI evaluation is crucial for confirmation of tumor and surgery scope. If a salvage surgery has to be performed, the resection margin must be safe.
- Characteristics of soft tissue
- Bone is closely connected with soft tissues. In tumor resection, some soft tissues often need to be removed to obtain safe surgical margins. If the tumor involves tarsal tunnel area, medial and lateral plantar nerves and blood vessels or most plantar soft tissues should be removed. After the surgery, the bottom of foot will lose sensations. This is a relative contraindication for limb salvage surgery.
- Biomechanical characteristics
- Three-point load is an important biomechanical characteristic of foot. Since amputation of toe tumor has little influence on function, reconstruction is unnecessary. Limb salvage surgery is mainly to restore or reconstruct load walking function. So, surgical design and choice should be aimed at the load three-point area and the connected mid-foot area. If two or more sites in the load three-point area and mid-foot area need to be removed, the surgery will be complicated and the function will not be restored perfectly after reconstruction. So limb salvage surgery is not advisable.
- Choice of reconstruction methods
- Foot reconstruction methods include prosthesis, allogeneic bone, free vascularized ilium, vascular-

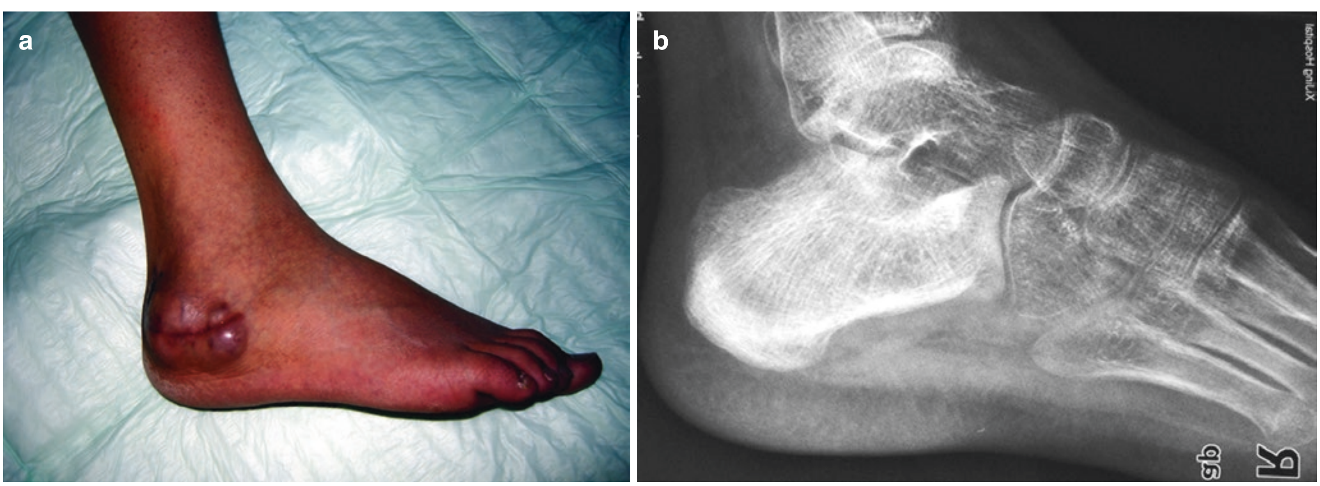


Fig. 21.6 (**a**) Soft tissue mass formed by calcaneal malignant tumor. (**b**) Preoperative X-ray. (**c**) Sagittal splitting of calcaneal tumors after total resection: The tumor grows diffusely in the calcaneus, with unclear boundaries, but do not protrude into the subtalar joints and the calcaneocuboid joints. The blue line in the picture shows the extent of the tumor in the bone. (**d**) Distal pedicled fibular flap was locally transferred to the defect area after tumor resection. *G* gastrocnemius, *PLM* fibula longus, *FF* fibula flap, *SF* fibula flap, *PA* distal pedicle of peroneal vessels, *D* defect after tumor resection. (**e**) Reconstructed the appearance. The fibular skin flap is used to repair the heel area and the donor area is closed by free skin graft. *OCFF* fibular flap, *SG* skin grafting area. (**f**) The load-bearing area becomes smooth (blue arrow) and the stress callus (yellow arrow) forms behind the fusion area of talus. (**g**) Reconstructed calcaneus SPET-CT shows that the two fibulas weight-bearing ends are fused and the reconstructed calcaneus metabolizes well. After weight-bearing, "calcaneal ossification" occurs in both fibulas

Fig. 21.6 (continued)

ized fibula, etc. Malawer reported a reconstruction with custom-made prosthesis for calcaneus tumor. Pure allogeneic bone reconstruction has disadvantages of infection, long-term collapse, impossibility to reconstruct soft tissue defects simultaneously. Because biological reconstruction, especially vascularized autologous bone transplantation, can simultaneously reconstruct bone and soft tissues, it is widely applied in clinic.

- Vascularized fibula has the following advantages as a reconstruction material for foot:
  - With the increase of load stress, living bone reconstruction can thicken modeling.
  - Because the fibular head is like the metatarsal head, it is an ideal material for reconstruction of forefoot load sites.
  - As cortical bone has enough strength, it can be used for heel area reconstruction after double folded to provide adequate load strength.
  - As fibular flap can simultaneously reconstruct bone and soft tissue defects, it is applicable for front-mid foot tumor which often involves soft tissue.
  - The close connection between bone and soft tissue flap is good for shock absorption and load functional restoration after reconstruction.
  - Since the flap is close to foot, reversed vascularized transposition without vascular anastomosis can be used to reconstruct foot defects.
  - Because complications at the donor site are few, amputation will not cause global sacrifice in case of tumor recurrence.

(b) Distal-pedicle fibular flap resection [27]

- Incision: It starts at the front of fibular head, goes along the anterior fibula margin towards the distal ankle surface, and connects the heel area in the posterior lateral malleolus.

- Cut along the anterior flap margin to beneath the deep fascia, upturn the flap from the peroneus longus surface to the posterior lateral crus interval and soleus surface to find the peroneal vessel cutaneous branches. Adjust flap size and direction in accordance with the positions of cutaneous branches.
- Upturn peroneus longus and brevis muscles forward to reveal anterior tibial interval and incise extensor hallucis longus and extensor digitorum longus from fibular surface.
- Dissect fibula from periosteum, cut it off at the preconcerted osteotomy plane, and then turn fibula outwards. Incise interosseous membrane to enter posterior tibial interval. Reveal fibular vessel on the proximal osteotomy surface.
- Incise proximal flap and posterior margin. Dissociate fibular vessels at the starting point, cut off and ligate it. Dissociate distal tissue flap, and protect the connection among fibular vessel, fibula and skin perforator vessel.
- Dissociate vascular pedicle on the distal osteotomy plane. Minimal involvement of soft tissues is good for reversed flap transposition. Dissociate fibular vascular pedicle toward the distal end until the fibular vessel sends out interosseous membrane perforating branches.
- Trimming of the fibula: Resect 2–3 cm in the mid-fibula, fold the left fibula and make sure the two parts are parallel and free of stress. Rub down the load surface. Insert the fibula in the bone groove between the astragalus and articular surface.
- Fix the fibula and astragalus with Kirschner wire.
- Anastomose calf lateral nervus cutaneous and dorsalis pedis interior nervus cutaneous to rebuild flap sensation.

(c) The surgical key points

- Confirm the anastomosis of peroneal vessels and anterior and posterior tibial vessels by per-operation angiography. This is the key to the feasibility of fibular flap surgery with reversed blood supply.
- When fibular vascular pedicle is dissociated towards the distal end, certain muscle sleeves should be reserved to avoid unwanted interference with the pedicle.
- Residual distal fibula is a typical reason for the difficult dissection of the distal pedicle. This fibular part can be resected first, and then replaced and fixed after vascular pedicle dissociation.
- After the transposition of composite fibular flap, torsion or press on the fibular vascular pedicle must be carefully observed. Special attention should be paid to the torsion of cutaneous branches and proper adjustments should be made as soon as possible.
- After the transposition of distal pedicle, the most common complication is flap crisis or even necrosis in some flaps due to inadequate venous return. After transposition fixation, carefully observe flap color and fullness of the fibular vein trunk. Hindered return or vein trunk distension should be handled properly at once. The great and small saphenous veins can be anastomosed with the fibular vein to increase venous return. If a flap crisis occurs 1–3 days after operation, the fibular vein should be cut open. Meanwhile, skin drainage can be used to establish temporary arteriovenous balance. One week later, after the left and right collateral branches are anastomosed, the crisis can be mitigated.

6. Children epiphysis reconstruction

(a) Indications

There are two challenges in the reconstruction after en bloc resection of malignant bone tumor involving children long-bone epiphysis. One is the reconstruction of articular cartilage surface and the other is the reconstruction of longitudinal growth ability after epiphyseal plate resection. However, the two problems cannot be resolved by non-circulatory autologous bone, allogeneic bone or artificial prosthesis, etc. After the transplantation of vascularized fibular proximal epiphysis, the growth plate has the potential of longitudinal growing ability. Articular surface can also be remolded by stress stimulation. The biological advantages make vascularized fibular proximal epiphysis transplantation particularly suitable for reconstruction following the malignant tumor resection involving children epiphysis [28].

An important sign for the success of epiphysis grafting is survival of the growth plate as well as existence of certain physiological functions. In the early stage, based on anatomy study on the epiphysis circulation and experimentation on animals, two types of grafting surgery with two different blood supplies were established. However they did not achieve ideal clinical effects. Tsai reported eight cases of double blood-supply fibular epiphysis grafting for reconstruction of congenital bone defects or epiphysis blockage caused by trauma or infection (six cases adopted descending genicular artery and anterior/posterior tibial artery and two cases adopted descending genicular artery and peroneal artery). The ages of patients were between 2 and 11 years, and the duration of follow-up was 1–4.5 years. The growth rate of epiphysis was 0–1.2 cm/year or so. At the end of follow-up, 4 patients' epiphysis still had some growth potential. The other 4 patients' epiphysis closed in advance. It was inferred that the failure was caused by warm ischemic injury to the epiphyseal plate cells or vascular grafting failure due to epiphyseal plate damage or excessive time of grafting.

Anatomy perfusion study shows that anterior tibial artery and tibial vessel anastomose in both outer periosteum and inner medullary cavity. The perfusion study on proximal anterior tibial artery shows that after perfusion, both fibular proximal periosteum (11.8 cm) and inner medullary cavity (10.9 cm) are colored, indicating that single blood supply by anterior tibial vessel can supply blood for 12 cm proximal fibular diaphysis. Based on this, Menezes used anterior tibial vessel as the blood supply to the fibular epiphysis and the proximal 1/2 part to reconstruct defects after humerus proximal osteosarcoma resection for a child. The follow-up proved that the epiphyseal plate survived and grew. Fibular head was shaped and matched with the humerus glenoid [29]. Innocenti believed that the anterior tibial recurrent artery could provide adequate blood for epiphysis to complete free epiphysis grafting. Periosteum branches of anterior tibial artery can supply blood for the 1/2 proximal fibular diaphysis [28]. He used anterior tibial artery reversed blood supply to conduct proximal grafting (including fibular epiphysis) in 24 children. All the bone junctions got healed within 3 months, and 85% of the epiphysis survived and had the ability to grow and remodel. The longitudinal growth rate of epiphysis plate after grafting is 0.92 cm/year [30] (Figs. 21.7 and 21.8). Fibular epiphysis grafting can not only be applied to reconstruct the bone defects with a similar caliber, such as the distal radius & ulna and proximal humerus, but also in children femur proximal tumor resection through singular or composite massive allogeneic bone transplantation. The reconstruction can also achieve good modeling and growing ability.

(b) Resection reconstruction (Fig. 21.9)
- Advantages and disadvantages
- The anterior tibial artery reversed blood supply has the advantage of simple operation, rare vascular

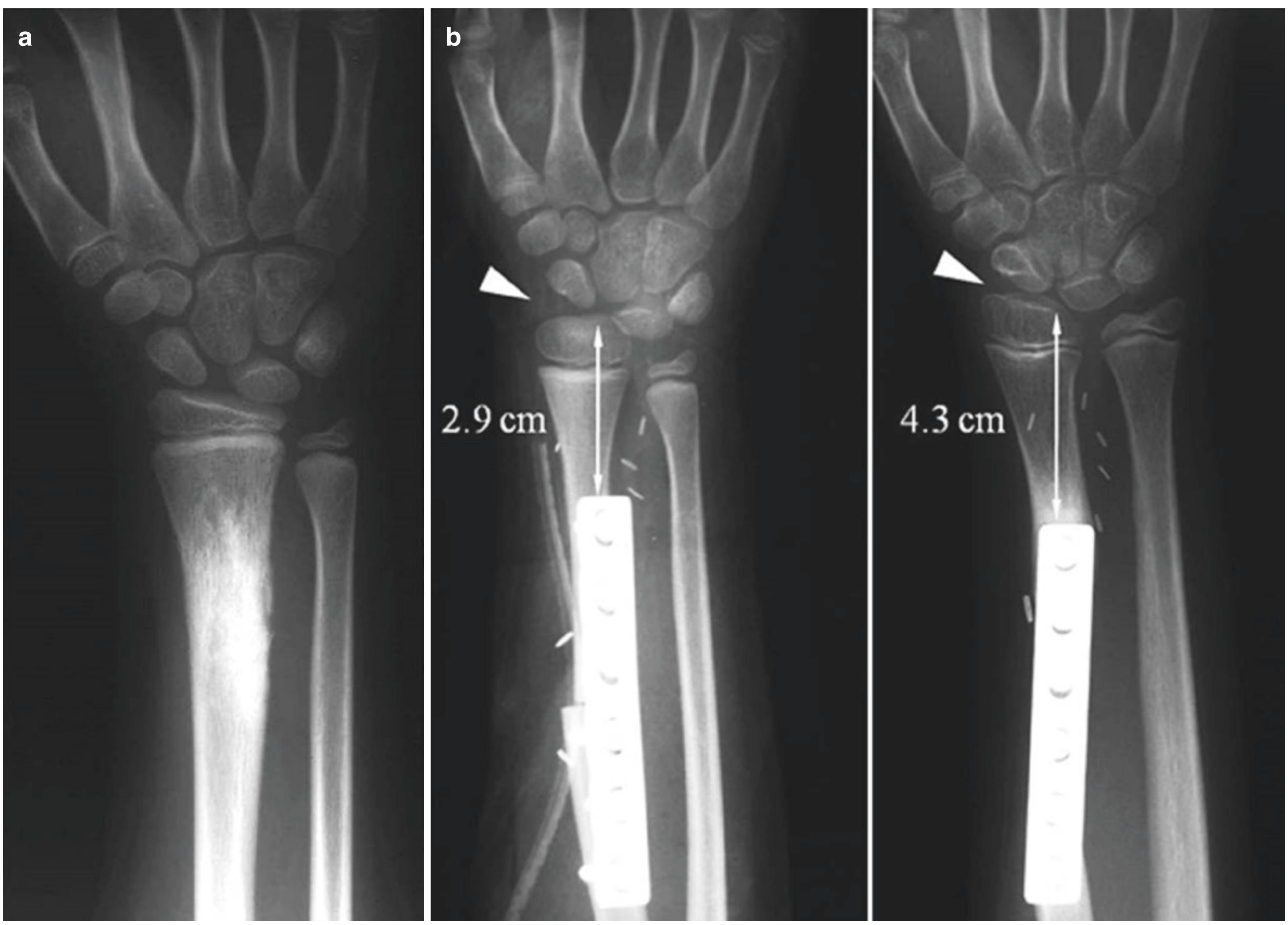


Fig. 21.7 (**a**) Osteosarcoma of the distal radius. (**b**) Proximal fibula epiphysis transplantation for reconstruction of distal radius defect after tumor resection. The left image is post-operative, and the right one is 20 months post-operative. The transplanted fibula grew 1.4 cm longitudinally. Pay attention to the reconstruction of fibular articular surface: the articular surface is horizontal immediately after operation, and the slope is reconstructed well with scaphoid bone at follow-up. (Provided by Professor Innocent)

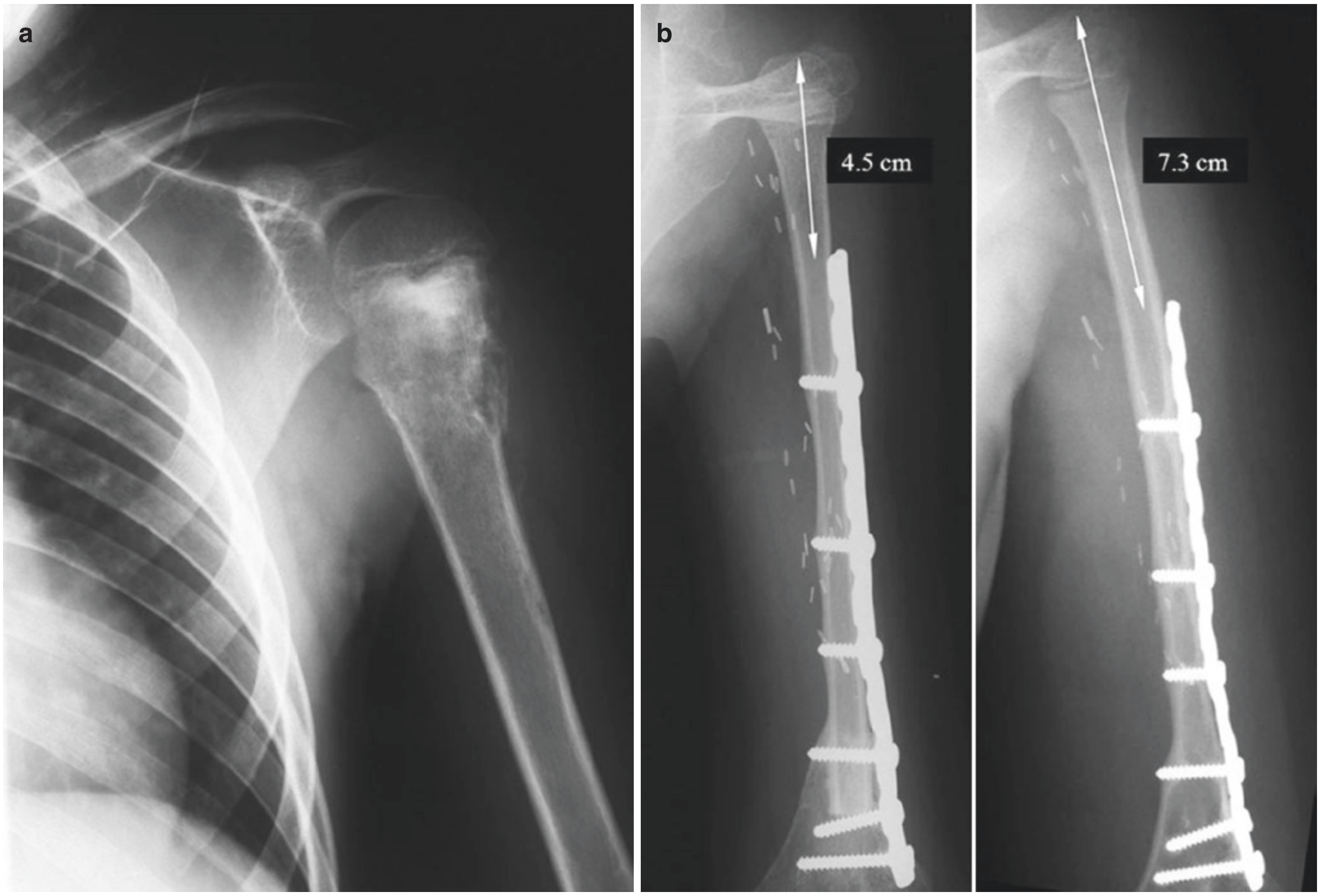


Fig. 21.8 (**a**) Osteosarcoma of proximal humerus. (**b**) Immediate (left) and follow-up X-ray films showed an average longitudinal growth rate of 0.9 cm/day. (Provided by Professor Innocent)

crisis and high revival rate of epiphysis plate. The disadvantage is a relatively high rate of complications at the donor site. Some branches of proximal deep tibial nerve often need to be cut off, making 2/3 patients suffer transient deep tibial nerve paralysis, and 1/8 patients suffer permanent incomplete paraplegia of crus anterior group muscle. Moreover, this method is not applicable in grafting of more than 1/2 fibular.

- Operation method (retain the epiphysis recurrent artery and fibular carotid artery of the anterior tibiofibular recurrent artery).
- Dissect the anterolateral incision between extensor digitorum longus and anterior tibial muscle.
- Dissect deep peroneal nerve from anterior tibial artery nerve tract and pull it to the tibial side, and pull the anterior tibial artery to the fibular side. Note: carefully protect the nutrient branches that come out from anterior tibial artery and feed fibula periosteum through extensor digitorum longus.
- Sharply cut the starting point of peroneus longus and extensor digitorum longus, where the common peroneal nerve occurs in the plane of anterior mesooecium. As the epiphysis recurrent artery is embedded in proximal muscle sleeves, the proximal muscle sleeves should be resected together with the fibular head.
- In the proximal fibula, the branches of deep peroneal nerve intersect with anterior tibiofibular recurrent artery that comes from tibial anterior vessels. Sometimes, the nerve branches that get stuck between anterior tibiofibular recurrent artery and periosteum should be cut off. After the resection of bone flap, the nerve branches can be micro-anastomosed.
- During the dissection of fibular diaphyses, we should reserve as many periosteal branches as possible. The interosseous membrane and some longitudinal muscle bundle and blood vessels should be retained in the fibular side.
- Incise the periosteum in 2–3 cm from the preconcerted osteotomy plane, upturn it towards the proximal until the osteotomy plane, and then complete distal osteotomy. Carefully protect the posterior fibular blood vessels. The osteotomy plane should not exceed 1/2 of the whole length, or oth-

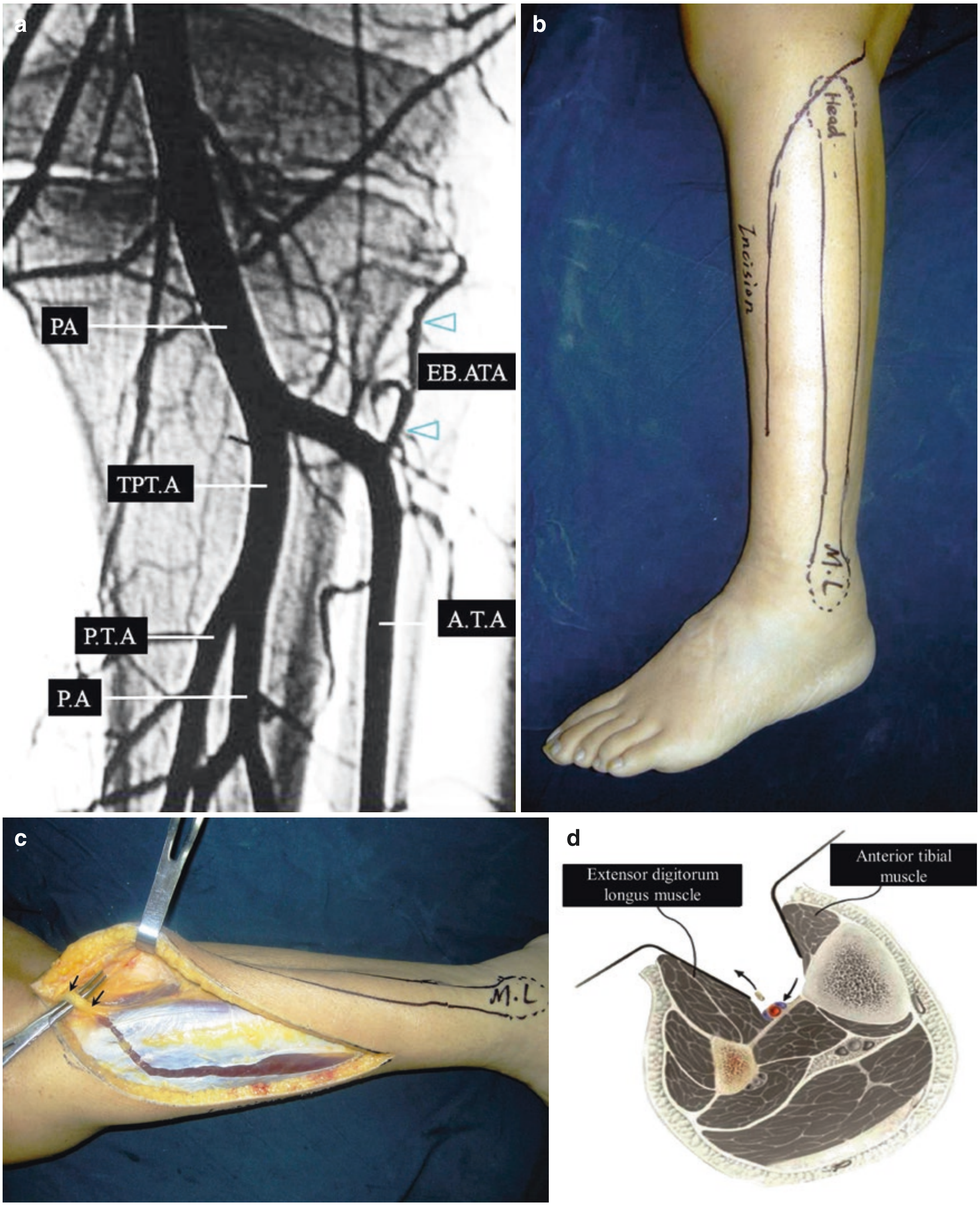


Fig. 21.9 (**a**) Pre-epiphyseal fibular transplantation angiography is performed to determine the choice of blood supply vessels (anterior tibial recurrent artery is the main blood supply vessel in the figure, so anterior tibial artery can be selected as the blood supply vessel). *PA* popliteal artery, *P.T.A* posterior tibial artery, *A.T.A* anterior tibial artery, *TPT.A* tibioperoneal trunk artery, *P.A* peroneal artery, *EB.ATA* epiphyseal branch of anterior tibial artery. (**b**) Shows the location of the fibular epiphyseal incision. (**c**) Common peroneal nerve (arrow) exposure and deep fasciotomy plane. (**d**) The deep anatomical plane is located between the extensor digitorum longus muscle and the anterior tibial muscle. (**e**) Separation is made between the extensor digitorum longus and the anterior tibial muscle, and the common peroneal nerve is exposed by muscle incision about 1 cm away from the origin of the fibula longus and extensor digitorum longus. *EDL* extensor digitorum longus muscle, *TA* anterior tibial muscle, *PL* fibula longus. Common peroneal nerve (arrow), Deep peroneal nerve (triangle). (**f**) Longitudinally incises the deep fascia (black arrow) and sutures the deep fascia partially intermittently to the extensor digitorum longus muscle to protect the anterior tibial artery and its periosteal branches to the fibula (blue arrow). *TA* anterior tibial muscle, *EDL* extensor digitorum longus muscle. (**g**) The relationship between the common peroneal nerve, the anterior tibial artery and the anterior tibial recurrent artery is revealed. AS: fibula articular surface, EDL: extensor digitorum longus PL: fibula longus muscle. The black arrow points to the peroneal vessel, the red arrow points to the common peroneal nerve, and the arrow part is the branch of the anterior tibial vessel supplying the fibular head. (**h**) The relationship between the common peroneal nerve (yellow arrow), the anterior tibial artery (black arrow) and the anterior tibial recurrent artery (red arrow) is shown during the operation. *EDL* extensor digitorum longus. (**i**) The relationship between blood vessel and muscle after proximal fibular epiphyseal plate osteotomy (specimen). *AS* articular surface, *ATA* anterior tibial artery, *EDL* extensor digitorum longus, *PL* fibula longus, *PB* fibula brevis

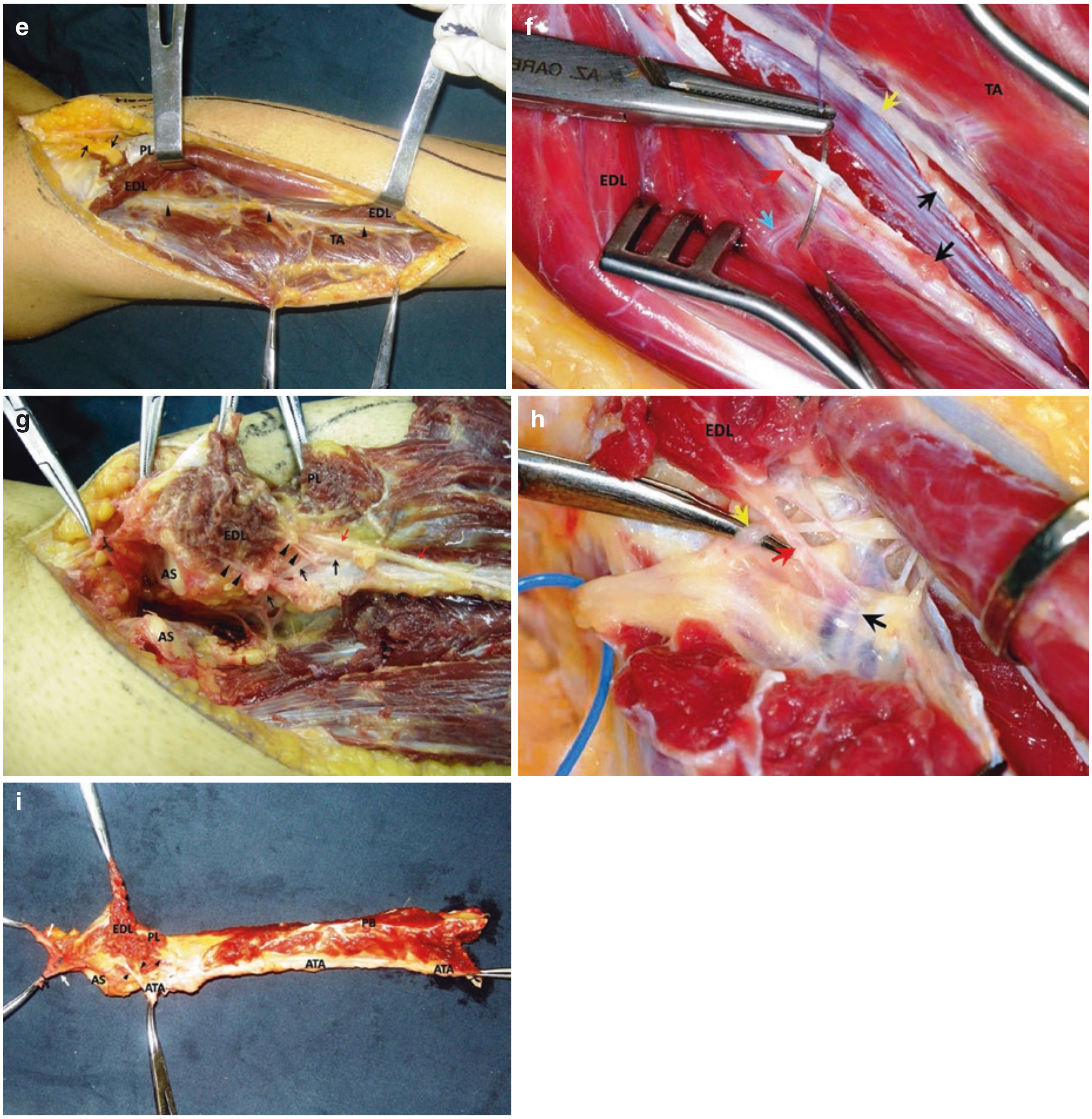


Fig. 21.9 (continued)

erwise the distal circulation of fibular flap will not be sufficient.

- Incise the proximal tibiofibular joint capsule and retain the lateral accessory ligament of the knee joint as far as possible. Longitudinally split the biceps femoris tendon, harvest the latter half together with fibula to reconstruct the ligament in the recipient area.
- Split anterior tibial artery towards the proximal to the origin of the popliteal vessels, cut off and ligate anterior tibial artery to finish the acquisition of vascularized fibular epiphysis.
- Use non-absorbable sutures to fix the retained first half biceps femoris tendon and residual lateral accessory ligament to the lateral side of the tibial metaphysis. Evaluate the stability of the knee joint and fix it for a month with brace.
- For circulation reconstruction, the method of reversed blood supply of anastomosis distal anterior tibial artery can be used. Carefully retain the connection between veins. A better anastomosed vein can guarantee the back-flow of flap blood supply.
- Key points:
  – It is beneficial to choose suitable surgery after observation of the epiphysis blood supply by per-operation angiography.
  – Incise the extensor digitorum communis muscle and proximal peroneus longus along nervus peroneus communis plane, and retain the proximal end in the fibular head. Since the proximal muscle sleeves contain epiphysis recurrent artery, it is vital to avoid injury to the artery during the dissection.
  – The nerve branches of the extensor digitorum communis muscle often need to be cut off. Retaining some of the muscle bundles in the fibula side can protect the fibular periosteum of the anterior tibial artery.
  – Longitudinally split the biceps femoris tendon carefully and protect the inferior lateral genicular artery. Before the artery enters the meniscus, it sends out downward the epiphysis branches which should be protected. Firstly, horizontally split the biceps femoris tendon from the proximal posterior side, find out the trunk disengagement from the popliteal vessels, and carefully ligate it. Then split it down outside until the epiphysis.
  – If the blood vessel can be dissected, anastomose the anterior tibial artery proximal end and the inferior lateral genicular artery proximal end. Since the distal anterior tibial artery can supply blood through the anterior tibiofibular recurrent artery and descending artery epiphysis, the survival rate can be enhanced.

21.1.3 Part 3: Composite Biological Reconstruction for Segmental Bone Defects: Theory and Clinical Practice

21.1.3.1 Common Reconstruction Methods for Segmental Bone Defects

Reconstruction for segmental bone defects after bone tumor resection is often performed by the following methods.

1. Internal fixation material-compound bone cement. It is rarely used now, and mainly in palliative treatment for patients with metastatic cancer whose expected survival time is limited or for temporary filling of infective wounds.
2. Segmental prosthesis. The prosthesis is connected to a bone stump by inserting its two ends into the stump. It is convenient in use, but may lead to such common complications as long-term loosening, fatigue breakage, etc. In order to improve press-fit between the prosthesis and the bone, some scholars treated the prosthesis-bone contact site by microporous surface modification (ceramics, fibre metal or titanium) in recent years. Other scholars used bone grafting and osteogenesis following osteocyte differentiation by stem cells at the contact side to enhance the stability of the prosthesis, but the clinical effect was not definite.
3. Lengthening by external fixator. It is mainly used for reconstruction of bone defects about 5 cm. Adjuvant chemotherapy after the operation may increase pin track infection risks and affect bone formation quality.
4. Autologous non-circulation cortical bone. Embed three autologous cortical bones to the broken ends, with each end overlapping another at least 3 cm. The surrounding is grafted with autologous cancellous bone. The advantages of this method are free of bone resorption caused by immunoreaction, and activation of both surfaces of the graft by 3–4 mm within 1–2 years. The disadvantages are relatively great invasion to the donor site and inapplicability in reconstruction of defects over 10 cm. Rigid fixation is needed; otherwise fracture will occur during the period of dead bone activation.
5. Massive allogeneic bone transplantation. This is an important way to treat segmental bone defects. As a biological SPACER, massive allogeneic bone can accurately match the recipient area, providing good supporting strength and bone conduction. However, the rate of long-term complications after massive allogeneic bone transplantation is up to 55–84%. The most common complications include bone ununion, infection and fracture. The complications have something to do with

lack of blood supply and osteogenic cells in allogeneic bone. For the limb salvage in children with growth potential, simply massive allogeneic bone has insurmountable barriers.

6. Vascularized fibular grafting. Vascularized free fibular grafting has the feature of living bone. Bone healing time is about 3–5 months, and the healing rate is over 90%. It leads to good clinical results in the reconstruction after excision of the radius, ulna and metatarsal which have a similar diameter. It is not good for lower limb reconstruction because the fibular diameter is too small so that the incidence of post-operation stress fracture is high. Since it is hard to have reliable fixation near a joint, the joint has to be fixed sometimes affecting its function. In fibular reconstruction of bone defects, the fixation is difficult. Fixation with plate and screw might affect the blood supply to the fibula. During the union with the host bone, microfractures and stress fractures of different extents might occur.

21.1.3.2 Theoretical Basis for Composite Biological Reconstruction

1. History

   Vascularized fibular grafting was used in revision of allogeneic bone fracture or bone ununion. Enlightened by this, Capanna first described the primary reconstruction of large long bone defects at lower limb using vascularized free fibula combined with massive allogeneic bone in 1988 [31]. This technique combined the advantages of two methods. Allogeneic bone provides immobilizing matrix for internal fixation plate and mechanical support at the initial and medium stages meanwhile the allogeneic bone can be activated by vascularized fibula with osteogenic activity. The sandwich blood supply makes the whole activation of allogeneic bone possible. The theoretical and practical advantages of the method have been recognized by multiple bone tumor centers. The surgical methods and indications are gradually expanding [18, 32, 33]. The reconstruction expands from the lower limb tibiofibula to the pelvis, calcaneus, humerus, from free grafting to pedicled transfer [34], from allogeneic bone composition to deactivated bone composition [35, 36].

   Indications: Reconstruction after malignant bone tumor resection in four limbs in children and juveniles or patients with long lifetime expectancy; revision after failed allogeneic bone reconstruction due to infection, fracture or other reasons; reconstruction of segmental resection after invalid repeated local curettage of benign or invasive lesions.

   Contraindications: advanced age. Infective wound is an absolute contraindication of reconstruction. Poor coverage of local soft tissue is a relative contraindication. Limited lifetime expectancy is a relative contraindication.

2. Theoretical advantages

   (a) Massive allogeneic bone provides early protection for fibula grafting

   After grafting, massive allogeneic bone can prevent displacement of the fibula in the early healing process and reduce the possibility of stress fracture. Inserting the fibula centrally to the host bone can acquire better contact space and improve healing. Meanwhile, certain stress stimulus may help evenly thickening remodeling.

   (b) Fibular graft protects allogeneic bone fracture at the middle and advanced stages 80% of the external surface can restore to 1–2 mm at 2 years after the allogeneic bone grafting. Fracture may happen during the course of restoration, but the preliminarily healed fibula maintains the overall strength of the graft (Fig. 21.10)

   (c) Overall multicortex reconstruction enhances reconstruction strength

   In lower limb reconstruction through fibula grafting, vascular anastomosis failure might lead to bone ununion or fracture. However, the reconstruction can still be reliable if the fixation is reliable, because the grafting with composite allogeneic bone in the cases of vascular anastomosis failure is equivalent to multicortex reconstruction. (Fig. 21.11)

   (d) Allogeneic bone provides a position for internal fixation

   Composite allogeneic bone provides a reliable position for plate-screw internal fixation to avoid its influence on blood supply.

   (e) Embedding the fibula with circulation into the allogeneic marrow cavity provides anatomical basis for surface activation of the allogeneic bone. Meanwhile, the fibula with circulation and osteogenic capability remarkably facilitates the first-stage bone healing at the broken ends of allogeneic bone and host bone (Fig. 21.12).

   (f) Embedding the fibula into the allogeneic marrow cavity increases the soft tissue coverage in the allogeneic bone surface. It is of certain significance for the reduction of infection rate. The ultimate integration of the fibula and allogeneic bone can make the reconstruction reliable and long-lasting.

   (g) Since the reconstruction of near-joint parts (proximal humerus, proximal femur, proximal tibia, etc.) simply with the fibular graft cannot result in reliable attachment of soft tissue surrounding the joint, the stability and functional recovery of the joint can be affected. Allogeneic bones provide good soft tissue attachment for the reconstruction.

3. Clinical outcomes

   If the grafted fibula survives, the outcome of the composite rests with initial fixation strength and allogeneic bone union. (1) Firm fixation and allogeneic bone union may lead

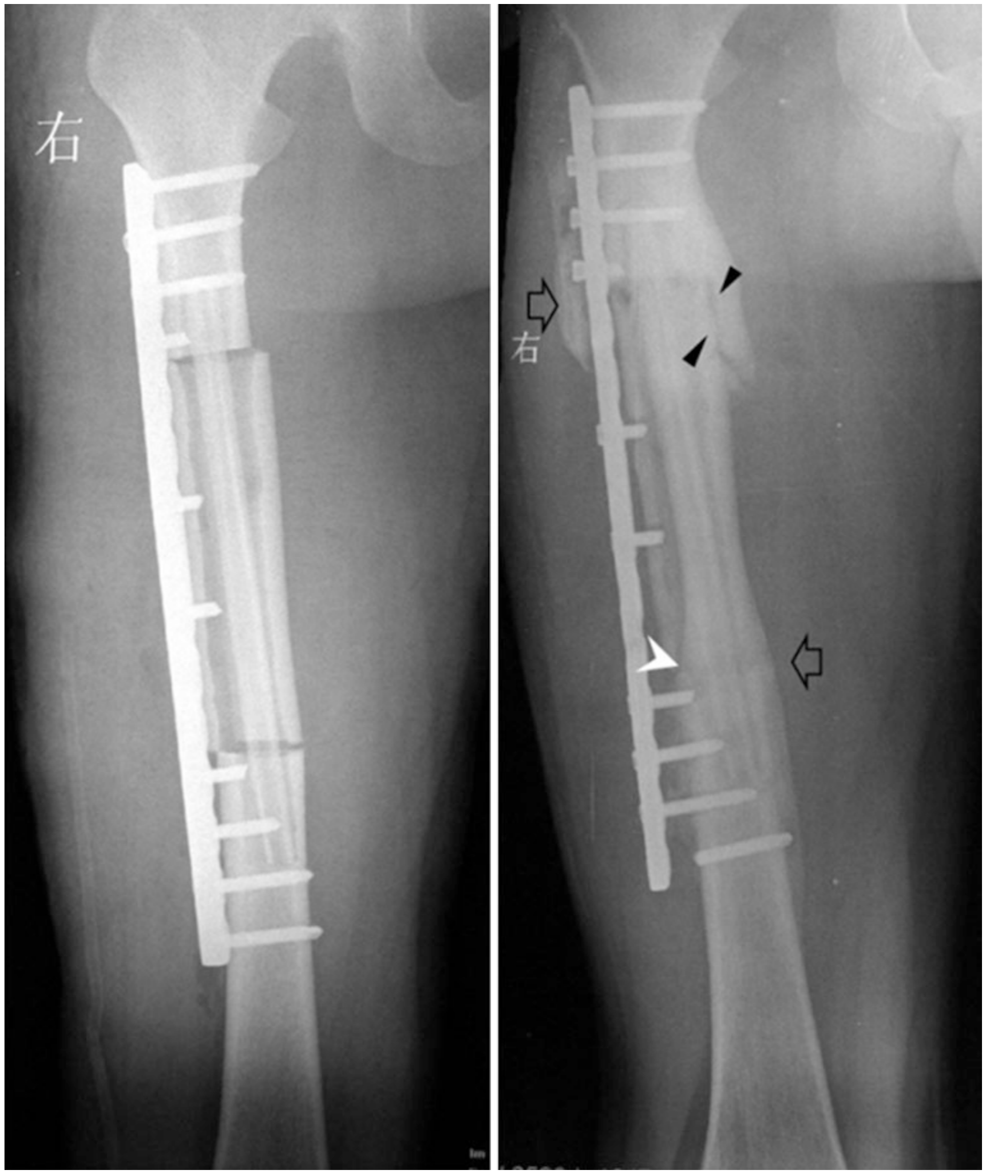


Fig. 21.10 Despite the failure of the implant due to early loading, the initial healing (arrow) of the fibula and the recipient bone one year after the operation preserves the overall reconstruction. External callus formation is not only an initial unstable biological response, but also a healing mode of allogenic bone and host bone. In this case, the distal autogenous bone crawling towards allogenic bone has made allogenic bone and autogenous bone heal, while the proximal callus formation has not completely made the junction image healing

to even and slow thickening of the fibula (Fig. 21.13). (2) If internal fixation fails, allogeneic bone is not united or the fibular stress increases due to fracture in the course of allogeneic bone recovery, the fibula takes on irregular thickening, the density of cortical bone increases and a restoration callus between the fibula and allogeneic bone can be seen (Fig. 21.14). (3) In the cases of good allogeneic bone union, firm internal fixation and absence of fibular stress, the fibular cortical bone takes on osteoporosis.

21.1.3.3 Technical Points of Composite Biological Reconstruction

1. Fibular resection and treatment

   The following points should be noticed in harvesting the fibula:

   (a) The vascular pedicle should be as long as possible. The amputation plane of the peroneal vessels should be at the junction of tibiofibular diaphysis and peroneal vessel.
   (b) In the course of composition, the free fibula is often embedded into the allogeneic marrow cavity. Therefore, unlike pure free fibular grafting, the free fibula should be as “slim” as possible. That is to say, under the premise of protecting the main and arcuate vessels, the less muscular tissue, the better. It has two effects: one is to prevent the allogeneic marrow cavity from expanding too much, holding the fibula and maintaining the mass of allogeneic bone; the other is to make the fibular periosteum directly touch the allogeneic bone, facilitating the long-term bone union.

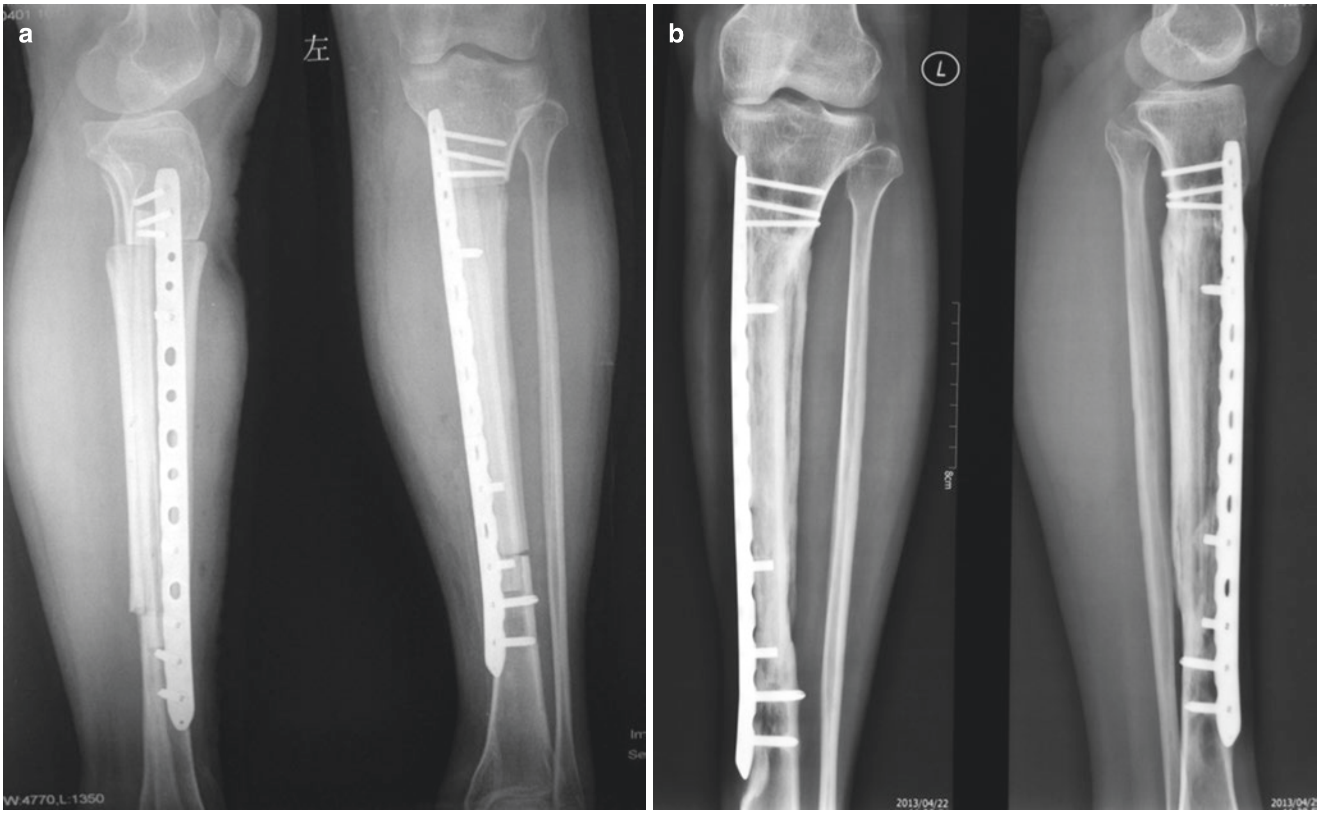


Fig. 21.11 (**a**) After resection of tibial shaft tumors combined with biological reconstruction, bone scan showed failure of fibular circulation after transplantation. (**b**) Despite the failure of fibular vascular anastomosis, good healing is achieved between allogenic fibula and autogenous bone 4 years after operation

(c) Length of the incised fibula: It is often 4–6 cm longer than the length of reconstructed defect. That is to say, the fibula embedded into the broken end on each side should be 2–3 cm (Fig. 21.15).

(d) Fibular surface treatment: Grind the cortex opposite to the fibular vascular pedicle until bleeding to increase the contact with the internal surface of allogeneic bone. This is good for the union of the fibula and allogeneic bone.

2. Preparation of allogeneic bone

For preparation of allogeneic bone, you should note the following three aspects:

(a) Appearance: It should be chosen based on different ages and positions. For adults, its diameter should be similar to or a little larger than that of the recipient. For children, its diameter should be larger than that of the recipient to meet the demand of future growth.

(b) Marrow cavity: It can hold fibula and protect the fibular vascular pedicle from compression.

(c) If it is still hard to embed the fibula or the vascular pedicle is compressed after the cavity of allogeneic bone is reamed, allogeneic bone with a larger diameter should be considered or a vertical slot is made so that the vascular pedicle is not compressed. The slotting position should not interfere with plating, and it should allow for convenient vascular anastomosis. Under the premise of avoiding vessel compression, the slot should be as narrow as possible to minimize its influence on the allogeneic bone strength.

3. Composition

Composition refers to the composite integration of the fibula embedded into the allogeneic bone. After composition, there are two ways to pull out the peroneal vessel. If the allogeneic bone marrow cavity is large enough to hold the fibula and does not compress the vascular pedicle, the peroneal vessel can be pulled out through a reamed opening. If the allogeneic bone marrow cavity can hold the fibula but may cause compression on the vascular pedicle, the peroneal vessel can be pulled out through a vertical slot (Fig. 21.16). Composition of allogeneic bone and fibula should meet the two requirements: (1) There is no compression on the vascular pedicle. (2) The fibular bone surface without muscle enthesis touches the allogeneic bone as closely as possible to facilitate bone union.

4. Fixation

After tumor resection, the residual marrow cavity often needs expansion. Medullary expansion should be 1 mm larger than the external diameter of the fibula. If the

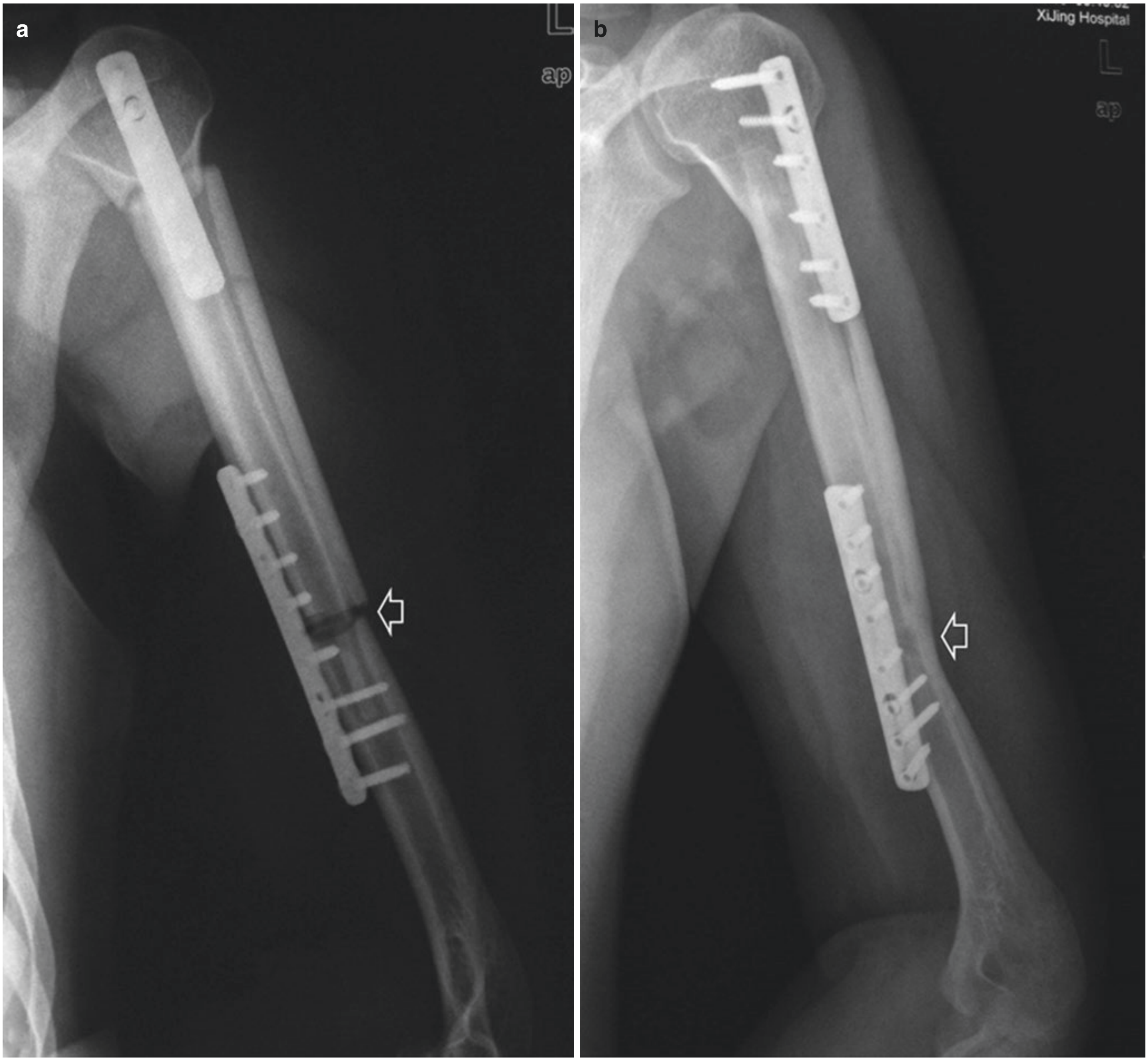


Fig. 21.12 Biological effects of fibula osteogenesis: Although the joint between allogenic bone and autogenous bone is not good, and the gap between the broken ends is more than 1 cm, the osteogenesis of fibula results in perfect healing between allogenic bone and autogenous bone. The arrows in the left and right figures indicate the location of fracture and healing, respectively

medullary cavity expands too much, the fibula does not contact well with the cortex in the residual medullary cavity. Locking plate is an ideal fixation for the composite. On the one hand, rigid fixation is good for early vessel protection in the early fibular grafting; on the other hand, it is an important guarantee for the union of grafted bone after failure of vascular anastomosis. The fixation of allogeneic bone cortex through locking screws can avoid the influence on fibular circulation of the composite. The ideal final fixation should lead to: (1) Three-dimensional osseous contact. The bone surface in the allogeneic bone marrow cavity axially and closely contacts with the fibular surface without muscle enthesis; the broken ends of allogeneic bone contact well with the cross section of the host bone; the fibula connects closely with the host bone in the marrow cavity. (2) No compression to the vascular pedicle. (3) Mechanical supporting strength great enough before bone union maintained by more than three screws at the two ends of the host bone (Fig. 21.17). (4) Good connection between broken ends. It is an important premise for allogeneic bone union, particularly in cases of no blood supply to the grafted fibula.

5. Circulation reconstruction

The preparation of blood vessels in the recipient area is quite important. Choosing the nearest blood vessel is the basic principle. A second consideration is the diameter of blood vessel in the recipient area. Generally, end-to-end anastomosis is used for circulation recon-

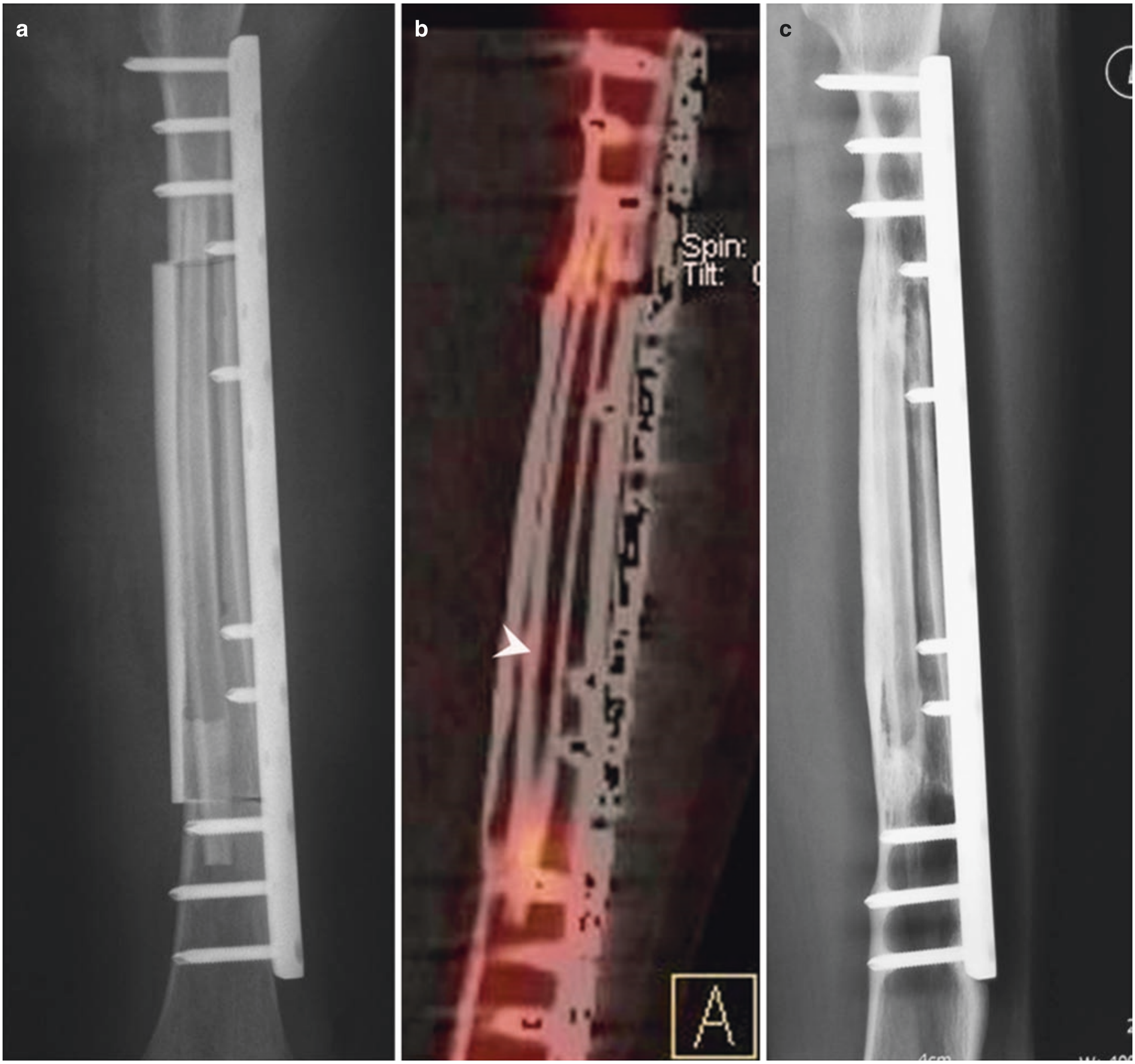


Fig. 21.13 Metabolism of fibula is weakened 3 months after transplantation, but the active metabolic area is still visible. One year after transplantation, the distal and proximal triple junctions heals well, fibula do not grow thicker in two years after transplantation, and the internal plant stability is good. The arrowhead indicates the transplanted fibula

struction. The arteries that can be used for humerus reconstruction include anterior humeral circumflex artery, deep brachial artery and ulnar collateral artery. The arteries that can be used for femur reconstruction include lateral humeral circumflex artery, descending genicular artery, medial femoral muscular branch and deep femoral artery. The arteries that can be used for tibia reconstruction include anterior tibial artery and peroneal artery. If there is no branch vessel near the recipient area, end-to-side anastomosis can be used for connection of the main vessel, such as femoral artery and brachial artery. The venous return of the free fibula often adopts a thicker artery, and the other can be ligated. Veins in the recipient area often adopt accompanying veins. If the diameter of a deep vein does not match, we can also choose some superficial veins to anastomose the fibular vein, such as cephalic vein, basilic vein, great saphenous vein, etc.

As there might some distance between the blood vessels in the recipient area and those at the donor site, we should consider before fixation of the composite if it is necessary to conduct vessel transplantation to make up for the length discrepancy. If necessary, we need to prepare vessels before fixation of the composite, such as freeing and cleaning bro-

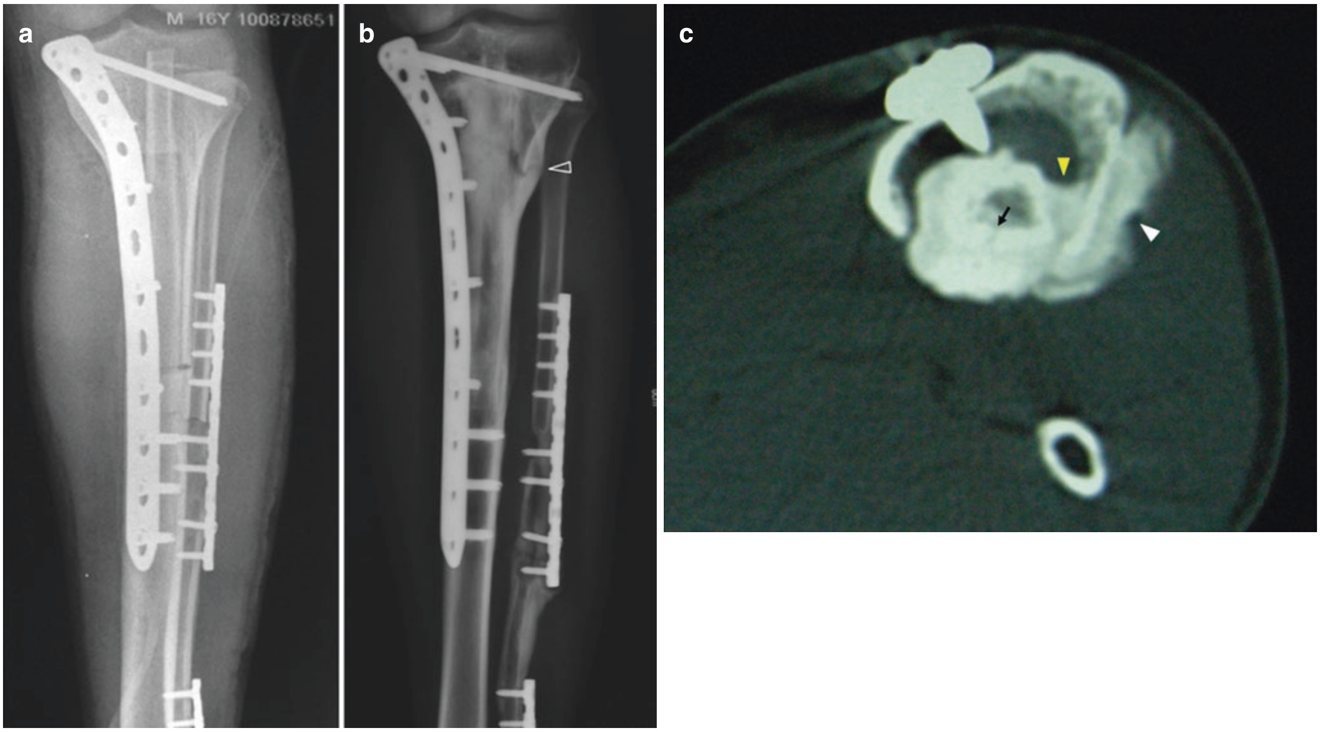


Fig. 21.14 (**a**, **b**) Fracture in the process of allogeneic bone remodeling due to partial instability of internal fixation. The fibula is significantly coarsened by stress stimulation and secondary microfracture and remodeling. (**c**) CT shows the microfracture of fibula (black arrow) and the formation of callus around fibula. Part of the callus (yellow arrow) fuses the allograft with fibula, and part of the callus (white arrow) is repaired on the outer surface of the allograft

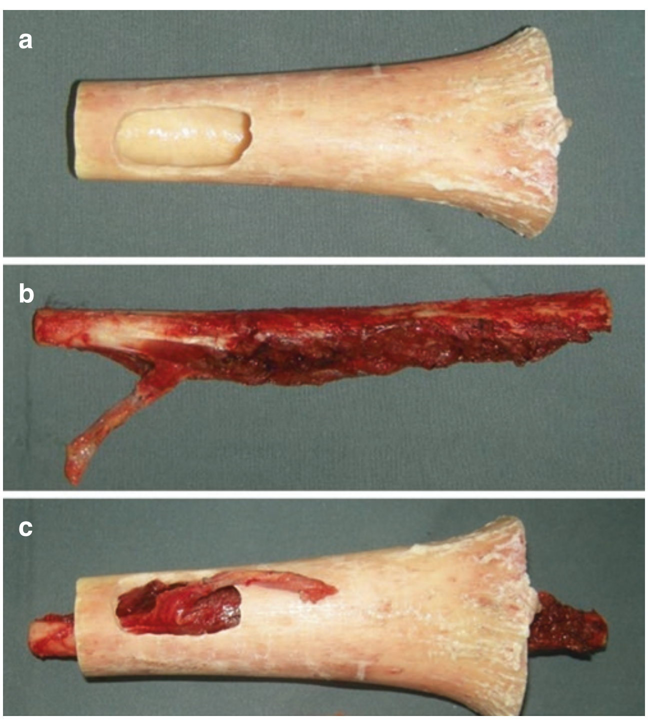


Fig. 21.15 Compound schematic diagram. (**a**) is allogenic bone, with the bleeding tube pedicle opened at the appropriate site; (**b**) is vascularized fibula; (**c**) is complex. It should be noted that the size of medullary cavity must be appropriate when compounding. Excessive enlargement of medullary cavity affects the strength of allogenic bone, and too small medullary cavity can easily make the vascular pedicle compressed

Fig. 21.16 If the medullary cavity may cause pressure on the vascular pedicle after reaming, a groove on the allograft bone is needed to ensure that the vascular pedicle is loose. If the vessel pedicle is too short in the recipient area, vascular transplantation is needed before implantation and fixation to avoid vascular tension in the anastomotic area

Fig. 21.17 Immediate (**a**) and one year (**b**) after operation. It should be noted that locking plate is an ideal method of fixation. Monocortical fixation of allogenic bone can minimize the possibility of fracture. Locking screw provides maximum initial stability

ken ends of the blood vessels in the recipient area, and anastomosis of the grafted vessel with the peroneal vessel or with the vessel in the recipient area to increase the length (Fig. 21.16). The advantage of preparation lies in the good exposure that can facilitate operation. During femur reconstruction, the lateral muscles are abundant and thick, so the blood vessel channel must be commodious to avoid compression on the vessels and reconstruction failure. After the surgery, strictly take microsurgical medication to avoid formation of blood vessel embolism.

21.1.3.4 Clinical Application

1. Allogeneic bone composite with vascularized free fibular diaphysis

   In 1993, Capanna reported the reconstruction of load-bearing bone in lower limb using the allogeneic bone composite with vascularized free fibular diaphysis and follow-ups of 3–17 years. Of the 90 patients, 57 received tibia reconstruction, and 33 femur reconstruction. Their average defect was 16 cm. The complications included infection in 7 patients (7.5%), bone ununion in 8 (8.8%), and fracture in 12 (13.3%). The rate of complication was much lower than that of pure allogeneic bone reconstruction. The 25 patients (27.7%) with complications were healed after an operation. The rate of reoperation was much lower than that of pure allogeneic bone reconstruction. Ultimately, 4 patients with infection and 2 patients with allogeneic bone fracture were not controlled, one of whom with refractory infection had to undergo amputation and the other 5 of whom received reconstruction once again. The success rate of composite reconstruction was 93.3%, much higher than that of pure allogeneic bone reconstruction. The excellent and good rate evaluated by MSTS was 92%. This method is mainly used in the reconstruction of femur and tibia. Li Jing et al. also applied this method in the reconstruction of humerus which achieved good outcomes (Fig. 21.18).

2. Allogeneic bone composite with vascularized fibular flap transfer (Fig. 21.19)

   Li Jing et al. [35] improved Capanna's method. They reconstructed the tibia with locally transferred allogeneic bone in conjunction with ipsilateral antegrade or reverse vascularized fibular flap. The defect after fibular flap

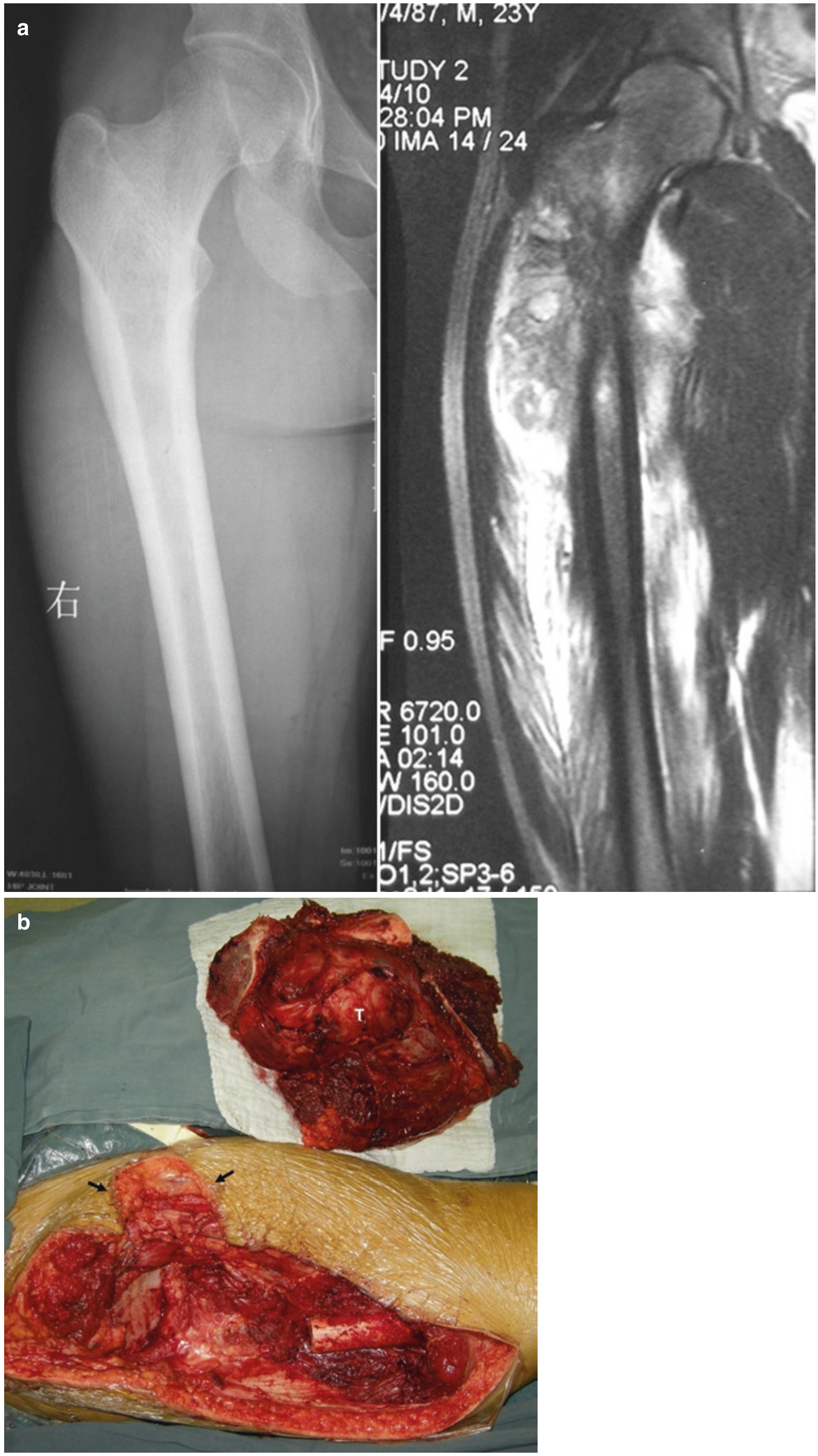


Fig. 21.18 (**a**) Ewings sarcoma of proximal femur. (**b**) Resection of tumors. Attention should be paid to the medial auxiliary incision (arrow) to facilitate resection of tumors, exposure of femoral vessels and subsequent vascular anastomosis. (**c**) Reconstruction. The trimming of allogenic bone should be matched as far as possible, and the medial groove is helpful for vascular anastomosis. (**d**) Because of the preservation of part of the greater trochanter and associated articular capsules and soft tissues, the blood supply of the femoral head and proximal femoral neck is still maintained. The slight bone metabolism of the fibula graft indicates the survival of the fibula graft

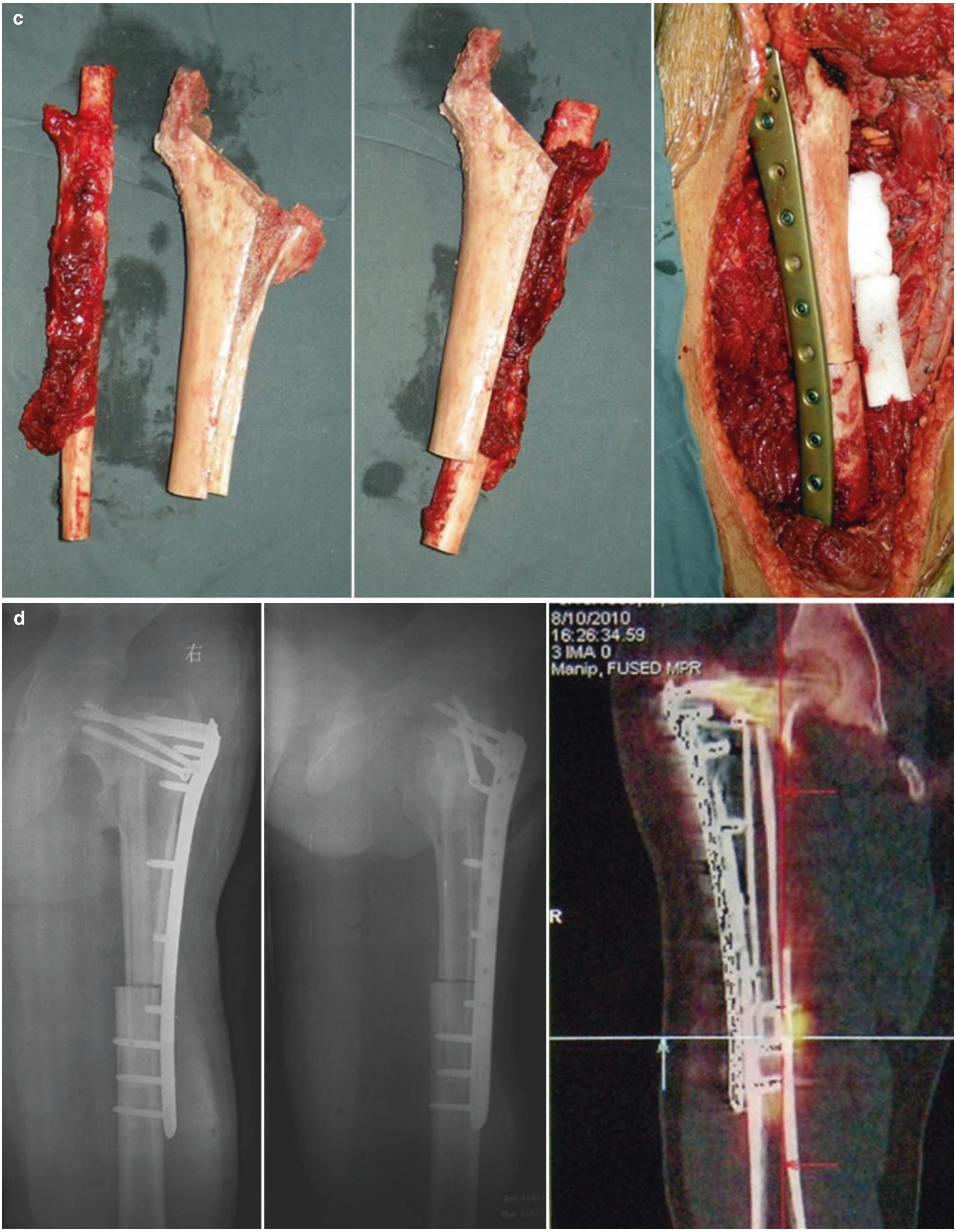


Fig. 21.18 (continued)

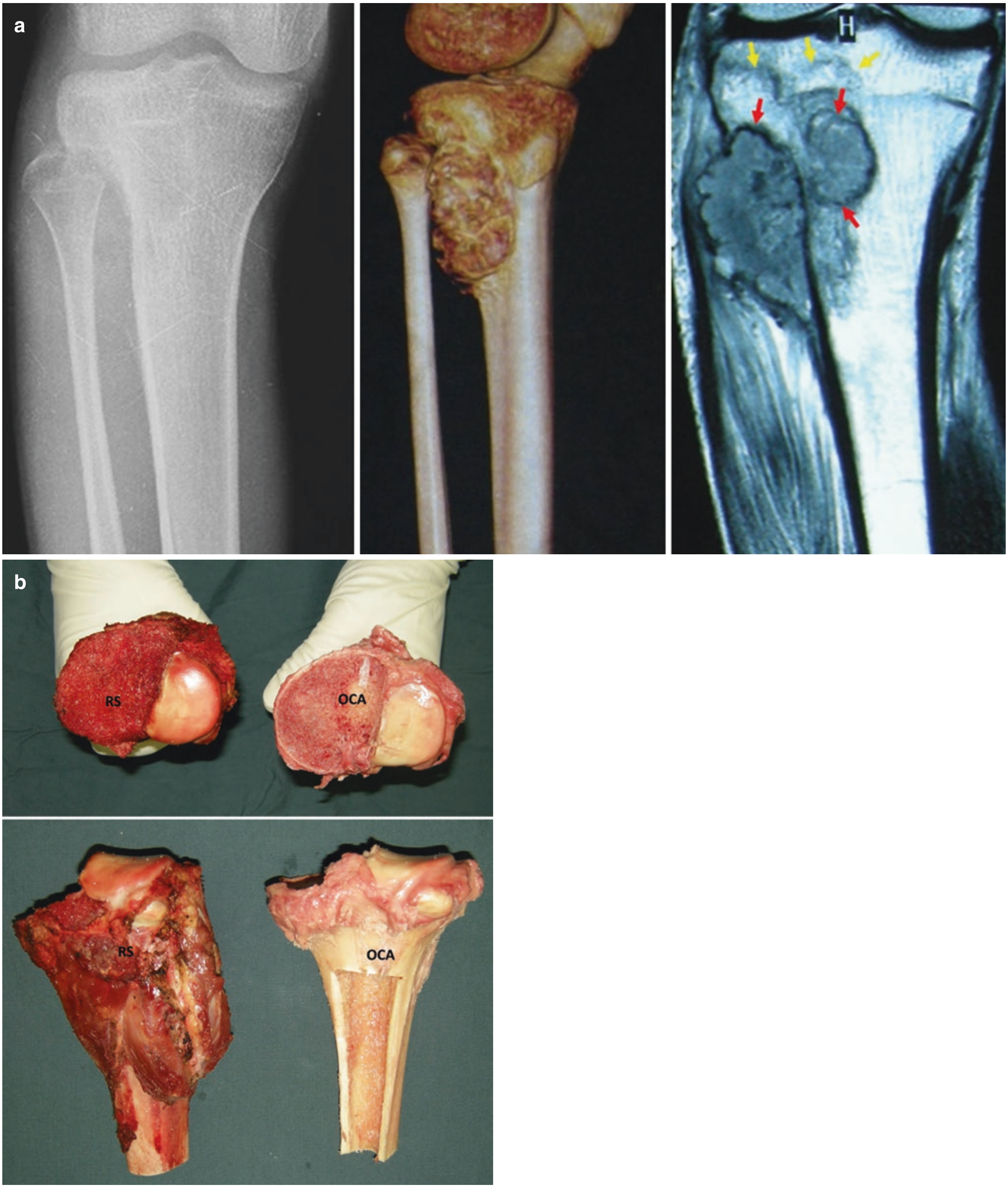


Fig. 21.19 (**a**) Osteosarcoma of the proximal tibia invades the subplateau bone. The red arrow shows the tumor area and the yellow arrow shows the edema zone area. (**b**) Tumor specimens removed and allogenic joints trimmed to match their size. *RS* removed specimens, *OCA* allogenic bone and joint. (**c**) Preparing for local vascularized fibular metastasis to be combined with allogenic bone. *OCA* allogenic bone and joint, *MP* medial platform, *F* fibular flap, *P* distal pedicle of fibular flap. (**d**) Pedicled fibula inserted into allogenic bone complex. *OCA* allogenic bone and joint, *MP* medial platform, *F* fibular flap, *P* distal pedicle of fibular flap. (**e**) Reconstruction of lateral fibula defect with a segment of allogenic bone. (**f**) Reconstruction of medial plateau preserves bone survival, fibula metastasis survives, and knee joint anatomical reconstruction

transfer was reconstructed with another segment of the fibula. The merits of this method are: (1) It avoids the complex vascular anastomosis, and maximizes the survival of grafted fibula. (2) Ipsilateral fibula grafting has no influence on the opposite normal limb. Even later amputation due to various reasons does not affect the other side limb. (3) The reconstruction of fibular defect increases the stability of the crus and decreases complications like ankle eversion, etc. (4) The operation time is much shorter than that of free grafting, and the rate of infection is also lower.

3. Allogeneic bone composite with vascularized fibular epiphysis grafting

   An ideal reconstruction after the resection of children's proximal femur tumor, should consider several factors: future hip growth as well as the function and duration of reconstructed joint. Pure allogeneic bone joint reconstruction has many long-term complications. Joint replacement has to sacrifice the articular surface of the acetabulum. Moreover, the child patients who have a long life need to undergo several operations. Mafirrina et al. designed composite reconstruction surgery [37]. They reconstructed the articular surface of the femur head with proximal fibular epiphysis grafting, rendering the reconstructed femur head the potentials of modeling and growth. Meanwhile, massive allogeneic bone was used to protect the grafted fibula and provide soft tissue enthesis to further maintain stability and strength of the joint. This method was applied in 6 patients, 2 of whom received good long-term results.

   Resection of the tumor which involves long bone epiphysis in children may result in hindered vertical growth and loss of articular surface. Vascularized fibular epiphysis grafting can simultaneously resolve the problems of bone defect and bone growth. It can be applied in the reconstruction of distal radius & ulna, leading to good clinical effects. However, it is not quite effective for the reconstruction of proximal humerus, because it cannot reconstruct the abducens devices of the shoulder joint. It is seldom applied in the reconstruction after proximal femur tumor resection. Manfrini et al. first applied the composite of vascularized fibular epiphysis and massive allogeneic bone in the reconstruction after resection of proximal femur malignant tumor in children. The fibular head in some children gradually grew, had a similar shape of the contralateral femur head and load-bearing function. Their long-term results were good. Li Jing et al. achieved good clinical outcomes after they applied for the first time the composite of vascularized fibular epiphysis and allogeneic bone or deactivated autologous tumor bone in the reconstruction after resection of proximal humerus tumor in children.

   (a) Techniques for reconstruction of humerus head
      - Since children's diaphysis has certain growth potential, in order to guarantee a good match between the growing humerus and allogeneic bone diaphysis, the diameter of the allogeneic bone should be a bit larger than that of the humerus. Diagonal osteotomy should be conducted at the anatomical neck plane of the proximal humerus, and trapezoid osteotomy at the distal. The enthesis points on the allogeneic bone for rotator cuff, latissimus dorsi and pectoralis major should be retained.
      - After the fibula is embedded into the allogeneic bone, the fibular head protrudes over the anatomical neck slightly. Blood vessels should be pulled out from the allogeneic bone corresponding to the broken end of anterior tibial artery.
      - Locking plate fixation.
      - Attach rotator cuff, latissimus dorsi and pectoralis major to the corresponding anatomical sites of the allogeneic bone.
      - 4–6 weeks' fixation with abducens brace after the surgery is good for soft tissue healing.

   (b) Techniques for reconstruction of femur head
      - Choose allogeneic femur bone whose diameter is a little bit larger than that of the autologous femur. Diagonal osteotomy is conducted at the proximal end in the base plane of the humerus neck, and trapezoid osteotomy at the distal end. Retain enthesis points for gluteus medius and gluteus maximus on the allogeneic bone.
      - Osteotomy is conducted after the soft tissue periosteum is stripped 3–5 cm below the fibular head. Pay attention to protection of the vascular pedicle. After the osteotomy, the fibula is embeded into the allogeneic bone. The fracture segment is angulated to fit the radian of the proximal femur.
      - Fix the allogeneic bone with locking plate.
      - Attach gluteus medius and gluteus maximus to the corresponding anatomical sites.
      - Active joint movements begin after fixation of the hip with abducens brace for 3 months and ambulant movements start under the protection of load-bearing brace for ischial tuberosity.

4. Allogeneic bone joint composite with vascularized fibular diaphysis [34] (Fig. 21.19)

   After allogeneic bone joint reconstruction, long-term joint metamorphosis often happens due to joint instability, infaust match and fracture under allogeneic bone articular surface. If some articular surface and stable structure (e.g. some genicular articular surface with anterior and posterior cruciate ligaments) can be retained, they can be composited with the allogeneic bone joint at some articular surface and the vascularized fibula. The composite reconstruction may positively keep joint stability, reduce or postpone long-term complications.

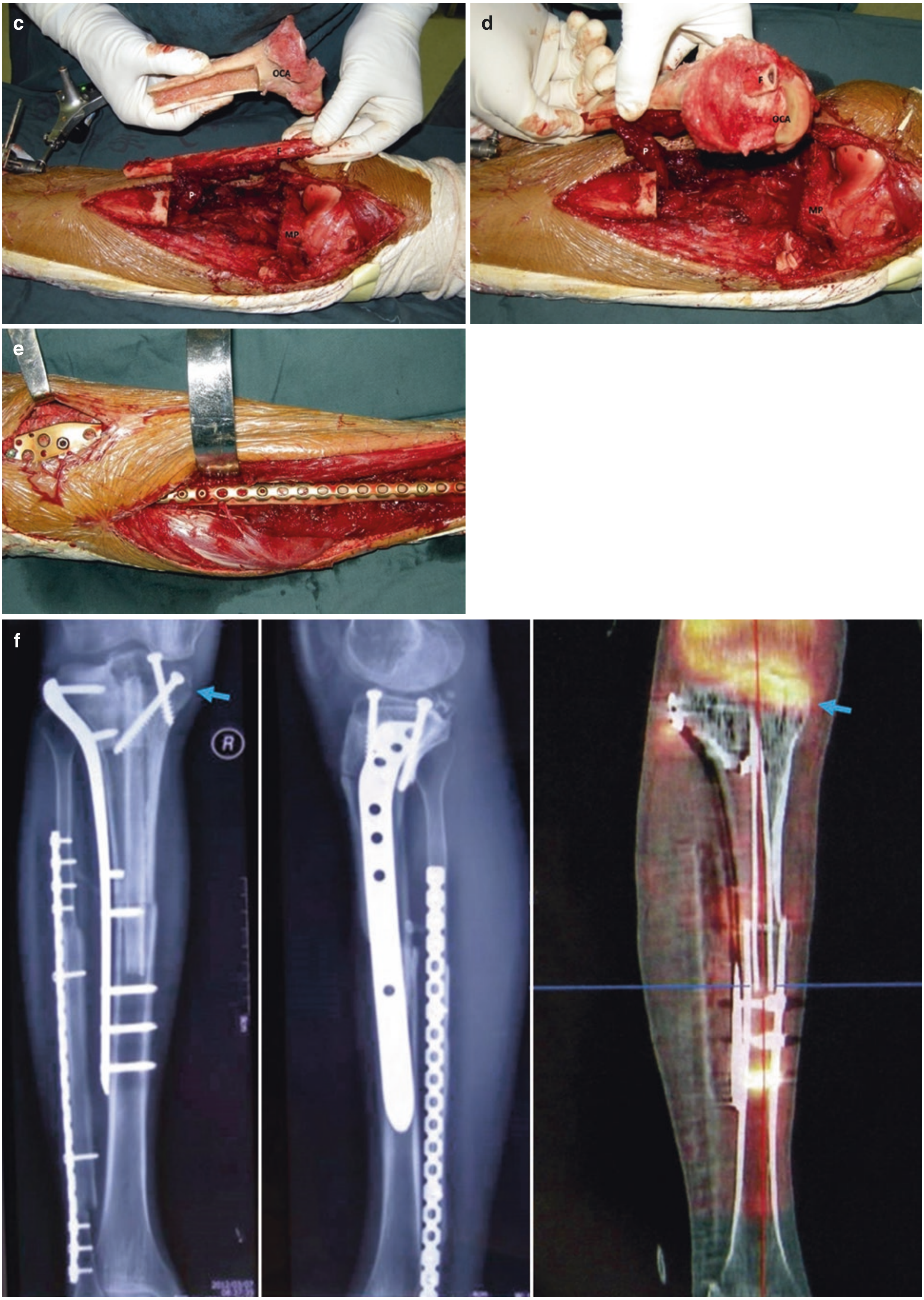


Fig. 21.19 (continued)

5. Deactivated bone composite with vascularized fibular diaphysis

   The composite reconstruction with vascularized fibular diaphysis and deactivated tumor bone (bone tissue is the main component) for segmental defects has two merits. It can utilize autologous tumor bone to maximize ideal anatomical compatibility and soft tissue reconstruction; the vascularized fibula can reduce the occurrence of complications (e.g. fracture) during the deactivation of tumor bone.

6. Reconstruction of calcaneal area (Fig. 21.20)
   (a) Common methods

   Reconstruction after resection of calcaneal defects can use pure allogeneic bone, autologous ilium or vascularized double fibulae. Allogeneic bone reconstruction is simple, convenient and allow early load bearing, but it has a high rate of short-term complications like infection and fracture. If allogeneic bone reconstruction is conducted in children whose other tarsal bones are growing, the metapodium will look short and small and its function will be affected. Vascularized double fibula folding reconstruction has the characteristics of living bone reconstruction. The increase of load bearing may lead to the thickening and calcanealization of the folded double fibulae. However, the operation is complicated, and the fixation is not reliable. The patient cannot bear load for a long time before the bone union.

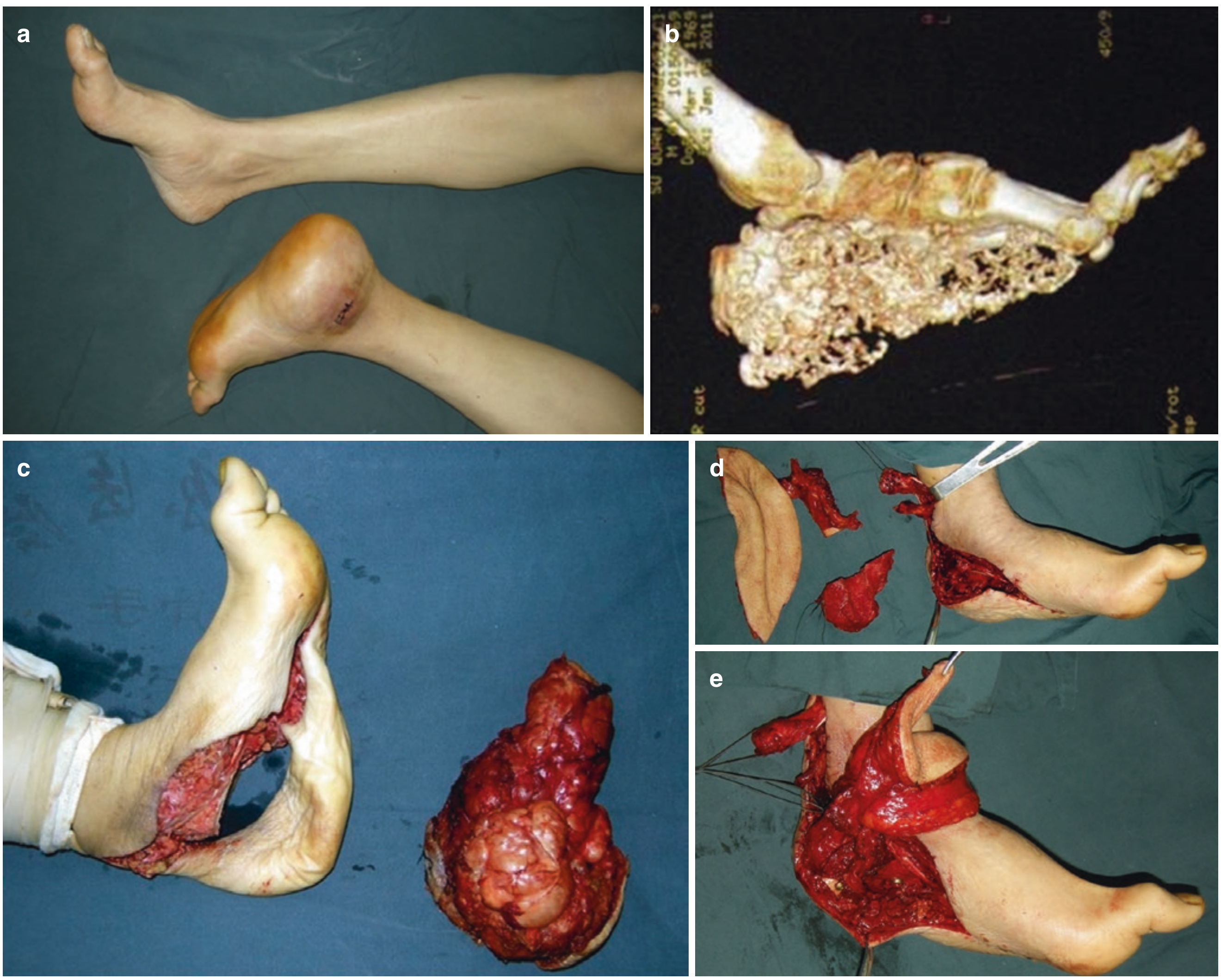


Fig. 21.20 (**a**) Calcaneal chondrosarcoma. (**b**) Three-dimensional reconstruction shows the extent of bone destruction. (**c**) Tumor mass excision. (**d**) Lateral Calcaneal groove for fibular flap embedding. (**e**) Fibular flap and calcaneus are fixed with screw. Achilles tendon is attached to allograft, and fibular vessel is anastomosed with posterior tibial vessel. (**f**) Reconstruction of fibular flaps. (**g**) SPET-CT showed that the allograft calcaneus is inactive but the fibula graft survived significantly

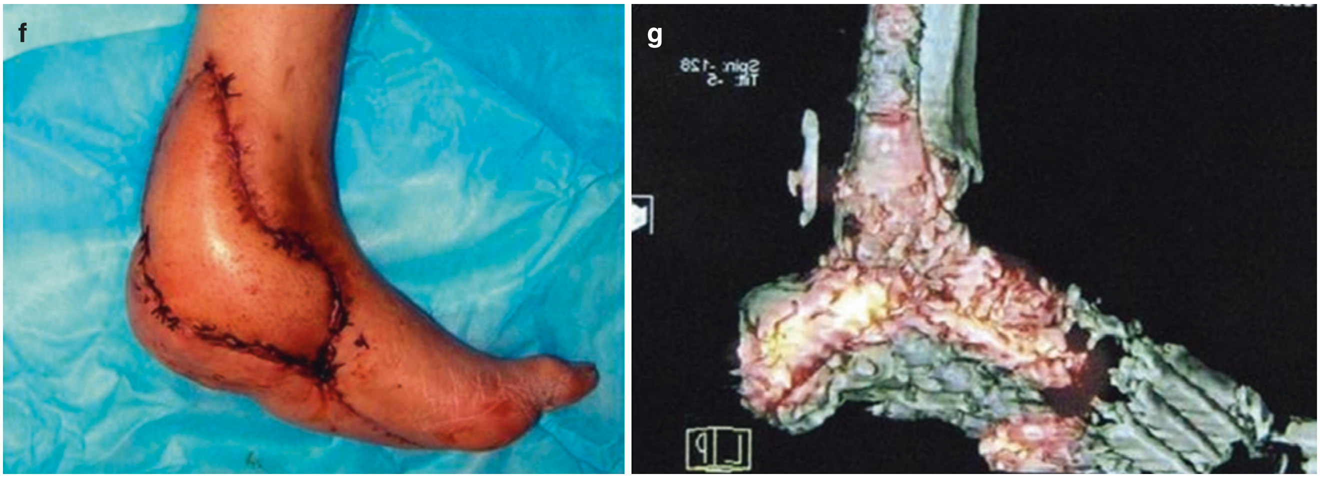


Fig. 21.20 (continued)

(b) Advantages of composite biological reconstruction of the calcaneus

Based on the characteristic of composite biological reconstruction, Li Jing et al. [38] designed structural bone-grafting with vascularized singular fibula composited with allogeneic bone to reconstruct the calcaneus after tumor resection. The advantages are: the allogeneic bone can support early load-bearing and protect the fibula while it can provide positions for plate-screw fixation. As a kind of living bone, the fibula can easily unite with the huckle-bone to support the metapodium together with the allogeneic bone. It is crucial for ultimate activation of the allogeneic bone. It also enhances the ability of local anti-infection.

(c) Technical key points for composite biological reconstruction of the calcaneus

- The allogeneic cortical bone is good for early load-bearing. The cancellous bone can easily fuse with the fibula and huckle-bone. So, the allogeneic calcaneus or allogeneic femoral head and neck are suitable graft materials. The femoral neck can be designed as the load point area. Its union with the cancellous bone at the contact end of the huckle-bone can be firmer. After marrow expansion in the central part, the fibula is embedded. If the vascular pedicle is compressed, a slot can be cut at one side.
- Embed the fibula into the bone slot of the huckle-bone, maximize the contact surface between the huckle-bone and the allogeneic bone. The two parts can be fixed with lag screws.
- It is good for stress dispersion to keep the fibula at the weight-bearing side parallel and level with the huckle-bone.

21.2 Microsurgery of Chronic Osteomyelitis

Chun Zhang

21.2.1 Introduction

Osteomyelitis, which is caused by bacterial infection in bones, is an ancient but modern bone infectious disease with changing epidemiology and increased incidence. It is categorized into two types, namely, hematogenous osteomyelitis and traumatic osteomyelitis. Hematogenous osteomyelitis used to be more common while traumatic osteomyelitis, also called chronic osteomyelitis, is more prevalent currently.

Definition of traumatic osteomyelitis: Traumatic osteomyelitis refers to mainly the osteomyelitis induced by direct pollution or infection from open fracture, open reduction and internal fixation, or firearm injury. It is characterized by infection which is mainly located at bone fracture site and accompanied soft tissue defect, bone defect, and bone nonunion. Its pathogenic bacteria are mainly *Staphylococcus aureus*. Because the blood supply to the tissues surrounding the focus is usually poor and simple systemic application of antibiotics can hardly lead to effective bacteriostasis or sterilization, thorough debridement by surgical operation is the main treatment.

Pathological mechanism of chronic osteomyelitis: Traumatic osteomyelitis is initially triggered by invasion of pathogenic microorganisms which pass through the outer defense system of skin and mucous membrane of the host and finally adhere to the bone. Normal bones can resist the adhered bacteria but injured ones are vulnerable to bacterial attack. Part of the mechanism is probably that a pathogen has many receptors for the host proteins which are turned into an open state due to bone injury. *Staphylococcus aureus* contains receptors of the exposed collagen and the fibrin that temporarily covers the injured tissue shortly after bone injury. In cases of open fracture, exogenous debris, even the free and necrotic bone fragments which have lost blood supply, may develop into a focus of bacterial attachment. Therefore, with expansion of osteonecrosis, more sites are exposed to the attachment of pathogens, resulting in sustainable development of the disease. In cases of chronic osteomyelitis induced by internal fixation, an internal fixator provides another kind of attachment site for pathogens which aggregate and reproduce in the inactivated tissues after successful attachment on the bone and the internal fixator. Microorganisms at an infection focus without blood supply can effectively escape the attack from host immune system and antibiotics for unrestricted reproduction through the culture medium formed by dead bone, blood clots, and dead space. Consequently, the infection expands as the bacteria spread to the adjacent bone and soft tissue. Rapid growth of the bacteria may result in formation of abscess and sinus. After formation of abscess and aggregation of fester in the adjacent necrotic tissue, abscess, drainage and sinus may attack the victim circularly. If the tissue without blood supply is not removed thoroughly enough using invasive surgical debridement, the chronic disease will relapse once again.

Classification of osteomyelitis: Osteomyelitis can be classified into haematogenous and exogenous (i.e. traumatic) kinds by the infection mechanism, and acute and chronic kinds by the presence of osteonecrosis. Currently, the most widely used classification is that proposed by Cierny and his colleagues in 1985. The system classifies osteomyelitis as follows: (a) According to the anatomic range of affected bone, there are four anatomic types, namely, intramedullary osteomyelitis, superficial osteomyelitis, localized osteomyelitis, and diffused osteomyelitis. (b) According to the immune activity of the host, there are three grades. Grade A refers to hosts with normal metabolic and immune status, as well as fine blood supply to the injured part. Grade B represents hosts with systemic or local factors that influence the wound healing. Grade C denotes hosts with disordered systematic function. Moreover, in accordance with different conditions, 12 clinical stages are divided. In practice, determining the anatomical range of osteomyelitis is more practical and important than remembering the stages.

21.2.2 Four Anatomical Types of Osteomyelitis

1. Intramedullary osteomyelitis: The lesion is located at the endosteum and merely limited to the intramedullary surface (acute hematogenous osteomyelitis or intramedullary infections, such as the postoperative infection of intramedullary nail).
2. Superficial osteomyelitis: This type is really an event of focal contact infection in which the outermost layer of bone is infected by an adjacent focus, such as a decubitus ulcer. After internal fixation of fracture by a plate, its surroundings are infected.
3. Localized osteomyelitis: In localized osteomyelitis, a hole that penetrates the whole cortex layer appears on a section of strong bone. This phenomenon is common for bone infections associated with an internal fixator of fracture or an adjacent internal fixator.
4. Diffused osteomyelitis: This type refers to the cases whose infection focus has spread to bone and soft tissue so that the infected bone fracture does not heal.

21.2.3 Diagnosis of Osteomyelitis:

21.2.3.1 Inquiry

Inquiry should cover cause and history of disease; therapies used and effects; presence of sinus and changes; property, color, odor and amount of oozy liquid; past medical history; systemic conditions (such as drinking, smoking, blood pressure, blood glucose, and functions of the heart, lung, liver and kidney), and peripheral neovascular lesions.

21.2.3.2 Physical Examination

Systemic and comprehensive physical examination cannot be ignored, especially for occult blood, glucose increase and peripheral neovascular lesions. In addition, acquaintance with disease history helps understanding the immune function. Check on the local limb should focus on presence of swelling, heat, and pain of soft tissue; size, degree and property of local scar; depth and direction of sinus; area of soft tissue defect; exposure of bone and internal implants; color and smell of oozy liquid; and abnormal activities of the limb as well.

21.2.3.3 Laboratory Examination

Most of the routine examinations of the peripheral blood from the patients suggest normal white cell count and a mild increase in erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP). The increase in all the three indexes is a manifestation of acute osteomyelitis or osteomyelitis activity. Results of secretion bacteriology culture show that about 30% of the patients are negative. In the cases we investigated, *Staphylococcus aureus* accounted for about 45% of the total number of bacteria. The results of bacterial culture are helpful to the choice of antibiotics application.

21.2.3.4 Imageological Examination

X-ray plain films play a very important role in the diagnosis of chronic osteomyelitis since they provide clinicians with necessary information on overall structure, morphology, implants, and union status of the bone of interest. However, it is probable that the osteomyelitis at the calcaneus, patella and ilium may not be revealed by radiology. At an early stage, it is often reflected as osteopenia, trabecular rarefaction, cortical bone thinning, and loss of trabecular structure in the cancellous field. Once part of the bone tissue becomes necrotic and is separated from the normal boundary by a shell, the dead bone shows a high density, which is easy to recognize on a plain film. CT observation is helpful for the preoperative assessment as it has a good discriminating effect on cortical bone and dead bone. Magnetic resonance imaging (MRI) is highly sensitive and specific to chronic osteomyelitis. Therefore it can provide very clear and detailed images about bone and soft tissue that are essential for formulation of an operation plan. MRI images also provide information on range of tissue edema and positions of hidden fistula and abscess. Preliminary examination usually consists of T1 and T2 images. The signal strength on the infected area is weakened on T1 images while enhanced on T2 images. The enhanced signals are induced by the high content of water in the granulation tissue.

21.2.3.5 Application of Microsurgical Techniques in Treatment of Osteomyelitis

Chronic osteomyelitis is one of the most serious complications. Treatment of chronic osteomyelitis, especially complex osteomyelitis accompanied by soft tissue defect and bone nonunion and defect, is often very time consuming, challenging and expensive. It likely compromises function, leading to a high disability rate. In treatment by microsurgical techniques, muscle and musculocutaneous flaps are used to cover and fill wounds on the bone graft bed after debridement of osteomyelitis focus, or vascularized osseous myocutaneous flaps are implanted for phase-one repair of bone and soft tissue defects. The excellent and precise efficacy of microsurgery cannot be achieved by other surgical methods.

Thorough debridement is the most basic and important step in surgical treatment of osteomyelitis. The debridement objects include scar surrounding the focus and fibrous hyperplasia granulation tissue following inflammatory reaction. The more thoroughly a lesion is eliminated, the larger a tissue defect, especially a soft tissue one, will be. Therefore, this poses a great challenge for wound closure that can be tackled by covering the soft tissue defect using muscular flap, musculocutaneous flap, or skin flap after bone grafting is closed. Meanwhile, the rich and reliable blood supply and the normal morphological structure of a muscular or a musculocutaneous flap may greatly improve the original poor blood supply and nutrition condition of the damaged bone and adjacent tissues. Consequently, anti-infection capability and graft union are enhanced. Moreover, if the patients can initiate their functional rehabilitation training early, the disability rate is reduced. Therefore, thorough debridement plays an extremely important role in reducing or even avoiding recurrence of osteomyelitis.

Since application of specific tissue flap transplantation has been depicted in detail in other chapters of this book, we will discuss in the following application of microsurgical techniques in five cases of osteomyelitis (at the proximal tibia, distal tibia, femur, patella and calcaneus, respectively) which were chosen from more than 300 cases of chronic osteomyelitis we had treated in clinic.

Typical Cases

Case 1 Osteomyelitis of the Proximal Tibia

Medical History

Case 1 was a male of 45 years old. On December 13, 2010, he was referred to our hospital due to wound rupture accompanied by bone exposure 40 days after an open fracture surgery on the left proximal tibiofibula. His admission number is 88032. Forty days before, the patient was treated in a local hospital for systematic multiple injuries caused by a traffic accident. He was diagnosed with traumatic brain stem hemorrhage, traumatic subarachnoid hemorrhage, skull fracture, brain contusion, open fracture of the left tibiofibula with peroneal nerve injury, and injury to the right brachial plexus. In emergency treatment, he underwent debridement, suturing, and active treatment. 25 days before when his condition became steady, open reduction and internal fixation was conducted for the left tibiofibula. Postoperatively, skin necrosis complicated with infection was observed. Six days before, debridement was conducted. After the debridement, he was referred to our hospital for soft tissue defect at the proximal left crus, bone and plate exposure, and concurrent infection. Physical examination before admission indicated as follows: thin appearance, an anterolateral soft tissue defect at the left proximal crus with an area of about 15 × 7 cm, tibial and plate exposure accompanied by a small amount of yellowish exudate with unobvious odor, dorsal foot skin hypesthesia, and dorsiflexion incapability (Fig. 21.21). X Ray showed that the bone fracture was reset well after internal fixation of the left tibial fracture (Fig. 21.22). Wound bacteria culture found the Bauman's composite calcoaceticus acinetobacter. Drug sensitive experiment suggested that all the bacteria resisted antibiotic drugs.

The problems needed to be solved:

How to control the infection? Should the plate be removed or not? If the plate is removed, how is the fracture fixed? How to repair the bone defect left after debridement? Is the bone defect repaired by multiple stages or by one stage? How to repair the soft tissue defect?

Fig. 21.21 Pre-operative wound showed exposure of bone and plate, the arrow showed proximal part of fracture and granulation

Fig. 21.22 Pre-operative X ray

Treatment Plan

Given that the pathogenic bacteria of the patient were drug-resistant Bauman's composite calcoaceticus acinetobacter, it is hard to be control the infection. Hence, thorough debridement of the infected tissues was of great significance. Moreover, the infection might have spread to the intramedullary since the fracture was visible from the wound (as arrowed in Fig. 21.21). Therefore, it was required to dismantle the plate during debridement and eradicate the infected focus in the medullary cavity completely. The bone stability was maintained using an external fixator. Because an external single-arm fixator produces poor stability though it can provide temporary fixation, an annular external fixator was used for three-dimensional fixation. The bone defect was filled with antibiotics-loaded calcium sulfate which might control and prevent recurrence of infection due to its slow-release of the antibiotics. In case of a massive bone defect, autologous iliac was implanted to promote the bone union.

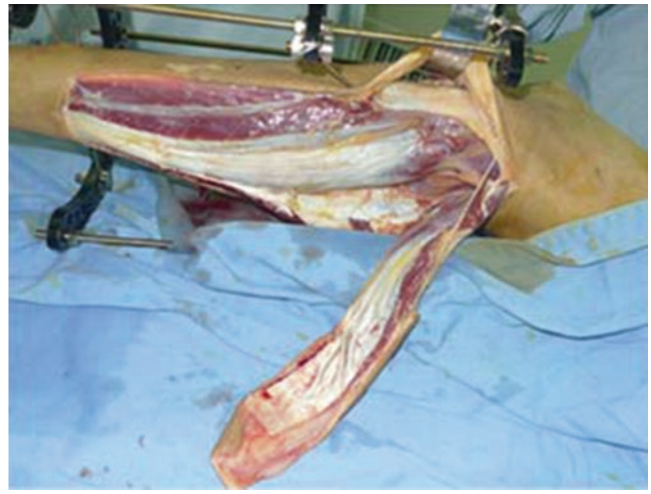


Fig. 21.23 Debridement, remove the plate and granulation in the fracture area and medullary space

The anterolateral soft tissue defect of the proximal crus, as well as the concurrent bone exposure, was usually repaired through transplantation of lateral gastrocnemius myocutaneous flap or free anterolateral femoral skin flap and reverse transposition of distal femoral anterolateral skin flap. However, the free flaps called for vascular anastomosis and the operation was complex and difficult. In addition, due to the difficulty in exposing the vessels in the donor zone, the methods above were not used commonly. Because reverse transposition of the distal femoral anterolateral skin flap is a complex operation process, it can be used in case of failed utilization of caput laterale and caput mediale.

Operation Process

Firstly the wound below the tourniquet was thoroughly debrided. The wound edge was removed by 2 mm. The steel plate was dismantled before the inflammatory granulation tissue was scraped on the wound surface. Intramedullary debridement from the fracture end was conducted to remove the intramedullary inflammatory granulation tissue and necrotic bone using curette before sending the specimens to laboratory for bacterial culture. The wound was rinsed for three times using physiological saline and hydrogen peroxide (Fig. 21.23) and disinfected using PVP-I to replace the napkin. The designed lateral gastrocnemius myocutaneous flaps were cut out and transplanted to the anterolateral crus (Fig. 21.24). Antibiotic-loaded calcium sulfate mixed with autologous iliac bone graft was used to fill the intramedullary bone defects after the debridement to prevent recurrence of infection caused by hematocele (Fig. 21.25). Moreover, before bone fracture reduction, sufficient bone mass was implanted into the intramedullary cavity. The vertical fracture line was firstly fixed using Kirschner wire before the bone stability was maintained by an external fixator installed

Fig. 21.24 Harvest the lateral gastrocnemius myocutaneous flap, and transfer the flap through the subcutaneous tunnel

Fig. 21.26 Keep the stability of bone by circular external fixation, and cover the wound by lateral gastrocnemius myocutaneous flap after bone grafting

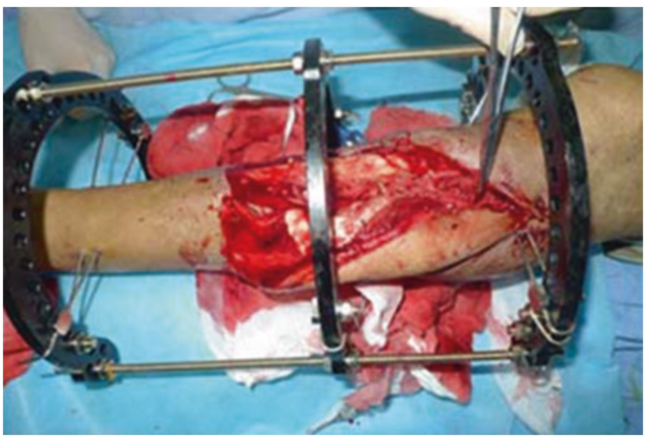


Fig. 21.25 Implant the autogenous iliac bone combined with antibiotic loaded calcium sulfate

Fig. 21.27 The wound was cured very well one month after operation, no infection recurrence

(Fig. 21.26). Muscle flaps under which drainage tubes were placed were used to cover the wound.

Follow-up: The first-phase flaps survived after operation (Fig. 21.27). The bacteria in the intramedullary cavity cultured intraoperatively were still Bauman's composite calcoaceticus acinetobacter. The follow-up of more than 3 years up to now has revealed bone union, infection-free recovery, and good function of the knee joint (Figs. 21.28 and 21.29).

Summary of the Key Points of Diagnosis

1. It was not easy to control the infection caused by the drug-resistant Bauman's composite calcoaceticus acinetobacter in the patient. According to the outward appearance and preoperative X image of the wound, it seemed that the infection was not serious and the intramedullary infection was likely to be neglected. Therefore, plate removal and intramedullary debridement were the keys to the successful operation.
2. The postoperative residual dead space is one of the important factors that lead to a failed operation for osteomyelitis. The space where hematoma has formed may become a medium for aggregation and reproduction of bacteria and is prone to develop recurrent infection. In our operation, the residual empty medullary cavity after intramedullary debridement was fully filled with antibiotics-loaded calcium sulfate and autogenous iliac bone graft. On one

Fig. 21.28 Follow with 3 years, no osteomyelitis recurrence, the function of knee was good

hand, the antibiotics in the calcium sulfate which was released slowly but at high-concentrations into the medullary cavity helped inhibit growth of the bacteria though they were insensitive to the drugs. On the other hand, the bone induction and bone conduction characteristics of the autologous ilium might have promoted the healing of bone fracture. Antibiotics-loaded calcium sulfate combined with autogenous iliac bone graft was another key to the success of this operation.

3. Maintaining bone stability is an important factor for fracture healing, especially when infection has occurred. The three-dimensional fixation of external annular fixator we had used was obviously more advantageous than a single-arm external fixator in maintaining the bone stability.
4. The patient underwent thorough debridement of the lesion, implantation of the antibiotics-loaded artificial bone into the wound medullary cavity (slowly released antibiotics to control and prevent infection), covering the wound surface with myocutaneous flaps, and bone fracture fixation using an external annular fixator. All the operations were completed at one stage.

Case 2 Osteomyelitis of the Distal Tibia

Medical History

Case 2 was a male of 53 years old. On October 10, 2012, he was admitted to our hospital due to repeated burst with pus on the left crus induced by trauma. Forty years before, he received medical treatment in a local hospital for a skin defect on the left crus induced by trauma. Subsequently, burst and suppuration was repeatedly observed on the skin of the original wound on the left crus. Ten year before, he received lesion debridement shortly after the sinus on the left crus ulcerated again, but the postoperative outcome was unfavorable despite treatments of anti-infection and dressing change. The internal sinus on the left leg still produced exudates. The patient had no fever but felt pain so that he came to our hospital for further treatment. Moreover, the patient had suffered from hypertension for half a year but the condition was well controlled. He had no diabetes, peripheral vascular disease, or history of hepatitis or tuberculosis. Physical examination before admission suggested skin chromatosis on the inside of the lower part of the left crus and a sinus that

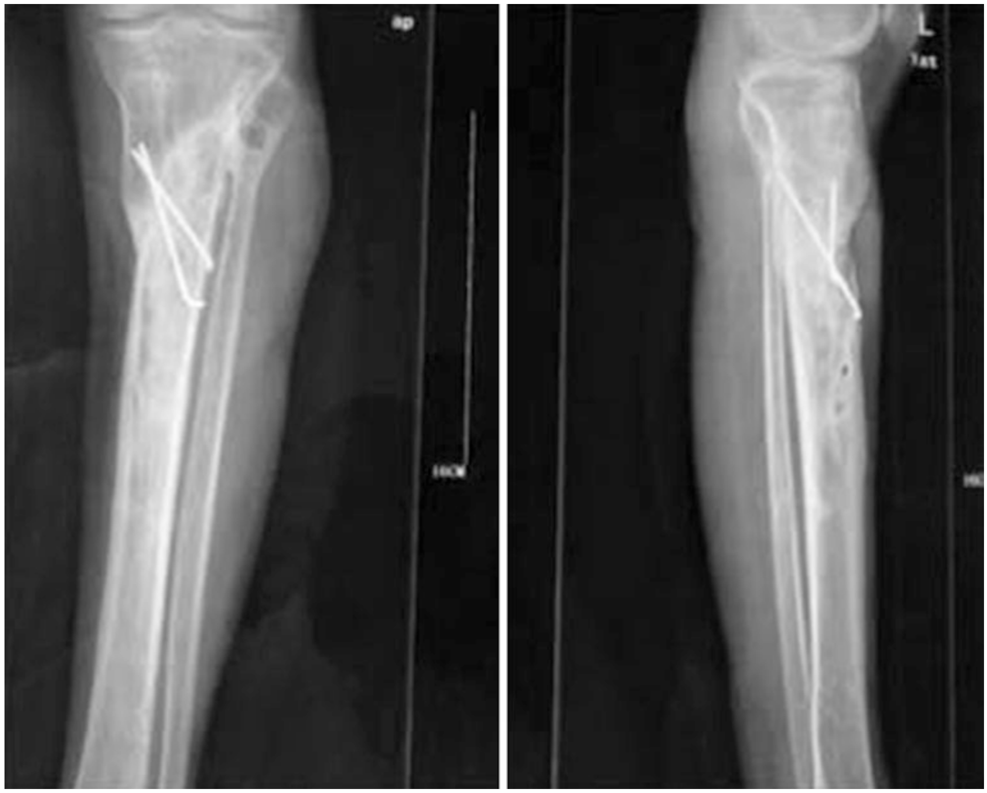


Fig. 21.29 X ray of 3 years after operation

straightly reached to the tibia above the medial malleolus (as arrowed in Fig. 21.30). The sinus was about 3 cm deep and discharged flaxen pus. Scar hyperplasia but no swelling was observed at the surroundings of the sinus. The ankle joint exhibited no range of motion and the left foot end presented with good blood circulation. The X-ray film demonstrated ankle joint fusion and patchy shadows of high density on the distal end of the left tibia with an oval area of low density in the middle (as arrowed in Fig. 21.31). CT signified a medial cortical defect of the left tibia and surrounding osteosclerosis (Fig. 21.32). MRI noted a low signal shadow on T1 image and a high signal shadow on T2 image of the medulla of the left distal tibia that was interlinked with sinus (Fig. 21.33).

The problems needed to be solved:

How to repair the defects of soft tissue and bone after debridement and determination of the lesion range?

Fig. 21.30 Pre-operative wound, the arrow showed the sinus, and Inflammatory scars and pigmentation around the sinus

Treatment Plan

Although the patient had only one sinus in the defective soft tissue, significant scar hyperplasia, chromatosis, and poor blood circulation developed surrounding the sinus due to his long-term and repeated inflammation. Therefore, during the debridement, after the scar tissue was completely eradicated it should be covered with normal tissue to improve the blood circulation and anti-infection ability of the area surrounding the lesion. Since the infected lesion in the tibia had lasted for 40 years, the treatment was difficult with the repeated hyperplasia and sclerosis of inflammatory callus. The relapses after multiple times of lesion debridement were possibly related to the halfway nature of the debridement or poor coverage of the defective soft tissue. Consequently, preoperative determination of the lesion range using CT and MRI was of great significance. During the operation, the sclerotic bone was to be removed using a grinding drill to completely clear the infected bone. Moreover, the antibiotics-loaded calcium sulfate and autogenous bone was implanted to prevent infection and to promote bone union.

Fig. 21.31 Pre-operative X ray, the arrow showed infection lesion, which was low density

Fig. 21.32 CT showed sinus and bone defect

Fig. 21.33 MRI showed bone infection range

The Operation Process

During the operation, the sinus and surrounding scar hyperplastic tissue was thoroughly cleared until normal tissue was exposed (Fig. 21.34). By windowing on the periphery of the tibia medial sinus, the sclerosis and inflammatory callus was cleared using abrasive drilling until even errhysis was shown on the bone surface (as arrowed in Fig. 21.35). Subsequently, the antibiotics-loaded calcium sulfate and autologous iliac bone was implanted to fully fill the traumatic space. It should be noted that no dead space should be left (Fig. 21.36)

The surface of soft tissue defect was covered with posterior tibial artery perforator flaps below which drainage tubes were placed (Fig. 21.37).

Follow-up

Postoperatively, flaps survived completely and the wound healed by the first intention. Follow-up of 15 months showed no relapse of osteomyelitis and control of infection (Figs. 21.38 and 21.39).

Fig. 21.34 Remove the sinus and scar tissue

Fig. 21.35 Remove the hardening and inflammatory bone callus by abrasive drilling, until bleeding on the bone surface (black arrow)

Fig. 21.36 Implant the autogenous iliac bone and antibiotic loaded calcium sulfate into the bone cavity

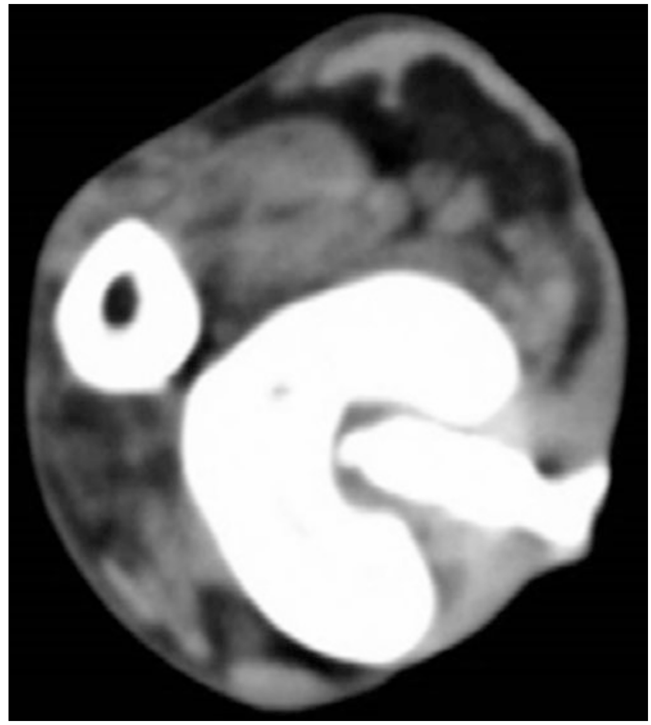


Fig. 21.37 Cover the wound by posterior tibial artery perforator flap

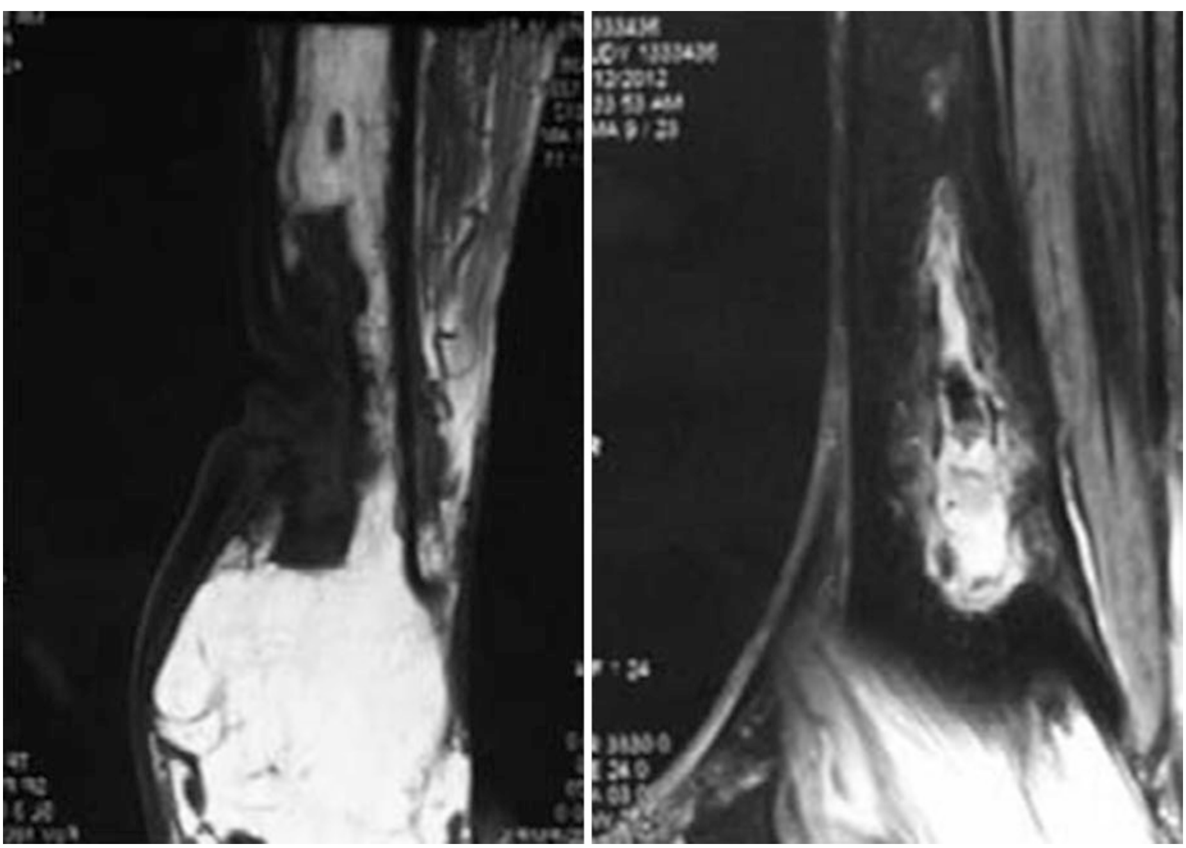


Fig. 21.38 Follow with 15 months, the wound was cured well, and no infection recurrence

Fig. 21.39 Follow with 15 months, Bone graft particles still can be seen on the X ray

Summary of the Key Points of Diagnosis

The major challenge of this case lies in that his osteomyelitis of a long history had not been cured by many times of operation. Determination of the range of osteomyelitis focus and complete resection of the focus were crucial for our successful operation. Prior to the flap coverage, the scar tissue surrounding the sinus should be thoroughly resected to improve local blood circulation. This was an important factor leading to the success of our operation.

Case 3 Osteomyelitis of the Calcaneus

Medical History

The patient was a female of 60 years old. On August 8, 2008, she was admitted to our hospital due to repeated burst and ulceration on the right heel. According to the patient, a yellow abscess of 1 × 2 cm with pressing pain appeared on her right heel with no significant incentive 1 year ago. Then she accepted an operation for abscess incision drainage at a local hospital. Because her wound refused to heal, she was referred

Fig. 21.40 Pre-operative wound, the arrow showed the sinus with a little effusion and scar hyperplasia

to a superior hospital for further treatment where she was diagnosed with osteomyelitis at the right calcaneus. Subsequently, sequestrum curettage was conducted and the space was filled with antibiotic cement. Since her wound still repeatedly oozed postoperatively, debridement was performed again and bone cement was removed. Due to the sustained wound nonunion, she was transferred to our hospital. The patient was healthy previously and had no history of diabetes, hypertension, hepatitis, tuberculosis, or long-term drug application. Physical examination before admission: a sinus directly reaching to the calcaneus was observed on the rear fat pad of the right heel, accompanied by a small amount of yellowish exudate with no obvious smell. Surrounding the sinus, there were scar hyperplasia and mild swelling with no obvious redness or skin temperature increase (Fig. 21.40). The X-ray film prompted irregular bone destruction of the right calcaneus, low density changes at local sites and a small amount of high density shadow at the surroundings (Fig. 21.41). CT examination after admission suggested a low-density dead space in the right calcaneus where patches of dead bone surrounded by sclerosis were observed. Moreover, the dead space was visibly connected with multiple low-density zones (Fig. 21.42).

The problems needed to be solved:

After 1 year of repeated relapse, the patient had a sinus and scar around the sinus grown so that the soft tissue defect was not obvious. As a result, the problem was how to close the wound after debridement? The low density zone on the X film was the focus. How to repair the bone defect after debridement? How to choose flaps?

Treatment Plan

In the 1 year of repeated relapse, the patient underwent three operations but the wound did not heal and the infection was

Fig. 21.41 The flap survived well

out of control. As the main cause was possibly the incomplete debridement, it was crucial to conduct thorough debridement to clear the sinus and surrounding scar, sclerotic and necrotic bone, and residual foreign substances. Moreover, because the chronic osteomyelitis of the calcaneus might have multilocular lesions, preoperative examination should be sufficient and operation should be careful. Since the focus was at the weight-bearing area of the heel, skin texture and skin sensation reconstruction were to be considered when flaps were designed. Flaps carrying the cutaneous nerve might help reconstruct the heel skin sensation and enhance anti-infection ability due to the hallucis abductor muscle carried. In addition, a peroneal artery perforator flap and a sural neurovascular flap might also serve as the alternatives, but their skin was thin and not abrasion-resistant enough so that they could not be used to reconstruct sensation.

The Operation Process

The sinus and surrounding scar tissues were completely resected by debridement under the tourniquet (Fig. 21.43). The necrotic and sclerotic bone and the residual bone cement were eradicated (Fig. 21.44). The operation site was washed

Fig. 21.42 Follow with 8 months, the wound was cured well, and no infection recurrence

Fig. 21.43 Pre-operative X ray, the arrow showed infection lesion, which was low density

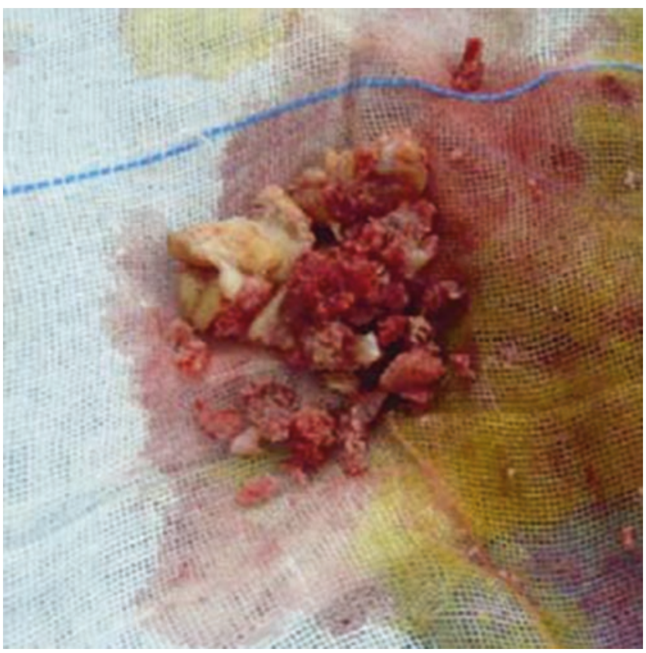


Fig. 21.44 CT showed cavity in right calcaneus, a piece of dead bone can be seen in the cavity, and hardening bone around it

using saline and hydrogen peroxide for three times. The drape was sterilized again before the medial plantar island myocutaneous flap designed was harvested to cover the wound (Fig. 21.45). The space left after the calcaneal debridement was filled with antibiotics-loaded calcium sulfate (Fig. 21.46).

Follow-up

Postoperatively, flaps survived completely and the wound healed by the first intention (Fig. 21.47). Follow-up of 8 months revealed that the wound on the heel healed well and the sensation recovered, indicating the calcaneal osteomyelitis was cured (Figs. 21.48 and 21.49).

Fig. 21.45 Remove the sinus and scar tissue

Fig. 21.46 Plenty of antibiotic loaded calcium sulfate in the bone cavity can be seen on the post-operative X ray

Summary of the Key Points of Diagnosis

Preoperative evaluation is very important. As for patients with chronic calcaneal osteomyelitis, preoperative CT or MRI check is necessary for the surgeons who should be fully acquainted with the lesion scope to achieve thorough debridement intraoperatively. The medial plantar island flap selected is similar in color to that of the donor zone and is wear-resistant. Moreover, it can recover the skin sensation and does not lead to ulcer formation easily.

Fig. 21.47 Dead bone and bone cement removed from the lesion

Fig. 21.48 Implant the antibiotic loaded calcium sulfate into the bone cavity, cover the wound by plantar medial island myocutaneous flap

Fig. 21.49 Follow with 8 months, calcium sulfate absorption and osteogenesis can be seen on the X ray

Fig. 21.50 Pre-operative wound, the arrow showed the sinus with a little effusion and scar hyperplasia

Case 4 Osteomyelitis of the Patella

Medical History

Case 4 was a female of 66 years old. On June 12, 2013, she was admitted to our hospital for repeated exudation from the incision after the surgery she had undergone for her fracture of the right patella half a year before. Postoperatively, incision exudation occurred and failed to be alleviated by anti-infection and dressing change. In April, her internal fixation was removed and anti-infection treatment was sustained. The wound still had exudates while the patient had no fever. Therefore, she was referred to our hospital for treatment. The patient was healthy previously and had no history of hypertension, diabetes, hepatitis, tuberculosis, or long-term drug application. Her physical examination before admission: A sinus of 2 cm was observed around the outside of the right knee, accompanied by a small amount of yellowish exudates without obvious smell. The patella was exposed without obvious red swelling on the periphery (Fig. 21.50). X-ray film demonstrated that her patellar fracture was not healed (Figs. 21.51 and 21.52). MRI T2 images showed a high signal shadow that was connected with the sinus. Besides, the joint cavity contained a small amount of dropsy and the peripheral tissues were in a state of edema (Fig. 21.53). Wound bacteria cultured after admission were *Enterobacter cloacae*.

The problems should be solved:

Was the patella kept or not? How to restore the function of the knee joint after operation?

Treatment Plan

According to the X-ray film and MRI images, her patellar fracture was in large fragments and the inflection had not aggravated all over the whole patella and joint cavity. So the infection was still relatively limited. The scar hyperplasia

Fig. 21.51 Fix the patella with tension band, cover the wound by medial gastrocnemius muscle flap through subcutaneous tunnel

Fig. 21.52 Followed with 12 months, the wound was cured well, the function of knee was good

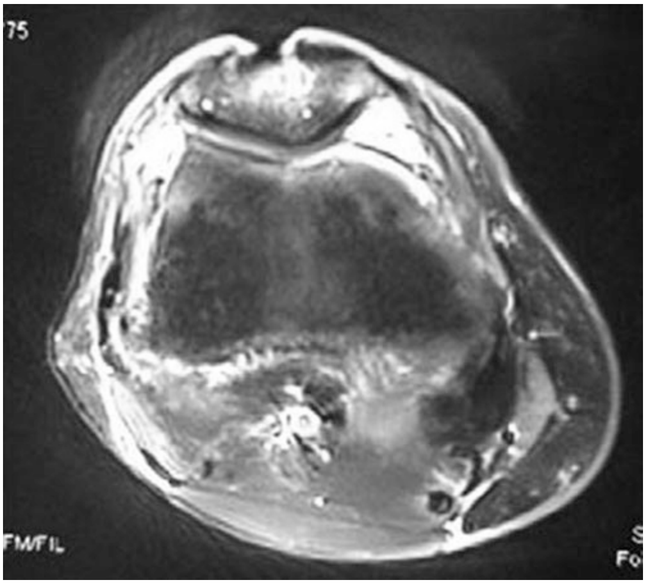


Fig. 21.53 Followed with 12 months, the wound was cured well, the function of knee was goods

Fig. 21.54 Pre-operative X ray showed nonunion of patella fracture with local hardening

and inflammatory tissues around the lesion were to be completely resected and the wound surface to be covered using flaps.

Operation Process

The scar tissues surrounding the sinus and the inflammatory granulation tissues at the fracture ends were completely resected by debridement under the tourniquet (Fig. 21.54). The patella was fixated using a tension band after the bone fracture was reduced; the muscle flaps were harvested from the medial head of the gastrocnemius to cover the patellar surface using the flaps through the subcutaneous tunnel; drainage tubes were placed below the muscle flap and a free skin flap was grafted on the muscle flap surface (Fig. 21.55).

Fig. 21.55 Pre-operative X ray showed nonunion of patella fracture with local hardening

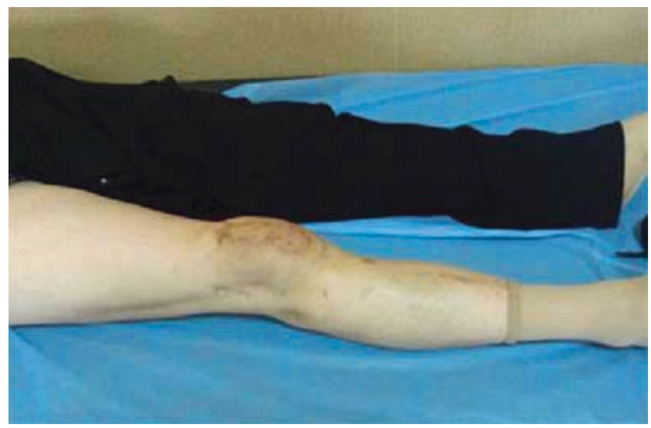


Fig. 21.56 Remove the sinus, scar tissue, and granulation of fracture area

Follow-up

Postoperatively, the wound healed by the first intention (Fig. 21.56). Follow-up of 12 months showed that the knee joint recovered favorable function following rehabilitation training and no obvious pain was felt in motion (Figs. 21.56 and 21.57). X-ray film review suggested translocation of the internal fixation of the patella, slippage of Kirschner wire, and separation of fracture blocks (Fig. 21.58).

Summary of the Key Points of Diagnosis

The osteomyelitis of this patient was successfully cured. Although loosening and translocation of the internal fixator resulted in nonunion of her patellar fracture, the knee joint recovered good function and had no significant pain in motion. The outcome revealed that relatively strong fibrous callus between the patellar fracture ends was possibly induced by the coverage of muscle flaps.

Fig. 21.57 Pre-operative MRI showed high signal of patella surface in T2 series, which connected with the sinus

21.3 Microscopical Repair of the Tibia Congenital Pseudarthrosis

Jianli Wang and Guangjun Liu

Congenital pseudarthrosis of the tibia (CPT) is a specific type of nonunion that is present at birth or after. It is a infrequent kind of deformity with low incidence. The relevant clinical knowledge is lack, and the aetiological agent is unknown. The treatment of CPT is difficult, and the recurrence rate is high. It is generally acknowledged CPT associated with the following factors, circubtion supply of the fetus in the uterus has obstacles, congenital defect, osteitis custica etc. But these are lack of adequate evidence. Neurofibromatosis is closely related with CPT which often occurs in patients with neurofibromatosis, Aggressive fibromatosis change occurred pseudarthrosis periosteum

Fig. 21.58 Followed with 12 months, X ray showed failure of internal fixation and nonunion of patella

and hyperplasia of fibrous tissue. After research, Wei Lei [39], etc confirmed that aggressive fibromatosis sample change is the main cause of congenital pseudarthrosis of the tibia.

21.3.1 Clinical Manifestation

Congenital pseudarthrosis most commonly involves the distal half of the tibia and often that of the fibula in the same limb. Ipsilateral leg is shorter and smaller than the healthy side. It often has angular deformity in the middle and distal segment, prones to fracture, develops into pseudarthrosis for the fail therapy, and may be born with fractures. There are no swelling, pain, and discomfort in the ipsilateral leg, but body skin often scatter light brown spots. Its X ray show variously. Some appearance is that the tibia perform anterior bowing with hourglass stenosis. It becomes tapered, rounded, and sclerotic, and its medullary canal vanish. Some performance occurs with a cystic change, usually near in the distal the tibia. Anterior bowing may precede or follow the development of a fracture. Other performance is that the tibia bone has sclerosis without diminution. Its medullary canal is partially or completely obliterated. Local tibial may occur stress fracture, and gradually developed into sclerosis bone. With completion of the fracture, healing fails to occur, and the fracture widens and becomes a pseudarthrosis. However, complete fracture is not healed, it form false joints.

21.3.2 Treatment

Congenital pseudarthrosis of the tibial in children can be blocked by using orthosis support during their early stage. This is helpful to children without fracture during the early stages, and the children could accept surgical treatment till an older age. And yet, few adults without surgical treatment have been reported bone healing, who suffered tibial congenital pseudarthrosis. Once diagnosed with congenital tibial pseudarthrosis, children usually need several surgical treatment. Currently, bone grafting procedures remain the primary treatment for that disease. There are two accepted good treatment. One is the intramedullary rodding technique described by Anderson, Schoenecker, Sheridan, and Rich. The other is vascularized fibular grafts. This section mainly elaborates the later method.

21.3.3 Indications

Indications for using vascularized fibular grafts is that the children who have severe shortening, larger gap pseudarthrosis or been suffered failure surgery (bone graft + internal fixation).

21.3.4 Surgical Technique

The transferring of vascularised fibular flap include free vascularised fibular flap and pedicled fibular flap.

1. **Free vascularised fibular flap** [40]**:** First, the visibly thick periosteum, postoperative scar and fibrous tissue surrounding between bone ends must be completely excised. Removal the pale hard bone ends, get through the medullary cavity, remove the distal sclerotic tibial intramedullary lesions and adipose tissue in medullary cavity and soft cortical bone. Dissect proximal anterior tibial vessels and its accompanying veins, prepare for microanastomosis with the vascular bundle of the same name in transplanting flap bone. According to the tibia length in recipient site, coupled with its length of embedded in both ends of the medullary cavity, design the cutting length of contralateral fibula. Using a lateral approach, enter through the clearance between the peroneal muscles and the soleus, find the vessels in the deep. Continue to dissect until peroneal artery bifurcation. Saw off the fibula between proximal and distal fibula, to be free before and after the flip (If conditions, carefully identify the septocutaneous perforators supplying the skin paddle), retained part muscle sleeves, ligated the distal end of peroneal artery and vein. At this time, only peroneal arteriovenous pedicle attached to the proximal fibula. Cut off the vascular pedical, when the recipient site is ready, and transferred the fibular flap to the recipient (Fig. 21.59).

   Both ends of the fibula were inserted into the medullary cavity, and were fixed by external fixation and Kirchner wires. If they were not tightly embedded, autograft or allograft would be implanted, then bundled and fixed with steel wire. Vascular microanastomosis was performed on the anterior tibial artery and its follow vein, respectively, after fibula fixed. Placed local drainage, sutured the incision successively, used conventional three anti-therapy (anticoagulant, anti-contracture, anti-infective) for 7 days.

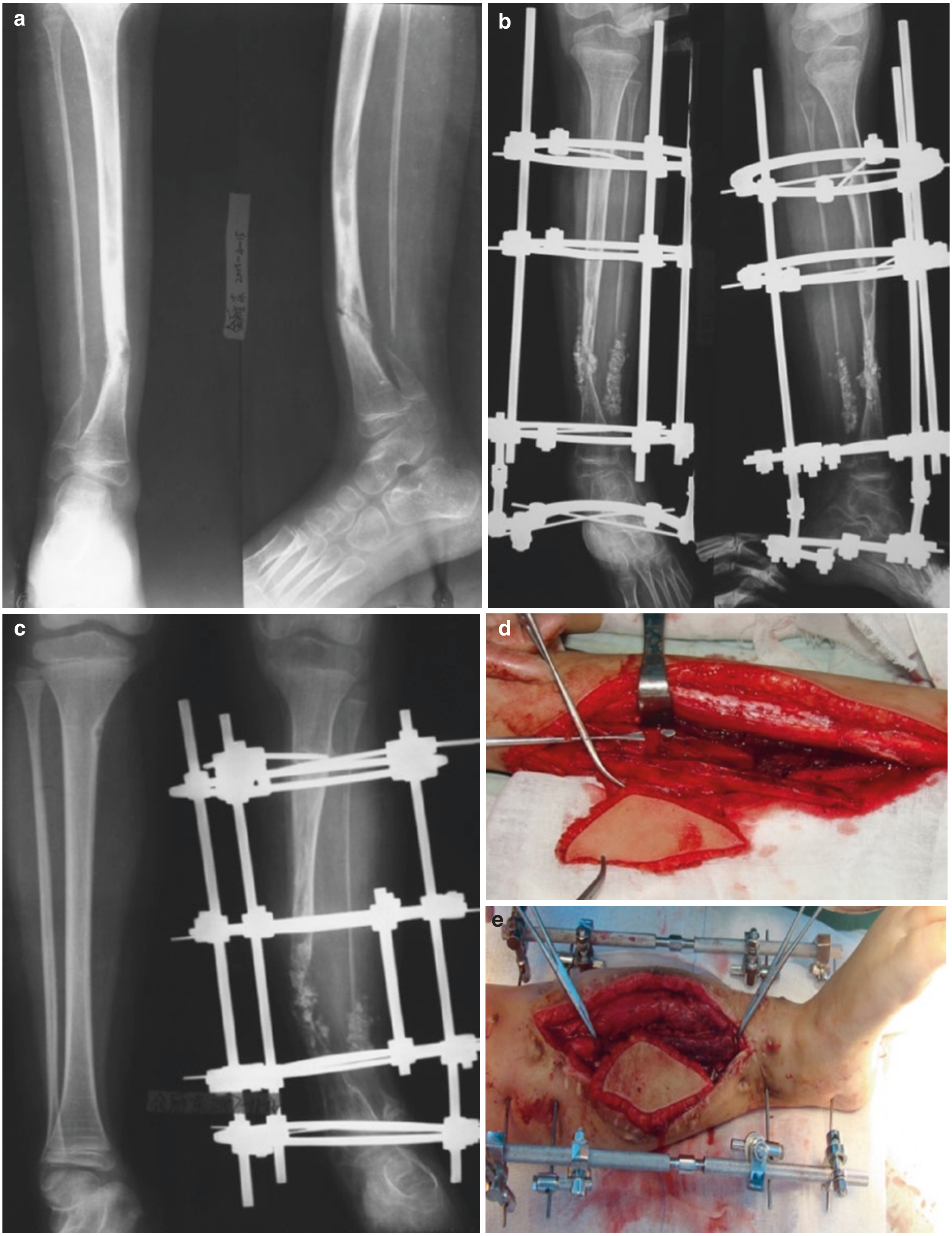


Fig. 21.59 (**a**) Preoperative X-ray. (**b**) Bone grafting after external fixation. (**c**) Postoperative bone absorption. (**d**) Free vascularised fibular flap. (**e**) Transferred to the recipient site. (**f**) The flap survival. (**g**) 10 days postoperative X-ray. (**h**) 1 years postoperative X-ray.

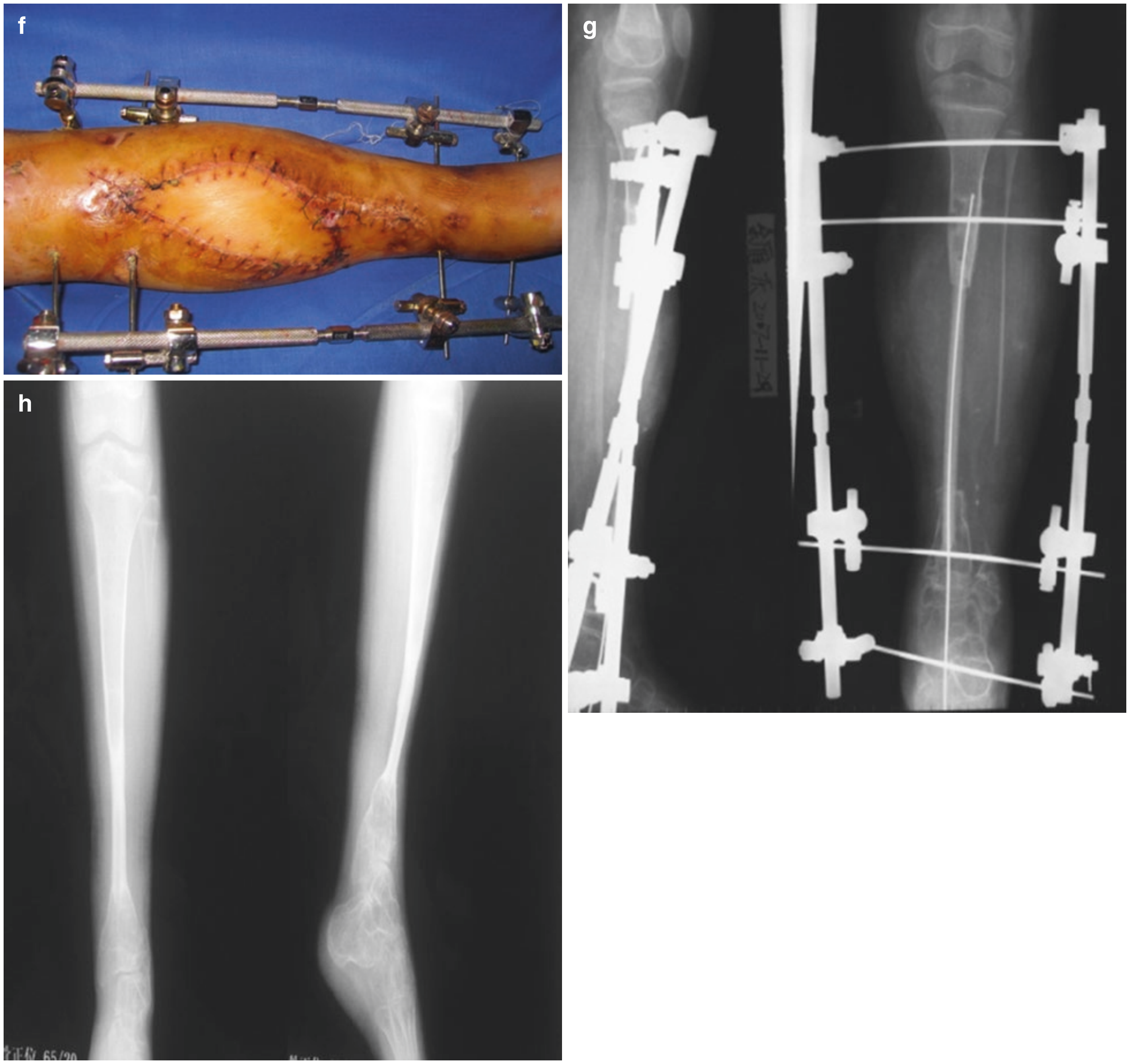


Fig. 21.59 (continued)

2. **Pedicled fibular flap** [40]: Between tibiofibula slightly lateral incision, the length and the starting point were decided by tibia bone defect after debridement. Cut the skin, subcutaneous tissue, the fascia, then along the outside deep fascia of leg superficial to tibial side, fully free and exposed tibial lesions and completely removed them. Along the periosteal surface, we separation and pull behind the outward to show fibula, thoroughly remove lesions on the far side of fibula. Stick lesions cleared after the fibula upper rear retrograde free and reveals the peroneal artery, protecting to fibula periosteum in vascular. According to the length expected we cut off the local proximal fibula tissue, and separate the neurovascular bundle from the fibula and soft tissue completely after cutting off the peroneal artery ligation vessels. We can lift the distal fibula flap and get rid of surrounding soft tissue, making sure that there are a certain degree of relaxation, then relax tourniquet and check fibula blood supply. Through the lateral crus muscle group from behind bular osteocutaneous flap is embedded into the tibial medullary cavity to fill tibia bone defect (Caring to avoid the vascular pedicle torsion in the process), and the bone are supported and fixed with Kirschner and external fixator. Suturing wounds after placing rubber drainages in the incision. Postoperative routine application of anti-infection treatment, analgesics treatment and anti-coagulant treatment in 7 days. (Fig. 21.60)

Fig. 21.60 (**a**) Preoperative appearance. (**b**) Preoperative X-ray. (**c**) Harvest ipsilateral fibula flap. (**d**) Postoperative leg appearance. (**e**) The appearance after removing external fixation. (**f**) 7 days X-ray. (**g**) 5 months X-ray. (**h**) 4 years X-ray. (**i**) 4 years appearance postoperative

Fig. 21.60 (continued)

Fig. 21.60 (continued)

21.3.5 Postoperative Complication

Applying vascularised bone graft to treat CPT, and it has definite on bone healing. But not all problems have been solved, and there are many complications, of that the most common is ankle valgus deformity. The causes may be the distal fibula involvement lesions cleared after ankle hole instability, and the tibia bone healing after growth line is not straight, which cases that the tibia angulation deformities gradually appeared in the process of growth of the tibia after bone healing.

References

1. Ueba Y, Fujikawa S. Nine year follow-up of a free vascularized fibula graft in neurofibromatosis: A case report and literature review. Jpn J Orthop Trauma Surg. 1983;26:5595.
2. Taylor GI, Miller GD, Ham FJ. The free vascularized bone graft. A clinical extension of microvascular techniques. Plast Reconstr Surg. 1975;55:533–44.
3. Yoshimura M, Shimamura K, Iwai Y, Yamauchi S, Ueno T. Free vascularized fibular transplant. A new method for monitoring circulation of the grafted fibula. J Bone Joint Surg Am. 1983;65:1295–301.
4. Goldberg VM, Shaffer JW, Field G, Davy DT. Biology of vascularized bone grafts. Orthop Clin North Am. 1987;18:197–205.
5. Goldberg VM, Stevenson S. Natural history of autografts and allografts. Clin Orthop Relat Res. 1987;(225):7–16.
6. Chew WY, Low CK, Tan SK. Long-term results of free vascularized fibular graft. A clinical and radiographic evaluation. Clin Orthop Relat Res. 1995;(311):258–61.
7. de Boer HH, Wood MB. Bone changes in the vascularised fibular graft. J Bone Joint Surg Br. 1989;71:374–8.
8. Bowen CV, O'Brien BM, Gumley GJ. Experimental microvascular growth plate transfers. Part 2. Investigation of feasibility. J Bone Joint Surg Br. 1988;70:311–4.
9. McKee NH, Haw P, Vettese T. Anatomic study of the nutrient foramen in the shaft of the fibula. Clin Orthop Relat Res. 1984;(184):141–4.
10. Bonnel F, Lesire M, Gomis R, Allieu Y, Rabischong P. Arterial vascularization of the fibula microsurgical transplant techniques. Anat Clin. 1981;3:13–22.
11. Restrepo J, Katz D, Gilbert A. Arterial vascularization of the proximal epiphysis and the diaphysis of the fibula. Int J Microsurg. 1980;2:49.
12. Tsai TM, Ludwig L, Tonkin M. Vascularized fibular epiphyseal transfer. A clinical study. Clin Orthop. 1986;(210):228–34.
13. Ono H, Yajima H, Mizumoto S, Miyauchi Y, Mii Y, Tamai S. Vascularized fibular graft for reconstruction of the wrist after excision of giant cell tumor. Plast Reconstr Surg. 1997;99:1086–93.
14. Taylor GI, Wilson KR, Rees MD, Corlett RJ, Cole WG. The anterior tibial vessels and their role in epiphyseal and diaphyseal trans-

fer of the fibula: experimental study and clinical applications. Br J Plast Surg. 1988;41:451–69.
15. Han CS, Wood MB, Bishop AT, Cooney WP. Vascularized bone transfer. J Bone Joint Surg Am. 1992;74:1441–9.
16. Gao YH, Ketch LL, Eladoumikdachi F, Netscher DT. Upper limb salvage with microvascular bone transfer for major long-bone segmental tumor resections. Ann Plast Surg. 2001;47:240–6.
17. Amr SM, El-Mofty AO, Amin SN, Morsy AM, El-Malt OM, Abdel-Aal HA. Reconstruction after resection of tumors around the knee: role of the free vascularized fibular graft. Microsurgery. 2000;20:233–51.
18. Li J, Wang Z, Guo Z, Chen GJ, Yang M, Pei GX. Precise resection and biological reconstruction under navigation guidance for young patients with juxta-articular bone sarcoma in lower extremity: preliminary report. J Pediatr Orthop. 2014;34:101–8.
19. Arai K, Toh S, Tsubo K, Nishikawa S, Narita S, Miura H. Complications of vascularized fibula graft for reconstruction of long bones. Plast Reconstr Surg. 2002;109:2301–6.
20. Zaretski A, Amir A, Meller I, Leshem D, Kollender Y, Barnea Y, Bickels J, Shpitzer T, Ad-El D, Gur E. Free fibula long bone reconstruction in orthopedic oncology: a surgical algorithm for reconstructive options. Plast Reconstr Surg. 2004;113:1989–2000.
21. Zwipp H, Flory P, Berger A, Tscherne H. Combination of cancellous bone grafts and free microvascular bone transplantation in large osseous defects [in German]. Handchir Mikrochir Plast Chir. 1989;21:235–45.
22. Minami A, Kasashima T, Iwasaki N, Kato H, Kaneda K. Vascularised fibular grafts. An experience of 102 patients. J Bone Joint Surg Br. 2000;82:1022–5.
23. Chang DW, Weber KL. Use of a vascularized fibula bone flap and intercalary allograft for diaphyseal reconstruction after resection of primary extremity bone sarcomas. Plast Reconstr Surg. 2005;116:1918–25.
24. Bae DS, Waters PM, Gebhardt MC. Results of free vascularized fibula grafting for allograft nonunion after limb salvage surgery for malignant bone tumors. J Pediatr Orthop. 2006;26:809–14.
25. Friedrich JB, Moran SL, Bishop AT, Wood CM, Shin AY. Free vascularized fibular graft salvage of complications of long-bone allograft after tumor reconstruction. J Bone Joint Surg Am. 2008;90:93–100.
26. Scoccianti G, Campanacci DA, Innocenti M, Beltrami G, Capanna R. Total calcanectomy and reconstruction with vascularized iliac bone graft for osteoblastoma: a report of two cases. Foot Ankle Int. 2009;30:716–20.
27. Li J, Guo Z, Pei GX, Wang Z, Chen GJ, Wu ZG. Limb salvage surgery for calcaneal malignancy. J Surg Oncol. 2010;102:48–53.
28. Innocenti M, Delcroix L, Manfrini M, Ceruso M, Capanna R. Vascularized proximal fibular epiphyseal transfer for distal radial reconstruction. J Bone Joint Surg Am. 2004;86-A:1504–11.
29. Menezes-Leite MC, Dautel G, Duteille F, Lascombes P. Transplantation of the proximal fibula based on the anterior tibial artery. Anatomical study and clinical application. Surg Radiol Anat. 2000;22:235–8.
30. Innocenti M, Delcroix L, Romano GF. Epiphyseal transplant: harvesting technique of the proximal fibula based on the anterior tibial artery. Microsurgery. 2005;25:284–92.
31. Capanna R, Manfrini M, Angeloni R, et al. Reconstructions of metadiaphyseal defects in bone tumors: an innovative technique (combined graft) compared with traditional reconstruction. J Bone Joint Surg Br. 1993;75(Suppl II):104.
32. Li J, Shi L, Chen GJ. Image navigation assisted joint-saving surgery for treatment of bone sarcoma around knee in skeletally immature patients. Surg Oncol. 2014;23:132–9.
33. Li J, Wang Z, Guo Z, Chen GJ, Yang M, Pei GX. Irregular osteotomy in limb salvage for juxta-articular osteosarcoma under computer-assisted navigation. J Surg Oncol. 2012;106:411–6.
34. Li J, Wang Z, Guo Z, Chen GJ, Li SW, Pei GX. The use of massive allograft with intramedullary fibular graft for intercalary reconstruction after resection of tibial malignancy. J Reconstr Microsurg. 2011;27:37–46.
35. Noguchi M, Mizobuchi H, Kawasaki M, Ueta E, Okanoue Y, Taniwaki Y, Tani T. An intramedullary free vascularized fibular graft combined with pasteurized autologous bone graft in leg reconstruction for patients with osteosarcoma. J Reconstr Microsurg. 2008;24:525–30.
36. Mottard S, Grimer RJ, Abudu A, Carter SR, Tillman RM, Jeys L, Spooner D. Biological reconstruction after excision, irradiation and reimplantation of diaphyseal tibial tumours using an ipsilateral vascularised fibular graft. J Bone Joint Surg Br. 2012;94:1282–7.
37. Manfrini M, Innocenti M, Ceruso M, Mercuri M. Original biological reconstruction of the hip in a 4-year-old girl. Lancet. 2003;361(9352):140–2.
38. Li J, Wang Z, Guo Z, Yang M, Chen G, Pei G. Composite biological reconstruction following total calcanectomy of primary calcaneal tumors. J Surg Oncol. 2012;105:673–8.
39. Wei L, Tian H-Y, Bo W-J, et al. Immunohistochemical study of proliferating cell nuclear antigen in congenital tibia pseudarthrosis. Chin J Pediatr Surg. 2000;21(5):302–3.
40. Dobbs MB, Rich MM, Gordon JE, Szymanski DA, Schoenecker PL. Use of an intramedullary rod for the treatment of congenital pseudarthrosis of the tibia. Surgical technique. J Bone Joint Surg. 2005;87:33–40.

Spine Microscopic Surgery

22

Huiren Tao, Donglin Li, Haodong Lin, Chunlin Hou, Shaocheng Zhang, and Wenbin Ding

22.1 Introduction

Huiren Tao and Donglin Li

With the development of medical technology, the era of minimally invasive techniques is coming in spine surgery. As one important branch of minimally invasive surgery, spine microscopic surgery aims at minimizing surgical trauma and achieving effective outcomes, using microscopy, endoscopy and special apparatus during surgical process. At present, spine microscopic surgery has been carried out in all areas of the spinal axis, including discectomy, laminectomy, intraspinal tumor resection, spinal disc fusion, vertebral fusion, anterior release operation for scoliosis or kyphosis malformation, etc.

In the middle 1970s, microscopy has been applied in spine surgery. Harold and Williams were the pioneers in microsurgical operation for treatment of lumbar disc diseases. Afterwards, the microscope became one of the most important tools in spine surgery. In 1990 McCulloch proposed use of microscopy and special instruments to accomplish lumbar laminoplasty for spinal stenosis, with lateral and central and intervertebral foramina on the decompression side. In 1997 Foley and Smith launched a new posterior approach microendoscopic discectomy (MED). This new concept lumbar discectomy is known as an important breakthrough in minimally invasive surgery and endoscopic spine surgery. With innovations in MED, its indications have gradually expanded to complicated lumbar disc herniation and lumbar spinal stenosis. In 2001 Adamson used posterior endoscopic system to conduct foramen decompression laminectomy and discectomy for unilateral cervical spondylotic radiculopathy, resulting in satisfactory surgical outcomes. In 2005 Isaacs firstly tried endoscopic thoracic discectomy in two cadavers. He concluded that compared with other decompression operations, the endoscopic thoracic discectomy could achieve similar therapeutic efficacy but decreased trauma obviously. In 2002 Yeung introduced Yeung's endoscopic spine system (YESS) and in 2006 Hoogland proposed transforaminal endoscopic spine system (TESSYS), the two methods of percutaneous transforaminal endoscopic discectomy. Compared with YESS, TESSYS has wider indications, as a more direct and thorough decompression technique. In a word, endoscopy can obtain clear images, making all kinds of operations simple and easy, and reducing trauma and operation cost.

In Europe, cervical spondylosis, lumbar disc herniation and other degenerative diseases are treated under microscopy mainly by neurosurgeons at a department of neurosurgery. However, surgical management of spinal diseases is basically undertaken by departments of orthopedics in China. Most surgeons make open operations, which greatly hinders the application of microsurgical techniques in spinal surgery. Although large-scale prospective clinical trials on microsurgical operation are far from enough, it is sure that with the development of science and technology, microsurgical operations will be greatly improved. More and more spine surgeons gradually accept the concept of minimally invasive spine operation, and endoscopic technology will become the mainstream surgical procedure in the future.

H. Tao (✉)
General Hospital of Shenzhen University, Shenzhen, P. R. China
e-mail: taohr816@fmmu.edu.cn

D. Li
Air Force Hospital of the North Theatre of the PLA, Shenyang, P. R. China

H. Lin · C. Hou (✉)
Department of Orthopedic Surgery, Changzheng Hospital, The Second Military Medical University, Shanghai, P. R. China

Department of Orthopedics, Changhai Hospital, Naval Medical University, Shanghai, P. R. China

S. Zhang (✉) · W. Ding
Department of Orthopedics, Changhai Hospital, Naval Medical University, Shanghai, P. R. China

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_22

22.2 The Microsurgery Treatment for Lumbar Disc Herniation

Huiren Tao and Donglin Li

With the development of microsurgery, microsurgical techniques are more and more widely applied in the field of spine surgery, especially for a common disease—lumbar intervertebral disc herniation. As early as in 1977, Caspar and Yasargil first described lumbar discectomy under a surgical microscope. Clinical case-control studies also confirmed shorter hospital-stay and rehabilitation time, and ultimately better clinical outcomes by the microscopic discectomy than by conventional surgery.

Classic microsurgery for lumbar disc herniation includes lumbar microdiscectomy and minimally invasive transforaminal lumbar interbody fusion and instrumentation (Micro-TLIF).

22.2.1 Introduction

Microsurgery treatment for lumbar disc herniation includes traditional surgical decompression with a surgical microscope (Fig. 22.1) or a pair of operation loupes (Fig. 22.2).

Fig. 22.1 A surgical microscope

The goals of these procedures are to reduce the morbidity associated with traditional posterior lumbar approaches, and at the same time to achieve effectiveness and safety. The microsurgery treatment has following features:

1. More accurately identify anatomical structures.
2. Hopefully minimize the risk of damage to dura and nerve root.
3. Epidural veins can be identified, protected, and coagulated preemptively, thus minimizing blood loss.

However, a surgical microscope is different from a pair of operation loupes (Table 22.1). Different kinds of surgical microscopes have been applied in spine surgery, neurosurgery, hand surgery and gynaecological surgery and so on. The spine surgical microscope must have a wide-field and a

Fig. 22.2 Operation loupes

Table 22.1 Advantages and disadvantages of surgical loupes and microscope

	Loupes	Microscopes
Magnification	Limited and fixed	Greater range and changeable during surgery
Motion	Long surgery causes neck fatigue and movement of loupes	No movement of microscope
Focus	Refocusing is necessary to restart surgery	Microscope in constant focus regardless of surgeon's attention
Illumination	Not parallel to the line of vision	Parallel to the line of vision and stronger
Deep three-dimensional vision	Limited with smaller skin incisions (<65 mm)	Maintained with even an 25-mm incision
Teaching	Assistants excluded	Assistants included
Surgeon neck	Fixed in flexion and requiring repositioning. Fatigue during long surgery	Spared, inclinable binocular head can be adjusted

stand high enough to allow lens with at least a 300-mm focal length to provide enough operating space between the microscope and the patient.

22.2.2 Lumbar Microdisectomy

22.2.2.1 Preparation, Positioning, Setup

General endotracheal anesthesia or epidural anesthesia is used. The patient should be placed in the prone position on an appropriately sized Wilson or Andrews spinal frame, with care that the abdomen hangs free. The frame should be slightly flexed to diminish the lordotic curve and widen the lumbar interlaminar spaces.

Surgeons generally stands on the same side of the disc herniation, unless there is associated symptomatic foraminal and/or extraforaminal root compression, whereupon they will be on the opposite side. The surgical microscope is positioned on the same side or opposite side of the surgeon.

When surgeons use operation loupes and head light during surgery, the height of the operation table should be adjusted according to the working distance of the loupes (Fig. 22.3).

22.2.2.2 Exposure

After localizing radiographically or with anatomical landmark, a skin incision is made in the midline. The incision is carried down through skin and subcutaneous tissue and fascia next to the spinous processes. A subperiosteal dissection of the paraspinous musculotendinous attachments is performed. Bleeding is controlled strictly. The facet joint capsule should be kept intact during exposure. Before entry into the spine canal, the surgeon should confirm the level again with the C-arm to avoid unnecessary removal of the bone and exposure of the spinal canal.

Fig. 22.3 Surgeons wearing operation loupes

22.2.2.3 Exposure and Disectomy

From this point on, the operation is performed with the aid of an operation microscope, which can avoid excessive bone removal during laminotomy. Also, the flavum ligament should be preserved as much as possible to reduce adherence of the dura sac to its surrounding tissues. Once the laminotomy has been performed, the nerve root should be mobilized to expose the disc herniation (Fig. 22.4) before disectomy is performed. Dissection through the epidural fat with bipolar forceps and coagulation of veins with bipolar cautery are frequently necessary. Preventing and controlling epidural bleeding is one of the key aspects of a discectomy operation which is expeditiously and safely performed. If on the other hand, it is difficult to control bleeding by preemptive bipolar electrocautery, then small thrombin-soaked pledgelets and/or cotton paddings above and below the disc herniation can be used to tamponade the bleeding.

22.2.2.4 Closure and Postoperative Management

The area of decompression is irrigated with normal saline. The most common complication is inadvertent dural tear (when possible, a watertight repair should be performed). Negative pressure drainage tube is put into the wound. The deep and superficial fasciae are closed in layers. The skin is closed with staples or Dermabond.

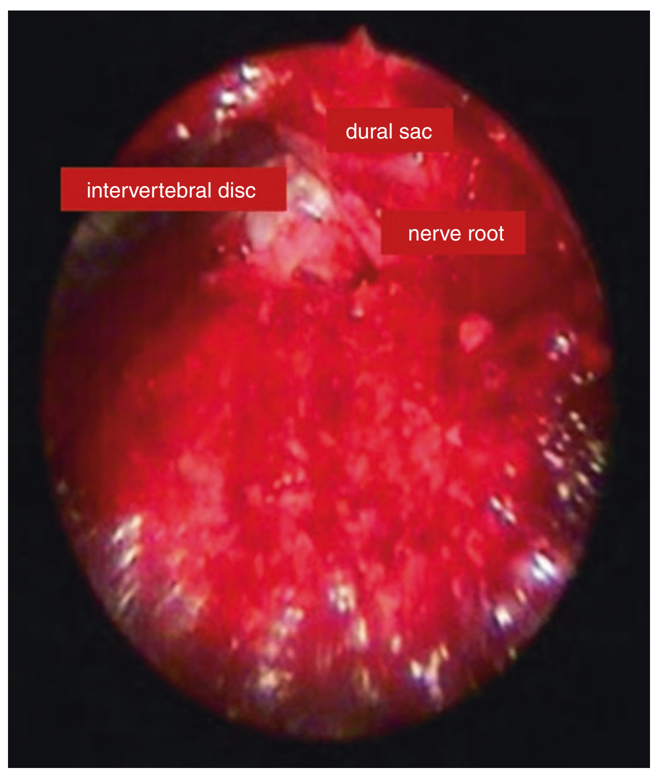


Fig. 22.4 A nerve root is clearly identified under a microscope

Antibiotics are routinely used postoperatively. The patients receive NSAID for postoperative pain relief and controlling inflammation around the nerve root. The drainage tube is removed on the first day postoperatively. Then the patient is encouraged to ambulate.

22.2.3 Transforaminal Lumbar Interbody Fusion and Instrumentation

22.2.3.1 Preparation, Positioning

General endotracheal anesthesia or epidural anesthesia is used. The patient is placed prone on a Jackson table (Fig. 22.5). It is important to keep the abdomen free to decrease venous bleeding. On the other hand, it is easier to restore the lumbar lordosis.

22.2.3.2 Exposure

The exposure method has been illustrated before, but difference also exists. In order to place the pedicle screws and perform foraminal decompression in the open surgery, the facet joint capsules of the rostral level and the lateral margins of the facet joint need to be revealed.

During the percutaneous placement of pedicle screws, a skin incision approximately 4–5 cm lateral to the midline is made, and then the entry point is exposed through bluntly muscle-splitting approach, which can decrease the damage to the surrounding soft tissues. However, this technique depends too much on the intraoperative radiography, so it increases intraoperative fluoroscopy time and radiation exposure of both the patient and surgeons.

22.2.3.3 Exposure and Disectomy

From this point on, the operation is performed with the aid of an operation microscope. To gain access to the posterior disc space, a unilateral facetectomy is performed and the flavum ligament is partly removed. The herniated disc is exposed after the nerve root and dura sac are retracted and protected. Dissection through the epidural fat with bipolar forceps and coagulation of veins with bipolar cautery are frequently necessary. Discectomy includes excision of the posterior annulus and disc material in order to expose a large surface area of contact for bone graft placement while preserving the osseous end plates. These maneuvers must be performed carefully in order to prevent violation to the subchondral bone of the end plates, especially in old female patients with osteoporosis. All bone resected is cleaned off soft tissues and saved for use as autologous bone graft.

In addition, care must be taken to avoid damage to anterior vascular structures during disc space preparation. The average depth of the disc space is 35 mm in the center of the disc and 25 mm at the level of the facet. Disc preparation instruments are commonly marked so that the depth they are placed into the disc space can be judged in order to minimize the risk of injury with repeated placement and removal of instruments.

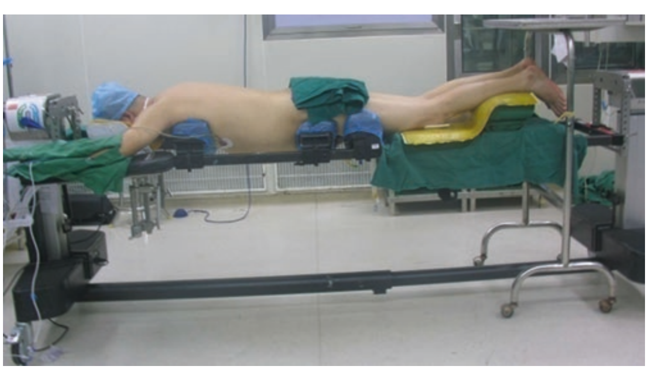


Fig. 22.5 Jackson table

22.2.3.4 Cage and Graft Placement

Once the disc space has been properly decorticated, trial spacers are placed in the intervertebral space prior to final placement of graft material. The determination of size is made based on preoperative and intraoperative radiographs, as well as direct visualization and trial implant tension. Local autologous bone graft may be placed anterior to or packed within the interbody device. Implant size is verified and one interbody cage/graft is placed. Once grafts are inserted, the neural elements are inspected to ensure that any direct compression or excessive traction from overdistraction is not present. The distraction instruments are then removed to allow the end plates to compress against the graft material and to prevent graft extrusion.

22.2.3.5 Pedicle Screw Fixation

Pedicle screw instrumentation may be performed before or after discectomy and placement of interbody grafts according to the surgeon's preference. Care must be taken to avoid injury to the rostral facet joint capsule, decreasing the risk of the adjacent segment degeneration. The C-arm is used to confirm the right position of the pedicle screw to avoid injury to the dura or nerves.

Care must be taken to avoid overdistraction against screws as this may lead to loosening of the screw-bone interface and jeopardize ultimate fixation. If distraction forces are placed on the pedicle screws, it may be advisable to exchange the screws for ones with a larger diameter following the distraction maneuvers to increase the fusion rate.

With the continuous development of minimally invasive techniques, percutaneous placement of pedicle screw has been widely used in clinics. Percutaneous placement of pedicle screws can reduce stripping of the paraspinal muscle, blood loss and soft tissues injury. Tag pedicle projection position in the skin with the aid of intraoperative fluoroscopy devices, then determine the lateral distance to the midline of the skin incision according to the thickness of the soft tissue, and insert Jamshidi needle through the skin incision. Finally the pedicle screw is placed with the guidance of the needle. In the process of placement, care is taken to ensure that there is always a bony "backstop" of residual vertebral body distal to the K-wire tip and it is monitored with frequent live fluoroscopic images to guard against inadvertent advancement.

22.2.3.6 Closure and Postoperative Management

The key points about closure and postoperative management have been described in the lumbar discectomy section. The drainage tube is removed on the second day postoperatively. Then the patient is encouraged to ambulate.

22.3 Endoscopic Surgery for Treatment of Lumbar Disc Herniation

Huiren Tao and Donglin Li

Endoscopic surgery to treat lumbar disc herniation mainly includes microendoscopic discectomy (MED) and percutaneous endoscopic lumbar discectomy (PELD). Discectomy, decompression and releasing of a nerve root can be performed with the help of endoscopy through a minimal incision. The main advantages of this technique are less invasive procedures, minimized trauma of the paravertebral muscles and soft tissue, and magnified spinal anatomy to clearly show the nerve root and disc herniation. With new techniques and new materials constantly emerging, the indications for endoscopic surgery become wider and wider. Previously, it was used only to treat lumbar disc herniation, but now also lumbar spinal stenosis; only discectomy was done under endoscopy, but now also the spinal internal fixation. Minimal invasion is the future of the spinal operation.

22.3.1 Application of Microendoscopic Discectomy

Microendoscopic discectomy is performed under the guidance of endoscopy. First of all, the working channel is established, with a diameter of about 1.6–1.8 cm. Then remove part of the lamina, and resect disc herniation using endoscopic instruments. The whole procedure is carried on with the help of a special endoscopic imaging system, which enlarges vision several times, and transmits the images to the video monitor by the optical fiber. So the nerve root is distinguished clearly, avoiding the risk of nerve injury (Fig. 22.6).

Fig. 22.6 Microendoscopic discectomy

22.3.2 Microendoscopic Discectomy

Operative procedures

1. The patient should be placed in the prone position on an open-frame operating table throughout surgery. The abdomen should hang free to reduce the intervertebral venous plexus pressure and reduce intraoperative hemorrhage.
2. The lumbar segment of interest is determined by preoperative imaging studies. The skin entry point is typically approximately 1.5–2 cm parallel to the midline to the desired surgical level. The guide wire is placed through the incision and directed toward the inferior aspect of superior lamina, which can be confirmed by C-arm. An incision about 1.8 cm is made just along the guide wire. Some surgeons believe the incision should cling to the spinous process, that is along the midline, which is chosen when bilateral discectomy needs to be performed.
3. Insert an initial cannulated soft tissue dilator over the guide wire. Once the fascia is penetrated, remove the guide wire and advance the dilator down to the inferior edge of superior lamina. The second, third and fourth dilators are inserted over the initial dilator down to the lamina and the tubular retractor is then inserted. Sequential dilators are removed to establish an operative corridor to the lamina and interlaminar space (Fig. 22.7). Remove soft tissue over the lamina and interlaminar space. A hemilaminotomy is performed and the ligamentum flavum is resected. Identify and separate the dural sac and nerve root. The herniated disc is demonstrated.
4. Remove the posterior longitudinal ligament and annulus fibrosus with a sharp knife. Remove herniated disc as much as possible.

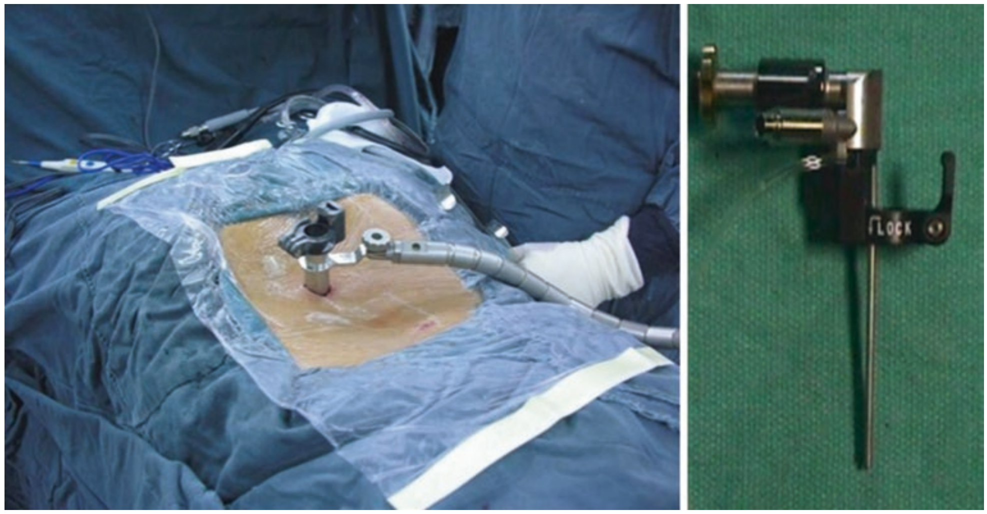


Fig. 22.7 Tubular retractor and endoscope

5. When necessary, decompression of lateral recess and nerve root canal should be performed.
6. A drainage tube is placed before closure.

Postoperative management: Antibiotics are used for 48 h. The tube is removed at 12–24 h, and patients are then encouraged to ambulate.

22.3.3 Microendoscopic Decompression, Interbody Fusion, and Percutaneous Pedicle Screw Implantation of the Lumbar Spine

Due to the development of endoscopic instruments and operative skills, microendoscopy is used to treat not only disc herniation, but also the lumbar disc herniation complicated with degenerative instability. Microendoscopy is reported to treat lumbar stenosis mainly using expandable channels (such as X-Tube) and B-Twin expandable spinal spacer. Since the latter is used rarely in clinic due to its more complications, it is not discussed here.

Unlike microendoscopic discectomy, an expandable introducer is used instead of a tubular retractor during posterior lumbar interbody fusion. After the expandable introducer is docked on the lamina, its diameter can be expanded to 4 cm by clamps. When the introducer is inserted, it should be inclined backward 15°, in order to facilitate the pedicle screw implantation.

Operative procedures

1. The patient should be placed in the prone position on a Jackson table to keep lumbar lordosis.
2. Locate and mark the desired surgical level and bilateral pedicles under C-arm fluoroscopy. Then draw a line along the ipsilateral pedicles. An incision about 3 cm is made just along the line. Insert a guide wire into the incision, and confirm the guide wire is on the desired level and facet joints.
3. Serial dilatation then proceeds. Use an expandable retractor to provide greater access through the incision. Using microendoscopy, remove any excess soft tissue so as to expose the interlamina and facet joints.
4. Tilt the retractor laterally about 15°. Percutaneous pedicle screw instrumentation is performed under C-arm fluoroscopy guidance.
5. Transforaminal lumbar interbody fusion (TLIF) or posterior lumbar interbody fusion (PLIF) can be selected according to the surgeon's preference. It is not necessary to expose exiting nerve roots, but the exposure of traversing one deserves extreme carefulness. Endplate preparation is performed with an appropriately sized reamer fitting snugly between the endplates. Reaming is performed under microendoscopy guidance until the subchondral bone is revealed. After completion of the endplate preparation, implant an appropriately sized cage mixed with bone chips into the disc space. Rods are placed via the minimally invasive tubular retractor.
6. The wound is irrigated and closed in a standard fashion.

Postoperative management: Antibiotics are used for 48 h. The tube is removed at 12–24 h, and patients are then encouraged to ambulate.

22.3.4 Percutaneous Endoscopic Lumbar Discectomy (PLED)

In 1997, a major improvement in minimally invasive surgery was achieved by introduction of the "Yeung Endoscopic Spine System (YESS)" by Yeung. Kambin's anatomic description of the neural foramen as the endoscopic access is also known as "safe triangle". The disc herniation can be excised directly through the access, not via the epidural space. However, because of facet joints, YESS could not be widely used for lumbar disc herniation. In 2003, Hoogland from Germany improved YESS and devised transforaminal endoscopic spine system (TESSYS) which enlarges neural foramen to make access amplified (Fig. 22.8). Transforaminal endoscopic discectomy has become an important and popular alternative in the management of lumbar disc herniation.

Operative procedures

1. The accesses of the procedure mainly include interlaminar dorsal access, far lateral or horizontal access and transforaminal access. Transforaminal access is typical and popular for PELC in the management of lumbar disc herniations. The skin point is typically approximately 8–11 cm from the midline and is projected to have 25° (from coronal plane) for L4–5, 35° for L3–4, 40° for L2–3, and 45° for L1–2. The ideal access is that the needle is positioned on the midpedicular line in the anteroposterior projection and on the posterior vertebral line in the lateral projection (Fig. 22.9).

Fig. 22.8 An endoscope

Fig. 22.9 A spinal needle is placed

2. After the skin point is confirmed, a transforaminal epidural infiltration through the spinal needle with 0.5% lidocaine is performed to prevent the approach-related pain and discomfort. After insertion of the needle, an intraoperative discography is performed with a mixture of 6 mL of contrast media and 1 mL of indigo carmine. The pathologic nucleus and annular fissure can then be stained for easy discrimination through endoscopy.
3. Insert a guide wire through the needle into the annulus, and then withdraw the needle and make a tapered cannulated obturator (with an outer diameter of 6.9 mm) sliding over the guide wire and introduced gently into the foramen. Remove the guide wire. A surgical sheath (with an outer diameter of 7.9 mm) with a beveled opening is placed over the dilator. The opening of the bevel-ended working sheath should be directed toward the undersurface of the superior facet and toward the caudal direction.
4. Then using a direct endoscopic view and continuous irrigation, decompression is performed. The working field is constantly irrigated with antibiotic-containing saline during the entire endoscopic procedure (Fig. 22.10). Make sure that the dural sac and the traversing nerve root are in free mobilization and released.
5. After full-scale lateral recess decompression is confirmed, inject a mixture of 7.5 mg of Limethason and 2 mL of indigo carmine into the foramen. And then remove the endoscope and the working sheath. A sterile dressing is applied with a one-point subcutaneous suture (Fig. 22.11). If there are no postoperative problems, the patient is permitted to mobilize three hours after operation, and be discharged within 24 h.

Fig. 22.10 Percutaneous endoscopic lumbar discectomy

Fig. 22.11 Postoperative wound and herniated disc

22.4 Functional Reconstruction of Bladder After Spinal Cord Injury via Neural Approaches

Haodong Lin and Chunlin Hou

22.4.1 Introduction

Spinal cord injury (SCI), caused by trauma or disease, is one of the most serious clinical disabilities. It not only seriously damages somatic motor and sensory functions of patients, but also causes Defecation dysfunction. According to reports about 12–15 years follow-up of spinal cord injury, urinary tract infection and renal failure are the main causes of late death in SCI patients. Besides, 49–66% paraplegia patients in Tangshan earthquake died in uremia. Therefore, the reconstruction of the bladder urination function of patients with spinal cord injury is very important to improve the quality of life and reduce the mortality of paraplegia patients. In the absence of major breakthroughs in spinal cord regeneration, functional bladder reconstruction via neural approaches in paraplegic patients has been a hot topic in the past 20 years.

The reconstruction method differs due to the spinal cord injury location. Functional reconstruction of spastic bladder patients, whose bladder storage and voiding function are impaired by injuries above the spinal cone, requires improvement of both urinary storage and voiding function. Flaccid bladder, caused by spinal cord cone injury, has normal urinary function but voiding dysfunction. Therefore, improving micturition function is the main purpose.

22.4.2 Selective Sacral Rhizotomy

Spastic bladder is caused by spinal cord injury above the cone. Reduced bladder capacity due to the detrusor hyperreflexia, and increased urethral outlet resistance caused by spasm of urethral sphincter, can lead to increased bladder pressure, urine reflux, and further lead to renal function damage. Treatment is based on the specific situation of bladder spasm, to cut off the corresponding nerve roots selectively, by blocking part of the nerve pathway, reducing malignant afferent, and ultimately improve the function of the bladder.

22.4.2.1 Indications

It is suitable for spastic bladder with high tension and high reflexes caused by spinal cord injury above the spinal cone.

22.4.2.2 Surgical Techniques

Cutting from the incision of lumbosacral posterior median, the S1–S4 nerve roots are exposed (Fig. 22.12), and then separate the anterior and posterior roots of them. The S2–S4 nerve anterior roots are stimulated by electromyograph with the same intensity (20 mV, 30 Hz, 5–10 s), and the reaction of bladder detrusor urethral sphincter are observed. The most sensitive nerve roots of the musculocutaneous sphincter are insured and cut off.

22.4.3 Electrical Stimulated Micturition: Brindley Procedure

The bladder micturition function can be reconstructed by electrical stimulation of the anterior sacral nerve roots, including skin electrode in vitro and electrode implantation in vivo,

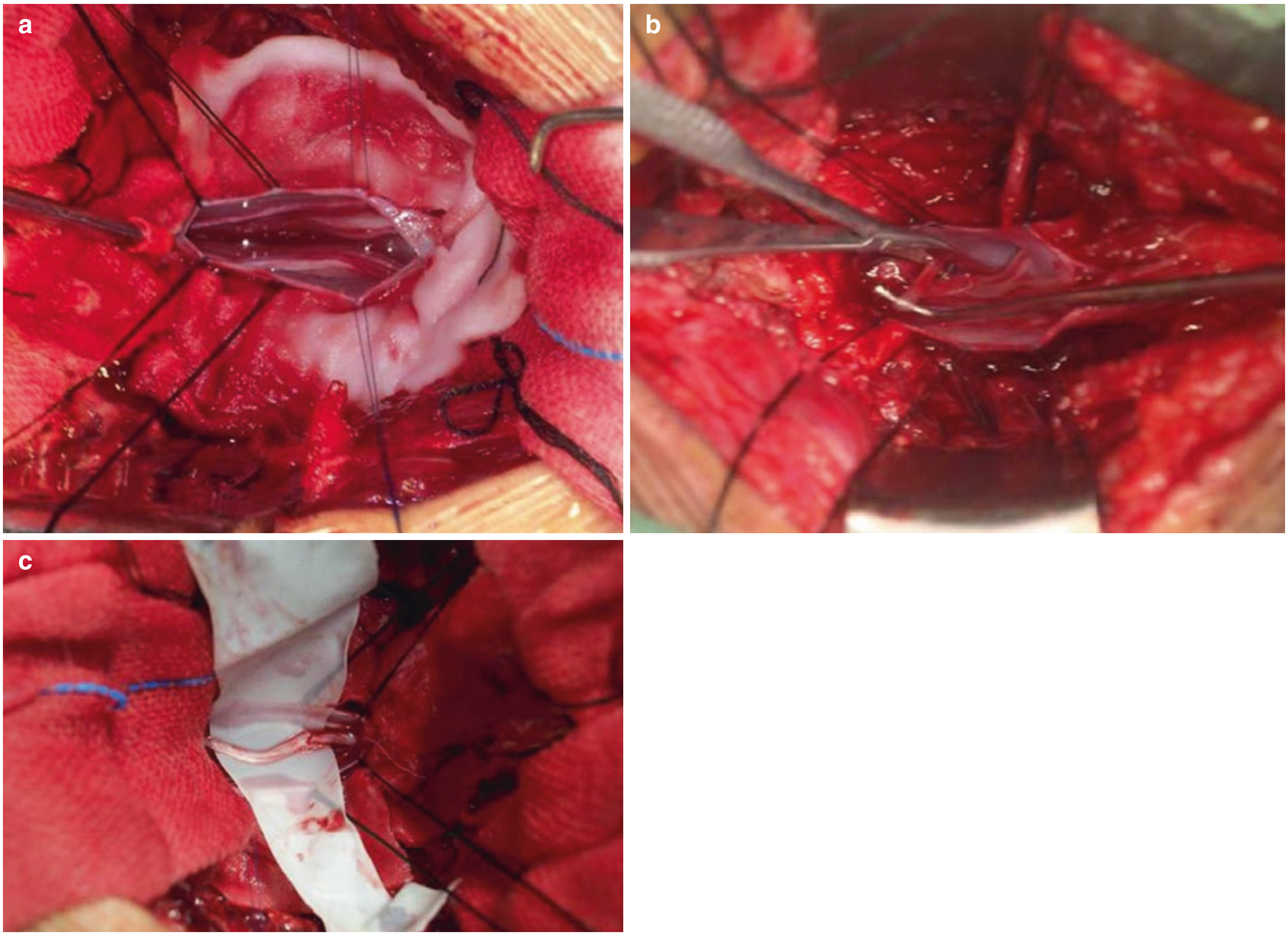


Fig. 22.12 Intraoperative photographs showing the surgical procedure to reconstruct the bladder reflex pathway in a 20-year-old man. (**a**) Standard laminectomies from L5 to S3 were performed with the patient lying in the prone position. The dura mater was opened up through a paramedian incision, exposing the dorsal and ventral roots of the S1, S2, S3, and S4 nerves. (**b**) The ventral roots of S1, S2, and S3 were identified and separated from their respective dorsal roots by microdissection. (**c**) The S1 and S2/3 ventral roots were anastomosed

as well as different implantation sites, such as the bladder wall, pelvic nerve, sacral nerve root and conus medullaris. The most widely used and effective method is Brindley Sacral Anterior Root Stimulator (SARS) combined with posterior sacral rhizotomy, can meet the clinical needs of bladder function reconstruction after spinal cord injury. The Brindley procedure includes anterior root stimulation and cut of the dorsal root to abolish neurogenic detrusor overactivity. Stimulation of the sacral anterior roots enables controlled micturition, defecation, and erection, while dorsal root rhizotomy (sacral de-afferatation) enables a good reservoir function. The Brindley procedure has been used in more than 3000 patients.

22.4.3.1 Indications

Electric stimulation of anterior sacral nerve root is only suitable for spastic bladder caused by spinal cord injury above the cone (above the T12 level). Since the flaccid bladder is caused by spinal cord injury at the conus medullaris, stimulating of sacral nerve cannot be used to micturate due to the injury of the spinal cord which innervates the bladder.

22.4.3.2 Surgical Operations

The patient is placed in prone position. The surgery includes two parts: dorsal root rhizotomy and electrode implantation.

A laminectomy from L3–4 to S1–2 is done for an intradural rhizotomy and intradural implantation of the electrode cuff. The dura and arachnoid are opened at the midline to expose the sacral nerve roots. The anterior and dorsal components of the roots, especially relevant anterior roots for micturition, can be identified intradurally by electrical stimulation of these components while monitoring the effects on detrusor activity, blood pressure, and somatomotor responses. A rhizotomy of the identified dorsal sacral roots is done. The anterior sacral roots are positioned into the electrode cuff. The connecting cables are subcutaneously tunnelled to a subcutaneous pocket (lateral thoracic) for the receiver.

Implantation of extradural electrodes requires a laminectomy from L5–S1 to S3–4. The dorsal rhizotomy is done at the level of the posterior ganglia of S2–5. Electrical stimulation tests are used to identify the anterior and dorsal components of the sacral roots. The extradural electrode is implanted and fixated to the nerve using a strip of silicone rubber sheet which is sewn to itself and surrounds the nerve. The connecting cables and the receiver are implanted the same way as in the intradural procedure.

22.4.4 Reconstruction of Bladder Innervation Below the Level of Spinal Cord Injury to Induce Urination by Achilles Tendon–to–Bladder Reflex Contractions

According to the different types of bladder dysfunction caused by spinal cord injury, different artificial reflex arcs can be used to reconstruct the urination.

22.4.4.1 Indications

It is suitable for spastic bladder caused by injury above conus medullaris. The lower limb tendon reflex exists in the patient. The artificial reflex arc of "tendon-spinal cord-bladder" is established by innervating the nerve root of tendon reflex to reconstruct bladder function.

22.4.4.2 Surgical Techniques

Preoperative catheterization should be given to patients. The catheter is connected with the infusion tube and the piezometric tube through a three way tube, so as to detect the bladder pressure during the operation. The patients are prone position for the L5–S2 posterior median incision to expose the S2–S4 nerve. Electrical stimulation is performed on the anterior roots of S2–S4 on both sides of the bladder. Pressure changes during bladder contraction are observed by using a manometer. The most robust nerve root that dominates the bladder is the one whose pressure rises quickly and finally the highest. The S1 anterior root and the strongest nerve root (usually S2 or S3) that innervated the bladder were cut off on the same plane, and the S1 anterior root and S2/S3 anterior root were anastomosed with a 9-0 line (Fig. 22.12).

22.4.5 Reconstruction of Bladder Innervation Above the Level of Spinal Cord Injury to Induce Urination by Abdomen-to-Bladder Reflex Contractions

In our previous experiments, we established a new skin–CNS–bladder reflex (abdominal reflex) pathway to restore controlled micturition in the atonic bladder. The new pathway was established in a rat model of SCI by intradural microanastomosis of the right T13 ventral root to the S2 ventral root with autogenous nerve grafting. After the new reflex pathway was reestablished, long-term function of the reflex arc was evaluated by electrophysiological, detrusor, electromyographic, and urodynamic studies over 8 months postoperatively. We found that the normal somatic reflex superior to the spinal injury level can be used to establish a reflex pathway by spinal ventral root anastomosis between the T13 and S2 nerve roots. The somatic motor root can reinnervate the bladder with a reconstructed efferent branch, and somatic motor impulses can be sent to the bladder through the reconstructed efferent branch and induce contraction of the bladder detrusor. Similar results were obtained in a canine model of SCI. Based on the results of these preclinical experiments, we attempted bladder reinnervation in patients with conus medullaris injury through functional suprasacral nerve transfer.

22.4.5.1 Indications

Flaccid bladder patients caused by complete conus medullaris injury can establish the artificial reflex arc of "abdominal wall-spinal-bladder" by using normal abdominal wall reflex above the injury plane and through the anastomosis between normal spinal nerve anterior root and the sacral nerve anterior root that innervates the bladder, to re-establish the nerve reinnervation of the bladder.

22.4.5.2 Surgical Techniques

After general anesthesia, the patient is placed in the prone position. The posterior median incision of T10–T12 is made, and the nerve roots of T10 (or T11) are separated. Meanwhile, L5–S2 posterior median incision is made to locate and separate the S1–4 nerve roots and its anterior and posterior roots. According to the distance between T10 (or T11) and S2, the sural nerve with a length of about 30 cm was cut intraoperatively, and the anterior root central terminal (proximal end) of T10 (or T11) and the sural nerve were anastomosed with a 9-0 noninvasive needle line. The distal end of the anterior root of S2 anastomoses with the other end of the sural nerve (Figs. 22.13 and 22.14).

22.4.6 Transfer of Normal Lumbosacral Nerve Roots to Reinnervate Atonic Bladder

22.4.6.1 Indications

Patients present with bladder atonia after conus medullaris injury and whose motor function of the lower extremities is preserved. Some patients with atonic bladder due to spinal conus injury had normal or partial lower limb motor function. The normal lumbosacral nerve root can be used as the power nerve to reconstruct the bladder urination.

22.4.6.2 Surgical Techniques

After general anesthesia, the patient is in the prone position for laminectomy from L5 to S3. The dura is opened through a paramedian incision, exposing the dorsal and ventral roots of the S1–4 nerves. The S1 nerve root is located using the L5/S1 intervertebral space as a marker; the S2–4 nerve roots are located in a descending order. The ventral and dorsal roots at the dural incision are identified according to their anatomical characteristics. The VRs of S1, S2 and S3 are identified and separated from their respective dorsal roots by microdissection. An electric stimulator is used to stimulate the S1 VR to observe muscle contractions of the lower limb in order to

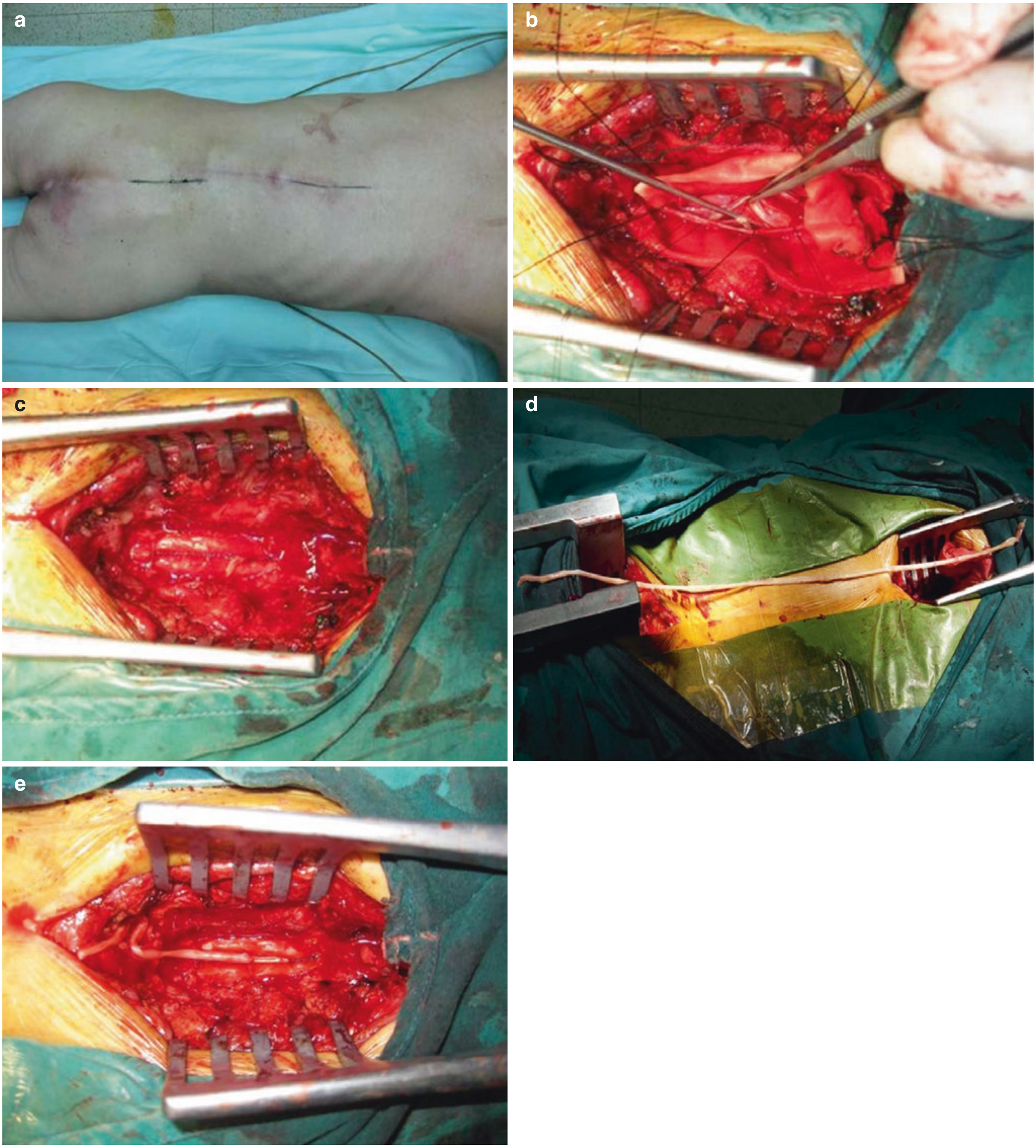


Fig. 22.13 Images of the surgical procedure to reconstruct the bladder reflex pathway in a 43-year-old woman. (**a**) Standard laminectomies from L5 to S3 and from T10 to T12 were performed with the patient lying in the prone position. (**b**) After the ventral root of T10 was identified and found to be functional, it was transected. (**c**) The dura was then closed, leaving the T10 ventral root outside. (**d**) A sural cutaneous nerve, about 30 cm in length, was taken for the nerve graft. (**e**) The T10 and S2 ventral roots were then anastomosed through a nerve graft

verify that the root is indeed the S1 root. If the function of the S1 root is normal, the unilateral S1 VR and the S2/3 VRs on the same side are transected using microsurgery and anastomosed with 9-0 non-absorbable sutures (Fig. 22.15). The wound is sutured in three layers with an external drain.

22.5 Microsurgical Repair of Injury to Spinal Cord and Cauda Equine

Shaocheng Zhang and Wenbin Ding

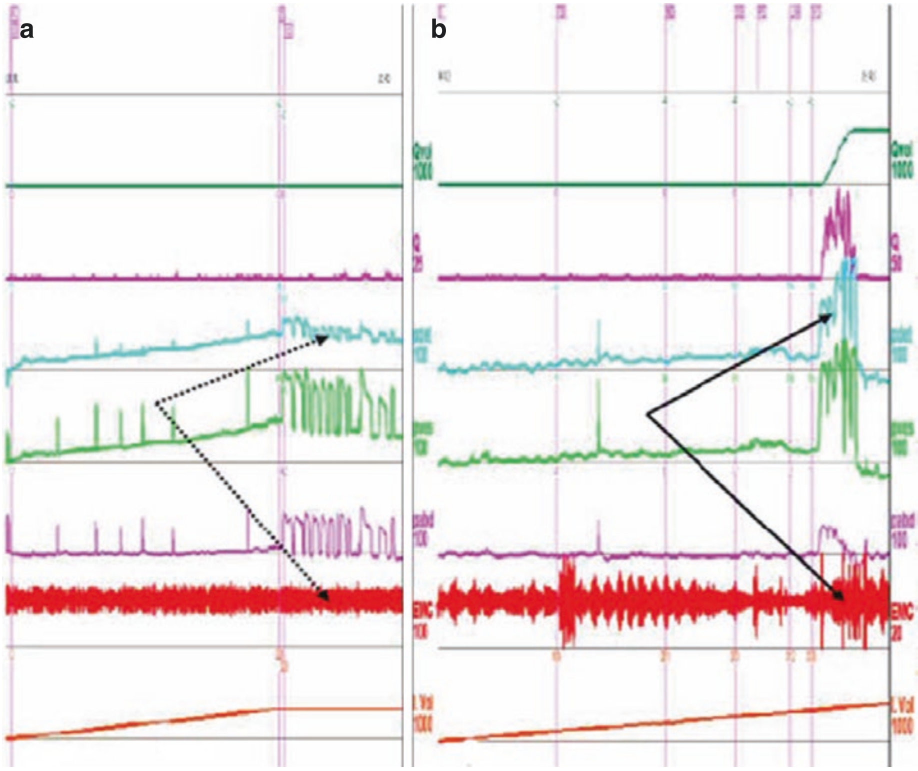


Fig. 22.14 Urine pressure and flow diagram from the urodynamic test. (**a**) Preoperative study showed that the detrusor had no reflection but the external sphincter was denervated. (**b**) Postoperative study showed that the detrusor had regained nerve reflex when the external sphincter was denervated: intravesical pressure increased quickly while abdominal pressure did not increase significantly

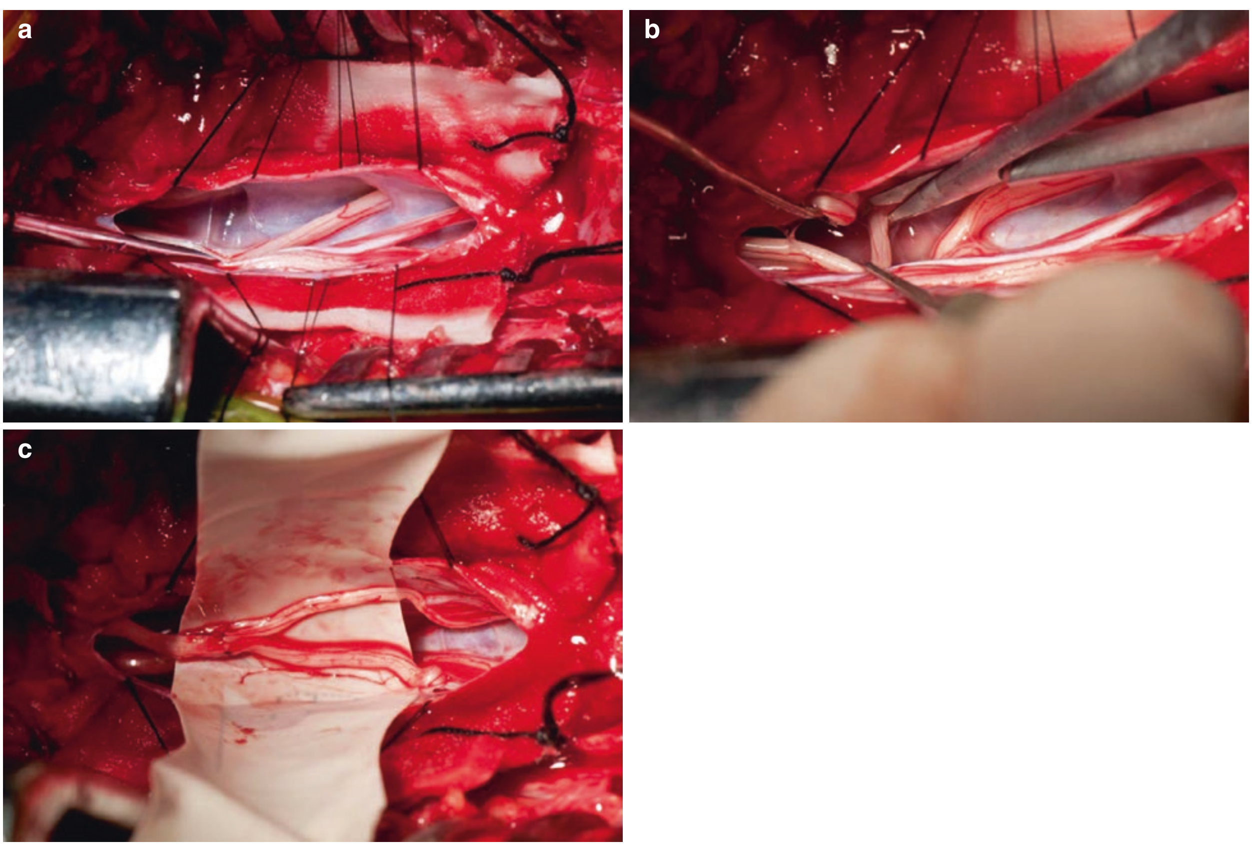


Fig. 22.15 Surgical procedure to reconstruct the bladder reflex pathway in a 25-year-old man. (**a**) Standard laminectomies from L5 to S3 were performed with the patient lying in the prone position. The dura was opened through a paramedian incision, exposing the dorsal and ventral roots of the S1, S2 and S3 nerves. (**b**) The ventral roots of S1, S2 and S3 were identified and separated from their respective dorsal roots by microdissection. (**c**) The S1 and S2/3 ventral roots were anastomosed

22.5.1 Introduction

The spinal cord, located in the middle of the vertebral canal, is flat cylindrical in shape, with a length of 40–45 cm. It can be divided into cervical, thoracic, lumbar, sacral and coccygeal regions. Its upper end is large and connected with medulla oblongata; its lower end becomes sharper, forming the conus medullaris. A strip from the conus medullaris, called filum terminal, travels down the spinal canal to end at the back of the second sacral vertebra. The adult spinal cord ends in the equivalent plane of the first lumbar vertebral lower edge or the second lumbar vertebral upper edge. The Spinal cord varies in thicknesses, with two enlargements, namely cervical and lumbar enlargements. The cervical enlargement is located at C4–T1, with its thickest part at C6. The lumbar enlargement is found at T11–L1; its thickest part is at T12. The spinal cord results from 31 couples of spinal nerves, including 8, 12, 5 and 1 couples of cervical, thoracic, lumbar and sacral nerves, respectively.

The cauda equina count is roughly 40, every stripe is divided into two bundles, connected with each other by loose connective tissues, surrounded by a loose capsule. Cauda equina has ventral and dorsal roots. Ventral roots start from the ventral anterolateral ridge of the lumbosacral spinal cord, as the motor; dorsal roots start from the dorsal posterolateral ridge of the lumbosacral spinal cord, as the sense. Ventral and dorsal roots are parallel to each other and drop vertically in the subarachnoid space, through arachnoid into a bundle, slightly in an oblique line. Cauda equina does not connect with each other in the subarachnoid space. The capsule of cauda equina is called spinal pia mater. The anatomical characteristics of cauda equina facilitate release of fiber tissues (Fig. 22.16).

Fig. 22.16 Anatomy showing cauda equina

Vertebral fractures and dislocations below the second lumbar vertebra are often combined with cauda equina damage. Some cases present with intolerable burning pain of lower limbs caused by adhesion in the subarachnoid space or around the cauda equina. Conventional surgical methods have several disadvantages, such as limited vision, bulky surgical instruments, difficulty in accurately and completely releasing the adhesion, and surgical injuries. Therefore, surgery outcomes are not satisfactory, and the treatments are often abandoned. With recent developments in microsurgical techniques, decompressing the cauda equina under a microscope can release the adhesions accurately, precisely and completely. This also reduces cauda equina damage, markedly improving the operation outcomes.

22.5.2 Microscopic Surgical Repair of Spinal Cord Injury

22.5.2.1 Early Microscopic Surgical Treatment of Spinal Cord Injury

Spinal cord injury is typically accompanied by spinal trauma, such as spinal dislocation or fracture. Early treatment aims at relieving spinal compression and/or maintaining spinal stability by means of reduction, internal fixation and decompression.

The early treatment of spinal cord injury with microscopic surgical repair includes myelotomy, durotomy, piotomy, etc.

Myelotomy

The indications are as follows: (1) neurologically identified complete paraplegia; (2) non-transection injury evaluated by radiography and clinical signs; MRI showing hemorrhage and edema of the spinal cord; (3) intact dura mater under surgical exploration, and subarachnoid space disappearance after the dura mater is incised, due to spinal edema; existence of the vasculature on spinal cord surface, with hardened parenchyma and elevated tension; also, myelotomy can be applied when cysts form inside the spinal cord, days to weeks after injury.

As for timing, it has been proposed that myelotomy should be performed as early as possible, since spinal function can only be restored within 10 h after the injury, that is, when intraspinal cysts are yet to form.

Spinal cord injury is commonly observed with the injury to the lumbosacral enlargement, due to thoracic and lumbar spine dislocations or fractures. The detailed surgical procedures are as follows: (1) the dura mater is exposed with a longitudinal posteromedian incision under local anesthesia;

(2) the incision should surpass the swollen part of the spinal cord in length, ideally accompanied by outflow of the cerebrospinal fluid; (3) the pia mater is incised, avoiding damage of the longitudinal blood vessels; (4) the surgical site is gently irrigated with Ringer's solution or saline; (5) suture of the incision is not likely to be achieved due to spinal edema; thus, a paravertebral fascia or artificial dura mater is covered and fixated with sutures at the incision.

Durotomy and Piotomy

The spinal cord is rapidly distended after injury, followed by disappearance of the subarachnoid space due to restraint from the dura mater, and a subsequent increase of intraspinal pressure. A longitudinal incision of the dura mater can release the tension and help improve blood flow. Under severe conditions, the pia mater should also be incised to achieve decompression. This presents the advantage of no extra damage to the spinal cord; for those without incision of the pia mater, the spinal tissue is not exposed to the surrounding tissues. The range of incision of the dura mater should be slightly beyond the swollen spinal edema, and the best case scenario is with cerebrospinal fluid outflow on both ends. Inadequate incision may increase the risk of herniation, thus worsening the spinal cord damage. The most severe edema is observed 3 days–8 weeks after the injury, and only completely disappears in 4–8 weeks, depending on edema severity. Young and his collaborators performed durotomy or myelotomy in 30 ASIA A or B patients 3–80 days after the injury, and observed improved physical function in more than half of their cases. Therefore, surgery timing, range and depth should be precisely designed after careful inclusion of cases.

22.5.2.2 Microscopic Surgical Treatment of Incomplete and Old Spinal Cord Injury

Dural Decompression

Objective: Dural decompression is beneficial for the patients with incomplete paraplegia who have obtained partial recovery of the neural function 3 months after traumatic injury but no further improvement following physical therapy 3 months thereafter.

Indications: It is widely acknowledged that decompression and deformity correction may further improve the neurologic function in patients with spinal fracture combined with spinal cord injury. Treatment of traumatic incomplete paraplegia is typically determined according to CT or MRI scans. We have observed, however, that MRI and CT scans fail to provide radiological support for patients with halted spinal function improvement, probably due to scars in the dural sac that compress the spinal cord. Thus, for the aforementioned patients in whom MRI or CT scans fail to reveal bony compression, spinal stenosis or spinal cord instability, preoperative MRI may reveal approximation of the spinal cord with the dura mater on multiple planes. Surgical exploration of the indicated units is recommended; more importantly, although the compressions are so thin and small that MRI and CT may fail to uncover, they are more direct and harmful, with no buffering of the adipose tissue or cerebrospinal fluid. Therefore, attention should be paid to the reconstruction of the "soft lumen" (i.e. restoration of the dural sac with dura decompression).

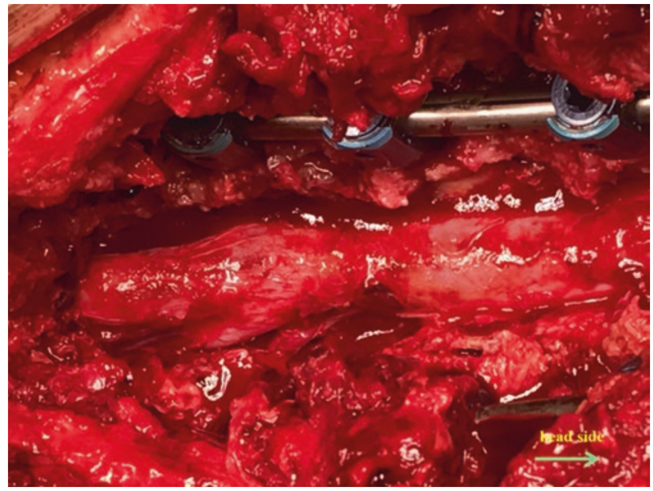


Fig. 22.17 The entire dura mater is exposed to the median approach

Surgical methods: General anesthesia is administered at lateral or prone position; a posteromedian incision is adopted to expose the dura mater. After removal of the internal fixation, the injured laminas with proximal and distal laminae are revealed. While closely looking for pulsatile movement of the dura, small incisions of 1 cm are made intermittently on hardened and thickened areas with scalpel, at a length that penetrates the entire dura while preserving the arachnoid membrane (Fig. 22.17), if no pulsatile movement is observed in 3 minutes, until a small amount of cerebrospinal fluid is leaking with restored pulse. The wound is irrigated after surgery with drainage input for 48 h, and covered with anti-adhesive membrane or a muscular flap. All procedures are carried out under a microscope. A marked restoration of dura's pulsatile movement should be observed. Compression and adhesion of the dura mater is a major factor that affects neurological restoration. Hence, this microscopic surgical technique effectively promotes the above procedure.

Intradural Lysis and Autologous Peripheral Nerve Implantation

Objective: Decompression and lysis of the spinal cord; treatment for incomplete rupture in old spinal cord injury.

Indications: (1) incomplete paraplegia, with early restoration of the neurological function after injury but no further improvement after 3 additional months of conservative treatment; (2) no marked bony compression, spinal stenosis or instability observed with MRI and CT scans, but adhesion of the spinal cord and the dura in at least one plane, with cerebrospinal fluid basically blocked. Surgical exploration should be performed accordingly for complete lysis of the scar tissue, removal of compression for improvement of blood supply and spinal function; (3) preoperative MRI shows approximation of the dura and spine, and no restoration of pulsatile movement after dural lysis.

Methods: A lateral position is adopted, with general anesthesia. A posteromedian incision is made to expose the dural sac. The arachnoid membrane, pia mater, nerve root, anterior and posterior branches are carefully explored, to look for bands, cords, or scars, as well as adhesion between structures, spinal cord deformity, thickened and adhered pia mater, and compression to the spinal cord. Then, a complete lysis is conducted in the arachnoid membrane, pia mater, denticulate ligament, nerve root, and surrounding adhesions, using microscopic surgical techniques. An autologous sural nerve should be harvested and trimmed to be longitudinally implanted in the corresponding areas or the lumen of cysts.

Microscopic Lysis of the Lacerated Ends of the Spinal Cord and the Nerve Root

Objective: To salvage the nerve root function at C5–C7 and T12–L2 in complete spinal injury patients, and improve quality of life in patients with paraplegia and quadriplegia.

Indications: Complete paraplegia in C5, C6, C7, and T12–L2, clinically classified as ASIA A or Francle A. Surgery is only performed in patients younger than 50 years old, considering better restoration of the nerve function and perseverance in rehabilitation in younger patients.

Methods: A lateral position is adopted under general anesthesia and a posterior incision made. Partial or complete removal of the internal fixation is made accordingly. The scar tissue is dissected and removed; generally, the proximal end is extended instead of the distal end. The proximal end is incised to form a cystic or sac-like dura in patients with completely ruptured spinal cord and dura, while a longitudinal incision is made in patients with an intact dura. The anatomically intact nerve roots are radically loosened from the beginning to the intervertebral foramen, with no suture of the thickened and scarred dura. An artificial dura or muscular flap is covered. Administration of low-dose corticosteroid should be applied for 3 days in addition to regular postoperative treatment (Fig. 22.18).

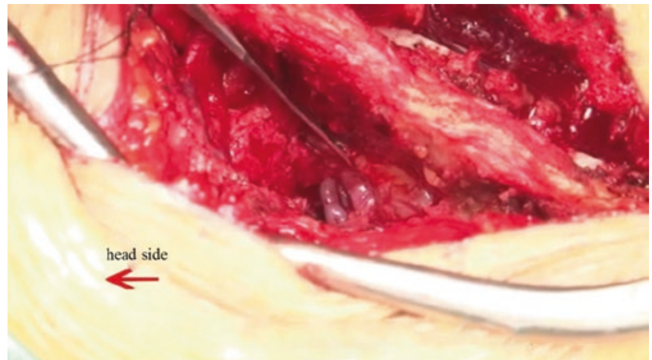


Fig. 22.18 Exposure of adherent nerve roots and venous plexus

22.5.3 Microsurgical Repair of Cauda Equina Injury

22.5.3.1 Cauda Equina Nerve Neurolysis

Damaged or oppressed cauda equina nerve is prone to adhere, which often occurs between the cauda equina or between the cauda equina and arachnoid. The adhesion could eradicate the subarachnoid, and block the cerebrospinal fluid flow. The above changes affect cauda equina repair. Held in prone position, local or general anesthesia is performed, and segmental vertebral plates are removed. The catheter probe is outside, in front of the oppression, even below the L3 vertebral fracture in front of the ward. As long as the lamina resection is done, oppression may also be lifted, especially the segmental nerve root canal. Then, one could open the catheter removal decompression, with the bone in front of the brain membrane covering the wound bleeding. Previous cut should be from head to tail ends to the middle of adhesion, especially from the far side. The cauda equina regiment and arachnoid boundaries could be distinguished after the surgery; cauda equina adhesion is separated from arachnoid blunt from bottom to top. Till the end, the cerebrospinal fluid flows out based on gradual separation between nerve roots into the intervertebral foramen. The cauda equina is separated from the second half of the subarachnoid; the cauda equina between adhesions is not easy to separate, and forced separation could damage the cauda equina. In the absence of dural defects, which can be stitched, saline solution is administered through catheter in order to maintain postoperative cerebrospinal fluid flowing. The scaring cauda equina and that with great tension cannot be sutured directly because of the risk of causing local stenosis. Compressed cauda equina can be repaired by artificial muscle flap or autologous fat tissue flap, and the wounds can be sutured conventionally. A low negative pressure drainage tube can be placed in the wound, but the scale and quantity of cerebrospinal fluid should be closely observed. Generally the drainage tube should be removed no more than 48 h. After the wound is oppressed for 24 h in the recumbent position, the head and shoulder should be gradually raised after around 3 weeks to the sitting and standing positions. When releasing the cauda equina, we adopt the hydraulic expansion method, from near and far end clearance of the adhesion horsetail, using preoperative bending TB syringe needle with appropriate thrust and speed. This is done in the center of the film adhesion cluster to the damage under the injection of 0.25% lidocaine hydrochloride encroach on progressive sharpness and blunt separation. Precisely, the adhesion degree of mild cauda equina shed gentle separation with hydraulic adhesion heavier using microscopic scissors and cut knife.

22.5.3.2 The Cauda Equina Suture/Bonding Technique

Since the 1960s, multiple studies assessing cauda equina injury have suggested the possibility of cauda equina nerve regeneration. Indeed, many experiments and studies have confirmed that cauda equina repair plays a major role in restoring the motor function. Therefore, it is particularly important for the repair of broken cauda equina with no obvious defects to be an early artificial suture. First, the injured cauda equina should be exposed and the bleeding cleared. Second, according to the thickness of different cauda equina fibers, nerve stumps should be aligned and the injured cauda equine carefully sutured. Lastly, the dura should be sutured. If the dura cannot be sutured easily, artificial dura, muscular flap or autologous adipose tissue flap can be employed to repair the dura, in order to avoid partial stenosis and cauda equina compression.

22.5.3.3 Nerve Transplantation for the Cauda Equina Defects

When the cauda equina is injured seriously, it is impossible to conduct normal direct suture without tension. Another nerve must be transplanted to bridge the injured cauda equina. We use a 4×-magnification microscope to explore cauda equina during operation. The motor nerve, which is thicker, is located in the front of the canalis vertebralis. If the nerve stumps shows obvious contusion, they can be decompressed and removed by microsurgery instruments. After the length of the defect is measured, a segment of sural nerve of the same length, whose perilemma has been removed, is taken under the microscope to bridge the cauda equina. We also use 2–3 sensory nerves to bridge one motor nerve by the same method. Anatomical repair should not be strived for too much, because expanding too many surgical fields increases the surgical trauma. The function of both quadriceps and hip muscle can be recovered in patients with fresh lumbar spine fracture and dislocation after cauda equina repair, indicating that recovery of the muscle function is related to nerve regeneration. But all the muscles below the knee do not recover, demonstrating the distance between muscles and injured area has an adverse effect on muscle recovery. No recovery in patients with obsolete injury shows that the curative effect is time based. It is pointless to repair the sensory nerve.

22.5.4 Microsurgical Management and Functional Restoration of Patients with Obsolete Injury to Spinal Cord and Cauda Equine

Bladder and bowel dysfunctions and spastic paralysis caused by complete high position spinal cord injury are difficult to restore effectively only by non-surgical treatment, such as the drug or physical therapy. It has been confirmed that some of nerve function of the brachial plexus with root injured can improve by transferring the normal peripheral nerve to it. This mature technique based on decades of the clinical practice of surgeons in many countries aroused the authors to improve part neurological functions of patients with complete high position spinal cord injury by using above theory, which connected normal peripheral nerves with nonfunctional nerves. As the patients suffer from limb spastic paralysis and their degeneration of peripheral nerves and their dominating effectors happens later and more mildly after spinal cord injury than those with brachial plexus root injury, the excellent rate of surgery is still higher than that of similar surgery for brachial plexus root injury. Moreover, after the donor nerve grows into the muscles innervated by the recipient, the nerve impulses causing the muscle to contract can also stimulate the synchronous contraction of the high tension synergistic muscle that can assist the completion of the function after rehabilitation training. However, the amount of nerve function that needs to be reconstructed in patients with paraplegia and quadriplegia is much greater than that in patients with brachial plexus injury, and the number of donor nerve fibers is relatively small, so the nerve function that can be regained is limited. How to accurately match the donor nerve fibers with the target nerve is critical. Another question to concern is how to prevent the recipient innervation muscles from atrophying before the new nerve fibers grow into the muscles during postoperative period. In view of the above two problems, we have cut the lateral adventitia and part of the perineurium of the receptor nerve, and selectively cut off some of the nerve fibers while preserving the proper muscle tension. Finally, the donor nerve is inserted in the incision of the receptor nerve, and sewed the outer sheath of the two nerves together. We call the procedure "nerve grafting" (Fig. 22.19) and the clinical results are quite satisfactory.

Next, we introduce the operative technique of peripheral nerve side-to-side interfascicular anastomosis. Take C2–C4 injury as an example: the nerve branch of accessory nerve is connected with the phrenic nerve.

C2–C4 injury: The nerve branch of accessory nerve is connected with the phrenic nerve.

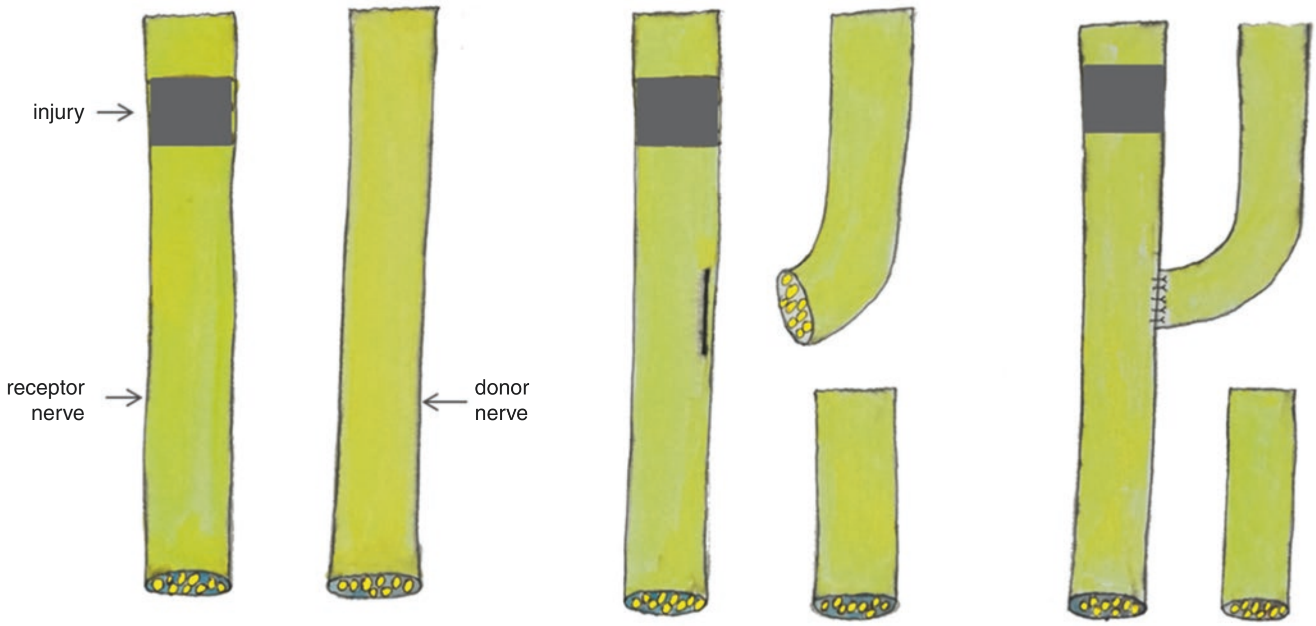
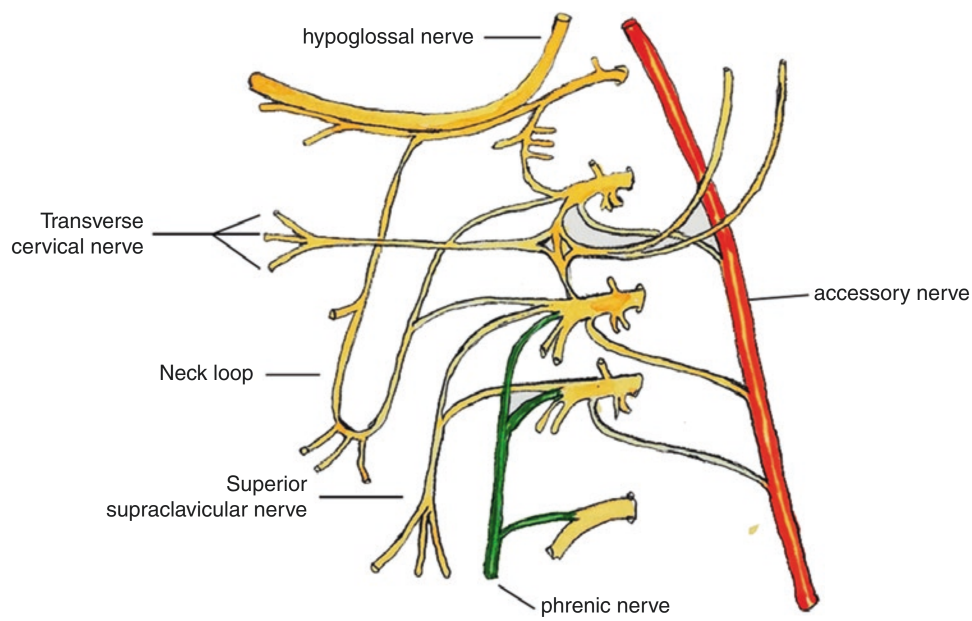


Fig. 22.19 Schematic diagram of end to side neurorrhaphy

Fig. 22.20 Surgical procedure showing the accessory nerve is connected to the phrenic nerve in the neck



Indications: Patients with C2–C4 injury who show no spontaneous breathing and require ventilator support and whose trapezius muscle is paralyzed at one side at the least.

Surgical objective: To restore partial function of diaphragmatic breathing, allowing the patient to breathe through the shrug movement without ventilator support in the awaken state.

Anatomy: Accessory nerve is composed of cranial nerve root and spinal cord root (mainly C1–C4), so the function of the accessory nerve is basically intact below C5 of spinal cord injury plane. The accessory nerve mainly dominated trapezius and sternocleidomastoid muscles and most of the nerve branches are dispersed in the dominant muscles. Therefore, cutting the accessory nerve in the plane above the clavicle will only affect part of the trapezius muscle strength without affecting other important functions.

Surgical procedure: Cutting the accessory nerve at the proximal end, and then "grafted" the nerve to the phrenic nerve in the manner of the side-to-side stitching (Fig. 22.20).

The detailed steps are as follows: The normal donor nerves in the paralytic area are fully exposed and properly released to close to the receptor nerves at the same site. The two nerve outer membrane of the adjacent area was cut from 1 to 2 cm. Then the fasciculus of some nerve bundles was cut and the nerve fibers were exposed. Cut the two nerves' epineurium on the adjacent segments, the length is 1 to 2 cm, and then cut the perineuriums of some nerve bundles separately to expose the nerve fibers. The donor nerve is inserted laterally into the incision at the side of the recipient nerve and the epineurium and perineurium are sutured to each other (Fig. 22.21). For example, if the tibial nerve is damaged and the common sacral nerve is normal, their adjacent segments are approximately 5 cm proximal to the branch, and the nerves can be displaced and stitched together by the above method.

According to our clinical observations, most patients with chronic spinal cord injury have achieved partial functional recovery after autologous peripheral nerve grafting and implantation. For patients with general paralysis, even bladder and bowel function is restored to some extent in addition to partial sensory and motor restoration, bringing about much convenience, reducing complications and greatly improving their quality of life. Since only a small number of nerves can be used for grafting, this series of microsurgery methods can only recover limited but important functions. More training is necessary for effective motor function after muscle contraction caused by pathological reflex and grafted nerve. Our follow-ups of 226 cases for 3–28 years revealed that effect active movement function (M3) was restored in 37%, sensation (S2–S3) in 76%, and reflection in 81%. Therefore, satisfactory results can be hardly achieved in patients who cannot persist in standard rehabilitation training. Such surgery is not recommended either for senior patients in poor general condition, or patients with financial difficulties.

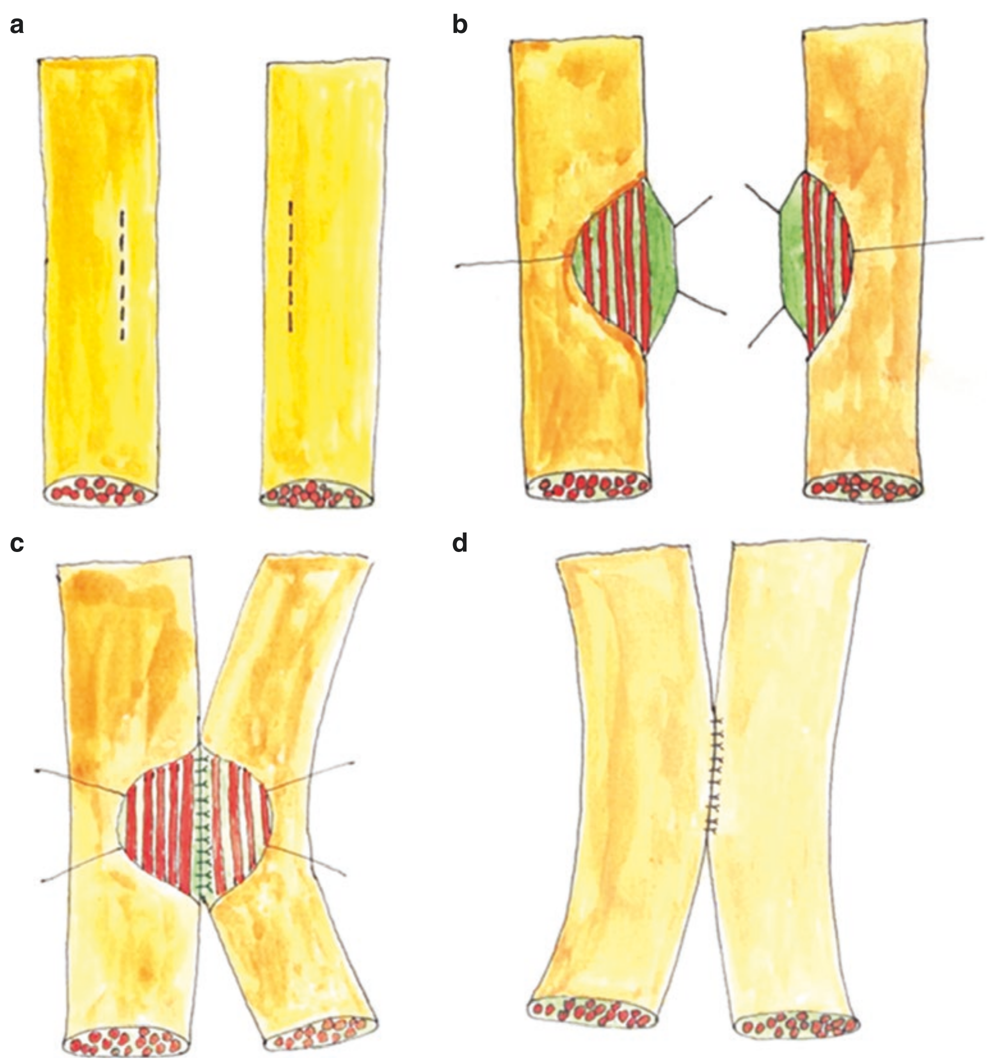


Fig. 22.21 Schematic diagram of side-to-side neurorrhaphy: (**a**) incise the epineurium of the two neighboring nerves; (**b**) Reveal two side of the perineurium; (**c**) suture one side of the epineurium; (**d**) suture another side of the epineurium

Bibliography

1. Caspar W. A new surgical procedure for lumbar disk herniation causing less tissue damage through a microsurgical approach. Adv Neurosurg. 1977;4:74.
2. Yasargil MG. Microsurgical operation of herniated lumbar disc. Adv Neurosurg. 1977;4:81.
3. Katayama Y, Matsuyama Y, Yoshihara H, et al. Comparison of surgical outcomes between macro discectomy and micro discectomy for lumbar disc herniation: a prospective randomized study with surgery performed by the same spine surgeon. J Spinal Disord Tech. 2006;19:344.
4. Chin KR, Sundram H, Marcotte P. Bleeding risk with ketorolac after lumbar microdiscectomy. J Spinal Disord Tech. 2007; 20:123.
5. Fang R, Zhou X, Liu Y. Orthopedics of minimally invasive operation [M]. Beijing: People's Military Medical Press; 2011. p. 880–6.
6. Xu S, Guo S. Basic and clinical study of spinal cord injury [M]. Beijing: People's Medical Press; 2012. p. 519–62.
7. Dang R, Zhang S, Ji R, et al. Applied anatomy of lumbosacral nerve roots corresponding to the T12-L4 vertebra. Chin J Anatomy. 1996;19:381–4.
8. Cigliano A, Scarano E, De Falco R, et al. The posterolateral approach in the treatment of post traumatic canal stenosis of the thoraco-lumber spine. J Neurosurg Sci. 1997;41:387–93.
9. Horvat JC. Spinal cord reconstruction and neural transplants. New therapeutic vectors. Bull Acad Natl Med. 1994;178(3):455, discussion 464.
10. Zompa EA, Cain LD, Everhart AV, et al. Transplant therapy: recovery of function after spinal cord injury. J Neurotrauma. 1997;14(8):479–506.
11. Giovanini MA, Reiter PJ, Eskin TA, et al. Characteristics of human fetal spinal cord grafts in the adult rat spinal cord: influences of lesion and grafting conditions. Exp Neurol. 1997;148(2):523–43.
12. Delamarter RB, Sherman J, Carr JB, et al. Pathophysiology of spinal cord injury: recovery after immediate and delayed decompression. J Bone Joint Surg Am. 1995;77:1042–9.
13. Zhang SC, Zhao J. Gatism treated with neuroanastamosis. J Neurol Orthop Med Surg. 1993;14:37–8.
14. Zhang SC, Ma YH, Liu HR, et al. Intradural lysis and peripheral nerve implantation for traumatic obsolete incomplete paralysis. Surg Technol Int. 2007;15:321–4.
15. Zhang SC, Zhang X, Ji RM. Functional reconstruction of peripheral nerves in paraplegia. J Neurol Orthop Med Surg. 2000;20(3):89–97.
16. Zhang SC, Zhao J. Gatism treated with neuroanatomosis. J Neurol Orthop Med Surg. 1993;14(1):37–8.
17. Zhang SC. Ulnar nerve transfer to the sciatic and pudendal nerves in paraplegia. J Neurol Orthop Med Surg. 1993;14(6):3–4.
18. Zhang SC, Laurence J, Zhang ZW. Restoration of stepping-forward and ambulatory function in patients with paraplegia: rerouting of vascularized intercostals nerves to lumbar nerve roots using selected interfascicular anastomosis. Surg Technol Int. 2003;11:244–8.
19. Zheng MX, Xu WD, Qiu YQ, Xu JG, Gu YD. Phrenic nerve transfer for elbow flexion and intercostal nerve transfer for elbow extension. J Hand Surg Am. 2010;35(8):1304–9. Epub 8 Jul 2010.
20. Sullivan J. Spinal cord injury research: review and synthesis. Crit Care Nurs Q. 1999;22(2):80–99.
21. Prochazka A, Mushahwar VK. Spinal cord function and rehabilitation-an overview. J Physiol. 2001;533(Pt 1):3–4.
22. Pearson KG. Could enhanced reflex function contribute to improving locomotion after spinal cord repair? J Physiol. 2001;533(Pt 1):75–81.
23. Zhang SC. Paraplegia treatment by anastomosis of lateral cutaneous nerve of thigh and ilioinguinal nerve with vascularized intercostals nerve for sensation reconstruction. Acad J Sec Mil Med Univ. 1998;19(3):264–5.
24. Zhang SC, Zang X. Functional reconstruction of peripheral nerves in paraplegia. J Neurol Orthop Med Surg. 2000;20(3):89–97.

23 Limb Allografts

Dayong Xiang, Guoxian Pei, and Jimeng Wang

23.1 Summary

23.1.1 Part 1: Experimental Research on Limb Allografts

Surgeons have been dreaming of reconstructing a defective limb (or trunk) through limb allotransplantation, but rejections as well as the ethical and moral values have greatly strangled the development of limb allotransplantation in clinic practice. Since 1960s when organ transplantation and the first replantation of severed limb were reported, many scholars have carried out experimental study of limb allotransplantation, only to find a great variety of obstacles on the way. Also occasionally clinicians carried out finger allograftings in which no anti-rejection measures were taken or even wrong allogenic fingers connected. Their results could be imagined. However, since Ecuador failed a limb allograft in 1964, there has been a successful allograft surgery in the world. With the progress in organ transplantation and immunology in recent 10 years, limb allotransplantation has been a great concern of the orthopaedic surgeons all around the world. In 1966 Goldwyn successfully performed the first dog limb allograft with mercaptopurine and azathioprine as the immunosuppressants. Furnas and Fritz respectively reported use of cyclosporine A as an immunosuppressant in the mouse limb allograft model. In spite of immune rejection of the skin, the survival time of all tissues was prolonged, and the CsA was more effective and less toxic than the broad spectrum immunosuppressants. In 1983 Arai et al. used FK506 as an immunosuppressant in limb allotransplantation in mice in which the short-term survival time of the graft after treatment was significantly prolonged.

D. Xiang (✉)
Department of Orthopedics, Nanfang Hospital, Southern Medical University, Guangzhou, China

G. Pei
Department of Orthopaedics, Xijing Hospital, Air Force Medical University, Xi'an, Shaanxi, China

J. Wang
Department of Orthopaedics, 81 Group Military Hospital of Army, Zhang Jiakou, Hebei, China

23.1.2 Part 2: Clinical Exploration in Limb Allograft

Organ transplantation for kidney, heart, livers, lungs and other organs are of single tissue type and the technology is currently mature enough. Limbs, however, are composed of skin, subcutaneous tissue, muscle, nerves, vessels, bone, bone marrow and so on. Automatically, the immune rejection after limb allotransplantation is more intense as limb allografts pertain to composite tissue allografts (CTAs). Although there have been experimental studies on limb allotransplantation since the 1960s, its progress is still slow-paced, largely due to the strong immune rejections. Moreover, people think lack of a limb or limbs is not as fatal as that of liver, kidney, lung or other organs. It is worth taking risk to undergo an organ transplantation, but the risk in transplantation of a nonessential functional organ (such as a limb) is controversial. However, this perception has been changed along with the progress in tissue matching technology, immunosuppressants and the comprehensive measures to reduce the immune rejections, long-term survival of allografted limbs, and inspiring results of limb allografting. On the International Conference on the Transplantation of Composite Tissue in 1991, the participators all agreed that it had been the time to carry out hand allotransplantation. But this agreement was not implemented owning to technology and other reasons for long. During Nov. 19 to Nov. 20 in 1997, in the United States, Louisville University and Jewish Hospital held the first international conference on composite tissue allograft transplantation. Microsurgeons, sociologists and ethics scholars from the United States, Canada and other European countries attended the meeting. Its main purpose was to probe into the feasibility of hand allografting technologically, clinically and ethically. The advantages and disadvantages of hand allografting were heatedly discussed.

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_23

Finally, it came to a conclusion that it was time for clinical research on limb allotransplantation since there had been ethical basis for current implementation.

23.1.3 Part 3: Clinical Situation of Limb Allograft

On September 23, 1998, the international team of the Herriot Edouard Hospital in Lyon, France, consisting of doctors from France, Australia, Britain and Italy, carried out the first hand transplantation for a Zelanian patient who suffered from trauma in his forearm and lost his hand 14 years ago. This marked the beginning of clinical research on limb allograft. Later the second successful transplantation was carried out by a group of doctors in the United States for a patient who had lost his left forearm for 13 years. On September 21, 1999, in Nanfang Hospital, The First Military Medical University (Southern Medical University now), Guangzhou, China, surgeons performed hand allotransplantations for two patients. In January, 2000, the French Lyon Herriot Edouard Hospital successfully carried out the world's first double forearm transplantation. In March, 2000, the second case of double forearm transplantation was performed in Innsbruck, Austria. Since then, many countries around the world have carried on clinical trials in limb allografts. According to the registry on International Registry on Hand and Composite Tissue Transplantation (IRHCTT) and the reports of Karim A. Sarhane from Johns Hopkins (Front Immunol:2013), about 100 cases of upper limb transplantation were carried out in the world by September 2013. The world's first double-leg transplantation was carried out in August 2009 in Spain. Among the 13 cases of allogeneic transplantation completed by Johns Hopkins University, five lost their upper limbs in Iraq and Afghanistan war and military training accident. Many countries including France, the United States, China, Germany, Austria, Italy, Poland, Columbia, Malaysia and Egypt have got involved in limb allotransplantation. Currently, the basic research and clinical development of composite tissue allografts have been highly concerned in western countries. China has carried out 12 cases (totally 15 sides) of limb transplantation (Table 23.1). The longest survival time of the allografted hand was over 12 years. Apart from improvement in appearance, some patients even regained some complex functions. In addition, we have successfully conducted transplantations of throat, ear, knee, femoral shaft, abdominal wall, uterus, penis and other organs so far.

Of the 12 cases of limb transplantation, one is especially worthy of introduction which was performed by The First Affiliated Hospital to Harbin Medical University on October 13, 2002 in a male patient (Fig. 23.1). With routine use of immunosuppressant agents, the patient had no obvious rejection. Regular follow-up of two forearms showed good function. In June 2014, 12 years after surgery, the follow-up showed: when the patient only took 2 FK506 per day, his blood glucose is normal with slightly elevated blood pressure; he did not feel any discomfort; he could do normal labor; his two hands looked completely normal and had normal feeling; his fingers stretched normally, but only the thumb abduction was limited due to tendon adhesion; no hand muscle atrophy was observed. After operation he only took single FK506, without any other treatment, but his physical health was good, without any complication or discomfort. In addition, the appearance, feeling and functions of the transplanted hands were completely normal (Fig. 23.2). This is really amazing! Is it only an individual case? Or is it universal? The causes and mechanisms need further research.

The current clinical effects show that limb transplantation can bring excellent function and good appearance in a short term. The grafts involve different upper limb planes, ranging from the upper arm and forearm to the digital part. Functions of the grafts are closely related to the time for reinervation. For patients with a lower plane the function of the internus

Table 23.1 Spatial and temporal distribution of limb allotransplantation in China

Time	Place	Position (case)		
		Unilateral	Bilateral	Fingers/palm
Sept. 1999	Guangzhou	2	0	0
Jan. 2000	Guangxi	1	0	1
Sept. 2000	Guangzhou	0	1	0
Jan. 2001	Harbin	0	1	0
July 2001	Harbin	1	0	0
July 2002	Harbin	1	0	0
Oct. 2002	Harbin	0	1	0
Jun. 2005	Jinan	0	0	1
Feb. 2005	Nanjing	1	0	0
May 2006	Kunming	1	0	0
Total		7	3	2

Fig. 23.1 The deficient foreparts of both hands

Fig. 23.2 The follow-up visit 12 years after forearm allograft showed both the shape and function of the two hands were in good condition

hand muscles must be restored while for patients with a higher plane we give priority to the recovery of externus hand muscles. With the survival time of the graft prolonged, there is still a risk of different neopathy.

For limb allograft, use of immunosuppressant agents is still the current bottleneck. Now it has been proved that the dose and regimen of immunosuppressant agents used in limb transplantation are similar to those in renal transplantation. The same goes for the immune suppression therapy, but the vascular changes caused by chronic rejections still remain. Furthermore, all the limb allografts have reported acute rejection, though at different times and to varying degrees.

Given that the technology and theory have been relatively mature, there is still some ethic controversy in the medical field over such a kind of transplant operation which is nonessential to life. Although allotransplantation can improve the quality of life for patients, it does have potential dangers. Hence the cases should be carefully selected. Moreover, a complete evaluation is needed.

At present, it requires joint work from transplant and HS (hand surgery) surgeons. Exchange of experience between different transplant centers should be strengthened and the basic research results be fully used. This kind of surgery is still worth waiting for, which can reconstruct the limb functions of the patients.

23.2 Donors and Receptors

23.2.1 Part 1: Indication for Receptors

The indications for the receptors should be strictly controlled because the medical expenses are huge, the patients have to use immunosuppressants for a long time, and the problems brought by limb transplantation still need to be further investigated. Although there is no international consensus on this issue, the criteria are mostly similar. We propose the selection criteria as follows:

1. 15 to 50 years of age;
2. no more than 3 years after amputation;
3. patients who have lost both hands or the dominant hand (It is evident that limb transplantation is more suitable for them.);
4. the amputation plane lower than the elbow because the lower the amputation plane, the better the recovery after transplantation, and the limb loss above the elbow is usually not taken into consideration;
5. patients who desire strongly for transplantation;
6. patients who have no other systematic or uncontrollable diseases;
7. patients who have made the definite choice to receive the surgery in normal mentality after they are fully informed of all disadvantages and advantages as well as all the information about the transplantation and immunosuppressants.

23.2.2 Part 2: Selection of the Donor

A test of ABO blood group, Rh group, panel reactive antibody (PRA) and human leukocyte antigen (HLA) of the donor is mandatory. In the meanwhile surgeons should take into account the age, gender, size of the limbs, skin color and matching degree. Before operation, the blood of the donor is checked again to ensure that the donor has no infection of hepatitis virus, HIV, syphilis or other infectious pathogens.

In addition, in selection of the donor, the skin color, texture, hair, thickness and difference between men and women should be taken into consideration. Only when the appearance of the transplanted limb is matched as much as possible to the other parts of the receptor, the receptor can really accept the transplanted limb.

23.3 Salvage and Preservation of the Limb

Development of limb transplantation is limited by the source of donors, like organ transplantation. It is necessary to make a reasonable limb harvest to guarantee the quality of the donor limb.

Conventional disinfection is carried out after death announcement. Make a circular incision at the plane 5 cm above the elbow. Dissociate the brachial artery first. After intubation, perfuse it with UW at 4 °C while irrigation is maintained. Then mutilate the forearm. Keep clysis till the fluid phegma is cool. Wrap the limb with aseptic dressing and encapsulate the wrapped with plastic bags. Put it into an insulation box of ice bags. In this way we can simplify the operating performance and ensure the clysis quality. Furthermore, it is easier to create an asepsis condition for the limb.

23.4 Limb Transplantation

23.4.1 Part 1: Anesthesia

In the aspect of anesthesia management and analgesia, prevention of vascular spasm and embolism is vital. Limb allotransplantation takes a long time and needs meticulous planning. So we should provide adequate analgesia, a silent operation theater and perfect postoperative analgesia. One of the important principles for microsurgery management is that it is forbidden to use blood vessel contraction drugs.

23.4.2 Part 2: Preparation of the Receptor's Stump

Limb allograft is a basic procedure referring to autologous replantation. The key to the operation is to arrange the order of tissue reconstruction and ascertain the graft plane of both receptor and donor limbs. As in the replantation of a severed limb, we can fully prepare and select the responding donor tissue flexibly and are not limited by the trauma of blood vessels, bones, muscles, nerves and so on. We can ensure the limb integrity and appropriate length. At the same time, we will have more time.

23.4.2.1 Examination of the Recipient Before Operation

Most of the limb allografts are hand or forearm transplantations. Before operation, we should observe the following: plane of the absent limb to make sure whether there are scars, sinus and swelling on the skin; local soft tissue; muscle tonus and muscle force; existence of innervation by EMG detection; activity of the shoulder, elbow, wrist joints, which means a lot to the recovery assessment; distance from the stump to the nearest joint; stump size; X-ray films to observe the conditions of bones and other trauma.

23.4.2.2 Preparation of the Recipient Site

Apply a pneumatic tourniquet to the proximal 1/3 of the upper arm. Have a tongue-like flap in the front and back of the stump. Make an incision on the skin and the subcutaneous tissue. Dissociate the capitis vein, basilica vein, ulnar artery, median nerve, ulnar nerve, radial artery, dorsal carpal branch of ulnar nerve, ramus superficialis of radial nerve and all the tendons of the extensor and flexor muscles, before marking them. Carry out step-shaped osteotomy of the radius and ulna as the preoperative design has planed.

23.4.3 Part 3: Preparation of the Donor's Limb

Referring to Sect. 23.3 of this chapter.

23.4.4 Part 4: Reconstruction of Limb Tissue (Taking the Wrist Joint as an Example, Fig. 23.3)

At present, there has been a large change in the sequence of tissue repair. However, arterial anastomosis and skeletal fixation are the first step in the whole treatment. In most cases, arterial anastomosis and skeletal fixation are followed by venous anastomosis and reperfusion, along with the repair of median nerve, cubital nerve, and radial nerve.

According to the basic procedure of autologous replantation, the key point in the operation design is the graft plane of the donor and the receptor in transplantation and tissue reconstruction sequence. The order of limb reconstruction is generally skeleton, arteries, deep tendons, superficial veins, nerves and then the skin.

23.4.4.1 Bone Reconstruction

Bone reconstruction is the first step in limb transplantation. In order to increase the contact bone area to enhance bone healing, cut the bone and make sure the involution is ladder-like. 4 AO cortical bone screws can be used for fixation. And use plate internal fixation in involution.

23.4.4.2 Arterial Anastomosis

Reconstruction of the vessels is the hinge in recovery of blood circulation. Arterial anastomosis should be conducted right after bone reconstruction. It not only determines the fate of limb allograft, but also influences the functions of transplanted limb. Sutures on the soft tissue around the fracture and deep in the vessels can prevent fracture fragments, provide a good vascular bed, eliminate dead space and reduce the tension when the vessels are sewn up. Join the ulna and radial arteries with No. 7-0 injury sutures under an operating microscope.

23.4.4.3 Suture of Deep Tendons at the Flexor Aspect

After the tension has been adjusted, the tendons are sutured using the Kessler method. Namely, use 3-0 non-absorbable sutures to have flexor pollicis longus muscle tendon and deep flexor tendon connected through crossing-over anastomosis. In this way we can reduce the risk of tendon adhesion, to lay a good foundation for functional recovery of limb allograft.

23.4.4.4 Venous Anastomosis

Reconstruction of limb allograft circulation means that there is enough artery blood to irrigate the tissue and enough venous return to keep a relatively balance of blood flow. When the balance is broken, even if the vessels are connected, ischemia or blood stasis still happens. The proportion of artery anastomosis to venous anastomosis is usually 1:2.

Fig. 23.3 Photos showing immediate post-transplantation

23.4.4.5 Suture of the Flexor Superficialis Tendon and Extensor Tendon

Sew up the flexor carpi ulnaris, flexor carpi radialis, palmaris longus, flexor pollicis longus, abductor pollicis longus, extensor pollicis brevis, extensor pollcis longus, extensor carpi radialis longus, extensor carpi radialis brevis, extensor tendon, extensor indicis, and extensor carpi ulnaris muscle tendon at different planes. In order to shorten operation time, reduce limb cross section of tendon suture that causes adhesion and to prevent bloated junction, sometimes we only have the flexor digitorum profundus tendons sutured.

23.4.4.6 Nerve Anastomosis

The neuroma should be removed to the normal axons in some patients who have nerve neuroma in their stumps. We use both interfascicular suture and epineural suture. We perform nerve anastomosis for the median nerve, ulnar nerve, dorsal carpal branch of ulnar nerve and superficial branch of radial nerve. The distance from the nerve anastomosis plane to the corresponding anatomical position is recorded for observation of the nerve recovery at a later stage.

23.4.4.7 Skin Suture

The skin near the end should be preserved as much as possible, except for scars. Dissect the skin on the donor site and remove excess distal skin before skin suture and half tube drainage at the skin incision. Some surgeons remove the donor's skin as much as possible to reduce the chance of acute rejection because the immunogenicity of the skin is intense in the composite tissue transplantation.

23.4.4.8 Fixation of the Transplanted Hand

Fix the transplanted hands which are placed in the extension position of the hand wrist and the opposition position of the thumb abductor with each finger slightly flexed with plaster.

23.5 Treatment and Psychotherapy After Transplantation

23.5.1 Part 1: General Treatment

The key to successful tissue transplantation is to smooth the blood vessels. The essential factor is vascular anastomosis under a high-quality microscope. However, clinical and experimental observations revealed that the surgery may fail due to vasospasm, thrombus and infection even when vascular anastomosis and intravascular patency are in good condition. So proper and positive treatment is important in prevention of neopathy after tissue transplantation. After transplantation of vascular tissue, nursing staff must be patient and carefully observe the patient. Problems should be discovered and thus dealt with in time. The nurses should pay attention to rewarming of the transplanted tissue and settle the patient in a special ward where the room temperature is 23–25 °C. Focus on the following indicators of local blood circulation: (1) skin temperature, (2) skin color, (3) capillary back filling test, (4) swelling degree, and (5) bleeding test. Watch the patient once per hour and record dynamic observations in a special form.

23.5.2 Part 2: Drug Treatment

1. Application of sedative and analgesic drugs.
2. Application of antibiotics to prevent infection after operation.
3. Application of anticoagulation and expansion drugs
4. Application of vasodilator spasmolysis drugs.
5. Treatment of immunosuppressive drugs.

23.5.3 Part 3: Observation of Immune Rejection

One of the main obstacles to allograft is lack of known criteria for acute rejection. The immune rejection criteria internationally recognized are as follows:

1. Clinical signs: According to the animal experiments and the reported limb allograft rejections, the clinical signs are usually erythema, blister, edema, hair removal, necrosis and so on.
2. Biopsy (skin, muscle and bone): Immune rejection is the main problem and the biggest obstacle. Most of the scholars believe that erythema, blister, edema, hair removal, necrosis, skin shedding and skin hardening may be the signs of immune rejections. Btittemeyer et al. maintain that since the diagnostic criteria are not systematic or standardized, it is difficult to compare different studies. On the basis of the criteria for diagnosis of cardiac rejection proposed by International Heart Transplantation Association, they have developed a set of relatively complete classification for diagnosis of limb allograft rejections (Table 23.2).

After classifying every type of tissue histopathologically, they calculate the average MRG of the four kinds of tissue. The MRG can be compared and classified in different researches. Typical infiltration of lymphocytes in the basal layer of the skin and around the vessels was recognized as the only diagnostic indicator of allograft rejection in the Second International Composite Tissue Allograft in May 2000.

Table 23.2 Classification of immune rejection of the tissues

	Skin	Muscle	Cartilago articularis	Bone
0	Normal	Normal	Normal	Normal
I	Focal mononuclear cell infiltration, basal layer cell vacuolization	Focal infiltration of the vessel, or occasionally diffuse infiltration of cells or focal infiltration	Focal absorption and granular tissue in cartilage	Periosteum infiltration and periosteum reaction
II	Bulla at the basal layer; mixed infiltration	Infiltration and muscle cells necrosis	Mononuclear cell infiltration with articular surface roughness	Bone trabecular space without vascular, cortical bone irregularity
III	Edema, vasculitis, and necrosis	Disseminated multiple forms of invasive, bleeding, vascular inflammation, necrosis or fibrosis	Necrosis of articular cartilage with or without the infiltration of mononuclear cells	Edema, vasculitis, and necrosis

Table 23.3 The standard of pathological classification of Banff in 2007

0	No or a small amount of inflammatory infiltrate
I	Mild: mild vascular infiltration; No involvement of skin structure
II	Moderate: moderate to severe vascular inflammation, with or without skin and/or accessory involvement, no skin necrosis
III	Severe: severe inflammation associated with apoptosis in epidermal epithelial cells; dyskeratosis and/or keratin hydrolysis
V	Acute rejection. Skin or other skin necrosis

On the ninth Banff CTA pathological science conference held in Spanish La-Corun on June 26, 2007, a CTA rejection pathological classification was proposed (Table 23.3). The format of the classification follows the National Institutes of Health (NIH) guidelines for development of a consensus on the project. The classification of acute skin rejection was defined as inflammatory cell infiltration, apoptosis, dyskeratosis and necrosis in the epidermis (and/or accessory structure), and the rejection was defined at five levels.

23.5.4 Part 4: Psychological Treatment

Implementation of psychological treatment in patients with limb allograft has a specific clinical significance. It is an important part of postoperative care. Limb transplantation is totally different from the substantive organ transplantation. Limbs are visible. Although limb transplantation is a dream for most of the patients, but when they wake up after surgery only to see a strange limb, they will refuse at first and find it difficult to accept. At this point, they are in urgent need for psychological comfort and treatment.

Postoperative psychological treatment mainly includes the following aspects:

1. Psychological hint and dredge.
2. Sedation, analgesia and targeted therapy.
3. Family visits and appeasement.
4. Improved environments including a quiet, ventilated and sunny ward.

23.6 Immunosuppressive Drugs and Treatment Regimens

23.6.1 Part 1: Immunosuppressants

There are no less than ten kinds of immunosuppressive agents for organ transplantation. Action mechanisms of some drugs have not been clarified. At present, immune suppression drugs for limb transplantation are mainly those for immunosuppression after organ transplantation, but the compatibility of drugs, dosage and medication time are different. Traditionally, according to their chemical types, immunosuppressive drugs can be roughly divided into corticosteroids, antimetabolitas drugs, calcineurin inhibitors, mTOR inhibitors and biological immune modulators.

23.6.2 Part 2: Immunosuppressive Drug Treatment Plan

According to the current international studies on clinical limb transplantation, there are different immunosuppressive plans, but they all include both an induction period and a maintenance period.

1. The induction period: Treatment includes anti-thymocyte globulin (ATG), tacrolimus, mycophenolate mofetil and hormone. Use of ATG usually lasts for 3 days, but can continue for 10 days in some cases. The dosage of the hormone (500–1000 mg/day) in the first week is reduced rapidly to 10–20 mg/day for the following 6–8 weeks. Another treatment is monoclonal antibody (Basiliximab), tacrolimus, mycophenolate mofetil and hormone.

   In recent years, using MP and Alemtuzumab (or Campath-1H, 30 mg, iv, once) as a substitution for ATG is a heated topic. Alemtuzumab has a long-lasting effect (10 months), fewer side effects and high safety. It has a particular clinical effect on the composite tissue transplantation.

2. The maintenance period: Take tacrolimus, mycophenolate mofetil and hormone. 12 months after transplantation, the blood concentration of tacrolimus ranges from 3 to 13 ng/mL. The dose of mycophenolate mofetil (MMF) is 0.5–2 g per day. The hormone dose is 5–30 mg per day 6 months after transplantation, but it decreases to 2.5–15 mg per day 12 months later.

In addition to immunosuppressive drug therapy, the cell therapy in the past few years has aroused great attention from the scholars so that it has developed rapidly. In the latest research, after composite tissue transplantation is combined with BMT, the microchimera comes into being. During the maintenance period, only a single and small dose of Tacrolimus is needed to keep the blood concentration at 5–10 mg/mL and it is gradually lowered to 3–7 mg/mL (1–2 mg taken orally Bid), causing no transparent injections.

It has been confirmed in some animal models and a few clinical cases in recent years that establishment of mixochimaera can induce immune tolerance to the donor after BMT. By building mixochimaera, we can achieve clonal deletion of immune activated T lymphocytes and specific immune tolerance to the donor while maintaining the immune activity to the third antigens. However, it is difficult in the field of composite tissue transplantation to overcome the problems as follows: the toxic reaction in marrow transplantation pretreatment; GVHD; difficulty in inserting the chimaera; a plan that induces the organ transplantation immune tolerance by bone marrow transplantation. In this regard, the composite tissue transplantation team of Pittsburgh and Johns Hopkins University, especially professor Lee Andrew et al. are the frontrunners. They successfully conducted the donor bone marrow transplantation in 10 patients undergoing limb transplantation. The patients were followed up for 5 years. They received a single dose of tacrolimus but the clinical effect was good. The amount of the donor bone marrow cells was very large (5–10 * 108/kg). The cells were obtained from the donor bone marrow. However, no clear and definite formation of the chimaera was observed in the follow-ups of the patients. It has been reported that a transient donor chimaera can induce immune tolerance, but animal experiments have confirmed although the early immune tolerance is induced by a transient donor chimaera and the drug dose can be reduced, chronic rejection may occur.

Cell therapy also includes stem cell transplantation and other immune cell therapies, such as application of DC cells. It is reported that mesenchymal stem cell transplantation can reduce the rejection. DC cells have been preliminarily applied in the trials on transplantations of the kidney and other solid organs.

23.7 Functional Recovery of Transplanted Limbs

After limb allograft, functional rehabilitation for the transplanted limb is very important. Functional rehabilitation after limb allograft is similar to that after limb replantation. It is essential that specialized rehabilitation doctors or other specialists make plans for short-term, mid-term and long-term rehabilitations which need to be implemented strictly and monitored for a long time.

23.7.1 Part 1: Early Rehabilitation (1~8 Weeks After Operation)

Physiotherapy: 1 week after operation, elevate the affected limb and fix it in functional position with plaster. When psychotherapy is given, the therapist should also give a centripetal massage to the metacarpophalangeal joints and interphalangeal joints gently. Ultra-short wave treatment should be given to alleviate edema and prevent ankylosis.

Two weeks after operation, the ultra-short wave treatment should be carried on. After the blood circulation of the transplanted limb and the surface return become normal, the following treatments can be given: (1) splint, (2) protective passive movement, and (3) impulse-transmitting practice.

Four to eight weeks after operation, the range of motion of the transplanted limb can be enlarged.

Ergotherapy: After discharge from hospital, the patient should gradually practice some simple daily activities under the guidance of doctor. For example, dressing, eating, using the toilet and writing with the healthy hand should begin as soon as possible. Self-help tools can be used if necessary. The goal is to increase the ability of living independently and enhance self-esteem and self-confidence.

23.7.2 Part 2: Mid-Term Rehabilitation (8 Weeks to 4 Months After Operation)

1. Wound surface and scar: massage, silica gel and ultrasound.
2. Edema: If edema appears at this stage, there must be some specific reasons. For example, overexercise or misplaced splints. The problems should be identified and resolved.
3. Training of joint motion: The whole ranges of passive, active and resistance exercises should be carried out gradually. Due to replantation or amputation, the range of motion in some joints may never return to normal. The volume of the intrinsic muscles may never recover.
4. Splints: good for drafting tendons and scars and increasing the range of motion of the joints.

5. Sensation of irritation: Sensory nerves begin to recover at this stage. Real sensory training should be started. The principles for early sensory training: three to four times per day and 5 min each time. The healthy hand is not allowed to touch the affected hand, in case that the brain may be confused after receiving two sets of sensory messages. Family and friends can join in the training plans.

During the sensory training, the patient is not allowed to touch a cold, hot, or sharp instrument. The handle of instrument should be as thick as possible. The transplanted hand should not hold a too long instrument and instruments should be changed frequently in case that the wound is under pressure for too long. Pay attention to the manifestations of skin compression, observing whether the skin is turning red, swollen or hot. If these manifestations appear, rest the hand. The hands should be kept soft and wet.

After the palms recover movement sensation or 30cps vibration sensation, the ability to distinguish should be trained between movement and immobilization, sharpness (like pencil) and bluntness (like eraser). The sensation of location should also be trained.

23.7.3 Part 3: Recovery Stage (4 Months After Operation)

At this stage, all kinds of tissue have recovered basically. The range of joint motion and the power of muscles need more improvement. Sensory training should be conducted actively. The activity level of limbs should be improved. Take further steps to enhance the recovery of proprioceptive sensation. For example, touch the numbers, letters and geometric figures to train graphesthesia; open and close the eyes alternately to train the sensory ability to finish a task with both hands; make the patient to pick the appointed item from a mix of sands, rice and beans; train some specific sensation needed in job so that the patient can return to his job.

Practical, targeted functional training: The patient should be encouraged to use the transplanted hand as much as possible in daily life, like dressing, washing face and rinsing the month, eating, playing chess, writing, playing basketball and so on. In addition, the patient should also practice picking crystal balls, clipping paper, ripping paper and do other movement trainings to recover the function of median nerve and ulnar nerve.

At this stage, the problems left on the patient should be considered, including personal, social and employment needs and the need to have a supplementary operation.

23.8 Monitoring and Functional Assessment After Transplantation

23.8.1 Part 1: Pathological Monitoring

Acute rejection is inevitable after organ transplantation and limb allograft. In experiments, we have found that the manifestations and severities of the rejection reaction are related to the species of animals. Tissue diversity is one of the features of composite tissue transplantation. Antigenicity varies with different kinds of tissue. The time when rejection reaction appears and the manifestations are different. The normal noticeable clinic and pathologic symptoms are as follows: skin erythema, temperature fall and color changing on the limb, desquamation of skin, limb swelling, unhairing, blacken skin and necrosis and so on.

The histological observations after animal composite tissue transplantation reveal that different kinds of tissue have different changing manifestations under microscopy as follows: edema, infiltration of lymphocytes and macrophages around blood vessels, noticeable thrombosis in the blood vessels of muscle. We performed an allograft in ACI mice and Lewis mice as donors and recipients respectively. We found that the main histopathologic changes were cellular infiltration, atrophoderma and vasculitic changes. At present, a lot of researches have reported that skin tissue exhibits the most severe rejection reaction while tendons of extensor digitorum longus and brevis the mildest. Skin tissue is regarded as the most typical tissue in rejection reaction in an allograft.

Immunological rejections should be observed after the patients take the latest immunosuppressive drugs. Reasonable and effective use of immunosuppressive drugs guarantees a successful allograft. Thus, monitoring immunological rejections after allograft helps guide the reasonable use of immunosuppressive drugs. This is very important, especially when specific indications of immunological rejections after composite tissue transplant are hard to find. Pathological observation and tracking after the first case of hand transplant in Lyons became the mirror to guide clinical drug use, setting an example for later hand allotransplant of the same kind.

The third and fourth cases of hand transplantation which were performed in Nanfang Hospital, China, in combination with the immunosuppressive drug-FK506, were tracked for 1 year. Nerves, muscles, bones, tendons, stroma, blood vessels and other tissues were all under regular tracking observation, in addition to the skin. Skin biopsy was conducted 1 day, 3 days, 1 week, 2 weeks, 3 weeks, 7 weeks and 7 months after operation. The material parts were the back, palm and fingers of the transplanted hand. At the same time, the skin from the responding part of the donor limb on the day of operation was used as a contrast. Biopsies of nerve and other tissues were carried out when the transplant operation was performed and when bone internal fixation was removed 7 months later. Biopsies were also carried out to examine the following tissues: median nerve, ulnar nerve, nerve tumor tissue of anastomotic stoma, a nerve tract of superficial branch of radial nerve in thumb-index web, scar tissue in anastomotic stoma of lumbrical muscle and tendon, bone tissue in the poroma moving line towards the distal end. The following are biopsy results of the two cases of hand transplantation in Nanfang Hospital, China.

23.8.1.1 Skin

The two cases of transplant were basically the same. The skin epidermis one day after allotransplantation showed nothing special when it was compared with the epidermis before allotransplantation. A small amount of neutrophil infiltration was seen around the dermal blood vessels and appendages of skin (Fig. 23.4). Three days later, slight hyperkeratosis appeared in the epidermis. Epidermal basal layer cells started to proliferate. Subcutaneous capillaries expanded and an active proliferation was observed (Fig. 23.5). Interstitial edema and focal hemorrhages were seen. A small amount of infiltration of inflammatory cells, mainly monocytes, was also observed around vessels. After 1 or 2 weeks, proliferation of epidermal basal layer cells and subcutaneous capillaries was still visible. Three weeks later, nothing was abnormal except that the epithelial angle extended. Seven months later, the epidermis and subcutaneous tissue showed no difference from the normal skin, except for a little infiltration of lymphocytes, monocytes and granulocytes (Fig. 23.6).

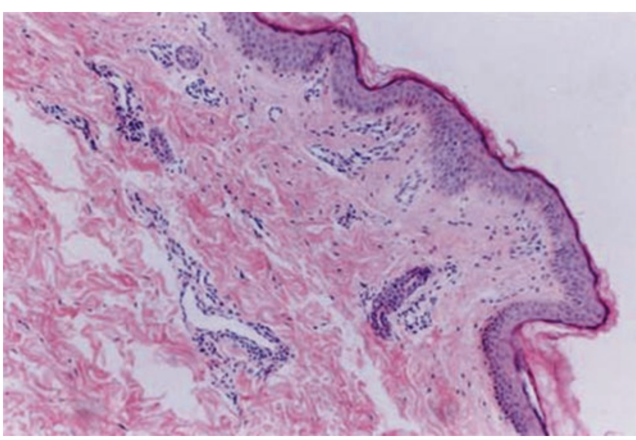


Fig. 23.4 On the first day, the skin and epidermis structure of the transplanted hand was normal. Only a small amount of neutrophil infiltration was seen around the dermal blood vessels and appendages of skin. HE´100

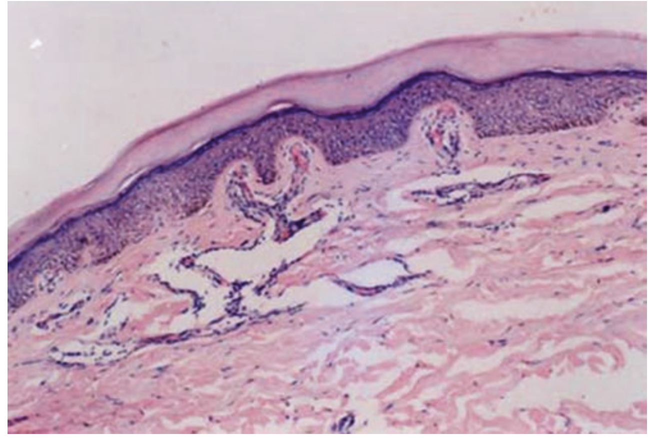


Fig. 23.5 On the third day, skin and epidermis of the transplanted hand had slight hyperkeratosis. Epidermal basal layer cells started to proliferate. Subcutaneous capillaries expanded in an active proliferation. HE´100

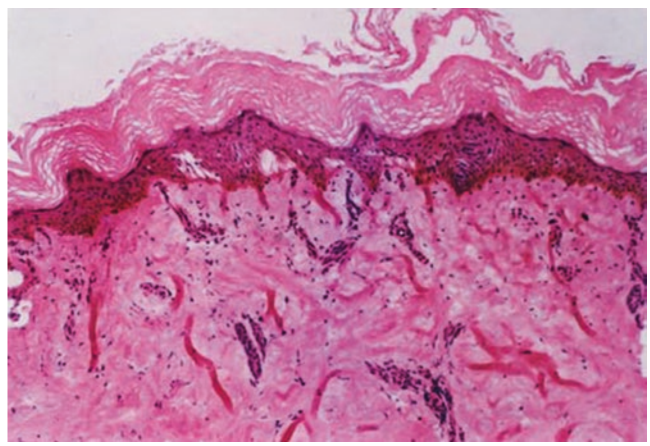


Fig. 23.6 In the seventh month, the epidermis and subcutaneous tissue showed no difference from the normal skin, except for slight infiltration of lymphocytes, monocytes and granulocytes. HE´100

23.8.1.2 Nerves

The nerves used for material biopsy (median nerve, ulnar nerve, radial nerve and epineurium of the above nerves) exhibited nothing abnormal under microscopy. The perineurium and epineurium of median nerve, ulnar nerve and radial nerve from the recipient showed a small amount of neutrophil infiltration. Muscles showed nothing abnormal.

The tissues used for material biopsy in the seventh month showed the following manifestations:

23.8.1.3 Muscle

Homogeneity degeneration, striation disappearance and other changes could be seen in some muscle fibers. Vascular wall thickened in some muscle interstitium. Infiltration of

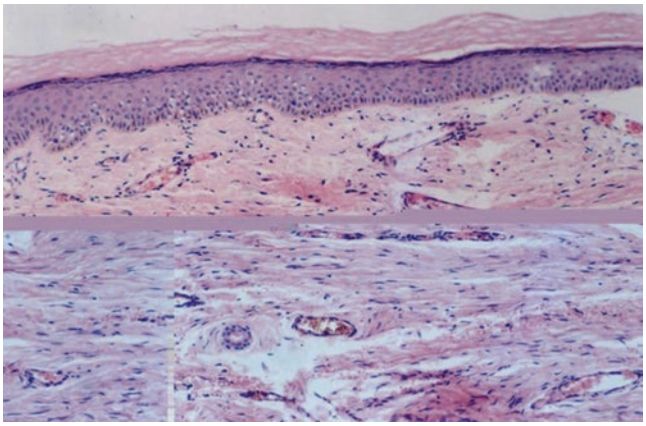


Fig. 23.7 Muscle of the transplanted hand in the seventh month. Some muscle fibers showed homogeneity degeneration. Vascular wall thickened in the muscle interstitium. Infiltration of inflammatory cells, mainly neutrophils, could be seen. HE´200

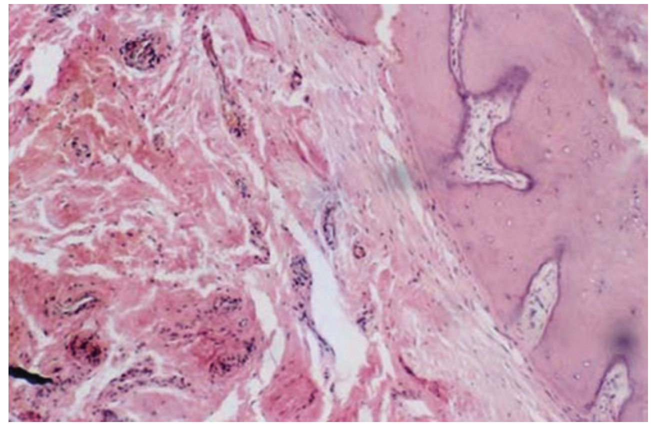


Fig. 23.9 The regenerative nerve fibers of the transplanted hand in the seventh month were in good condition. Infiltration of inflammatory cells, mainly monocytes and lymphocytes, could be seen around some vessel walls. HE´100

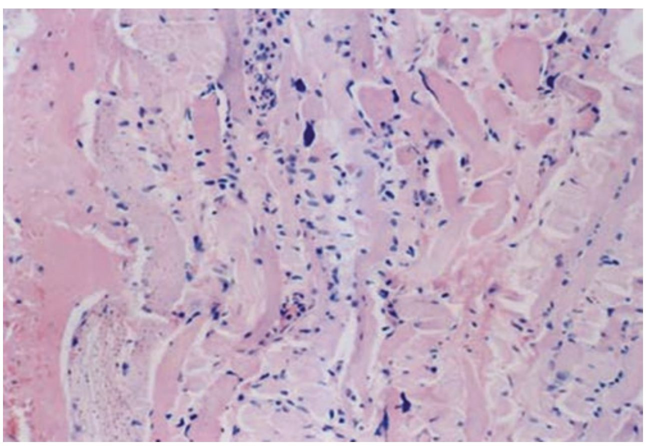


Fig. 23.8 Bone tissue of the transplanted hand in the seventh month showed no difference from the normal. HE´100

inflammatory cells, mainly neutrophils, could be seen (Fig. 23.7). There was nothing abnormal around blood vessels except for mild connective tissue hyperplasia.

23.8.1.4 Bone

The structure of bone tissue showed no difference from the normal (Fig. 23.8).

23.8.1.5 Scar Tissue of Tendon Anastomosis

Only the fibrous connective tissue in tendons developed hyperplasia while the scar tissue was the proliferous fibrous connective tissue.

23.8.1.6 Nerves

The regenerative nerve fibers (including median nerve, ulnar nerve, radial nerve and epineurium) of the transplanted hand in the seventh month were in good condition. Nerve capsule and peripheral connective tissue showed proliferation and blood vessels had endothelial proliferation. There was infiltration of inflammatory cells, mainly monocytes and lymphocytes, around some vessel walls (Fig. 23.9). There was no cell infiltration in the epineurium and perineurium, but their blood vessel walls still exhibited neutrophil infiltration and monocyte infiltration (Fig. 23.10). Neutrophils proliferated in some vessels.

Nevertheless, not much has been known about the various rejection reactions after composite tissue allotransplantation.

It is widely believed that severe immunological rejection will happen in composite tissues after limb allograft. According to a limited number of reports, the severity of rejection reaction after limb allograft is between that after heart transplantation and kidney transplantation. Skin is regarded as a kind of tissue that has strong immunogenicity. Since it is located on body surface, the skin is likely to be used as a biopsy material for clinic observation. Hand allograft experts overseas use skin biopsy to indicate the severity of immunological rejection in the skin which may guide medication of immunosuppressant agents. The skin observations in the above two cases of hand transplantation suggest that there may be no obvious rejections in the epidermis and blood vessels of the hypoderm except for mild rejection in some blood vessels at an early stage. Only the muscle and blood vessels of the epineurium developed infiltration of inflammatory cells, mainly neutrophils, at the early stage. In the seventh month, blood vessel walls and periphery of the epineurium still showed chronic vascular immune rejection, involving neutrophils, lymphocytes and monocytes. These observations show that rejection of muscles and blood vessels of the epineurium may be more intense than the

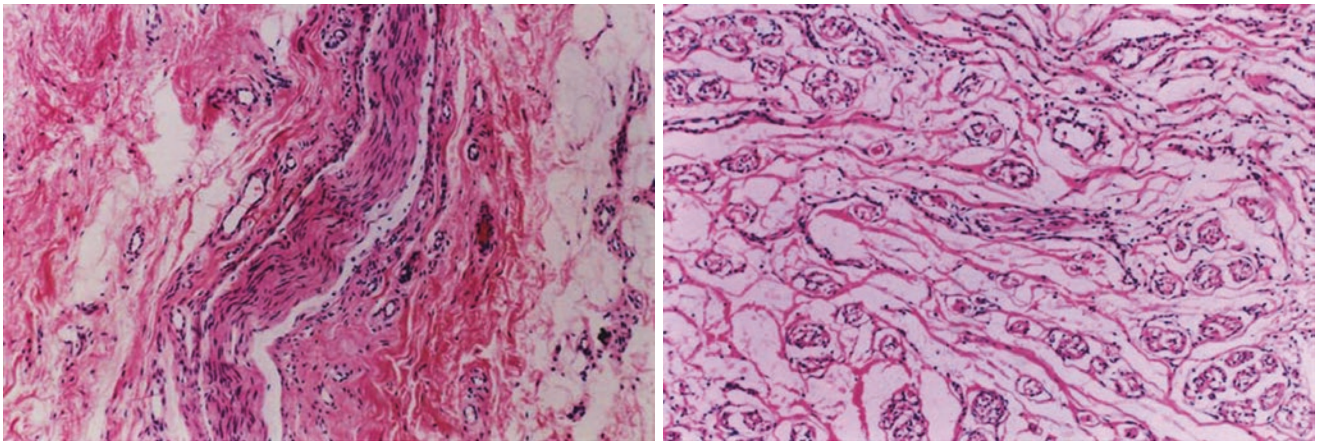


Fig. 23.10 The blood vessel walls of epineurium and perineurium of the transplanted hand in the seventh month developed neutrophil infiltration and monocyte infiltration. HE´100

blood vessels of skin. We have not known much about the mechanisms yet. It may have something to do with a variety of immunogenicity of different tissues, and their different reactions towards immunosuppressive drugs as well.

23.9 Current Problems and Countermeasures of Allograft

Although the present evidence has shown that the transplanted limbs can survive for a long time worldwide, there are still a lot of problems to be solved urgently.

23.9.1 Part 1: Tissue-Matching in Allograft

ABO blood type and Rh blood type are required to match in tissue-matching, but PRA, lymphocytotoxicity cross matching and HLA are not so clear at present. PRA test can estimate the degree of sensitization caused by HLA fluids and thus predict the possibility of hyper acute and accelerated acute rejection after transplantation. How much is PRA we believe that limb transplant can be safe? There has been no consensus concerning this problem. It is commonly believed that people who have a PRA level of above 40% should be treated differently. Before people with a high PRA level receive a limb transplantation, they must get special treatment (like plasma exchange and taking immunosuppressive drugs). In a lymphocytotoxicity cross matching test, the fewer lymphocytes die, the higher histocompatibility is. The dead cells are required to be fewer than 15% generally. If the number is higher than 15%, it is probable that hyperacute rejection may occur. If a donor and a recipient have a good match of HLA, the rejection will be mild after transplantation. At the same time, however, a good match of HLA may worsen the damage to the transplanted limb through HLA-restricted mechanisms, increasing the risk of graft-versus-host disease. In the first case of allograft who had 6 types (A, B, DR) mismatched in HLA, mild rejection of skin happened 8 weeks after transplantation, which was controlled after adjustment of drug concentration and application of immunosuppressive paste in certain part. With the use of effective immunosuppression, is strict match of HLA still a must for the survival of an allograft? If yes, what is the minimum requirement for HLA match? And what is the relationship between the level of HLA match and the concentration of immunosuppressive drug? Problems regarding the influence of HLA match on the survival time and functional recovery of a transplanted hand warrant further research.

23.9.2 Part 2: Determination and Implementation of an Optimal Plan for Immunosuppressive Medication

Combined application of immunosuppressive drugs is the key to a successful limb transplantation. The successful twenty cases of allograft were attributed to the most effective immunosuppression plan and combined application of the newest immunosuppressive drugs. However, what is the best plan? Is it still necessary to take adjuvant therapy? There are no definite answers to these questions. Our plan was to apply ATG, FK506, mycophenolic acid and prednisone. In addition, we applied fluocinolone acetonide to the transplanted hand the first day after operation. We believe a successful plan for drug use plays an important role in suppressing rejection to the greatest extent, avoiding drug toxicity, infection and malignant change.

According to the reports, skin grafting lacks tolerance. Skin has a complex immune system. The numerous dendritic cells in epidermis and dermis render the skin a strong immunogenicity. Marrow is the main source for allograft immune complement cells and the main target of immunological rejection. It is also the source for T cells of the donor. However, it can cause graft-versus-host disease in the recipient that has severe immunosuppression. Thus, we preserved the affected skin of the recipient and removed the marrow from the donor's ulna and radius as much as possible, so as to reduce immunogenicity of the transplanted hand. We also exposed one transplanted hand to radioactive rays, which showed little advantage but indicated that 8 gy X ray irradiation might not harm blood vessel endothelium of the transplanted hand or cause cramp of the blood vessels.

23.9.3 Part 3: Significance of Drug Concentration and Immunological Indicators Test

What are the best concentrations for the antirejection drugs? What are the generally accepted criteria for the rejection reaction? These questions concerning noninvasion and sensitivity still need further study. One of the major problems of composite tissue allograft is lack of a generally accepted standard for acute rejection. At present, we depend mainly on clinical observation, C-reactive protein and skin biopsy. Skin biopsy proves to be the most reliable indicator of the skin's rejection reaction. The deep tissues still have no reliable indicators. In the first case of hand allotransplatation, we still could not exclude the possibility that occult mild or partial rejection reaction might happen in the tissues other than the skin. Moreover, we imitated kidney transplant by monitoring natural killer cells [CD−/CD (16 + 56)+] and activated T cells [CD3+/CD (16 + 56)+, CD3+/HLA-DR+] with flow cytometry.

23.9.4 Part 4: Chronic Hypofunction or Afunction of the Transplant

What is the long-term therapeutic effect of the transplant? Even if acute and subacute rejection reaction does not happen, it is still unknown whether a long-term chronic hypofunction affects the survival and functions of the transplant or not. Long-term clinical observations should be conducted before a conclusion can be drawn.

At present, the main problems endanger long-term survival of the transplant are chronic hypofunction or afunction of the transplant. In addition to immunological factors, we now pay more and more attention to non-immunological factors.

1. Immunological factors:

   (1) acute and chronic immunological rejection, including cellular immunity and humoral immunity; (2) irrational plan for immunosuppressive drug use; (3) HLA match degree; (4) T cell costimulation signal system.

2. Non-immunological factors:

   (1) marginal organs; (2) donor with cerebral trauma/brain death; (3) ischemia/reperfusion and physical injury due to surgery; (4) cell aging; (5) virus infection, including hepatitis and CMV infection (6) damage caused by immunosuppressive drugs (chronic toxic reaction); (7) recurrence of the original disease; (8) new tumor. Some neopathy, like diabetes, high cholesterol, progressive renal hypofunction, high blood pressure and osteoporosis, have something to do with the long-term use of immunosuppressive drugs. What is more, it has been shown that long-term use of immunosuppressive drugs may also cause infection and occurrence of new malignant tumor, the major risk of death in the long term. Thus, we should implement an individualized treatment plan. In addition to immunosuppressive drug use, we should also take preventive measures against the above non-immunological factors.

23.9.5 Part 5: Critical Shortage of Limbs Available for Transplant

In the world, about 1/5 of the patients die because they cannot get organs for transplantation in time. Just like other organs, limbs for transplant are in critical shortage. This not only risks the life of the patients, but also hinders the technical development of organ transplantation. If we could not resolve the problem of shortage, we would still have trouble carrying out limb transplantation effectively even after some related problems are solved.

23.9.6 Part 6: Financial Problem

The expense of organ transplantation is high. This kind of operation is a luxury road which is made of gold. Only a few millionaires have access to this road while many others are blocked outside the door. High casts and narrow range of application decrease the value of organ transplantation. The operation fee is also unacceptably high. The patients losing a limb can still survive without risking their lives. But if they receive the transplantation, they will spend a large sum of money on immunosuppressive drugs in their whole life. This critical situation seriously hinders the development of allograft.

23.9.7 Part 7: Social Problems Concerning Allograft

23.9.7.1 Legislative Problems of Allograft

Organ transplantation brings a revolutionary change to the medical circles, but severe shortage of donor organs and lack of quality promise limit the clinical practice of organ transplantation. Moreover, legislative problems of organ transplantation are still unsolved. Thus, it is a very important task to settle down the legislation of allograft.

Limbs are organs that are not necessary for survival. The goal of allograft is to rebuild complete limbs, recover the function of limbs and improve the life quality, but the surgery still brings about the following disadvantages: the patient needs a long time, maybe a life-long, administration of immunosuppressive drugs which may cause graft-versus-host disease; immunological rejection against the transplanted hand may cause physiological and psychological damage to the recipient, increasing the chance of infection and tumor. It is acceptable in ethics to have the patient decide himself whether to receive the operation or not.

23.9.7.2 Ethical Problems of Allograft

The Problem of Allograft's Value

The essence of allograft's value is to the trade-off between its costs and benefits. Patients who lack a limb suffer not only from the psychological pain but also the physical dysfunction brought by a deficient limb. A limb with a good appearance performs multiple functions, like standing, walking, working, communicating, expressing feelings and maintaining physical and psychological health and dignity. These patients long for a limb rebuilt, but currently immature allograft is not a perfect resolution yet. Since specific immunosuppressive drugs targeted on transplanted tissues are not available yet, they have to take immunosuppressive drugs all their life, facing a risk of secondary infection and tumor. If a limb is essential to survival, undoubtedly the risk is worthwhile, but it is hard to make a choice when the organ is not necessary for survival (like a limb). The psychologically normal patients should be well informed of all the advantages and disadvantages of limb allograft and weight improved life quality against possible serious secondary complications. If they make a decision to have an allograft, we should ask them and their family to sign related legal documents.

All new technological achievements have two sides. Science has its innate rules. No ethical limitations will stop science, and people's ethical ideas will change with the development of science.

Moral Restraint and Ethics of Surgeons

Encouraged by the achievements in allograft and replantation, surgeons are eager to try out limb rebuilding or regenerating. We have succeeded in animals for a long time. In an international composite tissues transplantation symposium hosted in America in November, 1997, experts discussed about the moral ideas and feasibility of allograft and came to a conclusion: with the research development in immunological rejection and antirejection drugs, it was time to do clinical allograft research.

Since allograft has just entered into a phase of clinical research, it is beyond doubt that allograft operations will improve the proficiency of surgeons and increase the impact and popularity of hospital, but also brings critical ethic problems to the surgeons.

Allograft requires that surgeons should meet certain qualifications and finish some tasks as follows. They should (1) have worked on microsurgery for a long time; (2) have rich experience in microsurgery; (3) master transplantation immunology and related drug use; (4) consult pertinent literature before operation; (5) prepare for the operation carefully; (6) determine monitoring indexes and drug use in and after the operation; (7) be sure about the operation; (8) think about predications and measures after operation. After operation, patients must be hospitalized in a sterile laminar-flow ward. In short, it is a must to make enough preparations in technique, knowledge and hardware.

The first case of allograft was performed by a group of doctors from France, Australia, England and Italy, in France. The second case of allograft was performed by doctors from two hospitals. The third and fourth cases were performed by us in Nanfang Hospital in Guangzhou, an affiliated hospital to the former First Military Medical University, China. Many departments of this hospital made a joint effort to accomplish the two allografts, including Traumatic Orthopedics Department, Kidney Transplant Department, Blood Bank, Radiotherapy Department, Rehabilitation Department (psychology), Pathology Department, Clinical Laboratory and Pharmacological Department. Nanfang Hospital is known for a high level of kidney transplantation and rich experience in kidney transplant. It is the third Chinese hospital which broke the record of 1000 cases of kidney transplant. Kidney Transplant Department of this hospital provided guidance on the design and application of drug use in the whole course. The support and command of the leaders also contributed to the success of the operations. They mobilized the above departments many times before operation, encouraging them to work together to overcome difficulties. They also conducted and organized the operations. Moreover, they organized consultations after operation. It was them who guaranteed the smooth progress of the whole operations.

Surgeons must make sure that patients be well informed of the operation and be completely willing to receive the operation. After they are discharged from hospital, surgeons should keep a close contact with them, providing guidance and regular physical examinations and monitoring their drug use. Allograft has a high rate of survival, but can also cause some neopathy, mainly due to the strong immunosuppression. Infection is one of them. It is important to notice and treat infection as soon as possible because it directly influences the success of allograft. After operation, a long-term use of immunosuppressive drug and chronic actinic damage may lead to skin cancer. Surgeons should make an assessment of the risk factors of skin cancer a patient may have. The risky patients should be informed of preventive measures against skin cancer, like ultraviolet-proof, frequent self-check of skin and regular skin check. If skin cancer happens, patients should get an active treatment.

Doctors and patients live in different environments and have different moralities. If a disease does not respond to the current treatment, the patient may ask his doctor to try a new hopeful treatment, so as to improve quality of life or even save life. Out of the same reasons, a doctor may adopt a new treatment. However, at this time the doctor has to decide which is more responsible, carrying out or rejecting the new treatment, especially when this new treatment does not have any legal or mechanical grounds.

In short, the goal of allograft is to rebuild integral limbs, recover limb functions and improve quality of life. Its disadvantages are as follows: patients need to use immunosuppressive drug for a long time, probably causing graft-versus-host disease and increasing the risk of infection and tumor; immunological rejection against the transplanted hand may cause physiological and psychological damage to the recipient. It is acceptable in ethics to have the patient decide himself whether to receive the operation or not. It is noticeable that the present allograft is still immature and long-term effect is not guaranteed. Only when the patient is willing to receive the operation, surgeons are technically proficient, and legal documents are sufficient, can we carry out the operation carefully and observe the course strictly. Under no circumstance can we carry out the operation blindly.

24 Tissue Engineering and Orthopedic Microsurgery

Dan Jin, Su Fu, Tao Wu, Lei Wang, Yongtao Zhang, Song Liu, and Kuanhai Wei

24.1 Introduction

Dan Jin and Su Fu

Tissue engineering has developed rapidly since 1980s, with constant specialization and expanded scope. Now its unique advantages and technical improvements have been widely recognized and its social and economic benefits have attracted great attention from research institutes, commercial companies, and clinicians worldwide. Fundamentally, tissue engineering is to use bioactive substances cultured or constructed *in vitro* to reconstruct or repair organs and tissues. With biological and engineering techniques, embryonic or adult stem cells are used as seed cells for directional induction and formation of cell-scaffold composites before biologically functional tissues and even organs are constructed *in vivo* or *in vitro*, which can then be used for tissue repair and replacement. Thus far, achievements of tissue engineering research have been applied in various areas of clinical medicine. A variety of tissue-engineered constructs, like bone, cartilage, skin, and tendon, have been preliminarily tried in clinic, demonstrating promising prospects for clinical use. Three-dimensional tissue engineering has been intensively explored and widely applied in orthopedics. When tissue engineering is closely combined with common clinical orthopedic techniques, especially microsurgery, its feasibility, efficacy and applicability in clinical settings will be greatly enhanced.

Bone tissue engineering is closely associated with microsurgical techniques. To date, microsurgical techniques have been widely used in various aspects of bone tissue engineering for isolation and culture of seed cells to obtain pure functional cells, construction of human tissue-like extracellular matrix scaffolds under microscopy, microsurgical suture of implanted engineered tissue, and vascularization of engineered tissue. Moreover, these techniques can be used to address difficult problems encountered in vascularization, construction, and implantation in tissue engineering. Free-tissue grafting using microsurgical techniques (e.g., muscle flap implantation, fascial flap wrapping, periosteal flap wrapping, and vascular bundle implantation) improves the otherwise poor vascularization in bone defect repair with tissue-engineered bone. In addition, for isolation of cells (e.g., hair follicles, osteoblasts, and tenocytes) from the dermis, microsurgical techniques can effectively remove excess tissue to construct pure engineered tissue. It is foreseeable that an effective combination of orthopedic microsurgery and tissue engineering will diversify research in tissue engineering, and provide brand new strategies and effective technical procedures for clinical orthopedics.

24.2 Application of Microsurgical Techniques in Engineered Tissue Construction

Tao Wu and Dan Jin

When combined with microsurgical techniques, one cornerstone of surgery, tissue engineering has witnessed rapid development and increasing maturity. Microsurgical techniques are essential for the clinical applications of tissue engineering and the efficacy of engineered tissues and organs while tissue engineering techniques are expected to provide a new platform for the development of microsurgery. Microsurgical techniques have been applied in all aspects of engineered tissue construction (Fig. 24.1).

D. Jin (✉) · S. Fu · T. Wu · L. Wang · Y. Zhang · S. Liu · K. Wei (✉)
Department of Orthopedics, Nanfang Hospital, Southern Medical University, Guangzhou, Guangdong, China
e-mail: nfjindan@126.com; gzkhwei@163.com

G. Pei (ed.), *Microsurgical Orthopedics*, https://doi.org/10.1007/978-94-024-1625-1_24

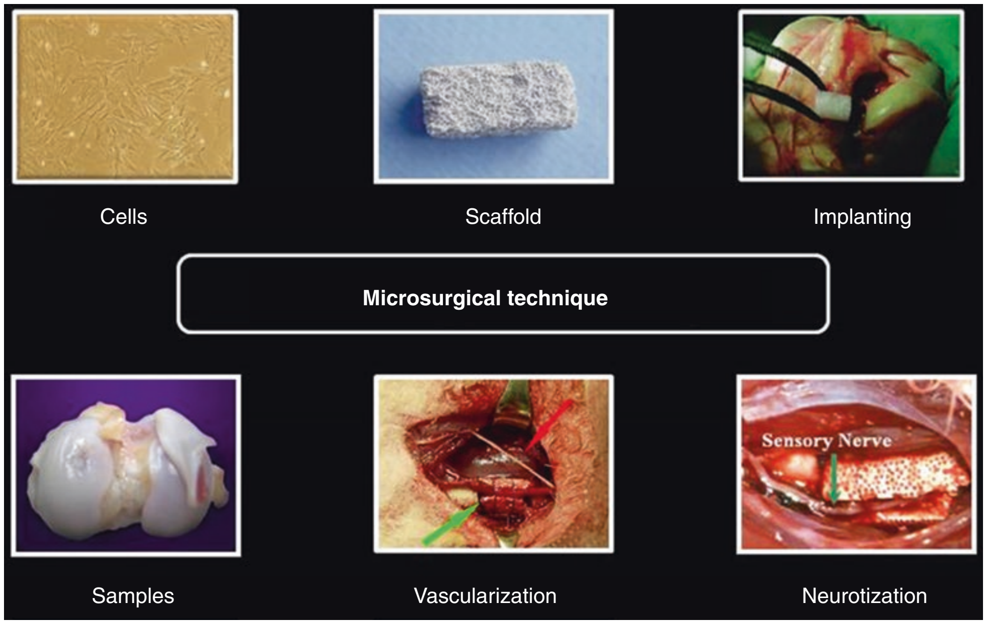


Fig. 24.1 Applications of orthopedic microsurgical techniques in tissue engineering

24.2.1 Application of Microsurgical Techniques in Tissue Engineering

24.2.1.1 Cell Isolation and Culture

One of the fundamental tasks of tissue engineering research is to select pure target cells by isolation and culture of seed cells. This task is a great challenge because the majority of human tissues are multicellular composites. Even in the case of articular cartilage composed of only chondrocytes, contamination by synoviocytes or other cells can occur during sampling. To reduce contamination by multicellular components, microsurgical techniques are often employed. Sampling is performed under a microscope to remove unnecessary tissue and to retain the tissue desired. For example, in isolation and culture of tenocytes, non-invasive microsurgical instruments are used to completely remove the epitendineum under a surgical magnifying glass or microscope to retain only the tendon so that contamination by fibroblasts from the peripheral tissue is minimized. Then, tenocytes are isolated by enzymatic digestion or explant culture. Another example is isolation and culture of periosteal osteoblasts, in which sampling is performed under a magnifying glass or surgical microscope to remove extraperiosteal tissue and subperiosteal bone tissue as much as possible. After nonfunctional cells are removed during culturing, the pure osteoblasts obtained are used to construct engineered tissues (Fig. 24.2).

24.2.1.2 Cell-Scaffold Combination

Another important task of tissue engineering research is to construct extracellular matrix scaffolds resembling human tissue that can be combined with seed cells and cultured *in vitro* to obtain living tissue-engineered constructs for implantation. Construction of scaffolds that simulate *in vivo* tissue must take into consideration important features such as structure, porosity, and pore size. Operation under magnification is necessary to weave and pre-construct a frame around normal human tissue, which is then examined microscopically to assess pore distribution and pore size. Additionally, when seeding cells, microscopic techniques help ensure accurate inoculation of seed cells into the scaffold, from planting method to quantification and timing of cell seeding. Moreover, during *in vitro* culture for cell-scaffold combinations, cell behaviors (adhesion, growth, expansion, migration and differentiation) on the surface and in the interior of the material, and structural changes of the material as well, must be assessed by regular microscopic observation (Fig. 24.3).

24.2.1.3 *In Vivo* Implantation

As small animals such as nude mice, mice and rats are often chosen for engineered tissue implantation, engineered tissues constructed *in vitro* are usually small. For implantation of small constructed tissue blocks into a small animal body, the implant and the tissue receptor site must be sutured under a microscope or magnifying glass. Microsurgical suture under a microscope is required for certain pre-constructed engineered tissues, such as blood vessels, tendons and nerves. This approach ensures accurate apposition between the implant and the recipient tissue, allowing the tissue-engineered implant to grow into the recipient tissue. Microsurgical suture is a very important step in tissue engineering research. Only when the suture quality achieved is as high as it is in autologous tissue grafting can reliable results be ensured. In engineered tissue construction, biodegradable polymer materials are often mixed with other materials to form composites of particular shape, such as polyglycolic

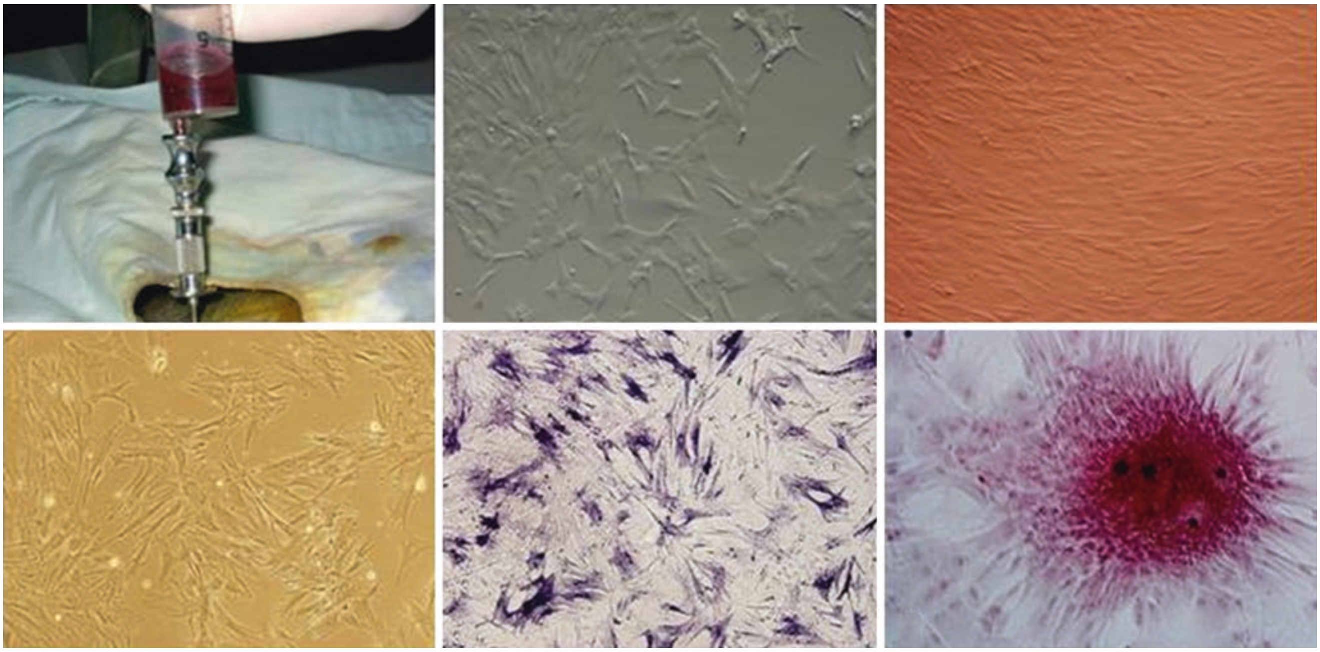


Fig. 24.2 Microsurgical techniques for isolation and culture of seed cells to be used in engineered tissue

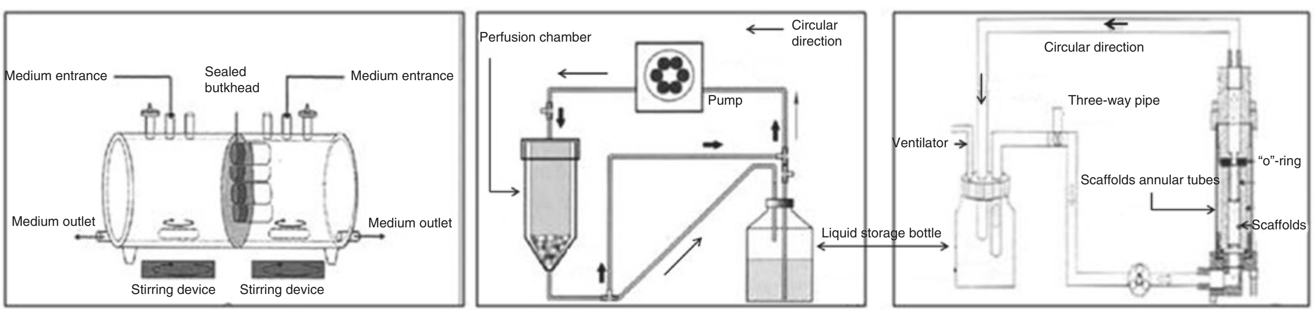


Fig. 24.3 Dual-cell agitation, oscillation and perfusion bioreactors

acid (PGA)-carbon fiber composites and collagen-PGA composites. These composites are often more rigid and less elastic than autologous tissues, resulting in greater difficulty in microsurgical suture during implantation. Conventional microsurgical suture techniques (e.g., 7-0 suture) cannot produce accurate end-to-end anastomosis in these cases. Thus, invagination suturing is commonly used to repair peripheral nerve defects, and relatively thick suture needles and lines (e.g., 3-0 to 5-0) or braided sutures are chosen to repair tendon defects (Fig. 24.4).

24.2.1.4 Engineered Tissue Sampling and Examination

After implantation *in vivo* for some time, regular sampling should be conducted for histological, morphological, and ultrastructural observations of the implanted engineered tissue to examine its metabolic changes, healing, and biomechanical properties. Because adhesion and healing after implantation may cause the tiny engineered tissue to get integrated with surrounding tissues, it is sometimes difficult to locate the implant and decide its proximal/distal ends. If absorbable sutures are used in surgery, identification to sample the grafted tissue will be more difficult. Incorrect sampling will affect accuracy of research results. It is very misleading if normal autologous tissue is harvested and mistaken for grafted tissue. Therefore, colored and nonabsorbable sutures are useful tools for demarcation of the proximal and distal ends of the implant. Additionally, microscopic identification of the acquired tissue is an essential step in accurate sampling of the implanted tissue.

24.2.1.5 Vascularization for Engineered Tissue

Engineered tissues constructed *in vitro* are cell-material composites with no inherent source of nutrition. After implantation *in vivo*, the small tissue can obtain nutrients through peripheral tissue fluid. Alternatively, vascular ingrowth

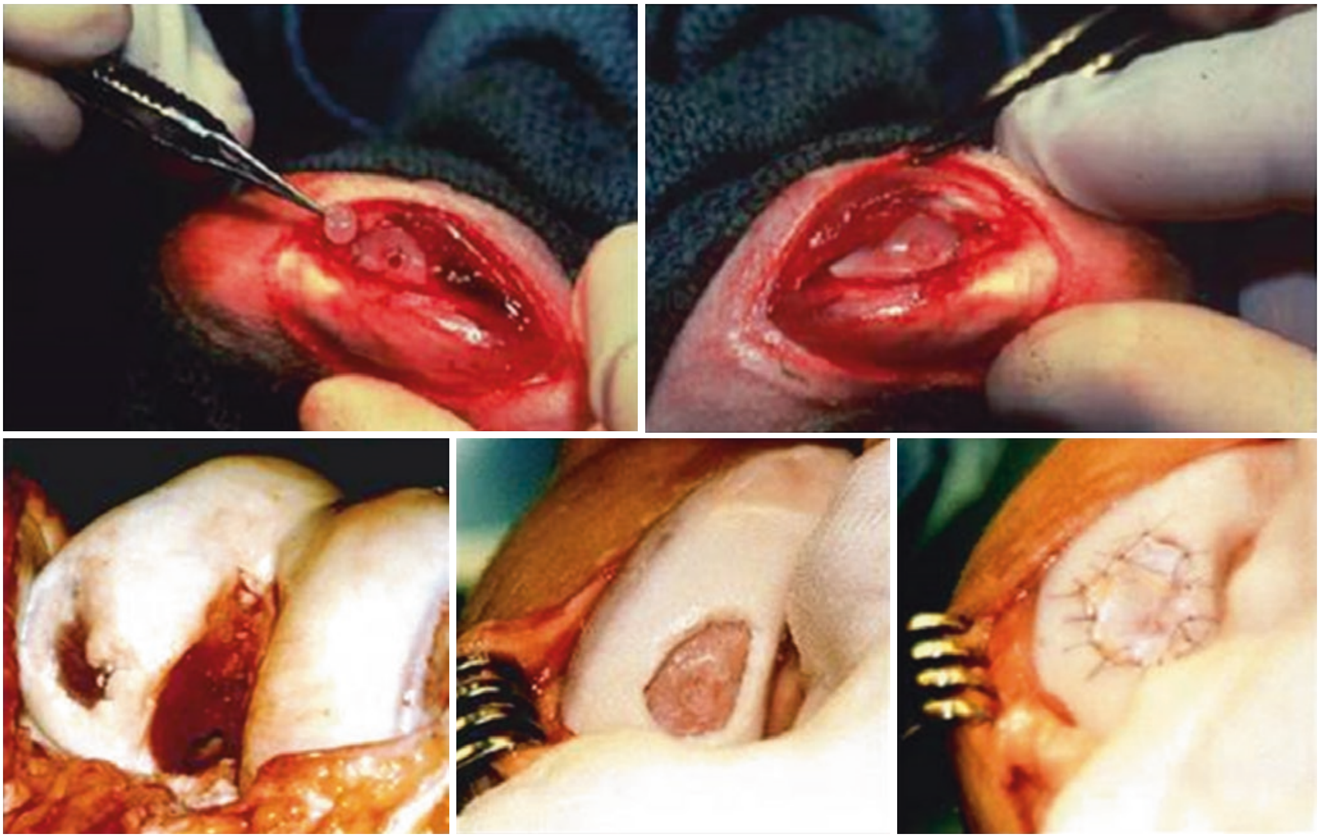


Fig. 24.4 Microsurgical techniques for engineered tissue implantation *in vivo*

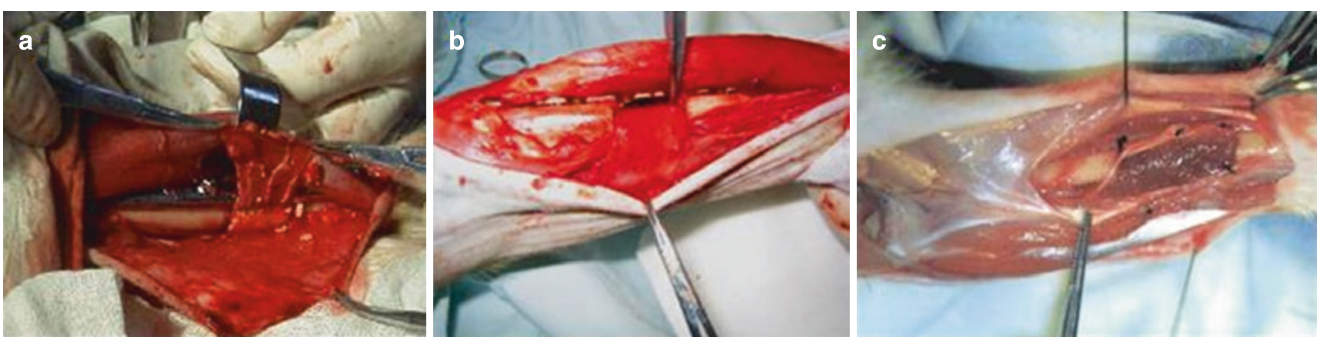


Fig. 24.5 Microsurgical techniques for vascularized engineered tissue construction: (**a**) fascial flap wrapping; (**b**) vascular bundle implantation; and (**c**) vascularized muscle flap wrapping

from the periphery enables the implanted tissue to gradually establish blood circulation with its peripheral tissue and thereby obtain nutrients. However, when large blocks of engineered tissue are constructed, vascular ingrowth from peripheral tissue is too slow, and it is difficult for blood vessels to penetrate deep layers of the tissue. Consequently, cells embedded in the material will die before new blood circulation is established. Studies indicate that only seed cells within 150–200 μm around blood vessels can survive via nutrient diffusion. Thus, rapid establishment of a microvascular network within the graft is vital to construction of ideal tissue-engineered composites. With mature microsurgical techniques which have been widely used in clinic (e.g., pedicled fascial flap packing, vascularized muscle flap, or vascular bundle implantation), it is possible to concurrently establish blood supply during construction of engineered tissues, thereby producing vascularized engineered tissues. Vascularization and microsurgical techniques for engineered tissue are important topics for tissue engineering research (Fig. 24.5).

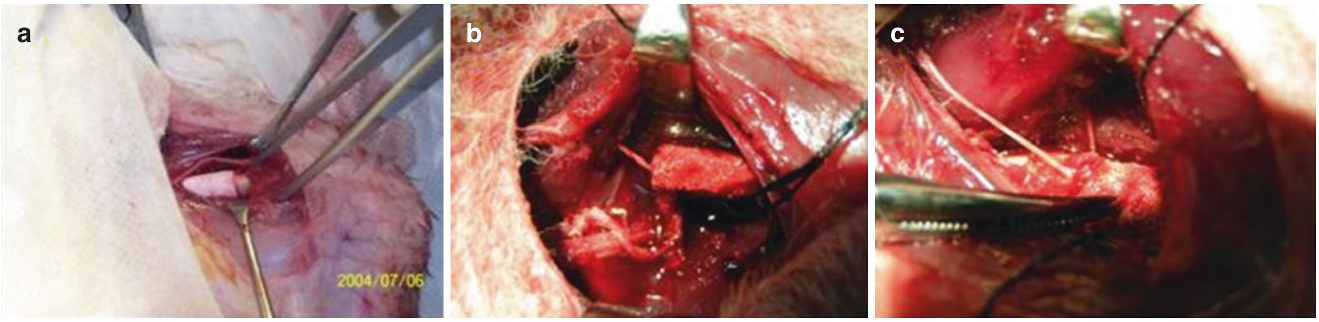


Fig. 24.6 Microsurgical techniques for construction of neuralized engineered tissue: (**a**) sensory nerve implantation; (**b**) motor nerve implantation; and (**c**) sensory + motor nerve implantation

24.2.1.6 Neuralization for Engineered Tissue

Microsurgical techniques and methods play an important role in construction and application of not only vascularized engineered tissues but also neuralized engineered tissues. For example, construction of tissue-engineered skeletal muscle not only requires adequate blood supply but also neuralization to implement proper function. Another example is construction of tissue-engineered bone, in which nerves are implanted to restore a positive role of sensory nerves in regulating bone repair. Thus, microsurgical techniques can be used to implant nerve fibers in construction of vascularized engineered tissues, thereby producing engineered tissues with morphology and function that approximate or even recapitulate those of normal tissues (Fig. 24.6).

24.2.2 Value of Microsurgery in Clinical Application of Engineered Tissues

In clinical repair of adjacent defects, engineered tissues only need *in situ* vascularization which can be done by transferring a fascial (or muscle) flap with vascular pedicle or by implanting a non-primary vascular bundle dissected from the recipient site. *In situ* vascularization can rapidly establish blood circulation and complete tissue repair in one surgery, demonstrating great prospects of application. However, surgeons are often confronted with such problems as poor condition of the soft tissue in the vicinity of a defect and unavailability of a fascial flap, muscle flap or vascular bundle. To tackle these difficulties, an alternative approach is ectopic construction of vascularized engineered tissue before secondary repair of defects through vascularized tissue grafting using microsurgical techniques. Casabona et al. combined bone marrow-derived mesenchymal stem cells cultured with hydroxyapatite and then implanted the composite into a prepared vascularized dorsal latissimus flap from a nude mouse. Their results revealed adequate bone tissue formation and blood supply in the implanted muscle flap 8 weeks later, indicating successful formation of a tissue-engineered vascularized osseous myocutaneous flap. This approach offers a potential to completely replace autologous bone graft with new tissue-engineered bone. Despite its shortcomings, this approach provides valuable experience and insights for *in vivo* implantation of engineered tissue. It represents a typical application of microsurgical techniques in construction and application of vascularized engineered tissues. Using an experimental model of rhesus monkey to construct ectopic vascularized tissue-engineered bone, Pei et al. implanted into the latissimus dorsi muscle a cell-material composite with a graft of thoracodorsal vascular bundle. Their success provides a new method for primary composite repair of bone defects associated with local defects of soft tissue or unhealthy soft tissue in clinic (Fig. 24.7).

24.3 Construction of Tissue-Engineered Skin

Su Fu and Dan Jin

24.3.1 Overview

Skin defects are common in clinic. They are primarily caused by acute (e.g., burn and surgical wound) and chronic injuries (e.g., bedsore and diabetic foot ulcer). Autologous skin grafting, which is widely used in clinical practice, is the gold standard for treatment of skin defects. However, when donor autologous skin is inadequate to cover a large area of skin defects, as in a patient with severe burns, autologous skin grafting will enlarge the patient's skin defects, jeopardize his or her epidermal barrier and immune function, and likely lead to concurrent bacterial infection that makes it even more difficult to achieve a satisfactory therapeutic effect. Since the concept of tissue engineering was proposed in 1987, its techniques have been widely used in a variety of organs. Tissue-engineered skin and cartilage were the first series of tissue engineering products approved by the US FDA. The skin

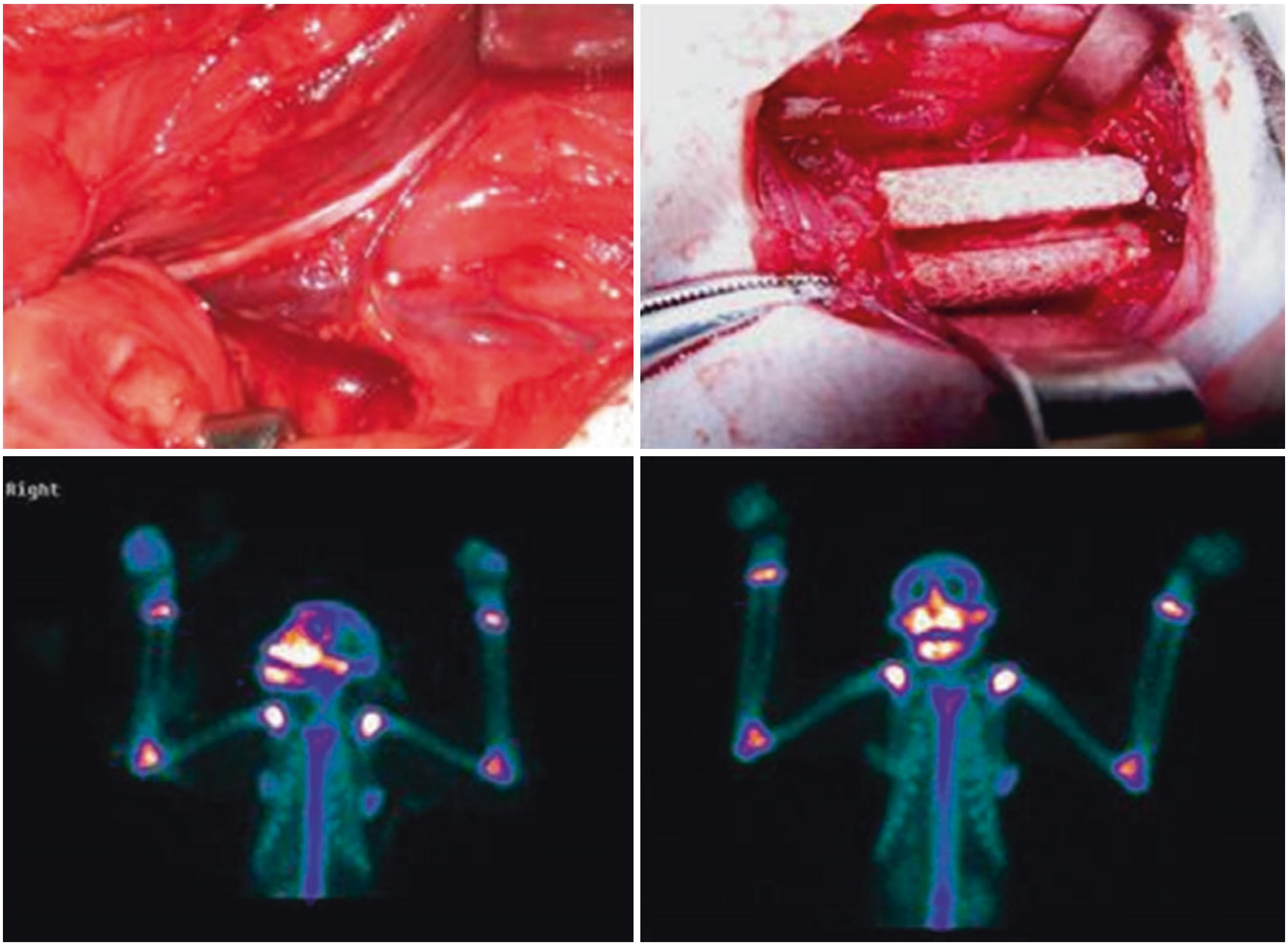


Fig. 24.7 Ectopic construction of vascularized tissue-engineered bone

products have the following advantages: (a) As skin substitutes they can be implanted and grown *in vivo*, reducing the need for donor tissue. (b) They rapidly cover a large area of acute wounds, reducing wound scarring and scar shrinkage. (c) They are loaded with exogenous growth factors to promote wound healing. Their advantages enhance their bright prospects of extensive application in clinic.

Human skin is composed of epidermis, dermis, and subcutaneous tissue, containing skin appendages, blood vessels, nerves, and lymph. The epidermis relies on epidermal basal cells, stem cells in the basal layer and hair follicles to maintain epidermal regeneration. There are also melanocytes and Langerhans cells in the epidermis. The dermis is composed of the papillary layer close to the epidermis and the underlying reticular layer. Fibroblasts in the dermal layer primarily secrete collagen and proteoglycan, which constitute the major extracellular matrix (ECM) of the dermis. Subcutaneous tissue is primarily composed of loose connective tissue and fat. Moreover, there are skin appendages, such as sweat gland, sebaceous gland and nail, and a large number of lymphocytes which have specific functions beyond forming the skin barrier.

Tissue-engineered skin is used to repair a variety of acute and chronic skin defects and to form nearly normal skin in the defective area. Therefore, three factors must be considered in construction of tissue-engineered skin: safety, efficacy, and convenience for use. Because grafted cells and ECM materials (e.g., bovine collagen) may harbor disease risks (bacterial or viral infections), source of grafted cells and biocompatibility of scaffolds should be considered to ensure safe construction of tissue-engineered skin. In order to play an effective role in repairing skin defects, tissue-engineered skin should physically resembles normal skin, fits the wound bed, and is free from host toxicity and immune rejection. Production processes and storage conditions of tissue-engineered skin should be simple. Yannas et al. proposed basic principles for artificial skin construction, covering physical chemistry, biochemistry, and mechanics.

Tissue-engineered skin is used not only to restore anatomic structure of the skin but also to reconstruct blood vessels and nerves. Microsurgical techniques boost clinical application prospects for tissue-engineered skin. In repair of skin defects, a skin flap or composite tissue flap with vascular pedicle or anastomotic blood vessels, which is constructed using microsurgical techniques, provides adequate blood supply to the defective area and results in primary closure of the wound. Microsurgical techniques are indispensable in construction and application of tissue-engineered skin—for seed cell preparation, cell-ECM combination, and small blood vessel/nerve anastomosis.

24.3.2 Strategy for Constructing Tissue-Engineered Skin

Construction of tissue-engineered skin involves three major components: seed cells, ECM scaffold, and cell active factor. Seed cells form the core of tissue-engineered skin. Current experimental studies are constantly improving selection of seed cells to make tissue-engineered skin resemble normal skin as much as possible. Proper selection of ECM scaffolds is also critical. A desired ECM scaffold has favorable biological stability and compatibility, does not cause any harm to cells, promotes cell growth, and will degrade *in vivo*. ECM scaffolds are primarily made of artificial copolymers. In a variety of ways, such as genetic modification, tissue-engineered skin is loaded with specific cell active factors to activate proliferation and differentiation of seed cells.

24.3.2.1 Seed Cells

Seed cells for tissue-engineered skin include mainly autologous cells and stem cells. Early studies chose simple autologous cells such as keratinocytes to construct tissue-engineered skin. In recent years, stem cells have become a good choice for tissue-engineered skin. The major types of seed cells for tissue-engineered skin include keratinocytes, fibroblasts, melanocytes, mesenchymal stem cells, adipose stem cells (ADSCs), and hair follicle stem cells (FSCs).

Autologous cells have disadvantages of substantially invasive harvest and limited proliferative capacity. In cases of massive skin defects, it is difficult to achieve skin regeneration through autologous skin harvest. Keratinocytes, accounting for 95–97% of the epidermal layer and readily available in superficial area, have been regarded as an important target for gene therapy. Since they are easy to grow and to be mixed into an epidermal cell suspension, And a good source for induced pluripotent stem cells as well, they are used in a large number of tissue-engineered skin products. Using retroviral recombination, Hamonen et al. and Erdag et al. transfected cell active factors, such as hepatocyte growth factor (HGF) and fibroblast growth factor (FGF), into keratinocytes to promote wound healing. Limat et al. used keratinocytes carrying autologous hair follicles in an epidermal substitute to treat ulcers. They observed that 70% of the defective epidermis was reconstructed and 32% of the ulcers was healed, an obvious curative effect 8 days after grafting. Fibroblasts secrete ECM proteins such as inflammatory cytokines, growth factors, and collagen proteins. When they are transfected with a variety of growth factors, fibroblast expression systems show promising application prospects. Zweers et al. observed that fibroblasts secreted tenascin-X and elastin after tissue-engineered skin was grafted to the wound surface. Taking advantage of the function of melanocytes in melanin secretion, Rehder et al. successfully constructed tissue-engineered skin similar to natural skin by seeding keratinocytes and melanocytes at a ratio of 40:1. Additionally, Sahota et al. reported that addition of epidermal microvascular endothelial cells in construction of tissue-engineered skin promoted angiogenesis in skin constructs.

Stem cells with potent capacities of proliferation and differentiation are ideal for tissue-engineered skin constructs. Theoretically, it is possible to use stem cells to construct full-thickness skin. Bone marrow mesenchymal stem cells (BMSCs) are capable of multi-directional differentiation into osteocytes, endotheliocytes, and neurocytes. They have a strong proliferative capacity and secrete a variety of growth factors. Perng et al. found that human BMSCs differentiated into epidermal cells when used to repair nude mouse skin defects. Badiavas and Falanga applied BMSCs to refractory wounds and achieved complete wound healing. However, acquisition of BMSCs requires extraction of bone marrow. Limited source and invasive extraction procedure have constrained wider use of BMSCs. ADSCs can be obtained by direct isolation from subcutaneous fat granules. Because of their rich source and less invasive isolation process, ADSCs exhibit great development prospects as seed cells for tissue-engineered skin. In 2001, Zhk et al. isolated ADSCs from lipoaspirate and demonstrated their capacity of multi-directional differentiation. Brzoska et al. observed that factors such as all-trans retinoic acid and dexamethasone induced directional differentiation of ADSCs into epidermal cells, as demonstrated by keratin 18 positive staining after induction. Thomas et al. sorted and purified ADSCs by flow cytometry and then injected the cells into skin defects of nude mouse, demonstrating transformation of ADSCs into epidermal cells *in vivo*. ADSCs have rich sources and can be easily acquired by extraction from adipose tissue and subsequent isolation and purification by collagenase digestion. Additionally, since ADSCs can secrete a variety of growth factors (e.g., VEGF and HGF) and facilitate secretion of collagen (types I and III) and fibronectin by fibroblasts, they promote wound healing. Potential FSCs that transdifferentiate into an epidermal cell phenotype in an early stage are precursors of epidermal stem cells. Because FSCs have a bi-directional differentiation potential to form either epidermis or hair follicles, like ADSCs, they also have great prospects for diverse applications. Stenn et al. have demonstrated that FSCs have a potential of multi-directional differentiation into different types of skin cells, such as epidermis, sebaceous glands, and hair follicles.

24.3.2.2 ECM

Components that constitute ECM of normal skin include collagen, connexin, fibrin, hyaluronic acid, and basement membrane. Tissue engineering scaffolds artificially simulate the ECM which provides space for cell proliferation and growth and maintains ambient temperature for cellular growth. Currently, ECM is made chiefly of synthetic biodegradable materials and natural materials. Because synthetic materials are difficult to produce and incapable of ideal cell loading, bio-derived materials (e.g., collagen and chitosan) are more commonly used in tissue engineering scaffolds.

As collagen is the most abundant protein in the body, it has been extensively used as a scaffold to load cells. Because collagen is susceptible to degradation, it is often used in conjunction with other materials to construct scaffolds. Apligraf is a relatively mature collagen gel scaffold, a tissue-engineered skin product. Chin et al. prepared a collagen-based scaffold by microfabrication that retains the fibrous structure of natural collagen and allows for relatively fast cell migration within the pores to provide a favorable environment for tissue growth. Powell et al. prepared a porous collagen scaffold by electrospinning, which is more conducive to cell and tissue growth than scaffolds prepared by freeze-drying and effective in reduction of wound contraction.

Since chitosan plays a role in activating macrophages, inducing expression of immune regulators and promoting cell adhesion, it is a favorable material for tissue engineering scaffold. Lim et al. prepared a bilayer chitosan skin scaffold which demonstrated good compatibility with cells with the pore size ranging from 50 to 100 μm and into which fibroblasts penetrated after 14 days of culture. Alginate, a natural polysaccharide extracted from brown algae, has good biocompatibility and immunogenicity. Hydrogel-based skin scaffolds are most commonly prepared using alginate. Porous calcium alginate-based scaffolds prepared by freeze-drying have an open porous structure that is suitable for cell growth.

A current research focus in the field of tissue-engineered skin materials is construction of composite scaffolds using particular methods to crosslink a variety of natural materials, like collagen/chitosan and alginate/chitosan ECM scaffolds. Collagen/chitosan scaffolds have been confirmed experimentally to have good biocompatibility, no cytotoxicity, and cell-proliferation-promoting activity. However, it takes a relatively long time for a collagen/chitosan scaffold to degrade *in vivo*. Ma et al. found that after crosslinking with glutaraldehyde, a porous collagen/chitosan scaffold exhibited enhanced biostability and promoted fibroblast adhesion and proliferation. In alginate/chitosan composite, alginate and chitosan form a polyelectrolyte by electrostatic complexation. Joeng et al. and Wang et al. prepared alginate/chitosan composites by "electrospinning" or "hydrospinning", both of which demonstrated good biocompatibility.

24.3.2.3 Epidermal Substitute Construction

In 1975, Rheinwald and Green prepared the first epidermal cell patch by epidermal cell culture and expansion and used in repair of deep burn wounds. It was constructed from a skin specimen (2–5 cm^2) which was taken from the patient admitted to the hospital and from which epidermal cells were isolated for culture and expansion *in vitro*. A study by Carsin indicates that keratinocyte culture and grafting for burns can improve the survival rate of patients. However, use of autologous epidermal grafting is controversial because of its shortcomings, such as time-consuming procedure, fragility of the cell patch, and high susceptibility to infections. Commercial epidermal substitutes are already available, like Epicel, EPIBASE, Laserskin, and Myskin.

Epicel and EPIBASE consist of autologous keratinocytes that can grow and fuse to form an epidermal cell patch within 15 days. These products have been used to successfully save lives of patients with extensive burns, but they are fabricated by conventional methods so that their usage is time-consuming and difficult.

Laserskin is constructed by culturing autologous keratinocytes on a microporous membrane of hyaluronic acid so that the keratinocytes can migrate to the wound surface. Hyaluronic acid can promote cell proliferation, cell migration and angiogenesis. Laserskin has advantages of a high successful grafting rate, good biocompatibility, and a low infection rate.

MySkin consists of a coated silicone-based scaffold that is loaded with autologous keratinocytes. This product is easy to use and its cell culture only requires a short time. MySkin is reported to be useful in the treatment of pressure ulcers, diabetic foot ulcers and burns. It can be used in conjunction with a mesh graft to repair full-thickness skin wounds.

24.3.2.4 Dermal Substitute Construction

Most dermal substitutes load cells into either natural dermis, as with alloskin (xenoskin), or synthetic dermis, such as hyaluronic acid. A variety of commercial dermal substitutes are available, including Integra, Dermagraft, and Alloderm.

Integra is an ECM containing collagen and chondroitin-6-sulfate without live cells, thus representing a permanent dermal substitute of xenogeneic origin. Its structural constituents are glutaraldehyde-crosslinked bovine type I collagen and chondroitin-6-sulfate with glucosamine, which are combined on a silicone membrane. Integra can induce host fibroblast ingrowth and promote angiogenesis. Its surface composition prevents water evaporation and bacterial infection. 15–20 days after it is used to cover the wound surface, the silicone membrane and mesh skin graft are detached. Advantages of Integra include a long shelf life, easy operation, reduced immune reaction, low risk of infection, and limited scar contracture. Integra has been widely used in the treatment of large-area burns and scar hyperplasia.

Dermagraft is constructed by culturing neonatal fibroblasts in an absorbable polylactic acid fiber network. The scaffold will degrade in 20–30 days while fibroblasts proliferate within the scaffold and secrete ECM components (e.g., collagen and mucopolysaccharides) to reconstruct the structure of the dermis. Dermagraft is similar to the dermis in structure and composition. It can be used for the treatment of chronic venous ulcers, diabetic foot ulcers, and burns.

AlloDerm is a human acellular dermal matrix that retains the epidermis. Because AlloDerm contains no live cells, it is easy to be applied to a wound without causing rejection. Basement membrane enables keratinocytes to migrate to the scaffold. AlloDerm can be used in conjunction with a razor-thin graft to repair burn wounds. Advantages of AlloDerm include good function and aesthetics of the skin repaired, but safety and ethical issues exist.

Biobrane is a bilayer membrane-like product. The outer layer is a silicone membrane and the inner layer is a nylon fiber mesh containing porcine collagen. The unique structure of Biobrane makes it possible to reduce dressing changes, mitigate pain and promote healing. This product is suitable for pediatric patients with superficial burns.

24.3.2.5 Composite Skin Construction

To construct composite skin, epidermal cells are usually seeded at the surface of dermal scaffolds to simulate anatomic structure of the epidermis and dermis of normal skin. Composite skin can be mass production products which are the most sophisticated and expensive compared with other skin substitutes. Currently, the structure of real skin cannot be fully simulated in commonly used composite skin substitutes which only consist of fibroblasts and keratinocytes. Since a few products use allogeneic seed cells that survive *in vivo* a limited period of time, they only serve as temporary skin substitutes. Common commercial composite skin products include Apligraf, OrCell, and PolyActive.

Apligraf is constructed by combining neonatal fibroblasts with bovine type I collagen for remodeling, and neonatal epidermal keratinocytes are then seeded on its surface. Thus, Apligraf is histologically similar to normal skin, and can secrete growth factors. It has a good therapeutic effect in clinical use. Waymack et al. applied Alpigraf in conjunction with an autologous mesh graft to gain better appearance and functionality. However, because Apligraf consists of allogeneic cells with a short *in vivo* survival time, it can only serve as a temporary skin substitute. Moreover, this product has disadvantages of short shelf life, high price, and a risk of disease spread.

OrCell is constructed by seeding fetal keratinocytes and fibroblasts cultured *in vivo* in the upper and lower levels, respectively, of a double-layered bovine type I collagen matrix. Keratinocytes are seeded in the upper layer of a non-porous collagen gel coating, and fibroblasts are seeded in the lower layer of a porous collagen sponge. This product can reduce scar contracture and facilitate wound healing, but it is also a temporary skin substitute.

In PolyActive, autologous keratinocytes and fibroblasts are loaded onto a bilayer skin substitute of ECM which is composed of polyoxyethylene esters and rigid poly (butylene terephthalate) to prevent substitute contraction. Since this product consists of autologous seed cells loaded on non-biodegradable biomaterials, it cannot be used as a permanent skin substitute.

TissueTech is an autologous grafting system that combines the dermal substitute Hyalograft 3D and the epidermal substitute Laserskin. As this product consists of autologous keratinocytes and fibroblasts, it can serve as a permanent skin substitute. When used to treat diabetic foot ulcers, TissueTech achieves a wound closure rate of 70.3% with a recurrence rate of 8.2%.

24.3.3 Application of Tissue-Engineered Skin

Tissue-engineered skin can be widely used for a variety of acute wounds, chronic wounds, and skin diseases, but its use has strict indications. Lacking immune function and skin appendages, tissue-engineered skin does not reproduce full functionality of the skin to achieve real skin reconstruction. A key to success in reconstruction of tissue-engineered skin is to ensure survival of grafted cells and to maximally maintain their functionality. A number of tissue-engineered skin products have been available in market, such as Apligraf, Dermagraft and Integra.

24.3.3.1 Extensive Full-Thickness Burns

Tissue-engineered skin is a new option for patients with extensive full-thickness burns. Full-thickness burns can lead to a complete loss of skin repair capacity. Burn mortality primarily depends on depth and extent of the burn and age of the patient. Conventional autologous skin grafting is the gold standard treatment for full-thickness burns, and combined mesh skin grafting allows it to maximally cover the wound. In some cases of extensive burns, however, it remains difficult for the donor sites to meet clinical needs. Tissue-engineered skin has been used to treat extensive burns for more than three decades. Its application achieves good results, and its efficacy is verified by numerous animal experiments. There is experimental evidence that efficacy of tissue-engineered skin in restoring the skin barrier is equivalent to that of razor-thin grafting.

A large number of clinical trials demonstrate that tissue-engineered skin is safe and effective. It can reduce the extent and thickness of donor skin, which is conducive to healing of a donor site. Tissue-engineered skin can be used in early wound cover and scar revision. Wisser et al. reported that

Integra was used to immediately cover 63% of the wound in a patient with a 76% burned area. Four weeks later, the patient underwent epidermal grafting. One-year follow-up data revealed good functionality and appearance of the skin. Hunt et al. reported five cases in which Integra was used as a temporary skin substitute to treat post-burn hypertrophic scars and anterior cervical contracture with satisfactory postoperative functional recovery. A multi-center randomized controlled trial by Waymack et al. showed that compared with mesh razor-thin skin grafting, tissue-engineered skin grafting (Apligraf) among 38 patients resulted in better repair appearance in 22 cases (58%), normal pigmentation in 17 cases (45%), and a normal degree of vascularization in 18 cases (47%). Additionally, compared with the control group, the tissue-engineered skin grafting group exhibited improved skin toughness, graft height, and Vancouver Scar Scale score. However, advantages of tissue-engineered skin need to be verified by additional randomized controlled clinical trials.

24.3.3.2 Chronic Ulcers

It is somewhat difficult to cure chronic ulcers, but tissue-engineered skin has been reported to be effective. With the increasing aging of modern population, most pharmaceutics companies are dedicated to research and development of tissue-engineered skin products for chronic skin ulcers. Since condition of a wound bed is essential for healing of chronic ulcers, a stable local wound microenvironment and ECM in tissue-engineered skin will reduce inflammation and increase nerve vascularization to promote wound healing. Tissue-engineered skin can be used in chronic ulcers of different causes, including venous ulcers, pressure ulcers, and diabetic foot ulcers. Commercial tissue-engineered skin (e.g., Apligraf) has been approved by the US FDA for treatment of venous ulcers and diabetic foot ulcers.

Tissue-engineered skin has a better therapeutic effect than conventional methods on venous ulcers, commonly as lower extremity ulcers. In a prospective randomized controlled trial involving 120 patients with chronic ulcer, Apligraf combined with compression therapy realized a significantly higher rate of complete wound healing (47%) than simple compression therapy (19%). Additionally, Falanga et al. reported a multicenter randomized controlled trial involving 293 patients in whom the Apligraf group had a higher rate of complete wound healing and shorter mean healing time than the control group (63% vs. 49%; 61 vs. 181 days). Moreover, Schonfeld et al. reported use of Apligraf in refractory ulcer patients incurred health care costs of $20,041 per year, significantly less than conventional therapy ($27,493).

Several trials have indicated that tissue-engineered skin promotes wound healing in diabetic ulcer treatment. In a large-scale prospective randomized controlled trial among 254 patients with chronic diabetic foot ulcers, wound healing by tissue-engineered skin (Dermagraft) treatment was 1.6–1.7-fold faster than by conventional treatment. Brem et al. reported that among the 23 bedsore patients who received tissue-engineered skin (Apligraf) treatment, 13 achieved wound healing over an average period of 29 days.

24.3.3.3 Skin Diseases

Tissue-engineered skin can be used to treat a variety of mucocutaneous diseases. Meggan et al. reported use of Apligraf for treatment of actinic purpura (AP) achieved satisfactory results after surgery by grafting tissue-engineered skin after removal of AP-affected areas. Andreassi et al. who treated 11 vitiligo patients with tissue-engineered skin observed satisfactory follow-up results (skin color almost fully recovered in 6 patients). de Imus G et al. presented a case report of a 26-year-old patient with pyoderma gangrenosum whose leg ulcers was treated by Apligraf. The treatment achieved 30–40% wound healing at 2 weeks and complete healing at 6 weeks. Because the pathogenesis of pyoderma gangrenosum is currently unknown, traditional therapies are primarily based on corticosteroids and immunosuppressive agents, whereas tissue-engineered skin is undoubtedly a new treatment option.

24.3.3.4 Laboratory Applications

In addition to clinical applications, tissue-engineered skin is extensively used in experimental studies. Skin test models built with tissue-engineered skin have multiple advantages in use. (a) They reduce the need for experimental animals. (b) They can be used to study the physiological characteristics of skin, such as the mechanisms of interactions between cell-cell and cell-ECM, skin barrier function, wound healing, angiogenesis, and pigmentation modes. (c) They can be used to study skin diseases such as vitiligo and melanoma. Unlike a conventional planar cell experimental setup, tissue-engineered skin is three-dimensional and can be combined with various skin cells, thus providing a good research model for experimental study.

24.3.4 Prospects of Microsurgical Techniques in Tissue-Engineered Skin Construction

With increasing technical maturity and accelerated commercialization, more and more tissue-engineered skin is used clinically, but it has not replaced human skin. There is still distinction between tissue-engineered skin and normal skin in physical properties. Tissue-engineered skin lacks specific components such as skin appendages. More experimental studies are needed to address selection of seed cells, methods of rapid vascularization and efficacy and safety of clinical treatment.

Repair of skin defects and wounds with tissue-engineered skin is a reconstructive process involving different tissue components such as blood vessels and nerves. Vascularized pedicled flaps constructed via microsurgical techniques are well-suited for large-area skin defects on the extremities, especially those associated with other tissue injuries to bone, tendon, or nerves. Numerous difficult problems need to be resolved in construction of tissue-engineered skin, such as those related to seed cell isolation, cell-ECM scaffold combination, and vascularization. Microsurgical techniques provide a potential avenue to address the above problems.

Microsurgical techniques can be used to remove nonfunctional cells and obtain pure seed cells for construction of tissue-engineered skin. For example, mechanical pulling is traditionally used to obtain hair follicles of the skin, but the tissue thus obtained often consists of incomplete follicles because of their deep location in the dermis. If microdissection is used to isolate hair follicles and papillae from the dermal layer, the intact hair follicles obtained are suitable for culture *in vitro*. By microdissection, Philpott et al. obtained a large number of intact individual hair follicles. Their protocol is as follows: a slicing knife is used to separate the dermis from subcutaneous fat to expose intact hair bulbs after removing fat. Next, a pair of microsurgical forceps is used to grip the outer root sheath of the hair follicle under a microscope before an intact hair follicle is extracted from the subcutaneous fat along the direction of the hair follicle. Following the above procedure, one can isolate more than 100 intact hair follicles from approximately 4 cm × 2 cm of scalp in 1–2 h. The number of hair follicles obtained by microsurgical methods is limited because skills and endurance of an operator are limited and hair follicles are vulnerable.

Microsurgical techniques allow for accurate use of tissue-engineered skin. When cultured *in vitro*, tissue-engineered skin needs to be examined microscopically to assess growth and distribution of cell components (e.g., keratinocytes and fibroblasts) on the surface and in the interior of a scaffold before cell type and quantity can be adjusted. For seeding cells, microscopic techniques help accurate inoculation of seed cells within a scaffold, such as in the case of using tissue-engineered skin for skin diseases. During implantation of cell-ECM scaffold composites into the skin, structure of artificial skin can be examined by microscopy to probe the integrity of local skin structures (e.g., epidermis, dermis, and skin appendages), to remove tissue-engineered skin in poor conditions (e.g., defective skin structure, missing epidermal or dermal layers, scanty seed cells such as keratinocytes, and scanty fibroblasts in the dermal layer), and to select appropriate skin for implantation. Microsurgical techniques also can be used to reconstruct a nerve vascular network which provides adequate blood supply to tissue-engineered skin if some damage to small blood vessels and small nerves in the skin may very probably exist after implantation.

24.4 Construction of Tissue-Engineered Bone

Lei Wang, Dan Jin, and Tao Wu

24.4.1 Overview

Bone tissue is capable of repairing and rebuilding fractures through its unique self-regulatory mechanisms. However, the self-regulatory mechanisms can no longer meet the requirements of bone repair when blood supply has been completely destroyed by severe traumatic nonunion or tumor resection or when massive bone defects have occurred. For fractures that cannot be repaired through self-regulatory mechanisms, clinical treatment mostly use autogenous or allogeneic bone grafting. Autogenous bone grafting has a few shortcomings, like repair of trauma with additional trauma and insufficient donor source. Allogeneic bone grafting has disadvantages of high cost, poor osteogenesis, easy absorption, severe immune rejection and potential of spreading serious diseases. The shortcomings of autogenous and allogeneic bone grafting have hindered their wide application in repair of large segmental bone defects.

Constant advances of bone tissue engineering research are overcoming the disadvantages of autogenous or allogeneic bone grafting, providing a new hopeful option to treatment of massive bone defects. Bone tissue engineering primarily focuses on seed cells, scaffolds and microenvironments to develop new treatment methods by combining bioengineering and clinical medicine. Classic construction of tissue-engineered bone primarily involves inducing differentiation of stem cells into osteoblast-like seed cells which are then combined with a scaffold of good biocompatibility. The composite is used to promote repair of bone defects in an *in vitro* or *in vivo* environment. In recent years, engineering techniques for bone tissue construction have become increasingly mature. A goal has been proposed to construct bioactive tissue-engineered bone that is more in line with normal physiology. Some research achievements have been used in clinical practice, and good therapeutic effects have been achieved in repair of partial bone defects in the ribs, tibia, fibula, and mandible. These research endeavors encourage development of tissue-engineered bone. Diversifying and interdisciplinary techniques of bone tissue engineering have been explored. Fundamentally, however, construction of tissue-engineered bone still focuses on two major elements—seed cells and scaffolds—which are introduced in the following section.

24.4.1.1 Seed Cells

Pluripotent cells in fat, bone marrow, umbilical cord blood, and embryonic tissues are rich sources of seed cells for construction of tissue-engineered bone. Induction *in vitro* can differentiate these cells into osteoblast-like and angioblast-like seed cells which are an important source for tissue-engineered bone. Seed cells obtained from the above sources have limitations, particularly limited number of cells, prolonged time needed for *in vitro* expansion and induced differentiation before treatment, and unavailability of certain sources due to ethical restrictions. However, a new technique of stem cell synthesis has been developed recently that overcomes these limitations. It enables ordinary human skin cells to gain the functionality of stem cells via gene transfer. The synthetic stem cells are called induced pluripotent stem cells (iPSCs). Since this new technique will significantly expand sources of seed cells for tissue engineering research and avoid ethical problems, iPSCs have demonstrated great research and application prospects, though a few problems associated with iPSCs remain to be addressed. For example, how can directionally induced differentiation of iPSCs into target cells be ensured? How can their stability be maintained while preventing carcinogenicity? At present, iPSCs are still used primarily in experimental research. A number of questions must be resolved before their clinical applications become conventional. Generally speaking, whatever type of stem cells should meet the following requirements before they can be selected as seed cells to construct tissue-engineered bone. (a) The tissue from which they are cultured and expanded should be obtained non-invasively or via minimally invasive surgery. (b) They should have strong division and proliferation capacity. (c) They should have osteogenic differentiation capacity. (d) They should elicit no or very little immune rejection and do not affect new bone formation. (f) They should be amenable to passaging and exhibit no alterations in their morphology, function, or genetic information.

24.4.1.2 Scaffolds

Scaffolds, another important element of tissue-engineered bone, have witnessed rapid development. They have used polymer, inorganic and composite materials. The polymer materials are represented by polylactic and polyglycolic acids, and the inorganic materials include tricalcium phosphate (TCP), hydroxyapatite and bioactive glass ceramics. In recent years, development of three-dimensional (3D) printing technology makes it possible to produce more uniform, sophisticated, and controllable biological scaffolds. With a mixed system of hydrogels and cells as printing materials, one study prepared tumor tissue with stereoscopic spatial structure within which the cell viability reached 90%. This technology makes it possible to construct tissue-engineered bone with 3D stereoscopic structure. Moreover, application and development of nanotechnology offer another possibility to produce more sophisticated and controllable biological scaffolds. Nanoscale scaffolds have facilitated construction of tissue-engineered bone. Numerous studies demonstrate that compared to conventional ones, nanoscale biological scaffolds have improved osteogenic effects. Scaffold materials used for tissue-engineered bone should have following characteristics: (a) sufficient mechanical strength, (b) good biocompatibility, (c) biodegradability and ability to be metabolized and (d) osteoinductive or osteoconductive activity.

In addition to acquisition of seed cells and design of scaffolds, other issues should be addressed in construction of tissue-engineered bone. Bioactivity of engineered bone tissue is thought to be an important key to successful construction of tissue-engineered bone, and sufficient blood supply is an important indicator of bioactivity. It is found that seed cells can survive through nutrient diffusion within only 150–200 μm around blood vessels. Promoting vascularization within a graft and rapidly establishing a microvascular network are critical steps in construction of ideal tissue-engineered composites. Therefore, it is necessary to conduct researches into construction of vascularized tissue-engineered bone. Microsurgical techniques provide a good means for such researches, like (a) tissue flap wrapping, (b) arteriovenous (AV) bundle implantation, (c) AV loop implantation and (d) nerve bundle implantation.

24.4.2 Application of Microsurgery in Construction of Tissue-Engineered Bone

24.4.2.1 Tissue Flap Wrapping

In tissue flap wrapping, after a tissue flap with rich blood supply, like a fascial, muscle or bone flap, is isolated and prepared by microsurgical techniques, it is used to wrap tissue-engineered bone. The flap is expected to resupply blood to the tissue-engineered bone through the vascular network in the tissue flap, eventually resulting in vascularized tissue-engineered bone. In the field of microsurgery, the most basic and crucial element with regard to survival and functional reconstruction of a graft is revascularization of the graft. This concept is consistent with that for construction of tissue-engineered bone. The tissue flap wrapping technique is actually to use a tissue flap wrapping a cell-biological scaffold composite to ensure vascularized and ossified construction. Several common techniques for tissue flap wrapping are introduced below while specific skills to construct tissue flaps refers to corresponding chapters of this book.

Fascial Flap

A fascial flap with a vascular pedicle contains a rich capillary network of blood vessels and has good permeability, allowing nutrients in the blood and body fluid to penetrate the graft. The nutrients feed osteoblast regeneration and contribute to construction of vascularized tissue-engineered bone. A research team led by Guoxian Pei first reported use

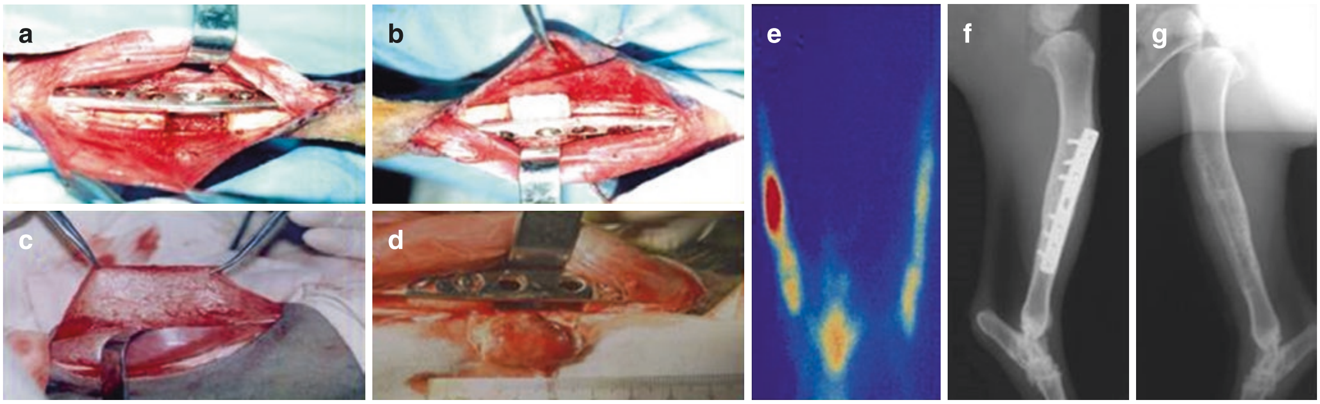


Fig. 24.8 Fascial flap wrapping of tissue-engineered bone (**a**) goat tibial defect model; (**b**) tissue-engineered bone implantation *in vivo*; (**c**) fascial flap dissection; (**d**) wrapping with fascial flap; (**e**) ECT image taken 8 weeks after surgery; and (**f**, **g**) X-ray scans before and after removal of internal fixation material 3 years after surgery

of fascial flap wrapping to construct tissue-engineered bone. Their fascial flap wrapping improved vascularization in goat bone defects and achieved complete repair 12 weeks after surgery. Their success could be attributed to the fascial flap containing a rich vascular network which played a role in inducing tissue vascularization. To clarify its role in bone defect repair in primates, Pei and coworkers combined fascial flap wrapping with bone tissue engineering to repair bone defects in a rhesus monkey model. A comparative analysis showed that the osteogenic effect was significantly better in the fascial flap wrapping group where a large number of new large-diameter vessels formed at the bone defect site 12 weeks after surgery than that in the non-fascial flap wrapping group. Ma et al. implanted a spherical β_2-TCP scaffold into the waist back muscle-fascial bag in rabbits without adding vascular endothelial cells or proangiogenic growth factors. After surgery, tiny newborn blood vessels were observed at the periphery of the scaffold at 2 weeks, and the first peak of vascularization occurred at 4 weeks. The second peak of vascularization occurred 12 weeks after surgery with formation of thick mature blood vessels. At 12 weeks after surgery, diameters of the blood vessels increased compared with those at other time points. These results indicate that the TCP scaffold wrapped with a fascial flap exhibits an obvious proangiogenic effect. Liu et al. built a beagle bone-periosteum defect model with a middle portion of the tibia. In the experimental group, a bone marrow mesenchymal stem cell (BMSC) + polycaprolactone composite wrapped in fascia was implanted into the left foot; in the control group, a BMSC + polycaprolactone composite was implanted into the right foot. The results showed that the process and speed of osteogenesis were appreciably better in the experimental group than in the control group. At 12 weeks after surgery, bone defects were completely repaired in the experimental group which was associated with massive cancellous bone formation, a relatively patent new marrow cavity, and firm continuous cortical bone. The new vessels were significantly better than those in the control group in terms of quantity, diameter, and distribution. These research achievements have provided a potential for future clinical application of tissue-engineered bone techniques (Figs. 24.8 and 24.9).

Muscle Flap

Bone flaps with attached muscle have been extensively used to repair bone defects. Inspired researchers have introduced this technique into tissue-engineered bone vascularization. An extensively used example is the latissimus dorsi muscle flap. Casabona et al. implanted a porous hydroxyapatite scaffold loaded with human BMSCs into a latissimus dorsi muscle flap in nude mice and obtained a tissue-engineered bone with a rich capillary network. Terheyden et al. implanted allogeneic bone as a scaffold into a latissimus dorsi muscle flap in miniature pigs and also achieved satisfactory osteogenic and angiogenic effects (Fig. 24.10). In a clinical case study on this basis, Warnke successfully repaired a mandible bone defect in a male patient using his bone graft which had been incubated and fully vascularized in his latissimus dorsi muscle flap. Burdick et al. implanted a human BMSC-hydroxyapatite composite cultured for 2 weeks into a prepared vascularized pedicled latissimus dorsi muscle flap from a nude mouse. Postoperative histological examination showed substantial bone tissue formation and rich blood supply in the pre-constructed bone flap. Other researchers implanted biomaterial composites into the thigh muscle of rats using various geometric scaffolds combined with recombinant human bone morphogenetic protein 2 (rhBMP-2). Since histological examination revealed formation of massive new bone tissue and presence of abundant capillaries, this approach was believed to be a feasible application of vascularized bone tissue in repair of bone defects.

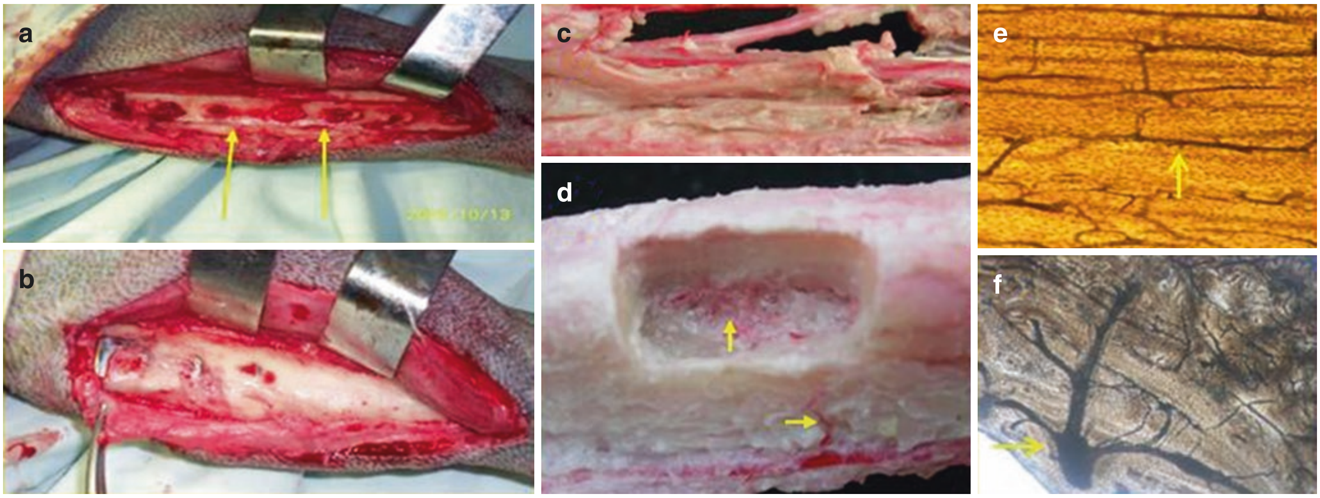


Fig. 24.9 Repairing effect of fascial flap wrapping of tissue-engineered bone. (**a**, **b**) Massive porosis was observed after removal of internal fixation material 2 years after surgery. (**c**–**f**) Many new blood vessels and an independent blood supply system formed in tissue-engineered bone

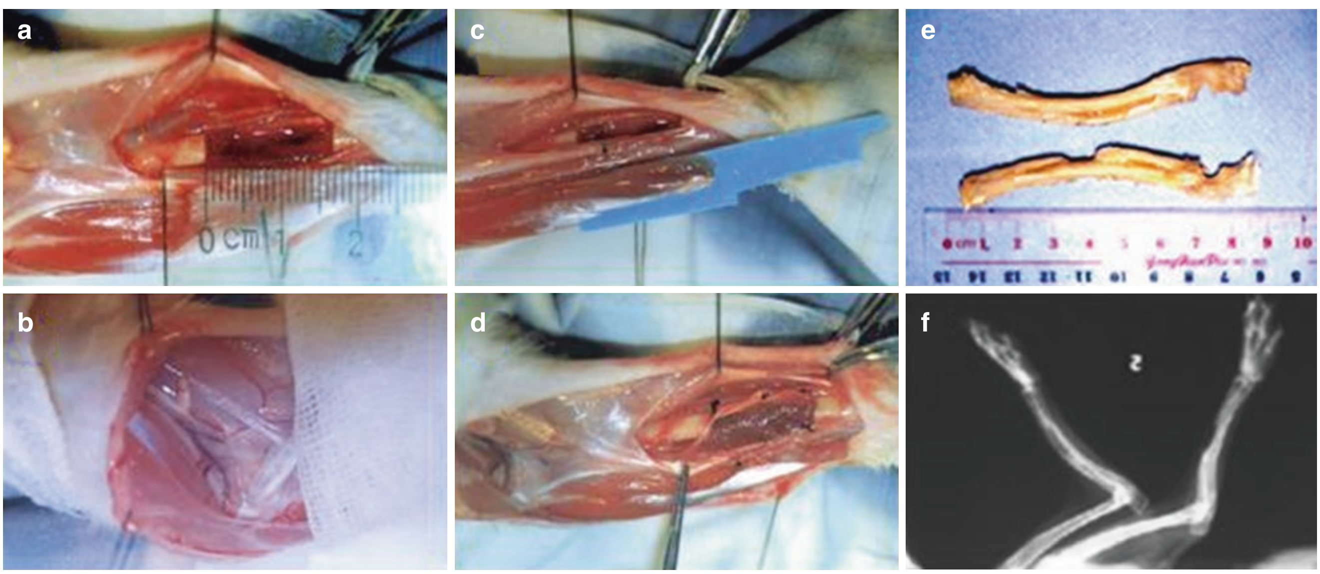


Fig. 24.10 Repairing effect of muscle flap wrapping in construction of tissue-engineered bone. (**a**, **b**) Rabbit model of radial bone defect; (**c**, **d**) Implantation of muscle flap + cells + BMP microspheres into the defect; and (**e**, **f**) Repairing effect (upper: muscle flap-wrapped tissue-engineered bone; lower: simple muscle flap-wrapping; left: muscle flap-wrapped tissue-engineered bone, right: simple muscle flap-wrapping)

Periosteum

Periosteum is the principal source for blood supply to bone tissue. It contains a large number of BMSCs of pluripotency that can be activated under certain conditions to proliferate and differentiate into osteoblasts. Therefore, periosteum-derived osteoblasts has been extensively cultured to provide seed cells in bone tissue engineering research. Additionally, application of periosteum can increase concentrations of bone morphogenetic protein (BMP) and various osteogenic factors around a local site of tissue-engineered bone where massive osteogenic cells in the periosteal cambium layer are directly stimulated to proliferate and differentiate into osteoblasts. This approach not only improves local blood circulation to provide rich nutrients but also generates endogenous effector cells to greatly accelerate the vascularization process. Vogelin et al. prepared a periosteal flap with the saphenous artery and vein as a vascular pedicle in the middle portion of a rat tibia to wrap a rhBMP-2 + polylactide matrix composite. An approximately 1-cm femoral defect in a rat model was then repaired by transfer of the composite wrapped in periosteal flap. Postoperative radiographic and histological observations showed good vascularized ectopic bone formation at the edge of the defect because of osteogenic effect of the composite wrapped in a bone flap. Similarly, Vogelin et al. prepared a tubular periosteal flap pedicled with the saphenous artery and vein from the middle portion of a rat tibia and implanted artificial bone material with or without rhBMP-2 into the tube. They next compared artificial bone materials wrapped by the tubular periosteal flap pedicled with the saphenous artery and vein, by a periosteal flap with its proximal vascular pedicle blocked and by no periosteal flap. Radiographic and histological evaluations revealed substantial *in situ* osteogenesis and a rich blood supply in the experimental group treated with rhBMP-2-containing artificial bone material wrapped in the vascularized periosteal flap. Despite its obvious advantages and reliable repairing effect in application, periosteum has inherent shortcomings, such as difficult acquisition, great difficulty in microsurgical operations, and limited volume of the local donor site. Moreover, periosteum is often missing or damaged during local trauma or tumor resection. Thus, it is difficult to meet the needs of clinical treatment using this technique.

Taken together, tissue flap wrapping has good effects in both vascularized tissue construction and osteogenesis. However, this technique still has some of the following common shortcomings: (a) it addresses the outside blood supply in a scaffold, but revascularization is slow inside a scaffold; (b) it often involves ectopic construction and inevitably needs secondary surgery, likely damaging the existing neovascular network and prolonging treatment duration; (c) even if *in situ* repair technique can be used, tissue flap wrapping cannot be used to repair various bone defects due to all kinds of local anatomical structure. Therefore, at present, tissue flap wrapping can only be used to adequately repair bone defects in specific cases. There are limitations in its application.

24.4.2.2 AV Bundle Implantation

To build large-volume tissue-engineered bone with a long tubular structure, a new scheme has been developed using microsurgical techniques. In this scheme, axial AV bundles are selected and implanted into the central area of a scaffold. Large-volume tissue-engineered bone is constructed based on the blood supply from the implanted vascular bundle to the scaffold. In fact, vascular bundle implantation has been used clinically for some time. This technique is useful and has a reliable therapeutic effect in the treatment of avascular necrosis of the femoral head, avascular necrosis of the carpal lunate, and nonunion. The method is advantageous because its operation is simple and it promotes generation of a neovascular network. However, because the new neovascular network has a limited range of action, it cannot meet the requirements for clinical repair of large-volume bone defects. Thus, investigators have introduced vascular bundle implantation into construction of tissue-engineered bone. An axial AV bundle is selected from the neck and femoral sites. After dissociated, the vascular bundle is implanted into the interior of the material. Alternatively, the material is prepared in a powdered form for wrapping around the vascular bundle with a silicone mold to promote graft vascularization. During secondary repair, tissue-engineered bone with a vascular supply is implanted into a bone defect site for further repair of bone tissue. The ultimate goal is to develop new methods for clinical treatment of large-volume bone defects by a combination of microsurgical techniques and tissue-engineered bone techniques. Pelissier et al. implanted an axial vascular bundle into the central area of a coral-like scaffold which was then embedded into muscle tissue in the body. The results showed that this construction scheme improved osteogenic and angiogenic effects of the ectopic scaffold. Wang et al. dissociated an axial AV bundle from the rabbit femur and implanted it into a TCP scaffold. They successfully repaired segmental bone defects in the rabbit femur. Additionally, it was found that vascular bundle implantation could promote release of vascular endothelial growth factors within the bone repair site. The released growth factors are conducive to formation of a local neovascular network to further improve the blood supply to tissue-engineered bone. The work by Wang et al. was the first study on repair of weight-bearing bone defects by a combination of axial vascular bundle and tissue-engineered bone (Fig. 24.11). Subsequently, Pei et al. took advantage of axial vascular bundle implantation and combined it with microsurgical techniques to successfully repair an ulnar bone defect model in rhesus monkeys. The study by Pei et al. described for the first time a successful application of axial vascular bundle implantation in primates. The above findings not only provide a new approach to constructing tissue-engineered bone but also offer new insights for clinical treatment of bone defects.

In recent years, tissue engineering research has focused on exploring endogenous vascularization. This technique attempts to grow blood vessels in a scaffold first and then implant seed cells. The early ingrowth of blood vessels in this way can rapidly provide blood supply and nutrients to a repair site. The theory underlying endogenous vascularization was proposed in 2003 by Cassell et al., who summarized vascular growth *in vivo* under physiological and pathological conditions. It was found that due to local stimulatory factors in the body, several collateral capillaries would grow out from the vascular bundle and fuse to form a capillary network. After the concept was proposed, endogenous vascularization was first used to construct soft tissue and later applied to bone tissue engineering vascularization. The method has achieved good outcomes in clinical treatment of patients with femoral head avascular necrosis or carpal scaphoid nonunion. Polykandriotis et al. pre-vascularized bovine cancellous bone granules prior to addition of osteoblasts and demonstrated that the cell survival rate and osteogenic effects were significantly improved.

24.4.2.3 AV Loop Construction

In recent years, arteriovenous loop (AV loop) construction has emerged as a new microsurgical technique for

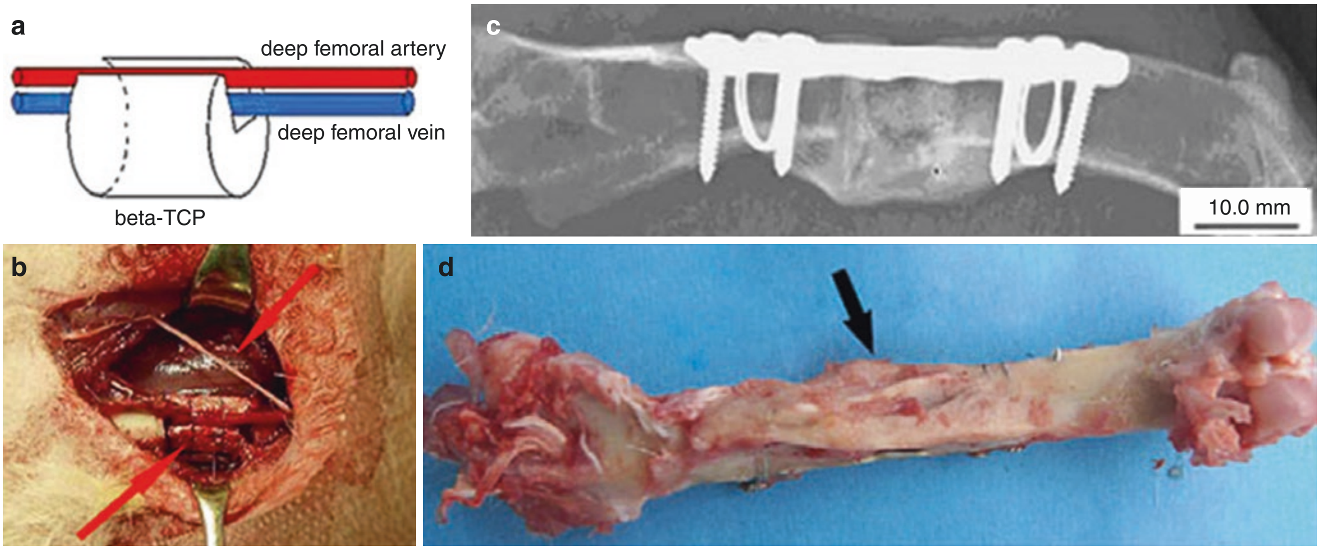


Fig. 24.11 Vascular bundle implantation for tissue-engineered bone construction (**a**) A schematic of axial vascular bundle implantation. (**b**) Intraoperative preparation. (**c**) X-ray examination 12 weeks after surgery. (**d**) General view of the repairing effect on bone defect in the middle portion of rabbit femur

bone tissue engineering construction. This technique, first proposed by Kneser, was designed to re-establish a blood-circulation supply to an implant through anastomosis of artery and vein bundles and to further establish robust scaffold blood supply through the anastomosed vascular loop that is capable of building a neovascular network. Studies demonstrated that the microvascular network constructed using this approach could sufficiently supply a scaffold and form rich vascular networks in segments of both the implanted artery and vein. Later examination found that this technique could not only improve blood circulation in the central part of a scaffold or a bone graft but also facilitate osteogenesis. Wu, a researcher in a team led by Yilin Cao, combined autologous BMSCs from beagles with a β-TCP scaffold and then constructed an AV loop based on ectopic osteogenesis in the lower extremity muscles of beagles. CT angiography was performed at 2 and 8 weeks, and ultrasound examination was conducted 6 months after surgery to detect blood flow signals in the AV loop within the tissue-engineered bone in the medial lower extremity and to test the long-term patency of the AV loop in the experimental model. Their results showed that the AV loop constructed with the saphenous artery and vein remained patent over a relatively long period. This finding fully demonstrated feasibility of using an AV loop as a vascularized carrier to construct vascularized tissue-engineered bone. This technique has been used in clinical repair of bone defects. Especially good effects were achieved in repair of mandibular defects. Eweida et al. reported the first clinical use of this technique to complete AV loop construction in the mandible *in situ* to repair a mandibular defect. A follow-up study found that the bone defect in the mandibular area was completely repaired with good appearance and no wound infection 2 months after surgery. This technique has good prospects for future clinical applications, though it is associated with a few disadvantages. For example, a neovascular network built with an AV loop is primarily distributed within the horizontal plane of the vascular loop, whereas new vessel branches in the sagittal plane of the material are limited in either quantity or range. Since this method only tackles the problem of nutrient supply in a limited plane of tissue-engineered bone, it is unsuitable for construction of a vascular network within a long tubular bone structure. Additionally, it requires intricate microsurgical operations involving isolation and anastomosis of tiny arteries and veins and meticulous evaluation of blood vessels before selection of vessels.

24.4.2.4 Nerve Bundle Implantation

Researchers have been focusing on roles of nerves in bone repair since construction of tissue-engineered bone with approximately normal levels of bioactivity was proposed (Fig. 24.12). Jin et al. found that neuropeptides play a pivotal regulatory role in both activity of osteoblasts and process of bone fracture repair, especially neuropeptide Y and substance P, which are released from sensory nerve bundles. Cytological studies suggest that these factors can promote osteoblasts to form calcium nodules and improve cell viability. Moreover, animal experiments show that these factors are expressed at high levels in the vicinity of a repair site of a bone fracture. Based on previous work, other studies employ microsurgical techniques for sensory nerve bundle implantation to explore roles of nerve bundles in construction of tissue-engineered bone. This implantation was expected to improve outcomes of bone defect repair and yielded encouraging results. The repair effect achieved after implantation of a sensory nerve bundle into tissue-engineered bone is equivalent to that after implantation of a vascular bundle. The repair effect of sensory nerve bundles is superior to that of motor nerve bundles. The upregulated expression of neuropeptide Y and substance P can be detected around the repair site of a bone defect, suggesting that sensory nerve bundles have an important role in bone repair. This functionality of sensory nerve bundles may be attributed to secreting nerve growth factors, increasing osteoblast activity, and promoting neovascular ingrowth. However, construction of neuralized tissue-engineered bone is still in its infancy. Its underlying mechanisms are not fully understood. It is necessary to further improve and standardize its preparation techniques. In-depth studies should explore relationships between nerves, blood vessels and osteogenesis. Such work will lay a foundation for further elaborating associated mechanisms and transformation into clinical application.

24.4.3 Future Prospects of Microsurgical Techniques in Construction of Tissue Engineered Bone

Development of microsurgical techniques has played a positive role in promoting construction of tissue-engineered bone. Microsurgical techniques have talked a number of problems that cannot be resolved by relying solely on materials science or molecular biology. Moreover, microsurgical techniques allow creation of tissue-engineered bone constructs that can simulate *in vivo* environments and endogenous bioactivity better. However, current construction of tissue-engineered bone by microsurgical techniques has to face the following problems: (1) Vascularized constructs are poor in homogeneity (2). Two surgeries are generally needed from construction to repair in tissue-engineered bone (3). Specialized training required for acquisition of microsurgical techniques hinders widespread application of microsurgical skills. To address the above issues, improvements have been made in seed cells and scaffolds. Traditionally, selected seed cells are typically osteoblast-like cells. Inclusion of vascular endothelial cells as seed cells to construct tissue-engineered bone to improve survival of seed cells and neovascularization is currently attracting substantial attention from researchers. Tsigkou et al. constructed a microvascular network in a scaffold using

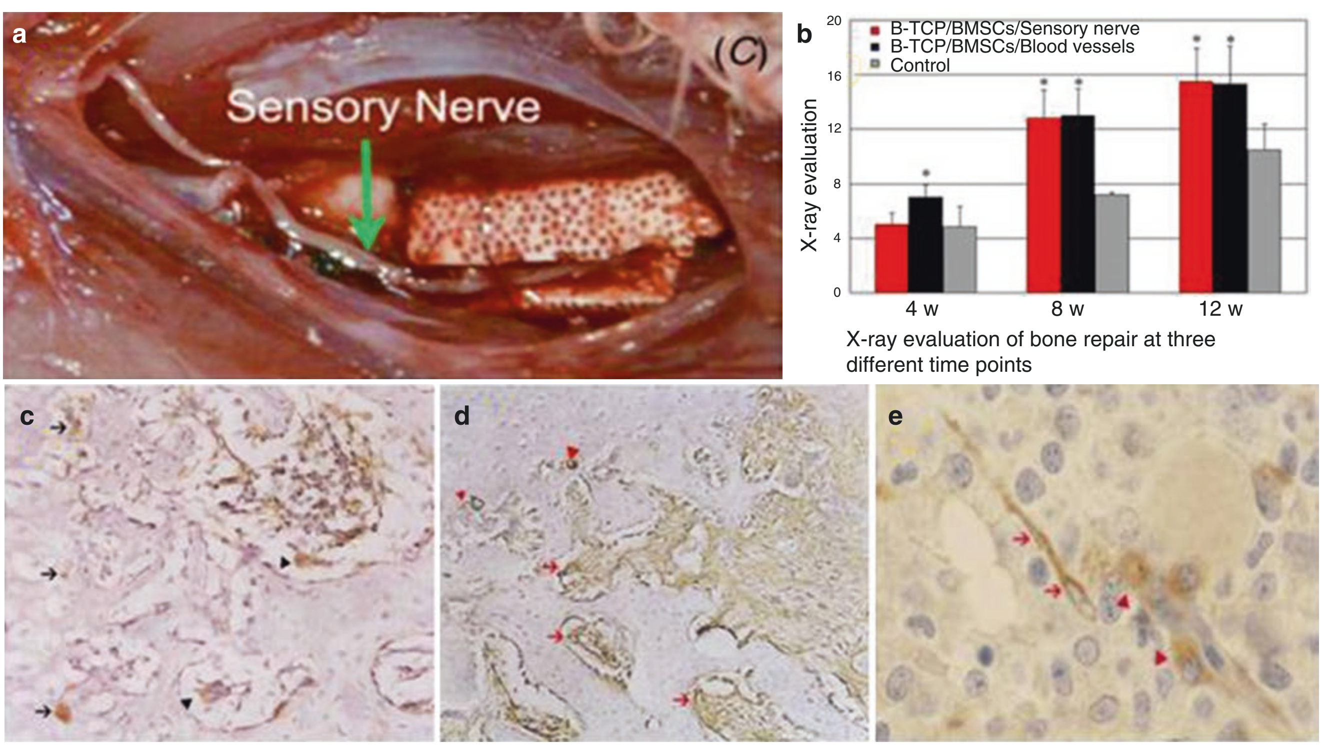


Fig. 24.12 Implantation of sensory nerve bundle in construction of neuralized tissue-engineered bone (**a**) A schematic of sensory nerve bundle implantation. (**b**) Increased osteogenic growth in tissue-engineered bone after sensory nerve bundle implantation. (**c**–**e**) Distribution of neuropeptides (CGRP, NPY, and TH) in bone tissue

vascular endothelial cells and osteoblasts. They observed significant improvements in osteogenic effect. A more recent study found that co-cultured vascular endothelial cells and osteoblasts interact by releasing cytokines, ultimately promoting neovascularization and contributing to osteogenesis. These research outcomes provide guidance for selection of seed cells to be used in construction of tissue-engineered bone. With respect to construction of scaffolds, different materials have been combined to take full advantage of their individual attributes. A variety of new composite scaffolds with good proangiogenic and proosteogenic effects have been produced. Kempen et al. who implanted vascular endothelial growth factor and BMP into a scaffold achieved good angiogenic and osteogenic effects due to sustained release from the material. They successfully constructed large-volume vascularized ectopic tissue-engineered bone.

In summary, construction of tissue-engineered bone is being developed rapidly, and microsurgery plays a role in supplementing and expanding its applications. However, many problems remain to be worked at. Future work should emphasize interdisciplinary nature of this research area and take full advantage of microsurgical techniques. Studies should explore new construction schemes through combination of microsurgical techniques with tissue-engineered bone construction. Only after repairing effects of tissue-engineered bone have been dramatically improved can this technique be extended from experimental research to clinical applications.

24.5 Construction of Tissue-Engineered Cartilage

Lei Wang, Dan Jin, and Yongtao Zhang

Articular cartilage injury and disease are common in clinic. Since articular cartilage contains no blood vessels, nerves, lymphatic tissue, progenitor cells or growth factors, its self-repair capacity is limited. Once it is injured, irreversible changes or degeneration will likely happen. Currently, joint debridement, microfracture and "mosaic" techniques are used to treat osteochondral defects smaller than 2.5 cm^2, but clinical outcomes are not ideal. A cartilage defect is repaired by fibrocartilage replacement, but because of poor mechanical properties of cartilage, damage and degeneration can easily occur with time and pressure. In recent years, development of tissue engineering based on seed cells, biomaterials, and cytokines has provided a new option for repair of cartilage injury. It was reported that cartilage repair using a tissue engineering technique by autologous chondrocyte implantation (ACI) achieved good outcomes over a short follow-up period. Hunziker described tissue engineering as a type of art of reconstructing structure and function of mammalian tissues. It mainly deals with the following: (a) research on properties of seed cells, (b) development of extracellular matrix substitutes, and (c) replacement of various tissue lesions with engineered tissue. Cartilage tissue engineering first cultures and expands cartilage seed cells *in vitro,* then constructs tissue-engineered cartilage by seeding the expanded cells onto a scaffold with favorable biocompatibility and biodegradability, and finally implants the composite into a tissue defect site to complete tissue repair and reconstruction. The ultimate goal is to obtain high-quality repaired tissue with long-term effective functionality and to eliminate patient's pain. In this sense, tissue engineering is the most promising approach to treatment of articular cartilage injury.

24.5.1 Seed Cells

24.5.1.1 Chondrocytes

ACI has been successfully used in clinical repair of cartilage defects caused by knee trauma in the following process: (1) Healthy cartilage tissue is obtained from a non-weight-bearing area of the knee to isolate chondrocytes (2). After *in vitro* culture and expansion, the cells are injected into the cartilage defect (3). A periosteal flap is sutured at the periphery of the cartilage defect to cover the wound and prevent loss of cell suspension. The second and third generations of ACI (matrix-induced ACI, MACI) use biodegradable materials (e.g., hyaluronic acid and collagen) as chondrocyte carriers, which helps avoid cell loss to some extent. In addition, arthroscopic operations help avoid injury caused by a secondary surgery. However, the biggest disadvantage of ACI and MACI is a limited source of cells, which cannot meet the need of repairing large defects. Moreover, seed cells can easily dedifferentiate during *in vitro* expansion and lose their phenotype. Additionally, the autologous cartilage sampling may cause damage and injury to the donor site.

24.5.1.2 Adult Stem Cells

Numerous studies have focused on *in vitro* chondrogenic differentiation of stem cells and its potential medical value. Adult stem cells can be isolated from bone marrow, fat, periosteum, and synovium. Cells from different sources have a similar phenotype, but their biological behaviors, such as proliferation and differentiation, show significant differences. For example, synovium-derived stem cells have stronger chondrogenic capacity. Human autologous bone marrow- and periosteum-derived stem cells are limited; the former can be extracted only in 10–25 mL volumes while the latter are even scanty. Therefore, stem cells derived from synovial tissue are being studied intensively. Synovium-derived stem cells can be sampled from a wide variety of sources through a relatively simple process. It was reported that statically cultured synovial cells exhibited approximately fibrogenic characteristics; when cultured in a three-dimensional (3D) environment, the cells immediately adopted chondrogenic characteristics without requiring growth factors. Sampat et al. seeded synovium-derived stem cells onto an agarose hydrogel scaffold. After 3 weeks of TGF-β3 stimulation, tissue-engineered cartilage was constructed with mechanical and biological properties approximating those of normal tissue.

Adipose-derived stem cells (ASCs) can be isolated from clinical waste materials like that from lipoaspirate. Similar to BMSCs, ASCs are pluripotent. Despite their relatively weak chondrogenic capacity, as shown in some studies, ASCs can be derived from a wide variety of clinical sources and are able to efficiently differentiate into chondrocytes under certain conditions. For patients who cannot obtain healthy bone marrow, autologous ASCs will become another pivotal source of seed cells.

Umbilical cord blood (UCB) collection is another source of stem cells. During *in vitro* culture, UCB-derived stem cells exhibit stronger chondrogenic differentiation potential than bone marrow-derived stem cells. Kogler et al. confirmed the chondrogenic potential of UCB-derived stem cells in nude mice. Fuchs et al. seeded UCB-derived cells onto a polyglycolic acid (PGA) scaffold and then placed the composite in serum-free medium containing TGF-β1. After 12 weeks of 3D dynamic culture, the constructed product exhibited histological and functional characteristics of normal cartilage.

24.5.1.3 Pluripotent Stem Cells

Embryonic stem cells (ESCs) can theoretically differentiate into any tissue under appropriate conditions. Researches have suggested that homogeneous fibroblast-like cells can be obtained from human ESCs (hESCs) by repeated passage after embryoid formation. The hESCs have a phenotype similar to adult stem cells, and can differentiate into chondrocytes when induced by BMP-7 and TGF-β3. What is more, when hESCs are co-cultured with mature chondrocytes, they will receive signal molecules from the chondrocytes and differentiate into chondrocytes. Toh et al. seeded cartilage pre-induced hESCs in a hyaluronic acid gel and then used the composite to repair full-thickness articular cartilage injury in rats. Cyclosporine A was administered after surgery by subcutaneous injection to inhibit immune rejection. Three months later, the defect site was filled with hyaline cartilage-like tissue and connected with peripheral cartilage.

Compared to adult stem cells, ESCs are still in their infancy with regard to application in cartilage tissue engineering. Due to their extremely active pluripotency, it is difficult to obtain relatively pure chondrocytes from ESCs. Precise control of differentiation of ESCs into chondrocytes remains a challenge. Moreover, other factors like tumorigenicity, ethical issues and difficulty in controlling spontaneous differentiation prevent clinical applications of ESCs.

Human fibroblasts can be dedifferentiated to generate induced pluripotent stem cells (iPSCs) by transducing specific transforming factors. Because fibroblasts can be isolated from a patient, iPSCs can be used for individualized stem cell transplantation therapy, resolving clinical difficulties like limited cell source and immune rejection. Although research on application of iPSCs in construction of tissue-engineered cartilage is still in its infancy, there is evidence that iPSCs can differentiate into chondrocytes (Fig. 24.13).

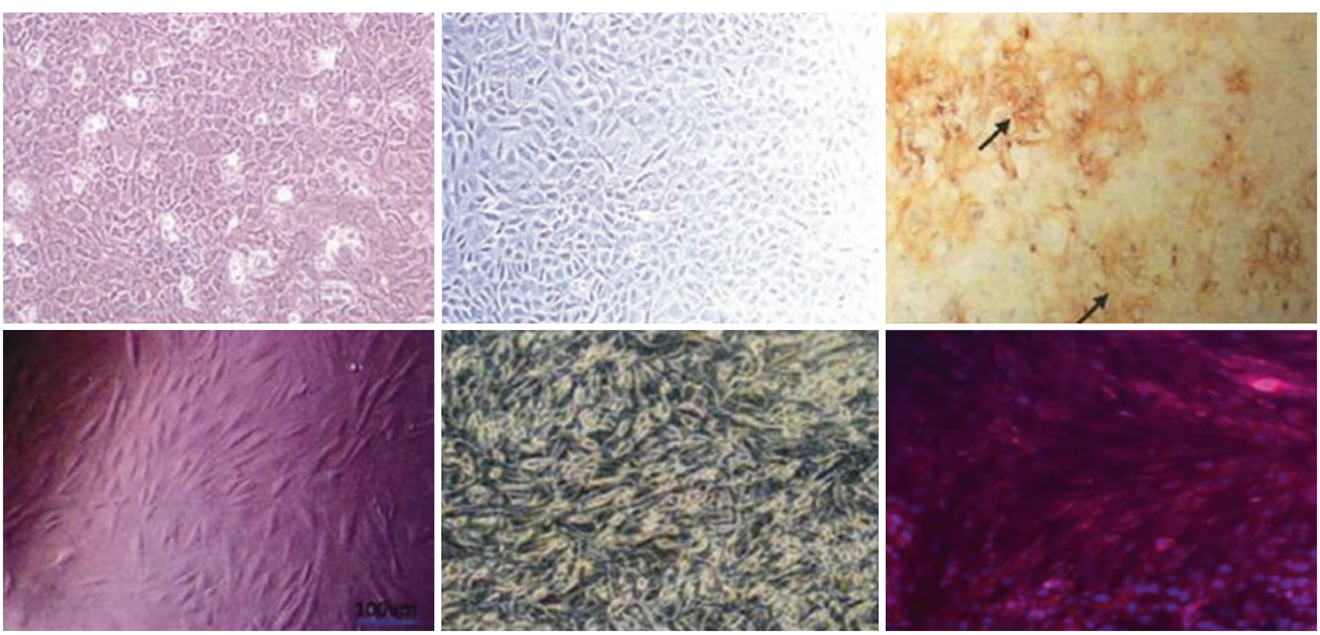


Fig. 24.13 Seed cells for tissue-engineered cartilage (bone marrow mesenchymal stem cells and chondrocytes)

24.5.2 Biomaterials

Cartilage tissue engineering scaffolds should simulate cartilage extracellular matrix in both structure and composition to provide an ideal microenvironment for migration, proliferation, and differentiation of seed cells. A desirable scaffold material must have the following characteristics: favorable biocompatibility, a degradation rate that matches that of new cartilage tissue formation, easy cell adhesion, ability to promote cell differentiation, and guaranteed mass transfer efficiency.

24.5.2.1 Natural Materials

Natural materials, including alginate, agarose, collagen, gelatin, chitosan and fibrin glue, have favorable biocompatibility. Also, these materials provide a good physiological environment to ensure cell adhesion, proliferation, and differentiation. Cheng et al. found that this type of scaffold supported differentiation of hACSs into chondrocytes in induction solution without exogenous cytokines. Recently, natural scaffolds, such as alginate, collagen, hyaluronic acid and silk fibroin, have been applied in the field of tissue engineering. Even collagen has been used as a carrier of chondrocytes in clinical repair of articular cartilage defects. However, the greatest obstacles to use of natural polymer scaffolds are their limited sources, potential immunogenicity, and pathogenic microbial contamination. Moreover, these natural materials have poor mechanical properties and will rapidly degrade *in vivo* without being cross-linked to other chemical components.

24.5.2.2 Synthetic Materials

Synthetic materials have been extensively used in tissue engineering research due to such advantages as simple synthesis, plasticity, and adjustable degradation rate. However, only a few synthetic polymers have been approved by the US FDA for human use, such as polylactic acid (PLA), PGA, and their copolymer PLGA. At present, these types of material are the focus of most researches because they have simple and stable plasticity. Their porous structure does not affect mechanical properties, their degradation rate can be adjusted in several ways, and good biomechanical properties helps tissue-engineered cartilage resisting sustained pressure. Ossendorf et al. combined a 3D porous polymer (BioSeed-C, based on PGA, PLA, and polydioxanone) with ACI to repair cartilage injury. A follow-up study two years later revealed good connection between new cartilage and host cartilage with significant improvement in joint function. Despite its good biocompatibility, this type of artificial material cannot promote cell adhesion the same way natural materials can. It is hydrolytically degraded *in vivo*, therefore locally decreasing the pH value and potentially causing inflammation (Fig. 24.14).

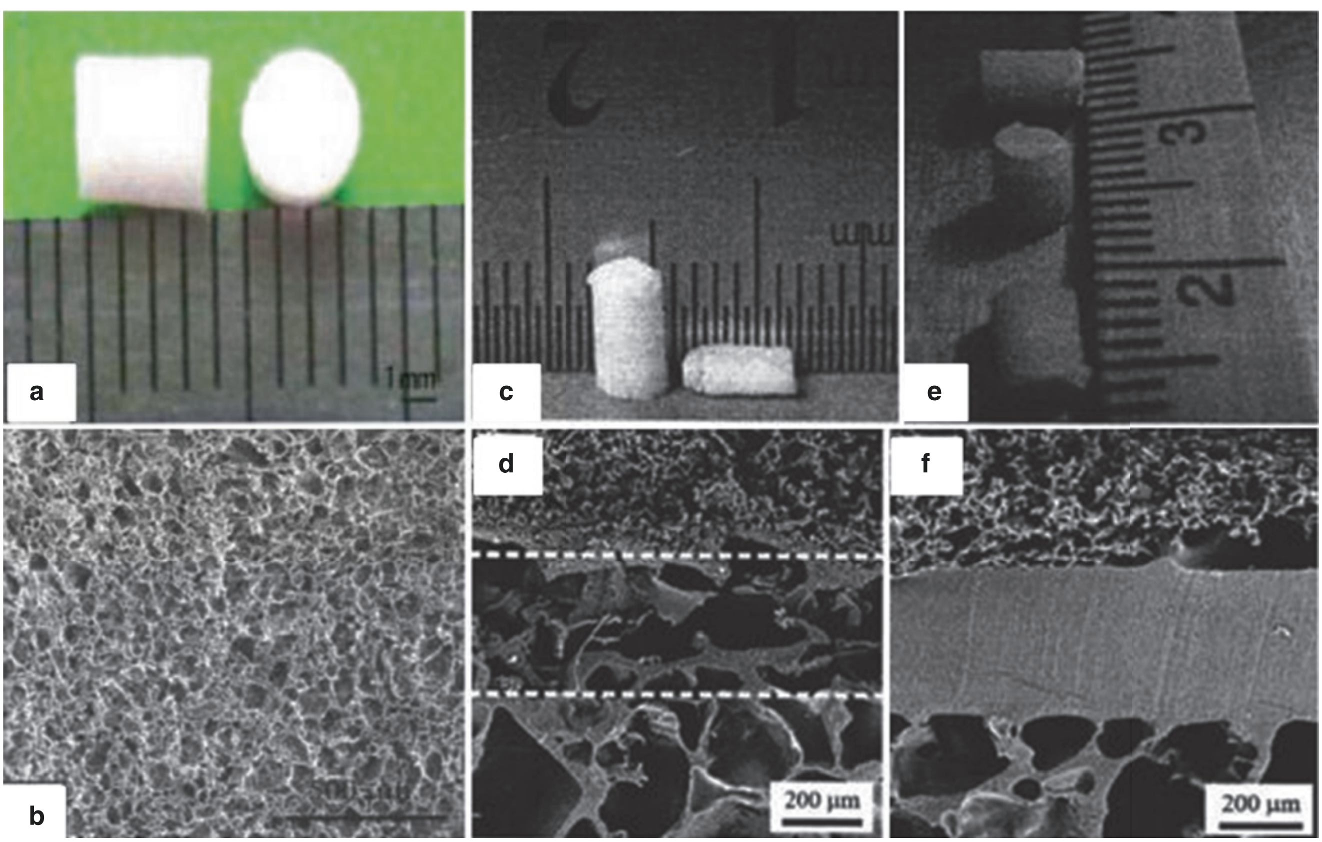


Fig. 24.14 Scaffolds for tissue-engineered cartilage (**a**, **b** PLGA; **c**, **d** dual-layer connected scaffold; **e**, **f** dual-layer unconnected scaffold)

24.5.2.3 Biomimetic Materials

Biomimetic polymer scaffolds present one direction of the developments in the related research area. Phase separation can be used to prepare poly-L-lactic acid porous scaffolds with a nanofibrous structure similar to that of collagen. Kon et al. prepared 3D biomimetic two-phase scaffolds composed of type I collagen and nano-hydroxyapatite to repair cartilage and subchondral bone respectively. The scaffold was used to repair full-thickness defects in the metacarpal bone and cartilage of horses. The results illustrated that new bone tissue and fibrous cartilage were developed at the osteochondral injury site. Besides, the scaffold was used to repair cartilage defects in the femoral condyle of goats. Six months later, histological and gross observation revealed good cartilage repair and excellent subchondral bone repair. Kon et al. conducted an early clinical study using the scaffold to repair 15 defects of cartilage degeneration in 13 patients: 4 lesions in the femoral condyle, 2 in the external condyle of the femur, 5 in the patellar articular surface, and 4 in the femoral trochlea (mean area of defect, 2.8 cm^2). A short-term follow-up by magnetic resonance imaging showed that the scaffold had good local stability with no need for auxiliary internal fixation. Histological examination revealed formation of new subchondral bone in the absence of residual biomaterial. Moreover, the repaired cartilage tissue had entered a mature stage. A multi-center clinical study of this technique has been conducted in 11 institutions in Europe, involving 150 patients.

24.5.3 Scaffold Pore Size

The pore size of scaffolds prepared with various materials can affect construction of engineered cartilage tissue. A small pore size can increase interactions between cells and facilitate formation of non-mineralized cartilage tissue. No standard pore size has been established for scaffolds to render them suitable for cartilage tissue engineering. However, current research on cartilage tissue engineering has mainly adopted scaffolds with a pore size less than 100 μm.

24.5.4 Growth Factors

Growth factors have been shown to play an essential role in proliferation, metabolism, differentiation, and apoptosis of stem cells. The differentiation of stem cells into cartilage is influenced by a variety of endogenous and exogenous growth factors. A large number of studies are focused on the following growth factors:

24.5.4.1 Transforming Growth Factor Beta (TGF-β) Superfamily

The TGF-β superfamily consists of a series of small molecule signal peptides that regulate cell proliferation and differentiation. Members of the TGF-β superfamily include the following: TGF-βs which regulate immune system and assist in wound healing, BMPs which regulate embryonic development, GDFs which regulate bone and cartilage formation, Acts and Inhs which regulate pituitary hormone release, and MIS which regulate gender formation during embryonic development. Abundant studies have confirmed that TGF-β1 can mediate differentiation and proliferation of MSCs into chondrocytes. Pelaia et al. noted that increased TGF-β1-induced IL-6 secretion may play a crucial role in cell proliferation. Another member of the TGF-β family, TGF-β3, has also been studied with regard to its potential role in regulating cell adhesion molecules, cytokines and their receptors. BMPs are homodimer molecules of the TGF-β superfamily. Tagil et al. proposed that BMP-2 may be the most effective chondrogenic factor in the TGF-β superfamily. Through a mechanism similar to that of TGF-β1 in MSCs, BMP-2 can increase cartilage extracellular matrix production and reduce expression of type I collagen gene. Additionally, BMP-4, BMP-6, BMP-7, and BMP-13 promote *in vitro* transformation of MSCs into chondrocytes. Substantial research has focused on chondrogenesis of stem cells induced by BMPs, but little is known about the role of BMPs in proliferation and survival of cells. GDF plays a significant role in cardiovascular disease. Research indicates that GDF-5 can also enhance chondrogenic differentiation of MSCs. However, this conclusion remains controversial. Some scientists believe that the role of GDF-5 in enhancing chondrogenic differentiation of MSCs may be related to its stimulation of transcription factor expression, while others have found that GDF-5 can stimulate cell hypertrophy of BM-MSCs when cultured *in vitro*, unfavorable for articular cartilage regeneration.

24.5.4.2 Insulin-Like Growth Factor-1 (IGF-1)

IGF-1, a hormone similar to insulin in structure, plays a role in growth and development of a number of normal tissues. Experimental study found that IGF-1 treatment could significantly improve the quality of cartilage repair tissue in a horse cartilage defect model. *In vitro* experiments have shown that IGF-1 regulates chondrogenic differentiation of MSCs by stimulating their proliferation and regulating apoptosis and expression of a specific chondrocyte phenotype.

24.5.4.3 Fibroblast Growth Factor (FGF) Family

FGF-2 and FGF-18 have been shown to play a role in response to damage and regeneration of cartilage. FGF-2 can activate cartilage biosynthetic pathway and reduce cartilage aggrecanase activity to resist cartilage injury and osteoarthritis. Additionally, FGF-2 can accelerate proliferation of MSCs and enhance secretion of mucin. Further studies have shown that FGF-2 can help MSCs maintain pluripotency during *in vitro* expansion. Similar to IGF-1, FGF-2 also increases production of type II collagen in an MSC-hydrogel composite. However, it is unknown whether this effect is direct. Because direct intra-articular injection will cause infection and osteophyte formation in animal models, this approach cannot be used in treatment of articular cartilage defect.

There is a trend toward using a variety of factors in combination or sequentially to complement advantages and limit disadvantages of the growth factors. Research has shown that TGF-β3 combined with BMP-6 or IGF-1 can promote differentiation of BMSCs into chondrocytes more effectively. Pei et al. found that with sequential application of TGF-β, FGF-2 and FGF-1, the constructed cartilage tissue exhibited optimal biochemical and biomechanical properties. Sun et al. combined platelet-rich plasma (PRP) containing abundant various growth factors with a composite PLGA scaffold before they implanted the *in vitro* constructed PRP/PLGA composite into New Zealand white rabbits. Their results implied that the new cartilage tissue possessed histological features similar to those of hyaline cartilage. Once activated, PRP can release a variety of growth factors, such as platelet-derived growth factor, vascular endothelial growth factor, TGF-β, IGF, and basic FGF. The combined effects of these growth factors *in vivo* may involve participation in autologous cell proliferation and differentiation, ultimately completing repair of cartilage defects. However, since not all combinations promote development of cartilage tissue, effective factors (type, dose, and mechanism) need to be explored by more in-depth studies.

The effects of growth factors rely on multiple factors, and different cells have varying responses to cytokines. Optimal regulation and repair depend on a deeper understanding of cell differentiation and further optimization of dose, timing and method of cytokine administration.

24.5.5 Cell-Scaffold Composite Construction

Cell-scaffold composites are built mainly by *in vitro* construction and subsequent *in vivo* implantation. Inoculation of seed cells is a vital step in this approach. Static inoculation is a common method for seeding cells. Cui et al. dispensed a suspension of ASCs into a PGA/PLA scaffold and implanted the composite into pig cartilage defects for construction after *in vitro* culture and chondrogenic induction. However, it is difficult to simulate regeneration process of normal cartilage using static inoculation of seed cells. Construction of tissue-engineered cartilage with good cartilage function often requires participation of multiple factors such as complex microenvironment and mechanical factors. Although static inoculation is simple and unlikely to cause contamination, it has a few shortcomings, such as limited number of cells for inoculation, low inoculation efficiency, and waste of the majority of cells during inoculation. When seeded by static inoculation, there are fewer cells in the central part of a scaffold so that the constructed tissue will have a "hollow" quality. Thus, application of dynamic inoculation (e.g., negative pressure, centrifugation and oscillation) has gradually increased. Different methods have different advantages and disadvantages of their own. Dynamic 3D construction remains a hotspot and a major challenge in current research. Application of various types of bioreactors facilitates simulation of a complex environment *in vivo*. Haasper demonstrated that a perfusion-circulating pressurized bioreactor enhanced differentiation of hBMSCs into chondroblasts. Specifically, perfusion of culture fluid induces type II collagen secretion, and circulating pressurization enhances type X collagen expression. Nikolaev et al. illustrated that a rotary bioreactor used to construct tissue-engineered cartilage increased synthesis, secretion, and cellular distribution of mucopolysaccharides. Because of relatively simple design of bioreactors, it is still difficult to replicate complex natural microenvironment when constructing tissue-engineered cartilage. Additionally, a standard method for inoculating seed cells in construction of tissue-engineered cartilage is lacking. Therefore, optimized design of a bioreactor and in-depth exploration of optimal cell inoculation methods, supplemented by use and intervention of various growth factors, will facilitate technical development in construction of tissue-engineered cartilage that replicates more closely regeneration process of normal cartilage (Fig. 24.15).

24.5.6 Fixation Methods

Repair mediated by biological fixation or tissue integration of tissue-engineered cartilage is still insufficient for clinical application. Still, few researchers are addressing this issue. A significant obstacle to clinical use is lack of understanding of the way biological fixation is achieved and micromotion at the interface between engineered tissue and normal tissue is prevented. For treatment of small osteochondral defects, most surgeons do not employ any fixation method. The stability of a scaffold is solely dependent on adhesion through gel or biological glue. Recent research has shown that biological glue cannot effectively improve the stability of a scaffold, whereas fibrin glue can maintain the integrity of a scaffold. Nevertheless, fibrin glue achieves poor adhesion to cartilage and subchondral bone compared with other invasive fixation methods.

One suture technique is traditional fixation method. However, there is great difficulty in suturing cartilage grafts, and the suture process will lead to graft displacement and increase surgical time. Suturing at multiple sites may cause cartilage destruction and result in cartilage absorption after surgery. Transosseous Kirschner wire fixation technique is

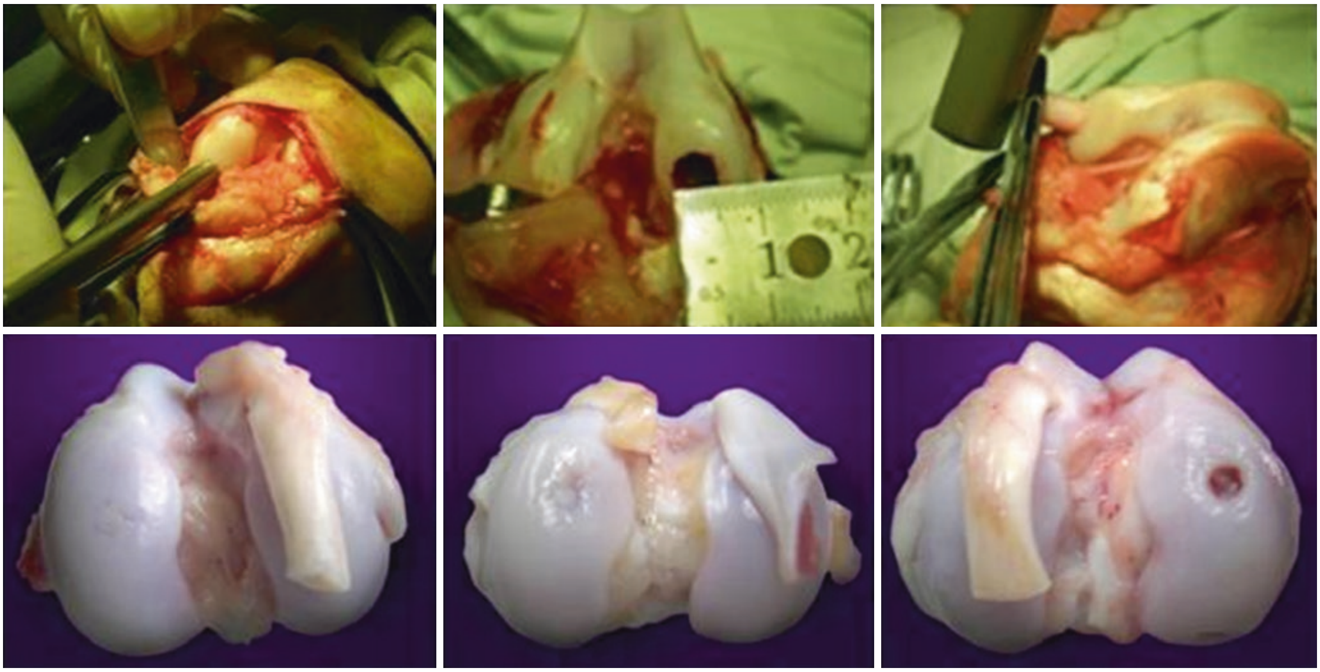


Fig. 24.15 Cartilage defect repair with tissue-engineered cartilage

expected to replace traditional suture technique. Kirschner wire fixation can significantly improve loadability and strength of absorbable scaffolds. Nonetheless, this technique relies on the biomechanical strength of a scaffold and therefore cannot be used to fix other types of material. Another fixation method is based on butyl-2 cyanoacrylate which can adhere to cartilage and cartilage grafts, but it cannot be used in clinic due to its limitations in both biodegradability and ability to bear flexion-extension stress. Recently, an innovative fixation concept was proposed involving fixation of a scaffold and a graft site by magnetic force. To achieve this goal, magnetic scaffolds have been developed to testy their biocompatibility via *in vivo* and *in vitro* experiments. For cartilage repair, development of integrated tissue-engineered osteochondral scaffolds that can simultaneously facilitate cartilage and bone tissue regeneration may represent one approach to overcoming the difficulty in fixing a tissue-engineered cartilage construct at the site of implantation.

In summary, research on construction of tissue-engineered cartilage will continue to focus on acquisition of ideal seed cells, development of scaffold materials with balanced biocompatibility and mechanical adaptability and optimization of culture conditions, inoculation methods, mechanical and dynamic culture environment, and suitable graft fixation methods. It is anticipated that studies in these areas, through multidisciplinary research and in-depth cross-collaboration, will rapidly develop clinical applications of tissue-engineered cartilage. Meanwhile, clinicians should establish objective criteria and references for technical indicators of tissue-engineered cartilage with respect to clinical application, postoperative inspection and follow-up.

24.6 Construction of Tissue-Engineered Tendon

Song Liu and Dan Jin

24.6.1 Introduction

Scientific advances in cell culture methods, grafting techniques and biomaterials have produced a completely novel artificial tendon substitute—tissue-engineered tendon which provides promising prospects for significant improvement in tendon defect repair. In tendon tissue engineering, vital tendon seed cells at high-concentrations are isolated and grown in a biocompatible and biodegradable carrier. After culture *in vitro*, the cells are implanted into a site of tendon defect, and a new functional tendon tissue will form to ultimately achieve complete biological repair. Compared with traditional tendon repair, tissue-engineered tendon has a number of advantages: (a) It eases the problem of limited source of donor tendon. (b) As it is vital and functional, it can morphologically repair and functionally reconstruct a defective tendon to permanently replace the defective tendon. (c) It can be freely molded according to morphology of a defective tendon, realizing a goal of concurrent functional reconstruction and morphological repair. Studies addressing construction of tissue-engineered tendon involve three primary aspects as follows: (1) source and selection of seed cells, (2) development of extracellular matrix (ECM) materials, and (3) research on combination of seed cells with ECM materials.

24.6.2 Basic Elements for Construction of Tissue-Engineered Tendon

24.6.2.1 Seed Cells

Since seed cells are a prerequisite for constructing tissue-engineered tendon, they must have following characteristics: (a) a fixed site and an easy sampling procedure that minimize the risks of contamination and interference with the human body, (b) strong capacity of *in vitro* proliferation and amenability to directed differentiation, (c) adaptability to scaffold materials and environment of a recipient site, and (d) easy genetic modification by molecular biology techniques which enables seed cells to yield richer phenotypes so as to increase potential applications. Current researches in tendon tissue engineering have focused on such seed cells as tendon cells, bone marrow mesenchymal stem cells, and skin fibroblasts. During culture and proliferation, seed cells are under a holistic influence of ECM material, culture media and culture environment. Thereby, there is a need to evaluate structure and function of seed cells by assessing whether their DNA structure has changed and whether proliferated cells have retained the same functionality as primary cells. Determination of how to obtain reproductive seed cells on a large scale is the most critical issue in tendon tissue engineering. In addition to the above three types of seed cells, scholars are studying a feasibility of using other cell types for tendon tissue engineering as seed cells. Adipose-derived mesenchymal stem cells (ASCs), tendon stem cells (TDSCs), and embryonic stem cells (ESCs) have potential advantages and have rosy prospects as seed cells in tendon construction.

24.6.2.2 ECM Material

Tissues are composed of cells and ECM. Similarly engineered tissues consist of seed cells combined with biodegradable materials. In engineered tissues, ECM produced by seed cells will gradually and ultimately replace a degraded scaffold to form a living tissue. ECM material, a key component in tissue engineering, not only provides a substrate for growth and reproduction of seed cells but also serves as a framework for formation of other ECM materials like collagen. Therefore, selection of a suitable scaffold material plays a decisive role in constructing tissue-engineered tendon. Over centuries, artificial tendon has been constructed from a variety of materials, such as human hair, nylon, silk, polyester, carbon fiber, and silicone. With scientific development of biomaterials, selection of materials for a desired tendon scaffold must meet the following requirements: (a) biodegradability—specifically, the material must be gradually degraded, metabolized, and absorbed in the body during cell proliferation; (b) non-toxicity and good biocompatibility; (c) a strong enough mechanical strength that can be maintained; (d) a good material-cell interface to support cell proliferation and differentiation, ECM secretion, and tissue formation; and (e) good processability—the material can be processed into a desired shape or structure. ECM materials currently used in tendon tissue engineering mainly include natural ones (e.g., collagen, fibrin, silk, and small intestinal submucosa), synthetic ones (polyglycolic acid, PGA; polylactic acid, PLA; and polylactic-co-glycolic acid, PLGA), composite ones, and nano-materials.

24.6.3 Construction of Tissue-Engineered Tendon

Appropriate use of culture methods can promote cell proliferation, differentiation, and function in a cell-scaffold composite, thereby facilitating tendonization of the seed cell-ECM composite. At present, for constructing tissue-engineered tendons, a cell-scaffold composite is typically cultured in the following three modes: static culture, static mechanical loading culture, and dynamic mechanical loading culture.

24.6.3.1 Static Culture

Traditionally tissue-engineered tendon is constructed by co-culturing seed cells with a scaffold under static culture conditions before finally implanted in the body to repair tendon defects.

Tissue-engineered tendon constructed under static culture conditions in a defective animal model has relatively poor biomechanical performance compared with a normal tendon, though the tendon is plastic. Cao demonstrated a feasibility of applying autologous tendon cells in construction of tissue engineered tendon, but the tensile strength of the constructed tendon was only 10% of that of a normal tendon. Ni et al. combined TDSCs with fibrin in a rat model of patellar tendon defect to effectively promote repair of a rat patellar tendon, but the maximum stress and elastic modulus of the constructed tendon were still lower than those of a normal tendon. Chen et al. who used pig skin fibroblasts to construct tissue-engineered tendon found that their tissue-engineered tendon was similar to a normal tendon in histological features and collagen arrangement direction, but the maximum tension of the 6-week composite was only 60% of that of a normal tendon.

24.6.3.2 Static Mechanical Loading Culture

Tendon is composed of uniaxially oriented collagen fiber bundles of dense connective tissue that connect muscle and bone. Tendon itself has no contractility but possesses relatively strong compression resistance, tension stress, and friction reduction. Mechanical stimulation signals can induce a series of reactions (e.g., changes in distraction receptor and adhesion sites) at cell surface, thereby changing the biological characteristics (e.g., nutrition) around tendon cells.

Deng et al. found that static mechanical stimulation resulted in development of more mature tissues which were associated with longitudinal fiber formation, collagen secretion, and good mechanical properties. When a designed U-shaped spring was applied to exert sustained tension onto a dermal fibroblast-PGA composite, the experimental group showed relatively ordered collagen arrangement and cell distribution compared with the control group. This result indicates that not only is the orientation of the PGA fibers relevant, stress also plays a key role in the growth orientation of tendon cells and their secreted collagen fibers on PGA. However, collagen fibers in the experimental group became thinner at 18 weeks, possibly due to the applied force of sustained tension. Under sustained tension, the constructed tendon tissue was in a constant state of fatigue, thus resulting in thinner collagen fibers.

24.6.3.3 Dynamic Mechanical Loading Culture

In dynamic culture, a mechanical device is used to provide cyclic mechanical strain to stimulate directional growth of cells on a scaffold, promoting type I collagen secretion and enhancing exchange of nutrients and metabolic wastes.

Bioreactors are devices commonly used in dynamic culture. They can simulate an *in vivo* environment to provide suitable conditions for seed cell growth, factor secretion, and reconstruction of collagen fibers.

Xu et al. found in *in vitro* experiments that under cyclic tension TDSCs-P(LLA-CL)/Col composites promoted cell proliferation with high levels of ECM-related tendon gene and protein expression. After the material combined with cells was grafted into nude mice, both histological and immunohistological data revealed formation of high-quality new tendon under tension. Chen et al. found when *in vitro* mechanical stimulation was provided through a bioreactor, hESCs-MSCs were morphologically similar to tendon cells. Cell-scaffold composites have exhibited favorable mechanical properties in *in situ* experiments of grafted tendon regeneration. With the development of tissue engineering techniques, use of bioreactors to simulate a physiological environment for tissue growth has aroused extensive attention. Relevant research will promote culture of high-quality tissue-engineered tendon and accelerate industrialization and clinical application of tissue engineered tendon.

24.6.4 Examination of Tissue-Engineered Tendon

Successful construction of tissue-engineered tendon can be assessed by examining a repaired tendon (e.g., morphological restoration, functional reconstruction, and mechanical properties) after a defective tendon has been repaired by a tissue-engineered tendon. Examination of a tissue-engineered artificial tendon involves general observation of its morphology, color, and transparency for a preliminary understanding of degradation and absorption of the material. Then, the constructed tendon is compared to a normal tendon for consistency in color, length, diameter, wound healing, and biomaterial degradation.

Engineered implants are observed by light microscopy to assess growth and infiltration of seed cells in a scaffold. Transmission electron microscopy is used to observe fine structure of seed cells implanted and arrangement of collagen fibers in the regenerated tissue. PCR can be used to assay expression of type I collagen at the gene level. Histological examination is essential. Its commonly used methods include paraffin sectioning, hematoxylin-eosin staining, and Masson's trichrome staining. Mechanical strength of a tendonized artificial tendon is a usual focus of experimental studies. Mechanical properties of a tissue-engineered tendon are mainly examined by determining their major indicators, including tensile strength, maximum stress, and elastic modulus.

Molecular biology techniques are increasingly used to examine tissue-engineered grafts in the body. BrdU, an analog of thymine, can replace thymine in newly synthesized DNA molecules to label implanted cells. Antibody ligase or fluorescein is used as an indicator to detect whether the cells are surviving after implantation into the body. The BrdU labeling of seed cells is a common approach for determining the proliferative capacity of implanted seed cells; it involves no radioactive contamination and allows for direct observation of tissue sections.

24.6.5 Research on Preliminary Clinical Applications of Tissue-Engineered Tendon

Seed cells inoculated into ECM material, cultured *in vitro* for 7–10 days, and then implanted into an animal to complete tendonization in an *in vivo* nutritional environment and under the action of mechanical factors have been proven effective in reconstruction of tendon. Animals such as chickens, rabbits, pigs, and mice are commonly used for *in vivo* experiments of tendon tissue engineering.

Numerous studies have used cell-scaffold composites to repair tendon defects in animal models. The process of tendonization is accomplished in an *in vivo* nutritional environment and under the action of mechanical factors, demonstrating potential clinical applications of tendon tissue engineering. Substantial achievements of tendon tissue engineering have been made in repairing rotator cuff tendon, Achilles tendon, flexor tendon, and patellar tendon.

In clinical trials, Yang et al. found that it was a feasible surgical approach for repairing the coracoclavicular ligament with an artificial tendon that was constructed using tissue engineering principles. Their implanted allogeneic cells remained vital for at least 6 months with no obvious rejection. Li et al. seeded allogeneic tendon-derived fibroblasts (5×10^6 cells/mL) in a carbon fiber-polyglycolic acid fiber scaffold. After 5 days of *in vitro* culture, old Achilles tendon defects were repaired in 7 patients. A 46.9-month follow-up showed that all patients achieved primary healing with no systemic or local adverse reactions except postoperative delayed wound healing in one case. According to Yin's efficacy evaluation criteria, the patients were rated as excellent in 5 cases, good in one, and acceptable in one, indicating that tissue-engineered tendon can be used to effectively repair the Achilles tendon. Clarke found that injection of skin fibroblasts mixed with autologous plasma was useful in their short-term treatment of patellar tendinitis.

24.6.6 Prospects

24.6.6.1 Shortcomings and Future of Tendon Tissue Engineering

Development of tissue engineering has driven major changes in organ grafting and brought new hope for numerous diseases. New biomedical materials and constantly improving preparation techniques has resulted in encouraging progress in development of tendon scaffolds, which not only support seed cell adhesion and proliferation but also recapitulate tendon mechanics. However, there still exist problems in mass production for real clinical application of tendon tissue engineering. The following questions will need to be further addressed: (1) How do we implement large-scale stable expansion of seed cells *in vitro* and enhance their abilities to adhere onto a scaffold and proliferate and differentiate within a scaffold? (2) How do we maintain consistency between degradation rate of a scaffold and functional growth of cells, reduce antigenicity of scaffold material, and produce more intelligent ECM materials? (3) How will we implement *in vitro* simulation of an *in vivo* environment for successful construction of tendon tissue that consists of dense connective tissue connecting skeletal muscle and bone? Determination of how to embed artificial tendon into a hard bone surface has emerged as a more complex issue in construction of tissue-engineered tendon. Additionally, a better understanding of the molecular mechanisms underlying tendon development and self-healing will help construction of a tendon that resembles more closely a normal tendon in morphology. We believe that constant development and close coordination of life sciences and materials science will make tendon tissue engineering an ideal approach for tendon defect repair.

24.6.6.2 Tissue-Engineered Tendon and Microsurgery

Microsurgery provides certain conditions for construction of tissue-engineered tendon which in turn creates opportunities for development of microsurgery. To obtain TDSCs which have great potential as seed cells in construction of tissue-engineered tendon, microsurgical techniques are useful in intact tendon separation. To re-implant a cell-material composite, it is necessary to understand microscopic anatomy of tendon in tendon grafting; when anastomosis of small blood vessels and nerves is required, microsurgical techniques are necessary. Recent microdissection studies show presence of a complete blood supply system in the interior of a tendon. However, current tissue engineering research primarily uses simple seed cell culture. Without blood vessels penetrating a constructed tendon, severe adhesion is inevitable after re-implantation into the body. There is a great prospect for construction of vascularized tissue-engineered tendon using microsurgical techniques.

24.7 Tissue Engineering and Microscopic Orthopedics

Kuanhai Wei

24.7.1 Muscular Tissue Engineering

Repair of severe skeletal muscle injury often results in unsatisfactory outcomes. Many genetic diseases, such as muscular dystrophy, lead to severe functional impairment because of their inability to produce normal gene products. Traditional treatments cannot change the consequent fibrosis and pimelosis of the muscle tissue severely damaged, nor can they make the genetically defective muscle tissue repair its functional deficits by self regeneration. The developing tissue engineering technology provides research into repair of severe skeletal muscle injury with new insights. Nowadays, tissue engineering of muscular tissue has become a hot research interest which has led to some new achievements, though the research is not systematic or thorough yet, domestically or internationally.

24.7.1.1 Part 1: Regeneration of Muscle Cells and Skeletal Muscle Tissue

Under normal circumstances, satellite cells in skeletal muscle tissue have a certain ability to divide and proliferate, but their number will not increase with time. Because the myoblasts formed by cell division can be fused into the adjacent muscle fibers so that muscle fiber nuclei will increase, up to hundreds, while muscle fibers will thicken and elongate to complete the development. Once a skeletal muscle is damaged, irrespective of lesion form, such as frostbite, ischemic injury or some pathological injury caused by inherited myopathy, the regeneration of skeletal muscle is roughly the same. First of all, damaged muscle fibers exhibit different degrees of necrosis, and then macrophages appear in the affected areas to clear the necrotic muscle fibers with reservation of the basement membrane around the necrosis. At the same time, a large number of satellite cells are activated. With rapid division and proliferation in the first week after injury, the quantity of satellite cells reaches the peak. After that, a certain ability to split still maintains but the number gradually reduces. The reduced satellite cells are fused to each other to become myotubes in the primary muscle fibers along the residual basal membrane. Myotubes will continue to accept the newly born muscle cells, or merge with adjacent myotubes, to grow up gradually. Myotubes can synthetise myofibrils, which are childish muscle fibers. In the local microenvironment, childish muscle fibers gradually mature. The activation of satellite cells and their ability to proliferate rapidly in a short time are the start links of muscle regeneration. Cantini and his workmates found out that 48 hours after injury, the number of macrophages in the damaged region reached a peak, which was (3 days) earlier than that in satellite cells. Therefore, they believed that macrophages can activate satellite cells. By adding the primary culture of the muscle cells of rats into peritoneal exudate which contains a large number of macrophages and was obtained from peritoneal lavage of sterile peritonitis in rats, they found that the mixed culture of macrophages and muscle cells can significantly improve the ability of cell division, differentiation and fusion of the myotubule formation of muscle cells. In conclusion, on one hand, macrophages are responsible for cleaning necrotic muscle fibers. On the other hand, they secrete a factor which can selectively stimulate proliferation and differentiation into muscle derived cells so as to start the process of forming regenerated muscle fibers.

Regeneration of damaged skeletal muscle depends on three aspects: integrity of the basal membrane, reconstruction of the damaged muscle, nerve innervation of the damaged muscle. When the damaged muscle fibers are cleared by macrophages, the peripheral basement membrane can be preserved, like many hollow, “pipeline”-like stents. The micro-environment of the “pipeline” can induce the differentiation of regenerated muscle fibers, and arrange them along the direction of the original muscle fibers. In an animal model of skeletal muscle of frostbite, the basement membrane of damaged muscle tissue has an integrated structure, and can fully induce regeneration process. In the case of contusion and laceration, since the arrangement and structure of the basement membrane are inevitably damaged, regeneration of the basement membrane is not complete and out of order.

Hansen-Smith and Carlson studied the regeneration process of the whole extensor longus digitorum in free rats after suture in situ (no vascular anastomosis). On the first day after suture, the whole muscle was in a state of ischemia, only leaving some muscle fibers in relatively superficial areas, and a large number of satellite cells obtained nutrition from the adjacent tissue by osmosis. In the center of the muscle, muscle fibers necrosed, but the satellite cells survived as they migrated to the surrounding areas by chemotaxis. On the second day, there were sinusoidal capillaries growing inside from the surrounding normal tissue, and until the seventh day, they could reach the muscle center. Within the first week, the necrotic center was gradually reduced and absorbed, and the regenerated tissue moved to the center with recovery of blood supply. Generally, the regenerated striated fibers were visible in 3–5 days. On the tenth day, most of the muscles were made up of minor muscle fibers, and the regeneration of muscle fibers was complete. At the same time, the regeneration of nerve fibers was visible, usually with nerve fibers growing in after 3–4 weeks. By 60 days, muscle spindles came into being. Obviously, regeneration of nerves lags behind that of muscle fibers. In most cases, regenerated muscle fibers will spontaneously atrophy if they cannot receive good nerve regulation, and fat or fibroblasts will take the place.

24.7.1.2 Part 2: Muscle Cell Transplantation

Muscle cell transplantation is mainly used as a treatment for muscular dystrophy. Muscular dystrophy (MD) is a group of common refractory diseases most of which are related to genetic factors. In the recent 20 years, especially since the 90s, molecular biology research has made a great progress in the understanding and diagnostic level of a group of myonosuses represented by MD. Since Monaco et al. located dystrophin in DMD into the Xp21.2 gene for the first time in 1986, almost all of the common forms of muscular dystrophy gene mapping and the major gene products have been well understood.

Myoblast transfer therapy: After Partridge et al. managed to use MDX mouse model to prove that muscle cell transplantation is an effective treatment, Gussoni et al. carried out clinical study of DMD gene therapy. After that, Chinese Dr. Gai Luo developed a fast cultural method for myoblasts, built a cell therapeutic centre, used billions of myoblasts to conduct multipoint muscle implantation on hundreds of points on patients' whole body and obtained pretty satisfactory results, but the long-term effects were still followed up. Since it is thought that Dystrophin gene deletion is the most important nosogenesis of DMD, it has become a research hotspot to conduct dystrophin gene into morbid muscular tissue via isotopic carrier such as plasmid or virus (adenovirus, retrovirus). However, as the expression of the dystrophin gene conducted into morbid muscular tissue is not high, and virus as an isotopic carrier has disadvantages such as high antigenicity, the clinical application is limited. In recent years, although antigenicity transformation of the virus structure has been conducted in order to achieve the goal of reducing the antigenicity, the problem is still unsolved yet. Utrophin belongs to isomer of dystrophin. In normal tissue, it is distributed in neuromuscular junction and nerve endings, but its expression on skeletal muscle membrane is quite low. If its expression can be improved, it can restrain the disadvantages of dystrophin and prevent development of the state of illness. Therefore, improving the expression of utrophin gene has become a new method for DMD gene treatment.

Myoblasts can integrate into adjacent muscle fibers in a living body, which is a basic reaction in the growth of normal muscle fibers or in the regeneration of damaged muscle fibers. Research has found that once myoblasts integrate into muscle fibers, they stop expressing major histocompatibility complex class I (MHC-I) antigen. Improving the fusion ability of transplanted myoblasts (such as purifying the cultured myoblasts) can reduce the attack of parasitifer immune system against the transplanted cells. Fang et al. isolated MHC-I antigen negative cell line and found that the proliferation and differentiation ability in vitro of MHC-I antigen negative myoblasts had no difference with that of MHC-I antigen positive myoblasts.

Myoblasts are the only precursor cells that can divide, proliferate and migrate in quantity in mammals with the ability to integrate with parasitifer muscle cells, and can be widely used as an effective isotopic carrier for transfer of a target gene. So far, people have already obtained human factor IX (hFIX), erythropoietin (EPO), colony stimulating factor-1 (CSF-1), and ECT gene product as a muscle cell line through genetic engineering. After transplantation of these genetically engineered cells into the animal model of the disease, the gene product was detected in the peripheral blood of the recipient.

24.7.1.3 Part 3: Skeletal Muscle Tissue Engineering Research

Myoblast Culture

The seed cells used in skeletal muscle tissue engineering study are myoblasts. There are pretty mature techniques to culture myoblasts, the most classic of which is similar to Blau method, using trypsin and collagenase mixed fractional step by step enzymatic digestion to isolate myoblasts. Myoblasts usually require medium based on F12, which is normal growth medium or fusion medium made by serum of different concentrations with buffer solution.

In recent years, people have conducted research on the conditions and techniques of myoblast culture from multi-aspects, and have studied the factors that affect the proliferation and differentiation of myoblasts in detail, especially the growth factor and hormone. For example, insulin-like growth factor I can prevent myoblasts from apoptosis, and can promote cell proliferation under the action of cofactor, but it is not the direct stimulating factor. The function of insulin-like growth factor II is to promote the differentiation of myoblasts. Harper et al. studied the influence of 4 kinds of potential synthetic peptide hormones or growth factors on the formation of myoblast protein in differentiation medium, showing that insulin has the same function as somatomedin and it only works in high concentration; insulin-like growth factor I has activity even in low concentration when in not-murine primary culture medium or in L6 cell line differentiation medium; microcrystalline epidermal growth factor shows a high ability to promote anabolism in sheep primary myoblast medium; growth hormone collected from bovine serum has no influence on the growth of sheep myoblasts, but when cultured in L6 cell line murine myoblasts, growth hormone of high concentration restrains the resolution of protein, and so on.

By observing through electron microscopy and two-dimensional polyacrylamide gel electrophoresis of SDS, Kujawa et al. found that if myoblasts are cultured in medium with hyaluronic acid as the substrate, the integration of myoblasts is restrained, but since its macromolecular biosynthesis process is not started, the myoblasts blocked by fusion continues the differentiation. But when myoblasts are transferred to the medium with collagen as the substrate, the muscle cells will re-synthesize the characteristic proteins and form the multi-core muscle tubules. These indicate that hyaluronic acid has the function to promote the proliferation and restrain the differentiation of myoblasts, and its inhibition of the fusion of myoblasts is not permanent, which is different from the process of other inhibition of fusion and growth of muscle fibers.

Mastering the factors that affect the proliferation and differentiation of myoblasts cultured in vitro is the foundation for study on their various behavior in engine body and can provide clues for looking for suitable isotopic carriers for myoblast transplantation, which is also the basement for searching for a way to enhance the efficiency of transplantation as well.

How to Enhance the Efficiency of Myoblast Transplantation

To culture myoblasts through tissue engineering aims at repairing damaged tissue using engineered cells and improving the function of tissue. However, the repair efficiency of experimental myoblast transplantation is not satisfactory, no matter it is hereditary myopathy or seriously injured muscle tissue. Although there is abundant evidence to prove that transplanted myoblasts survive and integrate with the receptor tissue, the improvement in the receptor function is far from satisfactory. Promotion involved in various aspects of the process of myoblast transplantation will affect the improvements in the efficiency and more in the receptor function. Therefore, it concerns the prospect of myoblast transplantation or cell mediated gene therapy how to enhance the efficiency of myoblast transplantation at a deeper level.

Myoblast Suspension Concentration

Research finds that simple promotion to the concentration of cell transplantation cannot enhance the integration between transplanted myoblasts and host muscle fibers without limitation. When the myoblast suspension concentration is between 5 × 104/5 μL and 2 × 105/5 μL, the fusion rate has a positive correlation with concentration, but it will not enhance when the concentration is higher.

Multipoint Injection of Myoblasts

It has been proved by many researches that myoblasts lack of mobility. Research finds that injury does not induce mobility of moyblasts, but in DMD patients, dense muscle fibers and deposition of adipose tissue restrain the mobility of muscle precursor cells and affect the efficiency of forming muscle. To overcome the problem, many researchers adopt the method of multipoint injection of myoblast suspension. However, the injection points available for myoblast transplantation are limited. The improvement in distribution of the muscle cells is still unsatisfactory.

Preparations for the Receptor of Myoblast Transplantation

When myoblasts are transplanted into the receptor tissue, they persist, proliferate, differentiate and become heterozygosis muscle fibers through integration with host cells. The whole process is not only related to the activity of transplanted cells, but also closely to the state of the whole or partial body of the transplant recipient. Faced with different situations, targeted improvement of tissue conditions of the whole or partial body will benefit the efficiency of cell transplantation. For instance, to improve the mobility of transplanted myoblasts, notexin was used to pretreat receptor muscle to improve the efficiency of myoblast transplantation. However, as notexin has the risk of causing myoglobinuria and even renal insufficiency, its clinical feasibility is poor. Torrente et al. studied the effects of using notexin and metalloproteinases (MMPS) to pretreat a receptor muscle. By using transplanted myoblasts labeled by β-galactose enzyme and using immune inhibitor FK506 to exclude disturbances from immune respondency, they found that the mix of collagenase, matrix dissolution factor and notexin was much effective than the mix of collagenase and matrix dissolution factor, and the efficiency of notexin was the lowest. Torrente also found that MMPS was obviously available to the mobility of myoblasts.

Preparations for Myoblast Transplantation

Many researchers tried to improve the efficiency of myoblast transplantation through stimulation from growth factors. For example, 2 days before myoblast transplantation, Kinoshita added 100 ng/mL basic firoblast growth factor (bFGF) into mediums and found that the number of uninuclear myoblasts in the mediums increased 34% while the formation of myotube reduced. Afterwards, under the condition of using FK506 immune suppressor, he transplanted the myoblasts labeled by β-galactose enzyme into muscle without pretreatment. 3 days later, the number of transplanted cells in the experimental group was not significantly different from that in the control group. But after 4 weeks, the number of β-galactose enzyme positive muscle fibers in the experimental group was obviously greater than that in the group without bFGF (more than 4 times). Ito et al. used similar methods to add A20 μg/mL half concanavalin into myoblast medium 2 days before transplantation, and then transplanted the muscle tissue of the same kind of allograft without pretreatment. 4 days after transplantation, they found that the migration scope of myoblasts in the experimental group was 3 times greater than that in the control group. These experiments are meaningful explorations to improve the efficiency of transplantation of human myoblasts.

Choosing Timbering Material

In tissue structure, the skeletal muscle is composed of a large number of bundles of muscle fibers. It can be seen in an electron microscope that the cells are close to the basement membrane with the major chemical constituent of collagen IV. In normal circumstances, basement membrane is bestrewn with blood capillaries to nourish and support muscle fibers. But when injured, the basement membrane is a map for regeneration of muscle cells and can induce regeneration of muscle fibers. As long as the basement membrane is not damaged, such as when frozen, muscle tissue can be regeneratively repaired, completely recovering the muscle structure and function. The former whole basement membrane may induce the growth of a large number of capillaries along the basement membrane, forming new basement membrane. The regenerated basement membrane can be replaced by or coexist with the new one. Therefore it can be conceived that the basement membrane can act as a micro-skeleton or holder when regenerating to guide the regeneration of muscle cells. Then as a natural timbering material, the basement membrane is compatible with an engine body and can induce or even guide the regeneration. Since it can be resolved or replaced gradually, it is an excellent timbering material. However, in application, obtaining basement membrane or collagen IV is pretty difficult. If looking for its analogue, collagen gel I is one of the ideal timbering materials.

Collagen I itself has the function of promoting adherence, differentiation, fusion rate of myoblasts. Mixing myoblasts into collagen I solution can form collagen gel with live myoblasts in 37 °C incubator. If needed, the gel can be cast from liquid to solid under specific mechanical environments. It can be cast into tubuloses, screwed pipes, slices and so on. They can become a holder with live myoblasts which can be studied by human cast tissue engineering and can be used for various researches in cast tissue engineering, such as tissue engineering blood vessel, intestinal canal, esophagus and so on. But after collagen I is transplanted into a receptor, if degradation is not in time, it will also bring negative influence on the function of regenerated muscle tissue. Therefore, in recent years, many scholars are positively looking for new materials to enable the transplanted myoblasts to grow, breed, differentiate, mature and exercise its function better in the receptor.

When applying transgenic myoblasts in transplantation for treatment of neurodegeneration disease, Li RH et al. found that using wire with collagen packing polyethylene terephthalate (PET) as a support material is more effective than using pure collagen. After culturing myoblasts composited with a support material, by measuring their viability, shape and secretion of ciliary neurotrophic factor (CNTF), they found that complexus with PET as a support material could produce 8 times live cells more than that with collagen, and the secretion quantity of CNTF by the former was 4 times more than by the latter.

Transplantation Immunity Problem

Clinical application and research are challenged by the allograft problem. A normal method to overcome immunological rejection is using immune suppressor. Researches prove that, many immune suppressors for clinical use like cyclophosphamide, ciclosporin A have no or very little effect on restraining immune response caused by myoblast transplantation. In mice and primates, FK506 is an effective immune suppressor. In primate experiments, Skuk et al. found that using FK506 in myoblast transplantation could make the transplanted cells survive for more than a year, but once FK506 was recalled, the transplanted cells would be rejected. Smythe's research showed that consuming T cells was much effective than using FK506 and could obviously promote the migration scope of myoblasts no matter in a compatible or incompatible host. The researchers believed that it could be a long-term aiding method for myoblast transplantation. However, a dog experiment showed that no matter in an autograft or allograft, when immune suppressor is not used, CD4+ and CD8+ lymphocytes started to permeate in 2 weeks, signaling the presence of cell immune. Exclusive use of FK506 only restrained the presence of antibody, but the persistence of labeled transplanted cells was still unsatisfactory. Combined utilization of FK506 and cyclosporine A showed favourable efficiency of transplantation.

Since gene transfection product of p40 subunit of interleukin 12 (IL-12p40) can restrain immune reaction mediated by helper T cell, gene transfection of IL-12p40 is also a powerful means to restrain immune rejection of allogeneic and genetically modified cells. And application of monoclonal antibody is a promising therapy as well, such as applying OKT monoclonal antibody to treat the receptor. Some people apply monoclonal antibodies specific to anti T cell antigen receptor to prevent and cure rejection reaction in animal experiments while further clinical studies are needed. Schneider et al. combined temporary anti-CD154 antibodies with transgenic myoblasts which can express CTLA4-lg and obviously improved the survival time of allografts. Guerette applied a combination of monoclonal antibody on the surface of lymphocytes and recombinant CTLA-4 mainly for the transplantation of individuals with incompatible antigens. Using anti-CD4+, anti-CD8+, anti lymphocyte function associated antigen and CTLA-lg together led to a much higher efficiency of transplantation than using CTLA4-lg alone, but its long-term effect was still poor. Pavlath et al. temporarily used cyclosporine A, intracellular adhesion molecule-1 and monoclonal antibody of hemameba functional correlation-1 to enable the transplanted allogeneic myoblasts not to be rejected in a longer period.

Of course, to comb out transplantation immunity thoroughly, we had better use autogenous cells for transplantation. As for hereditary myopathy, we can obtain and amplificate myoblasts from autologous muscle tissue, then the normal gene can be transferred into the DNA of the cells by gene transfection before the cells are reimplanted back to muscle tissue of the body at last. When the cells fuse with muscle cells on the injection site, normal genes can express normal products, reaching the goal of curing disease. Moisset et al. used adenovirus with CMV promoter for multiple transfection to drive anti-amyotrophy gene of 6.3 kb, and tested its gene expression in vitro. In the culture of these cells, the expression of anti-anyotrophy gene RNA could be detected, whose value was proportional to the transfection rate of adenovirus. When the myoblasts (labeled with β-galactose) of MDX mice transfected with dystrophin gene were reimplanted into muscle tissue, a large number of labeled muscle cells expressed dystrophin gene 10 days and 24 days after the transplantation. Meanwhile, mRNA of dystrophin gene could be detected by RT-PCR as well. Further research shows that, in DMD, culture of its own myoblasts has a problem of poor multiplication capacity. Huard et al. transfected the myoblast gene into fibroblasts to introduce the MyoD1 cDNA coded by reverse transcription into the fibroblasts in the corium layer of TnI LacZ mice to translate it into muscle genoid, which is for transplantation after proliferation. Experiments in vivo or in vitro all find that transfected cells can fuse with its muscle cells, and can express dystrophin protein, muscle fiber protein and β-galactose. The positive spots of β-galactose are still obvious even 30 days after transplantation.

24.8 Construction of Engineered Peripheral Nerve

24.8.1 Part 1: Preparation of Animal Model

24.8.1.1 Characteristic of Experimental Model of Peripheral Nerve Tissue Engineering

As a substitute for autologous nerve grafts, tissue engineered peripheral nerve grafts have not matured yet. However, peripheral nerve is the most delicate tissue of human body, regeneration of which is very slow. The recovery of a defect of peripheral nerve is much slower, taking several months or years. Therefore, once the transplantation fails, the consequence is very serious even after reoperation. So peripheral nerve grafting must succeed in animal experiments before it can be carefully carried out in clinical trials, and it cannot be popularized until its effects are stable.

To perform animal experiments, the first question is what animals should be used. People usually begin with small animals. Rats are the first choice since it is economic and easy to conduct experiments in them. Rats are convenient to manage and easy to feed, have strong proliferation ability and a high rate of survival, and can be observed for 3–6 months. The rat ischiadic nerve is the most common peripheral nerve model, which is characterized by easy exposure, less bleeding, less damage, a relatively thick neural stem and easy nerve end to end suture. It is convenient for neural transplantation as well. It allows the outer membrane suture, and its beam can be divided so that the suture and transplantation can be performed between beam and beam. Since its surrounding soft tissue is abundant and has sufficient blood supply, it can recover better. Acquisition of specimens is easy in later reoperation. The shortcomings are that the limbs will be numb, anabrosis and even autotomy may happen, causing infection and other complications. Nervus peroneus communis of rats can be used as well, but it is quite small so that the requirement of operation is higher. Other animals like mice and guinea-pigs are under use since their nerves are small. New Zealand white rabbits are also a choice but it takes a long time to observe and it is difficult to take care of its skin disease.

Since rats are rodent animals and differ 100 million years from human beings in the history of evolution, their physiological anatomy is very far from that of human beings. The experiment results in rats are not necessarily consistent with those in human. As for important experiment results, it is often use the animals that are close to human beings. Primate animals are used to repeat experiments to see if they can work. Only after that can clinical experiments be carried out. There are more than 200 kinds of primate animals. Currently it is easy to get the Ganges Rlver monkey which differs three million years from human. That is to say the results of the Ganges Rlver monkey are still not the same as those of human. Although the Ganges Rlver monkey can stand, it walks still with four limbs touching down and the development of its brain is still far behind that of human. But now we can only use it to do the final level experiments before clinical trials can start.

The sense nervus cutaneus of the Ganges Rlver monkey is quite small and difficult to use while the huge nerve of limb is quite thick. The experiments had better to choose the parts that have little influence on function so as not to affect rising, jumping and other activities after operation. The best choice is the upper arm part of the ulnar nerve, which has the merits of easy exposure, less bleeding and less damage.

24.8.1.2 Repair of Sciatic Nerve Defect in Rats

Dissection

The sciatic nerve of rat is quite thick with a diameter up to 1 mm, which can expose 3 cm nerve section for various operations and is the most suitable for animal experiments on peripheral nerve. It is located in the rear thigh, downward between two muscles and semitendinosus of the femoral head, going into the popliteal fossa behind. The nerve is among the loose tissues of muscle interval, with no significant blood vessel going along. So it is easy to be exposed and little operation damage will arise. Meanwhile, around the nerve are soft tissues with sufficient blood supply, so it is easy to recover after operation. When a sample is harvested in reoperation, the nerve is easy to be exposed. If the reaction is severe, the nerve can be taken out even from a piece of adhesion without too serious damage.

Operating Procedure

The rats are enterocoelia anesthetized with 10% hydrate and fixed on the plate. Shave in the back of the thigh with 5% iodine and 75% alcohol to disinfect the skin, and cover with a disinfection cloth towel. Under sterile conditions, choose an arc notch in the middle of the back of the thigh, cut open skin and subcutaneous tissue, enter from the muscle interval between biceps femoris muscle and semitendinosus, and the sciatic nerve is exposed, which is up to the inferior border of the pear muscle and down to the central popliteal fossa. Since the overall length is about 3 cm, it is easy to cause 10-cm nerve damage. The operation requires microsurgery. The operators had better use an operating microscope, or at least amplification glasses. Use 10/0 micro suture to close the terminal, muscular fascia and skin. Generally do not put drainage. After operation, the animals are kept in different cages, and people should pay attention to the recovery of wounds and whether there is helcosis under the foot.

24.8.1.3 Repair of Nervus Peroneus Communis Defect in Rats

Dissection

It is the same as that for sciatic nerve in rats. The sciatic nerve of rate usually divides into nervus tibialis and nervus peroneus communis in thigh. So the nervus peroneus communis can be exposed in the notch mentioned above. The nervus peroneus communis is a little smaller than the nervus tibialis, with a diameter of only 0.3 mm, so it has a higher operation requirement, but its best advantage is reservation of the nervus tiibalis. Therefore, it only affects the pedal, and the thenar sense is reserved. The possibility of pelma helcosis is small after operation.

Operating Procedure

The rats are enterocoelia anesthetized and fixed. The skin in the back of thigh is preserved and disinfected and the sciatic nerve is exposed, as mentioned above in the repair of sciatic nerve defect in rats. Under the adventitia of sciatic nerve, it divides into two large bunches of nerve. The nervus peroneus communis is smaller, on the outside. It goes up to the inferior border of the pear muscle, down to the central popliteal fossa and can even extend to the fibular neck. Since the overall length is about 3 cm, it is easy to cause 10 cm nerve damage. The operation strictly requires microsurgery procedures. The nerve tissue will be damaged if an operating microscope is not used. Use 10/0 micro suture to close the terminal, muscular fascia and skin. Generally do not put drainage. After operation, the animals are kept and observed the same as mentioned above in the repair of sciatic nerve defect in rats.

24.8.1.4 Ulnar Nerve Defect Repair Surgery

Anatomy

Originating in the brachial plexus C8 and T1 nerve root, the ulnar nerve goes through the armpit, medial brachial intermuscular septum and neural groove on the distal humerus, then turns around at the back of the elbow, goes through the flexor carpi ulnaris between the head of humerus and the head of the ulna, turns into the ulnar side of the forearm, and then goes down between the flexor carpi ulnaris and the flexor digitorum profundus. On the juncture of upper and 1/3 middle of the forearm, accompanied by the ulnar artery and ulnar vein, the ulnar nerve keeps going under the flexor carpi ulnaris, and then into the palm on the ulnar side of the wrist. The ulnar nerve dominates the flexor carpi ulnaris, flexor digitorum profundus, hypothenar muscles, interosseus, adductor pollicis and the deep head of flexor pollicis brevis muscle. The length of the ulnar nerve in the forearm is about 5 cm, and its diameter is about 2.5 cm. The sensory branch dominates the sensation of one and a half fingers. And it completely meets the demand of the experimental model of the ulnar nerve which has a 4-km defect. Since the ulnar nerve is accompanied by the ulnar artery and vein, and with nutrition branches inside this part, we must be very careful when it is separated, so as to prevent hemorrhage after operation.

Operating Procedure

The rhesus is locked in a specially-made iron cage. After compressing the rhesus with a separation door, anesthetize its muscle, like injecting ketamine (0.4 mg/kg). When the anesthesia is done, put the rhesus on an operating table and fix its limbs. The hand used for operation is put on the abducent position and fixed on a secondary station. Then, unhair the forearms of the rhesus and disinfect its skin with 5% iodine and 75% alcohol. Cover it with disinfected cloth. Under aseptic circumstances, make a curved incision on the ulnar proper palmar of the forearms. Cut the myolemma on the radial side of the flexor carpi ulnaris before the ulnar nerve, ulnar artery and ulnar vein can be seen in the deep side of the flexor carpi ulnaris. Isolate the ulnar nerve carefully. Be careful to ligate the branches of blood vessels. Cut a defect in needed length and implant the nerve transplant. Suture the epineurium with 10/0 microscopic suture without stress. Bundle suture can be adopted. Suture the intermuscular fascia and skin.

24.8.2 Part 2: Construction of Tissue Engineered Peripheral Nerve

24.8.2.1 Introduction

Tissue engineering of peripheral nerve is to construct peripheral nerve grafts which can totally replace autologous nerve tissue to repair peripheral nerve defects by methods of tissue engineering. Specifically, according to the requirements of tissue engineering, tissue engineering of peripheral nerve is to select three important elements to construct tissue engineered peripheral nerve grafts firstly. The elements are seed cells, biological materials and three-dimensional structure of biological materials. Then researches are conducted step by step, in accordance with the basic theoretical aspects in tissue engineering. They are biocompatibility and adhesion between seed cells and biomaterials, degradability of biomaterials, constitute forms of peripheral nerve grafts and how to avoid immune rejection and so on. We start from small animal experiments and then proceed to primate experiments. We enter clinical trials after successful research on peripheral nerve defects from short ones to long ones.

The three elements in research of constructing engineered peripheral nerve are seed cells, biomaterials and three-dimensional structures.

Seed Cells

Because seed cells are main functional ones which construct the peripheral nerve tissue, it is easy to think that they are neurons. The problem is that what we are researching on is parts of the peripheral nerve, not the nerve center tissue. Strictly speaking, peripheral nerve injury is partial damage to neurons but the body part of the neuron cells is still alive. Now how we treat the injured parts of peripheral nerve is transplanting a part of peripheral nerve, usually taken from the peripheral nerve, to bridge them. The peripheral nerve consists of many parts such as axons, myelin, Schwann cells, epineurium, perineurium, endoneurial, perineurial cells, fibroblasts and so on. But after peripheral nerve injury, axons and myelin regress. And active cells are Schwann cells, fibroblasts, perineurial cells and phagocytes which are newly included. Among them, the fibroblasts do not play a leading role in the process of peripheral nerve regeneration. On the contrary, too many fibroblasts cause scarring. So fibroblasts are not main active cells. The perineurial cells are not active in the process of peripheral nerve regeneration and they are not directly related to regenerating axons. So they cannot be seen as active cells. Phagocytes invade after peripheral nerve injury, and they are responsible for clearing degenerating axons and myelin. After the clearing mission is finished, phagocytes will reduce. And they do not have much association with axon regeneration. Finally, Schwann cells remain. They are the most active cells in the process of peripheral nerve regeneration. In the regeneration process, Schwann cells are the only ones which expresses a variety of neurotrophic factors related to peripheral nerve regeneration, such as NGF, BDNF, CDNF, GDNF, SDNF, LTF, IL-6 and their receptors and so on. Schwann cells are also the ones which secrete essential extracellular matrix to constitute peripheral nerve such as ECM (including Laminin, Fibronectin, and Heparan Sulfate Proteoglycans) which constitutes basement membrane, CAMs (Surface Cell Adhesion Molecules: N-CAM, Ng-CAM/L1, N-cadherin, L2/HNK-1 and so on), Galain, Chondroitin Sulfate, Chondroitin-sulfate-proteoglycans and so on. They are also the builder of myelin surrounding axons, and they secrete all myelin-associated proteins and necessary proteins for unmyelinated nerves. Myelin-associated proteins include Protein 0 (P0), Peripheral Myelin Protein 22 kDa (PMP22), Connexin (Cx) 32, Myelin-associated Glycoprotein (MAG), Myelin Basic Protein (MAP), Periaxin and so on. Necessary proteins for unmyelinated nerve include Glial Fibrillary Acidic Protein, Growth-associated Protein 43 kDa, p75NTR, N-CAM, L1 and so on. Therefore, it is appropriate to select Schwann cells as the active ones of artificial nerve.

The development of tissue engineering aims at the clinical application in the end. In previous studies, Schwann cells were used as seed cells. However, as the number of autologous Schwann cells is limited, reoperation is needed, and allogeneic Schwann cells lead to immune rejection. Therefore, application of tissue engineered nerve in clinic will encounter an insurmountable bottleneck. Recent studies have found that bone marrow stromal cells (BMSCs) have characteristics of stem cells and multipotential differentiation. In 2001, Dezawa M cultured rat bone marrow stromal cells in vitro and made them differentiate to phenotypes of the analogues Schwann cells. But they were not applied to artificial nerves. We induced bone marrow stromal cells to differentiate into the analogues Schwann cells, and seeded them in absorbable polymer materials to construct artificial nerves. We succeeded in repairing defects of rat sciatic nerve (10 mm in length).

Biological Materials

Currently biological materials for tissue engineered peripheral nerve grafts have two categories: natural materials and synthetic materials.

Allograft nerve is the most appropriate natural material. However, because of existence of allogeneic cells and rejection after transplantation, allograft nerve grafts cannot be widely used. Freezing treatment can reduce rejection, but cannot resolve the problems completely either. In recent years, some people used chemical medicine to remove cellular components to eliminate rejection. Experiments prove that allograft nerves are good biological materials.

In synthetic materials, PLA and PGA have good biocompatibility. It is important to notice the degradability of biological materials, because biological materials are necessary places for seed cells to survive in tissue engineered tissue. However, when seed cells grow, develop and reproduce to a certain volume, biological materials should make room for the development of seed cells. That is to say, degradation of biological materials should be on the agenda, and its growth rate should also match the growth rate of seed cells so that seed cells can grow normally. Generally the growth rate of peripheral nerve is 1 mm/day. The experiments in rats showed that it would take one to two months to produce a nerve, of which the length was more than 1 cm. After 3 months, myelin also grows. Therefore, biological materials should be degraded in one to two months and they should make room for the growth of myelin. Metabolites and components of acid and basic produced in the degradation process should not have toxic effects on the nerve.

Three-Dimensional Structures

The most favorable three-dimensional structures for growth of nerves must be designed from bionics. That is to say, we should design with reference to the structure of peripheral nerve and the changes in recovery process after injury.

As we all know, in morphology of peripheral nerve, many nerve fibers compose nerve bundles, and many nerve bundles compose nerve stems. Just like a telephone line, nerve fibers are arranged in parallel but unrelated. They move straightforward in waves. After peripheral nerve injury, axons and myelin fragment and disintegrate in the distal nerve. Lots of the phagocytes invade to clear the fragments of axons and myelin. More importantly, the phagocytes stimulate division and proliferation of Schwann cells which are under rest. And the Schwann cells arrange in line along the intima and basement membrane of each nerve fiber nerve. It actually is a potential pipeline which is called Büengner cells zone. Regenerating axons growing from the near end grow in this potential pipeline, and extend to the end to recover the function. At the same time regenerating axons are surrounded and nourished by Schwann cells, and they produce myelin. Finally, they become myelinated nerve fibers.

The inspiration is that the morphology of biological materials should be conducive to inducing Schwann cells to arrange in line and form Büengner cells zone. So the structure should be convenient for newborn axons to approach and grow into cells zone, or for Schwann cells to wrap new axons sequentially. Therefore, the current biological materials which are commonly used, like spongy or gummy, cannot make newborn axons grow in line. We used chemical medicine to treat peripheral nerve segments and dissolve living cells out. The scaffold of remaining nerve fibers is the most appropriate and physiologically biological material. Schwann cells can grow straightforward along nerve fiber scaffolds in line and wait for the coming of newborn axons after addition of the acellular allogeneic nerve segments. Experiments have also proved that the nerve fiber scaffolds are the most consistent with the physiological requirement.

Overseas Hadlock T used PLGA to make large caliber tubes, of which the diameter was 2.3 mm. The pipes had five longitudinally aligned small lumens, each of which had a diameter of 500 μm. Hadlock T introduced Schwann cells to grow straightforward in line in small tubes, and made one segment of artificial nerve.

In China, early in 1998, Professor Jiakai Zhu from Zhongshan University designed a method which made Schwann cells grow and arrange in line with PLGA wires so that newborn axons could approach and drill into cells zone and grow to the distal end. It proved to be successful in experiments. This method is easier in operation than the method of using tubes. Therefore, at present we use peripheral nerve segments treated by chemical medicine, which are chemical extraction of allograft nerves and PLGA wires. The former has a limitation of using allograft nerves, but the latter is using reliable and inexhaustible biological materials.

Some scholars believe that the cytokines can replace the three-dimensional structure to be one of the three basic elements in tissue engineering. In fact, the three-dimensional structure of biological material is the essential condition for growth and development of seed cells. In fact, as long as seed cells grow well, they must be able to secrete cytokines. So there is no necessity to add extra cytokines.

24.8.2.2 Study on the Relationship Between Selection of Schwann Cells and Biological Materials

Schwann cells are main structures and functional cells of peripheral nerve regeneration. In the nerve regeneration process, Schwann cells provide Bungner zone, and get involved in axons formation, synthesis and secretion of a variety of neurotrophic substances and extracellular matrix components, expressing various cell adhesion molecules. And Schwann cells play an important role in nerve regeneration and function recovery. So it is the best choice to select Schwann cells as the functional cells for tissue-engineered artificial nerve. Compatibility, adhesion and degradation of biological materials decide survival state and biological activity of Schwann cells on the skeleton materials in nerve tissue engineering. It is the key to the success of nerve graft construction. However, at home and abroad, research in this area is mostly limited in morphological study of Schwann cells adhering to materials. Further researches should address gradual degradation of biological materials to make room for the growth of Schwann cells, biological compatibility and adhesion of material-cell interface, etc. Most researches are not perfect. Many basic questions must be re-studied comprehensively so that the study of tissue engineered peripheral nerve grafts can have a solid foundation. Researches should concern how to inoculate Schwann cells on biological materials to form Schwann cell scaffold material similar to peripheral nerve, culturing in vitro, and adopting MTT method, microscopic spectrophotometry and microscopic image analysis techniques, and single cell gel electrophoresis. People should also study inoculating biomaterials into neural stems and a regenerative chamber directly to observe the reaction. In order to analyze the relationship between Schwann cells and biomaterials from multiple aspects, we should research the adhesion and degradation of Schwann cells on biomaterials.

24.9 Construction of Tissue Engineered Blood Vessels

With the development of human civilization and continuous improvement of human nutritional status, arterial thromboembolic disease threatens more and more people’s lives. It has become the number one killer in the United States. All kinds of mechanical violence, traffic accident, gunshot also cause a lot of vascular injuries. Moreover, both morbidity and mortality of vascular injuries are high. Vascular injuries often cause amputation and death. People have been committed to finding a best vascular substitute for a long time.

24.9.1 Autologous Transplantation

(a) Autologous arterials (such as IMA, free peripheral artery) are considered to be the best substitutes so far, but their sources are very limited and their harvest may cause heavy sacrifice in supplying areas. Therefore, their clinical application is limited.
(b) Autologous saphenous vein grafts are the first vascular grafts applied, but resources of autologous saphenous veins are limited. Since saphenous veins stay in pulsing and a relatively high pressure environment in a long term, intimal fibrous hyperplasia causes stenosis, occlusion and progressive atherosclerosis.

24.9.2 Allogeneic Vein Graft

Ideas and methods of using allogeneic veins as vascular grafts have a long history. Nowadays, human umbilical veins treated with glutaraldehyde have been sold as a commodity. In recent years some people use a poly-epoxy compound as a cross-linking agent to improve tissue hardness, easy calcification, sensitization, cytotoxicity and other adverse reactions after being treated with glutaraldehyde. However, application of allogeneic blood vessels is limited, because their own degeneration, immune rejection and postoperative stenosis, aneurysm formation and other adverse reactions after transplantation.

24.9.3 Artificial Materials

With the constant progress in chemical synthesis technology, people turn their attention to artificial materials as vascular substitutes. Polyester fibers (Dacron) which came out in the 50s are the earliest application of artificial blood vessels. Because polyester fibers lead to activation of coagulation system, they can only have relatively short substitution effects on large caliber vessels. Afterwards, people develop polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), polyethylene (PE), Porous segmented Polyurethane, e-PTFE and other artificial materials. And they change the physical properties and surface characteristics of the materials through a variety of methods in order to meet the requirements of vascular implantation.

1. Punch in the artificial materials, so as to form microporous structures. First this can improve their material compliance and make the materials match with elasticity of autologous blood vessels. Second, this can make surrounding capillary endothelial cells grow into the intimal layer through the microporous structure, and cover the inner surface. Alexander W. Clowes confirmed that endothelial cell layer formation mainly relied on surrounding capillaries growing into the microporous structure instead of endothelial cells of anastomotic ends extending and growing after transplantation. (The length of the two ends is only about 2 cm.) And Alexander W. Clowes pointed out that complete intimal layer reduced excessive hyperplasia of smooth muscles.
2. Adopt various degradable coatings to reduce attachment of platelets and blood cells. We hope that endothelial cells creep and cover gradually with gradual degradation of coatings. Satoshi Niu et al. adopted polyepoxy compounds as a cross-linking agent and made a gelatin-heparin coating forming on the artificial vessels to inhibit agglutination of platelets and formation of cellulose, and facilitate the growth of anastomosis site intima.

   Hiroyukin kito coated chondroitin sulfate (CS) and hyaluronic acid (HA) on the internal surface of blood vessels prosthesis. He coated a gelatin layer on the external surface. The purpose was that the internal surface would resist the attachment of platelets and blood cells and the external surface attracted the growth of peripheral tissues. Aruma N set gelatin sponge soaked with endothelial cells around the vessels, of which intima exfoliated. It was conducive to migration of endothelial cells, reducing intima proliferation through paracrine effects, etc.
3. Research on artificial vascular endothelialization

   Since endothelial cells play an important role in anti-thrombosis, inhibiting platelet aggregation, and secreting vasoactive factors, people have contemplated forming endothelial cells lining on the surface of the artificial blood vessels in order to achieve the purpose of simulation of autologous vessels. Host endothelial cells migrate from anastomotic sites to artificial blood vessels only for 2 cm. However, mechanisms and effects of capillaries growing in through the wall and circulating endothelias deposition on the surface of artificial blood vessels are still unclear and further study is needed. So seeding endothelial cells freshly attained or cultured in vitro directly in the inner surface of artificial blood vessels becomes a preferred research direction.
   (a) First phase seeding of vein endothelial cells

       In 1978, Herriy first reported endothelial cells could form endometrial in artificial blood vessels. James et al. seeded endothelial cells in the treated Dacron materials, and used them in animal experiments. They significantly improved the patency rate and reduced the activation rate of platelets. Gherardini put a serum or collagen layer previously on e-PTFE, of which the inside diameter was 1.5 mm, and used rotation culture technique to culture endothelial cells. This could significantly improve the short-term patency rates when used in animal experiments.

However, due to a small number of cells available and poor anti blood flow shear stress of endothelial cells seeded, they led to poor results in clinical application. After 5 years' follow-up, Jenson found that the long-term patency rate of artificial blood vessels, no matter they had been seeded with or without endothelial cells, was very low without significant difference.

(b) First phase seeding of amplification endothelial cells

Matsuda used microcarriers and growth factors or heparin in combination to amplificate a great deal of endothelial cells and smooth muscle cells in a short term, aiming at seeding failures caused by lack of endothelial cells in conventional methods.

Jarrell reported that a large number of endothelial cells could be extracted from the omentum fat and subcutaneous fat. He seeded endothelial cells which were extracted from subcutaneous fat in the e-PTFE inner surface. The fluorescein analysis showed that monolayer formed after three months was primarily from seeding endothelial cells. And he used the monolayer in the dog's carotid artery replacement and achieved satisfactory experiment results. But so far, no success has been reported in clinic. The main reason may be false intimal hyperplasia caused by impure seeded cells.

(c) Culturing second phase lining of endothelial cells in vitro

Zilla seeded endothelial cells and incubated them in vitro for 8–9 days to enable endothelial cells to form complete endodermis with good anti-shear stress and anti-thrombosis, mainly because of differentiation maturation of the cytoskeleton. This is lining technique of artificial blood vessels with endothelial cells in vitro. Deutsch reported clinical results of this technique, and the effect was satisfactory.

However, artificial vascular endothelialization is also inadequate, because it has high requirements for experimental techniques, and it does not apply to acute or sub-acute patients. Further study needs to be done in aspects of the source of endothelial cells and lining technology. What's more important, long-term patency rate of artificial blood vessels with a caliber less than 6 mm is relatively low. The low perfusion is a major factor, and there are high resistance by special parts (such as below-knee parts, etc.), mismatched graft material elasticity, weak and lasting foreign body reaction, chronic inflammation, and implant infection caused by the accumulation of bacterial colonies and other factors. The above factors made artificial blood vessels unsuitable for transplantation of small diameter vessels. Sayers reported that the patency rate of artificial blood vessels with a diameter less than 6 mm was less than 40% after 6 months.

After these artificial blood vessels made from non-degradable polymer materials are directly transplanted into the body, they may produce a series of adverse reactions, such as formation of blood clots and lumen blocking. Biological treatments such as coat proteins, biological material or seeding vascular endothelial cells lining on luminal surface can control side effects, but in the body, as blood flow erosion causes shedding of the artificial blood vessel lumen surface of biological material, it is difficult to maintain luminal patency for a long time.

24.9.4 Research on Reconstruction of Tissue Engineering Vessels

With the concept of tissue engineering and deep-going researches, people turned to study a variety of vascular formal ingredients and biodegradable materials, aiming to synthesize tissue engineered blood vessels.

24.9.4.1 Scaffold Materials of Tissue Engineered Blood Vessels

Scaffolds for tissue engineered blood vessels are generally divided into two types: biological materials and abiotic materials.

Biological materials are those which are derived from a living body and constituted by natural biological macromolecules. They can also be divided into unstructured macromolecular materials, such as collagen gelatin and alginates, and acellular fibrous tissue structure materials, such as acellular small intestinal submucosa (SIS), acellular dermal matrix and acellular vascular lumen matrix and so on. Since biological materials have strong affinity for cells, they can provide ECM scaffold conditions similar to the natural growth and development environments of body tissue for growth and differentiation of cells.

Collagen is the most abundant and widespread structural protein in body. It contains arginine-glycine-aspartic acid (RGD) and cell specific identification signals. Because of this characteristic, it is widely used in construction of various types of tissue engineered scaffolds.

The acellular matrix materials refers to those whose cellular components of tissue have been removed but whose basic structural protein conformation maintained using some special methods in order to make them similar to the previous cells in structure, strength and other aspects. A variety of tissues (such as SIS, pericardium, fascia, blood vessels, dermis and other) have been prepared into decellularized matrix, and processed into small tubes as an alternative for blood vessels. Non-biological materials mainly are chemosynthesis macro molecular degradable polymers materials. The biodegradable materials most commonly used are polyglycolic acid (PGA), polylactic acid (PLA) and polylactic-polycolic acid (PLGA).

In recent years, there are polyhydroxyoctan (PHO) and polyhydroxyalkanoate (PHA) and more materials. They have many advantages. They can be synthesized in quantity. And their structures and degradation rates are easy to control. Insufficient natural affinity with the cells is their main drawback which can be overcome mainly through continuous modification of the material and linking to related cell recognition molecules.

24.9.4.2 Construction of Tissue Engineered Blood Vessels

Direct Transplantation of Acellular Matrix Material
Use natural biological materials to prepare abiotic (cell) tube-shape grafts. Transplant them into the body. Produce new functioning blood vessels through migration and proliferation of SMC, EC, etc. of receptor vessels, and integration of cells, ECM and skeleton materials.

Huynh et al. used porcine small intestinal submucosa acellular collagen matrix to make small tubes, of which the diameter was 4 mm. The cavity surface coated by bovine collagen fibers and treated by heparin complex inhibits the coagulation reaction. In animal experiments they performed arterial bypass operations in rabbits. Four, eight and thirteen weeks after operation, they checked that all the transplanted tubes were unobstructed. SMC and EC of rabbits gradually migrated into skeletons of small tubes. Three months after surgery, the collagen tubes of synthetical receptor cells were constructed to cellular blood vessels. Wilson used acellular blood vessels (carotid artery) matrix from dogs to conduct the homologous artery transplant experiments in animals, showing good compatibility. Love et al. applied a special fast transplant method of using the patient's own pericardium to make small caliber vascular skeletons. Small caliber vascular skeletons were made from six autologous pericardium (5 mm in diameter and 5.5 mm in length). Five months after carotid artery transplantation, the patency rate achieved 100%.

The method of preparing acellular tissue matrix as biomaterial grafts of inactive cells is simple, but it remains to be clarified that whether the grafts prepared by animal collagen may lead to immune rejection or not.

Simulating Vascular Development Physiological Environment In Vitro, and Constructing Bioactive Vascular Grafts
In 1976, Donald et al. cut elastic basement (400 μm in thickness) from the vessel wall, and cultured rat aortic smooth muscle cells on it. And later, more work was done focusing on using collagen I to prepare matrix material and using various types of cellular component of the vascular wall to synthesize vessel models. Weinberg et al. used collagen and vascular wall cells to construct a vessel model. And they firstly mixed the medium, collagen and SMC and injected the mixture into tube-shape containers. Then the mixture was condensed and collagen tubular mesh scaffolds (equivalent to tunica media) formed. And they sleeved polyester mesh over scaffolds. They inoculated FB to construct the analogues of vascular adventitia. After 2 weeks, the adventitia matured. They injected EC suspension into the tubes and cultured them in rotation. After one week, EC attached on the tube inner walls evenly. Synthetic artificial blood vessels were similar to muscular arteries. Electron microscopic observation showed that the SMCs fully differentiated and bipolar cells contained fiber bundles and a dense body; EC had Weibel-Palade bodies, and secreted von Willebrand factors and prostacyclin; the TEBV tolerance of cavity pressure was related to nylon mesh, collagen concentration, inoculation cell density and culture time. This experiment indicated that the body's blood vessels could be artificially constructed, and the human cells could be used to construct the vessels. However, because their TEBV elastin content was extremely low and SMCs and collagen fibers were arranged disorderly, the SMC density and collagen was only one-eighth to one-quarter of that of natural blood vessels, and the pressure resistance of vessel wall was poor. It was related to low collagen mechanical strength, and it was also the biggest obstacle in animal experiments and clinical applications.

L'Heureux et al. pre-cultured three kinds of vascular cells, and then combined them to form lamellar structure natural vascular biomaterials TEBV. They first cultured human umbilical vein SMC and human skin FB in culture flasks respectively. After being incubated with conditioning medium for 30 days, the membrane-like cultures were constituted by cells and ECM formed. They peeled the FB membranes from flask walls, and wrapped them over inertia tube axis for further culture. In maturity, membranes bonded closely, and produced cylindrical culture. FB tube membranes were made into acellular inner membrane (IM) after dehydration treatment. When assembling, they sleeved IM over multiple empty Teflon tubes axis, the external diameter of which was 3 mm. Then they wrapped SMC membranes to make tunica media. At this moment, they put the construction into a bioreactor, while the culture solution refluxed through the outer lumen and tube to support cells growth. Then they wrapped FB membrane as outer membrane. After vascular wall cells and ECM became mature, they removed center tube axis, and inoculated EC in the tube. They cultured TEBV similar to body vascular lamellar structure with active cells. SMC and EC of these vessel walls showed a differentiated state. And vessels had good blood compatibility, and they could withstand 2000 mmHg hydrostatic pressure. Short-term (7 days) transplantation in animals' body showed good operative suture. The construction of TEBV is a major breakthrough in vascular tissue engineering, and it shows a possibility of constructing and culturing functional blood vessels by cellular components. The mechanical strength of blood vessels is related to SMC and the matrix which are produced by vessels. Changing culture conditions can promote the secretion of ECM. In this construction model, devices in vitro are not complicated, and we can learn from it. But long-term patency rate and stability of blood vessel grafts in body remain to be investigated, and the mechanical strength of the wall needs further improvement.

Niklason et al. injected SMC suspension into a biodegradable polymer (PGA) tube scaffold. After cells' attachment, they cultured cells with a bioreactor which could simulate fetal development environment and produce pulsating flow and circulation. After 8 weeks of culture, SMCs migrated into the PGA skeletons, secreted collagen and other ECM when PGA degraded. When the tubes composed of ECM and cells together replaced PGA scaffolds, they inoculated EC in the tubes. The bioreactor made culture medium flow in the lumen constantly (producing certain shear stress) and made the fluid produce rhythmic pulse waves by controlling the pulse pump. They cultured cells to be mature. The experiment showed that pulsating culture conditions were conducive to SMC migration, differentiation phenotypic expression (the amount of myosin increased in cells, cells kept contractile response, and cell mitosis rate did not increase) and secretion of collagen cells/ECM. The cell density and collagen content of products which were cultured in vitro could approximate to those in vivo. The mechanical properties of vessels cultured in this physical environment and optimized medium were superior to those of the previous tissue engineered blood vessels. The tear degree/hydrostatic pressure was greater than 2000 mmHg, the suture holding strength reached 90 g, and the collagen content was more than 50%. The cells on vessel's wall had a good differentiation status, and the update rate was low. The vessels had contractile response on drug effects. Four weeks after animal autologous transplantation, TEBV was still unobstructed, blood flow was good, and allogeneic graft patency was greater than that of pulseless culture. Vascular cells had contractile response to prostacyclin. In histological examination, vessels did not have inflammatory reaction. This model pioneered pulsating culture and innovated in vitro incubation conditions of TEBV, but its facilities are complex, so it is difficult for common laboratories to configure.

Taking Advantages of Body's Inflammatory Response to Form Blood Vessels Through Heterogeneous Migration

Campbell et al. took silicon tubes of different diameters and inserted them into the abdominal cavities in rats or rabbits. Inflammatory reaction occurred in the abdominal cavities, and made the tube surface covered with myofibroblasts, collagen matrix and monolayer mesothelium. Then they took out silicon tubes and separated tubes and adherent tube-shape regenerating tissues. They turned tube-shape tissues over and built the analogues of artery tubes. The whole structure was similar to a normal vessel. Four months after autologous transplantation of rat abdominal aorta or rabbit carotid artery, the transplanted vessels kept unobstructed and continued to develop in the body. This experiment tried an unconventional way to use the adaptability of cells to the environmental influences. This graft was constructed of nonvascular component abdominal wall cells, and its original structure was not an artery or a vein. Once it was set in a physiological environment after transplantation, the body provided a potential limited atmosphere for differentiation. The cells oriented differentiation according to the environment demands.

Tsukagoshi et al. took a piece of 10 mm × 40 mm rat autologous dorsal fascia, and twined it over a silicon stick with a diameter of 1.5 mm. Then they transplanted the stick with dorsal fascia into rat middle thigh hypoderm and took it out after 4 weeks. They separated the silicon stick, and inserted a collagen fiber tube which was made from fascia after anticoagulant treatment into a femoral artery, and kept fiber tube unobstructed after operation. No arterial aneurysm grew. Five weeks after operation, the neointima expanded to 70%.

Constant deep-going research in tissue engineering makes various construction models of tissue engineered blood vessels. Although the best construction model has not been established, we all work hard for high level biocompatibility, plasticity, less foreign body reaction, no blood clots, no infection and other objectives. Tissue engineered blood vessels will be complete autologous vessels with the growth of tissues finally. This research will bring a bright dawn to the treatment of cardiovascular diseases, and even the transplantation and reengineering of tissues and organs.

Bibliography

1. Langer R, Vacanti JP. Tissue engineering. Science. 1993;260: 920–1.
2. Vacanti JP, Langer R. Tissue engineering: The design and fabrication of living replacement devices for surgical reconstruction and transplantation. Lancet. 1999;354(Suppl 1):132–4.
3. Fan H, Zeng X, Wang X, et al. Efficacy of prevascularization for segmental bone defect repair using β-tricalcium phosphate scaffold in rhesus monkey. Biomaterials. 2014. [Epub ahead of print].
4. Wang L, Fan H, Zhang ZY, et al. Osteogenesis and angiogenesis of tissue-engineered bone constructed by prevascularized β-tricalcium phosphate scaffold and mesenchymal stem cells. Biomaterials. 2010;31(36):9452–61.
5. Chen SY, Qin JJ, Wang L, et al. Different effects of implanting vascular bundles and sensory nerve tracts on the expression of neuropeptide receptors in tissue-engineered bone in vivo. Biomed Mater. 2010;5(5):055002.
6. Jin Y, Fan J, Li F, et al. Local sympathetic denervation of femoral artery in a rabbit model by using 6-hydroxydopamine in situ. Biomed Res Int. 2014;2014:874947.
7. Fan J, Bi L, Jin D, et al. Microsurgical techniques used to construct the vascularized and neurotized tissue engineered bone. Biomed Res Int. 2014;2014:685412.
8. Tuo Y, Guo X, Zhang X, et al. The biological effects and mechanisms of calcitonin gene-related peptide on human endothelial cell. J Recept Signal Transduct Res. 2013;33(2):114–23.

9. Zhang ZY, Huang AW, Fan JJ, et al. The potential use of allogeneic platelet-rich plasma for large bone defect treatment: immunogenicity and defect healing efficacy. Cell Transplant. 2013;22(1):175–87.
10. Kamel RA, Ong JF, Eriksson E, et al. Tissue Engineering of Skin. J Am Coll Surg. 2013;217(3):533–55.
11. MacNeil S. Progress and opportunities for tissue-engineered skin. Nature. 2007;445(7130):874–80.
12. Fan J, Mu T, Qin J, et al. Different effects of implanting sensory nerve or blood vessel on the vascularization, neurotization, and osteogenesis of tissue-engineered bone in vivo. Biomed Res Int. 2014;2014:412570.
13. Bi L, Cheng W, Fan H, et al. Reconstruction of goat tibial defects using an injectable tricalcium phosphate/chitosan in combination with autologous platelet-rich plasma. Biomaterials. 2010;31(12):3201–11.
14. Chen B, Pei GX, Jin D, et al. Distribution and property of nerve fibers in human long bone tissue. Chin J Traumatol. 2007;10(1):3–9.
15. Jiang S, Jiang Q, Zhang Y, et al. Why we need semisolid decalcification system in bone tissue engineering? A story begins with honeycomb. Med Hypotheses. 2010;75(2):225–8.
16. Fu S, Mei G, Wang Z, et al. Neuropeptide substance p improves osteoblastic and angiogenic differentiation capacity of bone marrow stem cells in vitro. Biomed Res Int. 2014;596023(10):23.
17. Mei G, Xia L, Zhou J, et al. Neuropeptide SP activates the WNT signal transduction pathway and enhances the proliferation of bone marrow stromal stem cells. Cell Biol Int. 2013;37(11):1225–32.
18. Temenoff JS, Mikos AG. Review: tissue engineering for regeneration of articular cartilage. Biomaterials. 2000;21(5):431–40.
19. Sharma P, Maffulli N. Tendon injury and tendinopathy: healing and repair. J Bone Joint Surg Am. 2005;87:187–202.