
Free Tissue Transfer for Fingertip Coverage

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Introduction

Amputation of the pulp of the fingers and thumb is a frequent injury in a hand surgeon's daily clinical practice. The hands are the second most vascularized and innervated region of the body after the face, thus allowing for multiple flaps to treat them. However, sometimes, because of the size, sensitivity, and aesthetic characteristics, pulp defect reconstructions need specific tissue supply from a region other than the hand. Due to its similar characteristics, the foot is the most suitable donor site for these tissue transfers.

Treatment of Fingertip Injuries

The basic objectives for the treatment of fingertip injuries are preserving the length of the digit when possible, and providing soft tissue coverage with protective sensation at a minimum and a painless fingertip [1]. There is a wide diversity of treatment options based on the characteristics and nature of the lesion (one of the most important is the size), the physical demands and preferences

of the patient, and the expertise of the treating surgeon and the health-care system. Management varies from healing by secondary intention to complex reconstruction or even replantation.

For lesions with pulp loss and no distal bone exposure, management options include primary closure, healing by secondary intention, skin grafting, and even completion amputation. When adequate soft tissue coverage is available volarly, primary closure or healing by secondary intention is preferable. Recovery of sensation after the latter has been found to be superior to other surgical methods, and two-point discrimination (2PD) approaches normal after healing, but the lesion needs several months for complete cicatrization. [1]

When there is bone exposure and no volar soft tissue coverage available, these injuries are candidates for pulp reconstruction, as long as 5 mm of nail bed distal to the lunula is preserved (as this amount of nail remains both aesthetic and functional) [2]. The use of flaps in such instances provides an important tool for coverage when more simple measures are inadequate [3].

Depending on the size of the defect, the pulp can be reconstructed using local, regional, distant flaps, or free tissue transfers. Local flaps restrict donor morbidity to the same injured digit, and furnish tissue coverage nearly identical in quality to the lost tissue, so sensation, aesthetic, and functional recovery are optimal; but they are limited in size and distance of transfer. For transverse or dorsal oblique amputations that need less than 1 cm of tissue advance, the Atasoy–Kleinert V–Y flap [4] is the best option for all digits.

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The Kutler lateral V–Y flap [5] is better suited for volar oblique amputations that have more tissue loss volarly than dorsally, but also it can be used for transverse amputations [1] as long as the advancement needed is less than 3–4 mm.

In the case of the thumb, one flap that has demonstrated good sensation recovery, but inferior aesthetic recovery is the Moberg flap [6]. This can be used when a defect is <2 cm and a V–Y advancement flap cannot provide adequate coverage.

It is true that other advancement flaps such as the step-advancement island flap and/or the oblique triangular neurovascular advancement flap allow more distance of advancement and they are also sensate flaps, but these are based on only one neurovascular pedicle, wherewith the sensation recovery would not be as good as other options that provide two pedicles. Some authors have reported what, in their opinion, are good results using homodigital transposition flaps such as the reverse digital artery island flap [7]. However, these flaps sacrifice one digital artery, involve extensive dissection, are prone to congestion, and result in abnormal sensation [8] since they are not neurosensory flaps.

When local flaps are inadequate, it is popular to use regional flaps such as the cross-finger flap and the thenar flap, or distant flaps such as the groin flap, chest flap, and cross-arm flap.

One must differentiate between the basic objective of the treatment and the best treatment. The fact that one treatment is technically easier, more reliable, or saves time or money does not make it the best option.

These very popular regional and distal flaps, because of their simplicity and reliability, have major drawbacks that should not be obviated: The cross-finger flap is a two-stage procedure, insensate nonglabrous skin is used, fingers are held in an awkward position and immobilized for 2–3 weeks, and a second digit is violated as a donor site. The thenar flap provides glabrous skin cover but otherwise shares the same problems as the cross-finger flap [8]. The same occurs with distant flaps, that in addition to being insensate flaps, rely on donor-site blood supply while the flap incorporates and can lead to stiffness sec-

ondary to the prolonged period of immobilization required for healing [1].

An excellent alternative to these flaps is the free flap or free tissue transfer, a procedure in which soft tissue with or without bone is harvested with its vascular pedicle and transferred to a recipient site, where the pedicle is anastomosed to local vessels, thus vascularizing the tissue [9].

Although using free tissue transfer flaps can involve breaking the guidelines of the reconstructive ladder, it is justified in select cases since the ideal objectives of fingertip coverage can be reached: highest sensory, functional, and aesthetic recovery, and avoiding the aforementioned disadvantages of simpler flaps. In addition, it has been demonstrated that free tissue transfer success rate in experienced hands approaches 99%, whereas local or regional flaps can be less successful because of initial damage to regional soft tissues. [10] We concur as Dr. Levin [10] reported in 2008, that frequently local flaps are used by individuals without microsurgical skills when a free flap is the best treatment. Local flaps are often damaged because of compromised inflow and outflow, therefore these patients will need a second and more complex operation, morbidity will be prolonged and will compromise the finger which finally often needs to be salvaged by free tissue transfer.

The interest in transplanting autologous tissue peaked and the earliest free flaps were described in the 1970s. However, the failure rate was high due to the complexity of the anatomy and that the field of autologous tissue transplantation was in the early stages of development. Pioneers such as Buncke, Acland, Shaw, and Tamai popularized the free tissue transfer for use in extremity trauma. Over the next 10 years, a variety of composite flaps evolved. But it was in the 1980s and 1990s when, with microsurgical evolution, new skin flaps were identified based on defined vascular territories, the evolution of perforator flaps, and the increased success of flaps. This expanded horizons for extremity reconstruction [10].

For fingertip repair, not every free flap can be used. Standard free flaps are too bulky, or not durable or sensate enough. Only flaps that allow ideal outcomes of fingertip reconstruction should

be used, like the ones that [4]: restore grasping function without slippage [11], restore the contour of the pulp with glabrous skin and no bulging mass [12], are strong enough to withstand friction [13], provide sufficient soft tissue for a cushion effect [14], and have sufficient sensory acuity for fine manipulation (discriminating sensibility) [15]. To accomplish these goals, several small free flaps have been developed in the last few years, although not all of them meet expectations. The most popular small flaps for fingertip coverage are:

- Thenar free flap
- Free flap from the flexor aspect of the wrist
- Arterialized venous flap (AVF)
- Posterior auricular free flap
- Free medialis pedis flap
- Free medial plantar artery perforator flap (MPAP)
- Great and second toe pulp neurovascular flaps

All provide glabrous or hairless skin coverage. The aesthetic similarity and functional capacity of tissue transfers from the foot are unrivaled. However, when patients refuse a flap from the foot, or they are not indicated (i.e., athletes), the other flaps offer acceptable outcomes.

The Thenar Free Flap

The free thenar flap combines a good match of the skin components (thick skin of similar glabrous texture and color to that of the digits) with the freedom of a free flap transfer when patients will not accept any transfer of tissue from the foot and local flaps are not indicated. It can be nourished by the radial digital artery of the thumb, as it was first used as a free flap by Tsai in 1991 [16], by the radial artery [17], or by the superficial palmar branch of the radial artery (SPBRA) [17–19], as is the free flap from the flexor aspect of the wrist. The most frequently used artery is the SPBRA, which offers a perfect match size for anastomosis to the digital artery.

Venous drainage is based on the volar superficial veins of the thenar eminence or the venae comitantes of the artery itself. The sensibility of this

area is mainly provided by the sensory branch of the radial nerve, which may be overlapped by the antebrachial cutaneous nerve [19].

Operative Technique

The first step consists of identification of the radial artery and the origin of its volar branch. This branch can be confirmed preoperatively by using a Doppler flowmeter. To locate them intraoperatively, the skin must be incised for 2–3 cm in a slightly angled fashion at the wrist crease. Sometimes, a perforator rising from the radial artery, distinct from the volar artery and supplying directly the thenar region, can be found. In this situation, the flap can be based exclusively on this perforator. Its origin is about 3 cm proximal to the wrist crease. For this reason, the initial incision is addressed to first find this branch [19].

If it is not available or the diameter is too small, we recommend moving 1–2 cm distally to isolate the SPBRA with one or two venous branches that run parallel to or across the SPBRA toward the thenar eminence. In addition, there are several branches of the antebrachial nerve radial to the SPBRA and they distribute to the thenar eminence. The design of the flap can be adapted so that the flap includes the terminal part of these branches [18]. Other authors do not include sensory branches in their dissections or include other nerve branches such as the palmar branch of the superficial radial nerve. After dissection of all these structures the flap can be elevated and then the SPBRA is sutured to the digital artery, the veins sutured to the dorsal digital veins and the nerve to the digital nerve in an end-to-end fashion.

The main indication for the thenar free flap is for the patient who would rather not sacrifice soft tissue from the foot when other local flaps are not usable.

Advantages of this flap are that it requires minimal dissection, the sacrifice of a nondominant artery, and the thickness and glabrous texture offer an optimal stability in palmar pinch. [17]

The main disadvantages are the possibility of an enlarged scar in the donor area, potentially unpleasant, and the variability of sensory recovery. For small skin defects, it has been reported that

even without neurotomy, the pedicled thenar has high possibilities to recover spontaneous reinnervation better than very popular regional flaps (i.e., cross-finger flaps). This is supposed to be a consequence of the higher presence of sensory receptors in the thenar area [20].

Free Flap from the Flexor Aspect of the Wrist

The distal portion of the flexor aspect of the forearm has been used as the donor site of several kinds of flaps. Sakai [21] described a free flap harvested from the flexor aspect of the wrist based on the SPBRA, with the intention of providing a thin, pliable, and hairless coverage for the fingertip without sacrificing the radial artery (what other traditional flaps from the forearm do).

This flap can incorporate a portion of palmaris longus and/or the palmar cutaneous branch of the median nerve to be used as a vascularized tendon and/or nerve graft for other defects of the hand and digits, but it is a non-innervated flap. This must be taken into account while reconstructing fingertips.

Results in sensibility obtained in the pulp using this flap have been compared with other frequently used nonglabrous local flaps, and seem to be similar (between 9 and 11 mm). The explanation for these acceptable outcomes given by some authors is that this flap is very thin and is applied to a sensitive area [22].

The operative technique for harvesting the flap follows Sakai's instructions: The flap is drawn transversely, with its palmar side along the distal wrist crease, so that the donor site can be closed easily and primarily. As for the draining vein, one or two subcutaneous small veins of sufficient length are marked from the flap to the proximal portion of the forearm. First, the skin incision is made down to the level of the radial artery to confirm the origin of the SPBRA. The skin incision is then deepened to the muscles and tendons along the margins of the flap. On the proximal side of the forearm, one or two subcutaneous veins of adequate size and length are

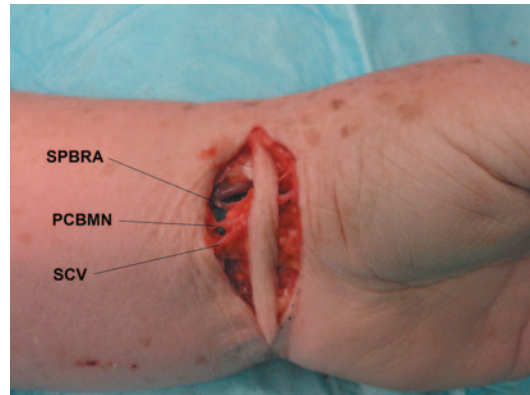


Fig. 8.1 Free flap from the flexor aspect of the wrist. *SPBRA* superficial palmar branch of the radial artery, *PCBMN* palmar cutaneous branch of the median nerve, *SCV* subcutaneous vein

chosen for drainage, and others are ligated. The flap is then raised over the muscles and tendons. At the distal wrist region or the thenar site, the SPBRA running into the palm is ligated and cut to the length that will be needed. The flap is then ready to be elevated and transferred. The donor defect is closed primarily.

The wrist flexor aspect free flap can be an interesting alternative for treatment, although lack of sensation and donor-site scar characteristics (which should be left in the distal wrist crease, otherwise it may suggest the wound is self-inflicted) are important drawbacks [21] (Fig. 8.1).

Arterialized Venous Flaps

Venous flaps are those in which the primary blood supply enters and exits the flap through the venous system. The exact vascular circuit or mechanism of physiologic nutrition, however, remains unclear [23].

There are several clinical applications for them in the reconstruction of hands and fingers when conventional flaps are limited or unavailable [24]. They can be used as pedicled venous flaps, free venous perfusion flaps, free arterial perfusion (arterialized) venous flap, and innervated AVF for different goals such as resurfacing soft tissue defects, skin and vascular defects,

reconstruction of circumferential injuries, and, of course, for fingertip reconstruction.

Several classifications of the venous flaps have been described in literature based on: vessels that enter and leave the flap as well as the direction of flow within these vessels [25], presence of an intravenous valve, the venous network of the donor site, the location, and the number of veins at the recipient site [26]. Probably the most commonly used venous flaps in plastic and microsurgery surgery are the three classification types of Thatté et al. [25] which are type I, unipedicled venous; type II, bipedicled; and type III, AVFs, which are perfused by a proximal artery anastomosed with a cephalad end vein and drained by a distal vein. The most reliable of these is the type III [27] and that is why clinical use has mostly focused on it.

Success in reconstructing skin defects of the digits with AVFs seems to be influenced by the donor site and size of the flap [27]. The influence of donor site on the survival of AVFs has been attributed to the configuration of the venous network of different donor sites. The most frequent donor sites for venous flaps are: the distal volar forearm, the dorsum of the foot and medial aspect of lower leg, and the thenar and hypothenar eminences [28]. The configuration of the dorsal skin of digits and hypothenar or thenar eminence is more favorable than that of the volar forearm, while the donor site of the lower leg, in which there is a poor venous network, is considered the last choice for venous flaps. Kakinoki et al. [29] showed that the size of the flap was the factor that correlated statistically with a successful result. AVFs with a surface area less than 767 mm² were less likely to develop necrosis of the skin (Fig. 8.2).

For fingertip reconstruction, the most indicated AVFs are the thenar and hypothenar flaps, first described by Iwasawa et al. [28], since the volar forearm and dorsum of the foot skin are not glabrous skin, have poor skin texture for volar surface reconstruction, and result in instability with pinching.

The operative technique of the AVF from the thenar and hypothenar eminences was described this way in the original paper:

The donor site is the lateral side of the metacarpophalangeal joint for the thenar venous flap and the lateral side of the hypothenar region for the hypothenar flap. A branch of the dorsal cutaneous vein is located in either the thenar or the hypothenar region. When elevating the flap, a segment of the branch of the dorsal cutaneous vein, the subcutaneous tissue and deep fascia of the thenar or hypothenar muscles are included. At the recipient site, a proper digital artery and dorsal vein are prepared at the interphalangeal joint level and microvascular anastomoses are performed between these vessels [28].

The skin of the thenar and hypothenar regions is not completely glabrous. However, it has a thick keratosis layer and deep fascia of the thenar and hypothenar muscles that provide durability for mechanical stress and good stability. None of these is a sensory flap. Nevertheless, good sensory recovery has been reported with thenar and hypothenar flaps by Iwasawa et al. The authors explained this recovery is due to the fact that palmar tissue has many sensory receptors [28].

Innervated AVFs have been described from the dorsum of the foot preserving sensation by anastomosing branches of superficial peroneal nerves with the digital nerves [30] but they are nonglabrous flaps. The authors explain that, “ideally, the volar side of the finger should be reconstructed with glabrous skin such as palm or instep. Although small arterialized venous flaps that use medial plantar skin are useful for finger pulp reconstruction it is difficult to harvest a thin and pliable arterialized venous flap from medial plantar skin. It is also not easy to include enough long cutaneous veins and cutaneous branches of medial plantar nerve in the instep venous flap.”[31]

Compared with conventional arterial flaps, the advantages of venous flaps are that they provide non-bulky and good-quality tissue, ease of design, and harvest without the need to perform deep and tedious dissection, no sacrifice of a major artery at the donor site, no limitation of the donor sites, and less donor-site morbidity with optimal postoperative contour. They could be a good option for reconstruction of small defects of the fingers, but it should be noted they are either insensate or nonglabrous skin flaps or both. Also, they have an unstable postoperative course and are difficult to monitor. They are not very reliable

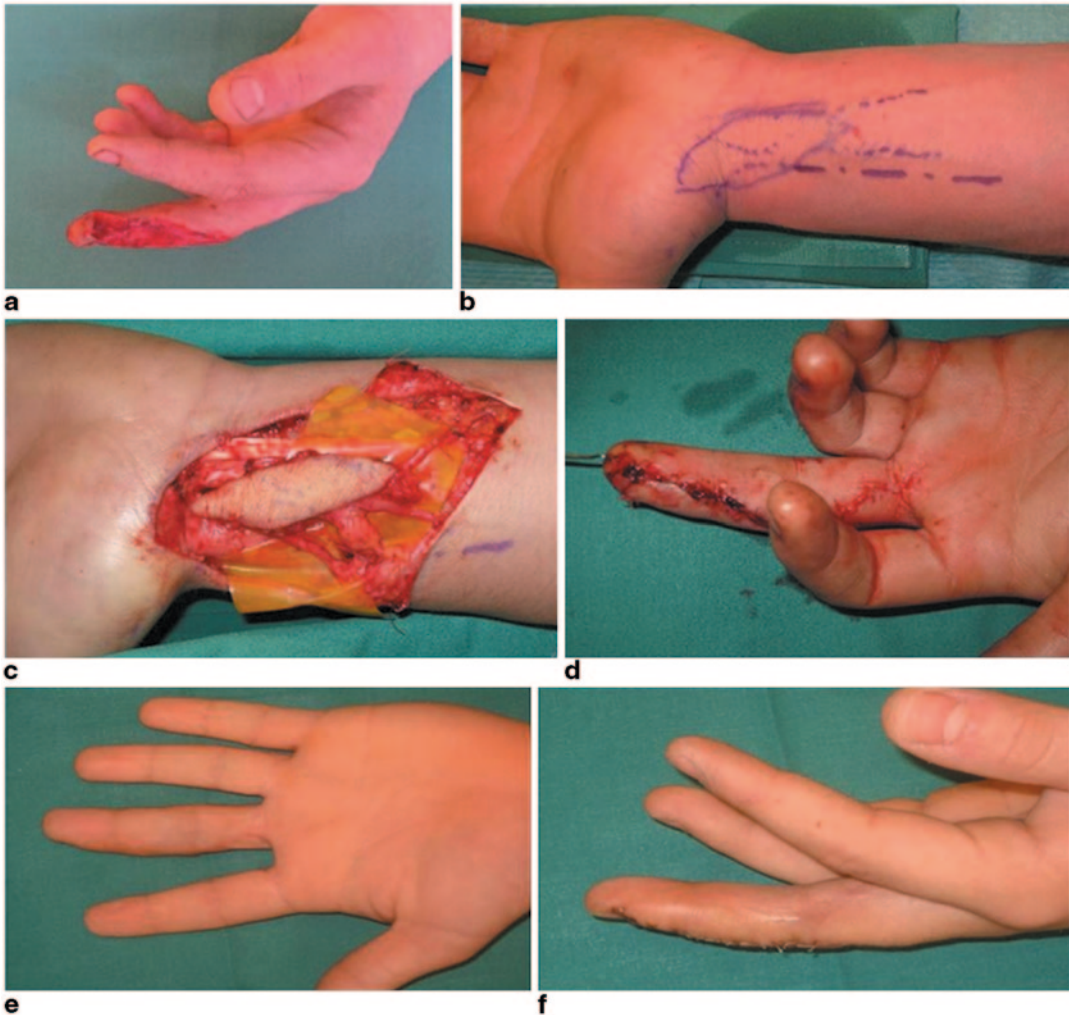


Fig. 8.2 Arterialized venous flap from the distal volar forearm. The terminal branch of the lateral cutaneous nerve of the forearm is included in order to provide a sensate flap. (Courtesy: Dr. Thomas Giesen)

due to their inconsistent survival and possible partial loss, but these problems may be solved by techniques such as surgical delay procedure, pre-arterialization technique, surgical expansion, and application of growth factors after meticulous preoperative planning. [23].

Posterior Auricular Artery Sensate Flap

This flap provides wound coverage while retaining sensation and negligible donor-site morbidity. It is used for fingertip radial-side pulp reconstruction and is based on the posterior

auricular artery. The first clinical success for the free retroauricular skin flap was reported by Wada and coworkers in 1979 [32], and it has been popular for intraoral and facial reconstruction for years. It was in 2009 when Hsieh et al. [33] first described this flap for fingertip reconstruction.

The posterior auricular sensate free flap is not simple but some authors consider it cost-effective because the sensation recovery is good and primary closure of the donor site is possible. The donor-site scar is located in the posterior auricular area, and it provides good aesthetic appearance of finger reconstruction area with no joint stiffness.

Surgical Technique

The posterior auricular vessels over the posterior auricular sulcus must be detected preoperatively using a Doppler probe. The posterior auricular vessel is identified after incision over the posterior auricular sulcus and meticulous dissection. A skin island in the posterior auricular area is designed over the entry area of the posterior auricular vessel. The flap is elevated from the layer beneath the posterior auricular vessel. The great auricular nerve is also identified in the posterior auricular area. The pedicle of the posterior auricular flap is anastomosed to the radial digital artery and dorsal vein, and the great auricular nerve is anastomosed to the radial side digital nerve. Primary closure of the posterior auricular donor site can be accomplished with no morbidity [33] (Fig. 8.3).

Widespread utilization of the posterior auricular free flap has yet to become popular due to a considerable amount of technical challenges, although previous success has been reported and can be promising. Technical challenges include a short vascular pedicle, a superficial venous system that is not always present, extremely small vena comitantes, anatomic variation [34] (for instance, sometimes posterior auricular vessels are too small to transfer in a free flap), tendency of the flap based on the superficial temporal vessels to become congested, and limited flap size (although this is not usually a problem when treating pulp injuries).

Since there are few reports of this flap as far as pulp coverage is concerned in the literature, it is difficult to draw reliable conclusions about its

indications and true functional and aesthetic results. Hsieh et al. [33] report 7 mm of static 2PD and good aesthetic recovery and consider this flap an alternative to foot tissue transfers.

Inversely, there are other flaps such as the posterior interosseous artery flap [35] or the temporo-parietal free fascial flap with a split-thickness skin graft [36] that are mentioned in the literature as useful for fingertip coverage. The former gives excellent cover but it is a nonglabrous skin flap, and the latter, even though it provides a pseudo-glabrous surface, is relatively insensate. These reasons are more than enough not to consider them ideal options for the replacement of pulp injuries.

Glabrous Skin Flaps

Defects on the volar surface of the fingers require replacement with specialized sensory cells that can only be found in the hand itself, on the toes, or on the sole area of the foot, what is generally known as glabrous tissue [37]. The best way to accomplish this replacement is by microvascular transplantation of glabrous skin from the foot [38].

The most widespread free flaps that can provide glabrous skin on a consistent vascular pedicle are the free medialis pedis flap, free MPAP flap, and great toe and second toe pulp neurovascular island (NVI) flaps. Free medialis pedis flap and free MPAP flap are interconnected and share anatomy and some properties. The complex vascular anatomy of the medial plan-

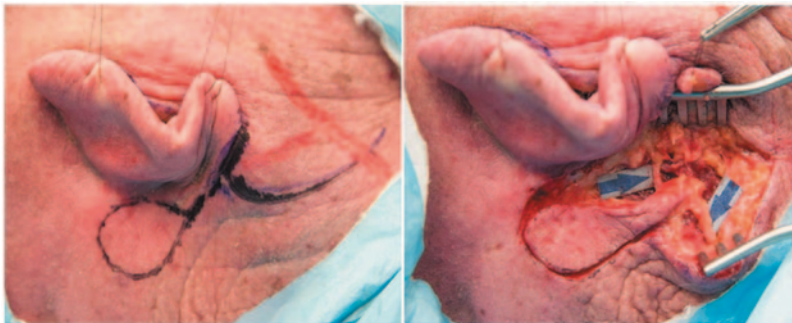


Fig. 8.3 Posterior auricular artery sensate flap. Cadaver dissection. Arrows show the vascular pedicle and the great auricular nerve. (Courtesy: Dr. Shih-heng Chen)

tar system was reported in 1990 by Masquelet and Romana [39]. The medial plantar artery is divided into the superficial and deep branches of the medial plantar artery. The deep branch of the medial plantar artery in turn subdivides into lateral and medial branches. The medial branch runs dorsally between the tibialis posterior tendon and the abductor hallucis muscle, after which it courses distally along the medial margin of the foot, proximal to the tubercle of the navicular bone. The artery is usually accompanied by one or two venae comitantes.

The medialis pedis flap receives its blood supply from the medial branch of deep division of the medial plantar artery. In contrast with this, the MPAP flap is nourished by superficial division of the medial plantar artery [40] (Fig. 8.4).

The *free medialis pedis flap* for resurfacing skin defects of the hand and digits was first reported by Ishikura et al. [22] based on Masquelet and Romana's studies [39] for soft tissue defects of the foot in which a thin and supple skin cover was needed. The advantages of this flap are: It is very thin in comparison with other standard free flaps; it can be used for small repairs; it possesses two draining venous pathways, the vena comitantes and the subcutaneous veins; the diameters of its vessels are similar to those of the fingers; it provides a good color and texture match for the

repair; and according to Ishikura, a good recovery of protective sensation is achievable.

This latter point is questionable since one of its main disadvantages is that it is an insensate flap. Other drawbacks are that skin grafting is usually necessary for donor-site closure and that in cases where the posterior tibial artery represents the dominant or singular inflow source to the foot, the harvesting of this flap could potentially compromise the circulation to the foot. Although it can be an appropriate flap for volar hand and digit injuries given that it provides glabrous skin coverage, its use is discouraged for fingertip lesions since it is not a sensory flap (Fig. 8.5).

The *free medial plantar artery perforator flap*, despite its anatomical proximity to the medialis pedis flap, has several positive differences: It is thicker, providing adequate cushioning surface; donor site can close primarily if flap width is less than 2 cm, and it can be sensate including the cutaneous branch of medial plantar nerve or saphenous nerve for anastomosing to the digital nerve [41].

Before 1986, when Hidalgo described favorable results using it for palm coverage [42], its utilization was limited for resurfacing feet and heel defects since Mir and Mir presented it in 1954 [43]. However, the first report of this flap as a neurovascular flap for pulp reconstruction was published by Inoue 2 years later [44] (Fig. 8.6).

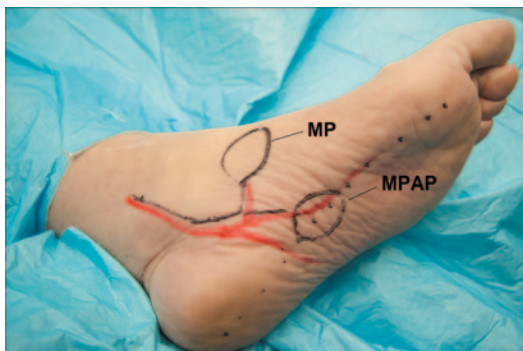


Fig. 8.4 Free medialis pedis (MP) flap and free medial plantar artery perforator (MPAP) flap schematic design. The red line indicates the posterior tibial artery trajectory with the medial plantar artery branch for MP flap and superficial division of the medial plantar artery branch for MPAP flap. Cadaver dissection

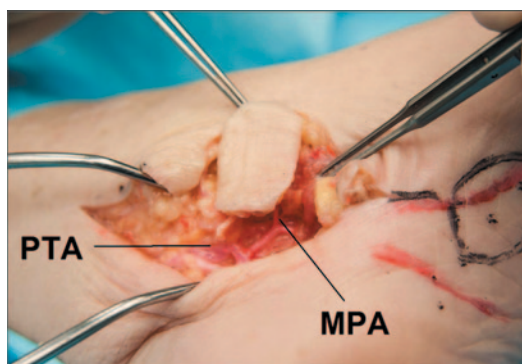


Fig. 8.5 Free medialis pedis flap. Cadaver dissection. PTA posterior tibial artery, MPA medialis pedis artery



Fig. 8.6 Free medial plantar artery perforator flap. Cadaver dissection

Operative Technique

The posterior tibial artery can be located by palpation posterior to the medial malleolus and followed downward to the instep groove between the abductor hallucis muscle and the flexor digitorum brevis muscle. The perforator can be easily identified by marking the septum between the abductor hallucis and the flexor digitorum brevis with a straight line. From this line, a perpendicular line is drawn to the navicular tubercle and the perforator will be located in a 2-cm-radius area from this line [40] and adjacent to the first cuneiform bone. This can be confirmed by Doppler.

The medial plantar flap is designed on the axis of the plantar surface of the first metatarsal with the perforator in the central area [38]. The plantar incision is made and the suprafascial plane is dissected until the perforators are identified. To expose the medial plantar vessels, a dissection between the abductor hallucis muscle and the flexor digitorum muscle is performed. Then, the lateral incision is made and the vein draining into the saphenous system is preserved, in case the comitantes veins of medial plantar artery are too small for anastomosis. The saphenous vein branch is also isolated with the saphenous nerve to innervate the flap. After releasing the tourniquet, flap circulation is evaluated and if there is no problem, the flap is harvested and inset on the finger. Inflow is provided by a digital artery and outflow is established via dorsal vein. The digital nerves are repaired to the saphenous nerve branch.

The advantages of this flap were well detailed by Huang et al. [40]: (a) It can be up to 7 cm long and 2 cm wide, providing a large surface area; (b) medial plantar vessels remain intact, therefore there is no compromise of the foot's blood supply; (c) provide cushioning and glabrous skin, (d) flap elevation can be performed quickly in experienced hands because a short pedicle does not require a tedious dissection; and (e) size and length of pedicle are compatible with the digital vessel.

It also presents disadvantages: Preserving small perforators without causing further injury is difficult and delicate surgical skills and sometimes microscope-assisted procedures are needed. When the donor area is more than 2 cm wide, it is necessary to use split-thickness skin graft to close. And mainly, there is some lack of good 2PD recovery although it is a sensate flap [45]

Great Toe Pulp Neurovascular Island Flap

Of all the free flaps utilized for digital pulp reconstruction, the free neurovascular toe flap provides a particularly efficient solution for loss of cutaneous substance [46, 47]. It not only restores the finger with a solid and well-cushioned cover but also with a dense population of specific sensory end organs attached to the flap [45]. That is the main advantage of these flaps in comparison with any other flaps, as they comply with one of the major surgical principles described by Sir Harold Gillies, the father of modern plastic surgery: “replace like to like” [48].

With the free neurovascular toe flap we not only provide tissue with the same unique mechanical and aesthetic characteristics of the finger and thumb pulp but also provide their same specific sensory functional pattern. From the mechanical and aesthetic point of view, the palmar aspect of the hand is gifted with anatomical characteristics of skin, subcutaneous tissue and appendages, suitable for carrying out its principal functions of pinching and grasping [49]. It is devoid of hair and the epithelium is of thick cornified stratified squamous epithelium, rich

in ridges and grooves that become thicker with usage [50]. Also, the epidermis is thick compared with that on other body areas and has abundant sweat glands but not sebaceous glands [49]. The connective tissue forms a dense array of tissue with numerous fibrous septa interconnecting the volar digital skin, periosteum, and synovial sheaths, and the connective tissue of dermis is more compact and less elastic. The subcutaneous tissue exists in many compartments in between these fibrous septa, adding a cushion effect and durability to an area constantly exposed to friction forces [41]. The pulp of the toes is the unique area of the body that has the same characteristics, so there can be no better option for replacement in case of this tissue loss.

As far as the sensory function is concerned, it is known that sensory endings can be divided into three general patterns: free sensory endings, sensory endings with expanded tips, and encapsulated sensory endings. Free nerve endings are encapsulated and are responsible for pain and temperature sensation. Sensory endings with expanded tips are the so-called Merkel's cell and the Ruffini complexes. Merkel's cell neurite complexes are only present in glabrous skin and are responsible for transmitting sensation of constant touch, pressure, and static tactile gnosis whereas Ruffini complexes are only present in hairy skin. The encapsulated sensory endings are found exclusively in glabrous skin. They are the Pacinian corpuscles and Meissner's corpuscles, highly sensitive converters of mechanical stimuli. Also, Meissner's corpuscles seem to provide the ultimate degree of sensitivity for tactile gnosis and discrimination. Both corpuscles are fast-adapting fiber mechanoreceptors that mediate sensory relays concerning moving touch, fluttering, vibration, and moving tactile gnosis [37, 38].

It is logical to assume that replacing specifically these specialized sensory endings by the same kind of sensory endings, we will be able to get the best critical sensory recovery. It has been observed that there is a correlation between the return of functional sensibility and the total number of Meissner's corpuscles in the transplanted tissue [51], which would demonstrate the necessity of using selectively glabrous skin tissue to

replace glabrous skin loss if we want to achieve the best sensory result. Despite these apparent logical advantages, the application of this flap has been typecast only for selective cases and patients.

Classically, it has been differentiated between manual laborers in whom fast functional recovery is the main purpose; thus, easy, quick recovery and reliable procedures are recommended (simple revision amputation, skin grafting, island flap, etc.) and sensitivity-demanding professions such as musicians, in whom sensitivity recovery is the priority and who need specific solutions to reach that goal.

The toe pulp NVI flap is typecast in literature as the ideal and almost exclusive indication for those latter patients. However, in our opinion its indications should be expanded for any patient when preserving functional and aesthetic appearance of the injured digit is the priority and the size of the defect contraindicates the use of local flaps.

History

Reconstruction of pulp defects with toe pulp NVI flap was described for the first time in 1978 by Buncke and Rose [46]. In their paper, they propose a new technique that offered durable skin cover which becomes innervated by the sensory nerve of the recipient finger itself, and does not result in deformity or anesthesia of an adjacent finger nor require cortical reorientation of stimuli, unlike Littler's technique [52].

Although only four out of six flaps they presented survived, they showed an innovative idea that has been applied by surgeons for pulp reconstruction all over the world. Precisely, this low flap survival rate at the beginning questioned this technique's reliability, and literary tradition has retained this idea for the last century without taking into account more recent results that show flap survival rates up to 99.7% in the largest series [53]. In fact, the current average survival rate has been shown to be 98% [54]. Undoubtedly, the development of microsurgery and technique refinement since the first reports have contributed to making this flap very reliable.

Another argument of the authors who criticize the reliability of toe to pulp NVI flap is its anatomy variability, which can complicate the dissection of the flap and the fact of sacrificing a major artery, which may adversely affect foot circulation during old age [33].

It is true that neurovascular anatomy of the foot is quite complicated and a significant amount of variations have been described. The first dorsal metatarsal artery (FDMA) originates from the dorsalis pedis artery when the latter dives plantarward at the base of the first intermetatarsal space. As described by Poirier and Charpy [55], the artery courses over the dorsum of the first dorsal interosseus muscle and divides into two branches—medial and lateral—at the level of the metatarsophalangeal joint of the big toe. The medial branch provides two dorsolateral collaterals to the big toe. The lateral branch terminates as the dorsomedial branch of the second toe. Distally, in the web space, the FDMA plunges plantarward and bifurcates into its terminal branches, both medial and lateral. The medial plantar branch forms the plantar hallucal arteries, both fibular and tibial, whereas the lateral branch terminates as the medial plantar artery of the second toe. The lateral branch of the first plantar metatarsal artery (FPMA) joins the FDMA at the level of its plantar bifurcation. The plantar tibial hallucal artery crosses transversely between the mid-segment of the proximal phalanx and the flexor hallucis longus tendon to reach the medial plantar aspect of the big toe, where it is joined by the medial bifurcation branch of the FPMA. Poirier and Charpy clearly state that it is the FDMA and not the FPMA that provides the three inner plantar collaterals of the first and second toes. The FPMA is considered a branch of the dorsalis pedis or a terminal branch of the lateral plantar artery. It arises at the level of the inferior border of the second metatarsal from the dorsalis pedis arterial area during its vertical course in the first intermetatarsal space. It is directed medially and anteriorly, separated from the FDMA by the first dorsal interosseous muscle. It is located deep to the level of the oblique head of the adductor hallucis and the flexor hallucis brevis. Initially applied against the lateral surface of the first metatarsal,

the artery passes between the bone and the flexor hallucis brevis muscle. At the level of the distal bifurcation triangle of this muscle, the FPMA divides into two branches: lateral and medial. The lateral branch courses between the two heads of the flexor hallucis brevis and then passes plantar to the lateral head of the short flexor. It turns around the lateral sesamoid, pierces the deep lateral sagittal septum of the plantar aponeurosis for the big toe, courses on the plantar aspect of the deep transverse metatarsal ligament, and joins the FDMA at the point of bifurcation in the first web space. The medial branch of the FPMA also emerges between the two heads of the short flexors of the big toe, passes around the medial sesamoid or between the two sesamoids, and terminates in the tibial plantar hallucal artery. This medial branch is joined by a thin branch from the medial plantar artery [56].

This thorough description given by Poirier and Charpy has suffered corrections or addenda and a significant amount of variations of the FDMA has been described in reference to: (a) the origin and principal source of supply (Gilbert [57], May Jr [58]), (b) the relationship with the first dorsal interosseous muscle and to the insertion of the adductor of the big toe (Murakami [59]), and (c) the relationship with the first dorsal interosseous muscle and to the deep transverse metatarsal ligament (Gilbert [57], Leung [60]). Also, variations of the FPMA, the tibial hallucal artery, and the dorsomedial hallucal artery have been described.

As far as the venous system is concerned, dorsal and plantar veins form in the toes and freely intercommunicate in the subcutaneous tissue of the web space. These veins drain deeply into venae comitantes accompanying the FDMA and FPMA and, in addition, subcutaneously into one or more large dorsal veins leading from each web space. These join and continue proximally as a single large vein (1.5 mm in diameter) to cross over the extensor hallucis longus tendon and join the medial greater saphenous system [58].

Nerve branches of the superficial peroneal nerve over the first metatarsal space are very small and terminate in the skin at the base of the toes in most cases. The larger deep peroneal nerve accompanies the FDMA and courses

beneath the extensor hallucis brevis tendon but remains superficial to the interosseus muscle and fascia. The nerve appears as two trunks, approximately 1 mm in diameter at or before the mid-metatarsal level, and each continues distally into either side of the first web adjacent to the dorsal digital artery to the region of the nail bed. The plantar digital nerves are separate structures, approximately 1.4 mm in diameter, as they course distally with the FPMA plantar to the transverse metatarsal ligament and the tendon sheath of the flexor hallucis longus. Each digital nerve remains plantar to its respective plantar digital artery as it continues distally toward the region of the tuft of the toe [58].

After seeing this, the criticism of some authors can make sense but we think that a good knowledge of the anatomy of the foot can guarantee a safe harvesting of the flap in caring and experienced hands.

Indications

This technique has two major indications: (1) the acute loss of the fingertip pad in the thumb and index finger and (2) the posttraumatic distal insensibility, with pulp atrophy, and distal neuroma, without any possibility of nerve anastomosis [47].

Operative Technique [38]

The NVI flap from the pulp of the great toe is a sensory cutaneous flap of glabrous skin. In general, it is preferable to use the homolateral foot as a donor site for the thumb and the contralateral foot for the index as this lines up better when using the ulnar digital artery of the thumb and the radial digital artery of the index as recipient arteries.

It is important to know whether the toe arterial supply is plantar or dorsal dominant, since this would condition the dissection. When the dorsal system is dominant, which occurs in 60% of cases, the dissection is simpler and a longer pedicle can be included with the flap, and a shorter incision is needed on the plantar surface of the foot. A Doppler examination will help to demonstrate the dominance.

The flap is designed as an oval with the long axis along the midaxial line of the lateral aspect of the great toe with 1–4 cm in length and 1–2.5 cm in width. The first incision should be done near the proximal end of the marked oval flap, extending proximally to find small tributaries in the subcutaneous tissue that may drain from the flap area. Once the venous tributaries are identified, then dissection can be carried out more proximally, identifying the major draining vein. When the vein has been identified, an incision continues into the web space and dissection is taken down through skin and subcutaneous tissue into the web space, identifying the lateral digital nerve to the great toe. This usually is on the plantar side of the digital artery. Once the digital nerve is identified, the artery supplying the toe will then be identified, and dissection of the artery is carried out proximally until finding communication between the dorsal and plantar systems. Care is taken at this juncture to identify either a plantar-dominant or a dorsal-dominant arterial system. If there is a dorsal-dominant system, then dissection is carried out proximally to whatever length is needed at the hand. If on the contrary, there is plantar-dominant system, which occurs in 40% of the time, the incision must be carried out more onto the plantar surface of the foot in between the first and second metatarsals, and dissect the plantar artery through this area. In this case, dissection can be difficult and tedious and this is one of the main causes of several authors' criticism to this flap.

If a long arterial pedicle is needed and dissection of the plantar digital artery is difficult, it is possible to just ligate the plantar artery and extend the arterial pedicle with a vein graft between the recipient artery and the plantar artery of the flap. Once the plantar artery, vein, and nerve are identified and dissected proximally, the rest of the incision can be carried out both dorsal and plantar around the previous markings. Dissection of the flap should be carried out through skin and subcutaneous tissue, identifying the major branches that go into the skin from the lateral digital artery supplying the flap.

Once the flap is elevated and adequate perfusion has been demonstrated, both of the flap and

the toe, the artery, and then the vein can be ligated, and the digital nerve divided. The artery is then repaired preferably end to end with the digital artery of the finger; then the vein is repaired end to end to a branch of the cephalic vein of the dorsum of the thumb or index and finally the digital nerve is repaired after circulation has been established. The skin is carefully closed using nylon 4/0 nylon threads, which cause limited irritation to soft tissue [45], although we usually follow Dr. Kleinert's recommendation and close the skin with 6/0 nylon in order to improve the aesthetic outcomes of the scar (Fig. 8.7).

There have been published technical refinements of this flap based on different pedicle types in order to facilitate the harvesting and simplify the operation, making the flap more reliable. Sun et al. [61] used a communicating branch of toe web veins as a venous return pathway of the free toe pulp, that is, a pathway from the accompanying veins of the plantar digital artery (small tributaries veins) to the communicating branch between the deep and superficial toe web veins to the superficial dorsal metatarsal veins. Accompanying veins are taken as return veins of free flap and the relatively larger dorsal metatarsal vein

is taken as the one for anastomosis. Direct anastomosis of thin accompanying veins is avoided; thus, the operation is simplified.

In addition, this flap admits a significant number of modifications in order to increase its indications. For instance, second toe pulp to hand flap, first web space flap, toe wrap-around flap, second toe-wrap around flap, combined lateral aspect of great toe flap and medial aspect of second toe flap, and combined lateral great toe and web space and medial second toe flap.

The second toe pulp is the next best choice for pulp reconstruction after the great toe flap. The great toe is larger and has a higher 2PD than the second (7–18 mm over 10–25 mm) [47], hence our predilection.

The first web space flap also has many similarities with the great toe pulp neurosensory flap in both its anatomic dissection and clinical application, but is usually used for larger defects.

The other ones have different indications than the pulp repair and are used, for example, for degloving injuries distal to the metacarpophalangeal joint with skeleton and tendons intact and complete amputations at the first distal phalanx of the thumb; therefore, they will not be discussed here.

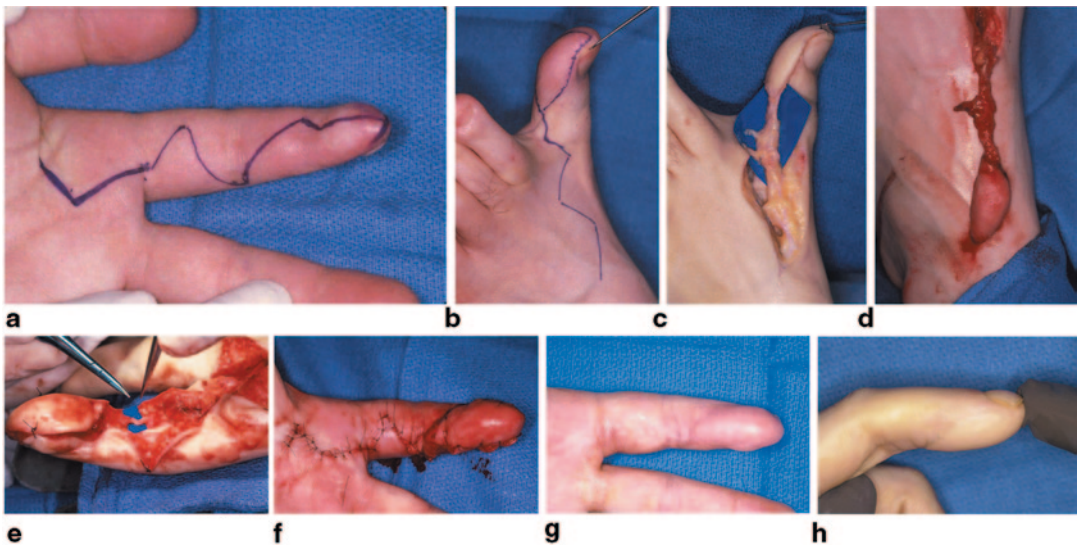


Fig. 8.7 Great toe pulp neurovascular island flap. **a** Post-painful index fingertip amputation with neuroma formation and unstable skin. **b** Design of the flap. **c** Flap's vascular pedicle. **d** Intraoperative confirmation of good

inflow and outflow of the flap before ligation and elevation. **e** Neurovascular anastomosis. **f** Immediate postoperative aspect of the flap. **g, h** Excellent aesthetic and functional recovery

Second Toe Pulp Neurovascular Flap

The second toe pulp neurovascular flap is a modification of the great toe pulp flap and shares with it all the anatomical and technical characteristics, except for the flap's design which is performed as an oval with the long axis along the midaxial line of the medial aspect of the second toe.

Usually it is used for small pulp defects, specifically in fingers other than the thumb because, as mentioned before, its 2PD is lower than the great toe, although the sensation recovery is also excellent.

In 2008, Lee et al. [53] developed an alternative technique for harvesting partial second toe pulp for transfer by means of a short pedicle. This technique uses the medial digital artery of the toe and subcutaneous veins as the pedicle instead of the dorsal metatarsal artery and veins as in most of the traditional cases for anastomosis, and avoids the more extensive dorsalis pedis artery harvest, facilitating a markedly decreased operative time with a >99% success rate.

First Web Space Flap

The first web space flap was first designed and studied by May and colleagues [58]. The first web space of the foot receives its arterial supply from the four digital arteries that arise from the first dorsal and the plantar metatarsal artery. It has a dual sensory innervation from the two dorsal digital nerves, which originate from the deep peroneal nerve, and two plantar digital nerves from the medial plantar nerve [58].

Based on this unique anatomic distribution of arteries and nerves, this flap can be harvested in diverse shapes and sizes and can be useful for larger defects and for other injuries of the fingers and the hand in addition to the pulp (first web of the hand contractures, volar defects of the hand up to 12 × 3 cm, pulp defects in two adjacent fingers). These larger injuries would be the best indication for the use of this flap.

According to this diversity of flap design and clinical application, some authors have tried to classify the first web space flap to ease the

clinical decision making facing a hand injury. An interesting paper was written by Woo et al. in 1999 [62] that classified it into four types: type I: web skin flap; type II: two-island skin flap; type III: fill-up web flap; and type IV: adjuvant web flap. But, although this classification is useful for other injuries, it is not very transcendent as far as selective pulp defects are concerned. (Fig. 8.8)

The outcomes of the toe pulp neurovascular island flap published in the most up-to-date reports are excellent in both function and aesthetic terms. Currently, it is the preferred option for digital pulp reconstruction for a significant number of authors, including ourselves.

The main drawbacks of this flap are related with the donor site. It has a considerable morbidity and hypertrophic scarring, partial skin necrosis, partial loss of toe, problems with walking, and postsurgical deformities have been reported. Also, it has to be noted that it is an operation on two distant areas and, as mentioned before, a major artery is sacrificed.

Another argument of detractors is that this is a lengthy procedure to perform, is technically demanding, and supposedly not very reliable. But new studies show that, at present, its reliability is no longer an issue and is comparable to that of any other free tissue transfer [54]. In addition, using easy flaps only to achieve flap survival is an old-fashioned idea from the early days of reconstructive microsurgery. Nowadays, the emphasis must be put in optimizing function and appearance [9], and that is what toe pulp NIV flap can guarantee, although minimizing donor-site morbidity should be also considered.

It is also true that there is a learning curve and much practice is required before making it a worry-free procedure [54], but good microsurgery training can minimize risks.

Conversely, the advantages of this procedure are numerous. As mentioned, it obtains excellent functional and aesthetic results with durable and glabrous skin, almost normal pulp contour (even including fingerprint), satisfactory sensory restoration, not only protective but also critical sensory restoration (static 2PD range 4–7 mm), and no need for cortical reorientation [54].



Fig. 8.8 First web space flap. Good option for larger injuries

It is interesting to mention that it has been shown that recovered sensation is more precise in the recipient site than at the donor site. Although several possible explanations exist, this phenomenon is probably best explained by cortical reeducation and adaptation with continuous, repetitive use postoperatively. Needless to say, an aggressive rehabilitative program is essential for this achievement [62]. This explanation has been supported by several investigators [47, 54, 63]

and especially Morrison et al. [64], who demonstrated that discriminative sensibility regresses to a state of mere protective sensation in the part of the body that is immobile.

Of course, as with any other procedure, the toe pulp neurovascular flap has contraindications and cannot always be used. Pulp defects shorter than 1.5 cm, concomitant injuries to the donor toe, concomitant acute infection, injury to the flap pedicle, and life-threatening associated injuries

are the absolute contraindications for using this flap [45]. There are also relative contraindications if there is need for rapid recovery regardless of the aesthetic or functional result, in which case simpler treatments should be suggested. The surgeon's inexperience or facility limitations could be a contraindication, in which case the patient should be referred to other surgeons or facilities.

Conclusion

Amputation of the pulp of the fingers and thumb is a frequent injury in the hand surgeon's daily clinical practice. There is a wide diversity of treatment options from healing by secondary intention to complex reconstruction. When local flaps are inadequate, if we want to offer the best treatment option for certain injuries and demands of patients, free tissue transfer is an option.

The most popular small flaps for fingertip coverage that provide glabrous or hairless skin coverage are the thenar flap, the free flap from the flexor aspect of the wrist, AVFs, posterior auricular artery sensate flap, and glabrous skin flaps.

The thenar flap is indicated for patients who would rather not sacrifice any soft tissue component from the foot. It requires minimal dissection and sacrifices a nondominant artery, but it can cause a potentially unpleasant scar in donor area and the sensory recovery is variable.

The free flap from the flexor aspect of the wrist can be an interesting alternative to glabrous skin flaps when they are contraindicated or not available. It is a versatile flap because it can incorporate a portion of palmaris longus and/or the palmar cutaneous branch of the median nerve as grafts and can be used for different defects in hand or digits, but being an insensate flap is one of its main drawbacks.

The AVF from the thenar and hypothenar eminences is an interesting reconstructive tool, despite the fact that it is not a complete glabrous flap or a sensory flap. Also, they have an unstable postoperative course, but when conventional arterial and glabrous flaps are not available its use should be considered.

The posterior auricular artery sensate flap is used for fingertip radial-side pulp reconstruction. Although good results have been reported, the fact of having a short vascular pedicle, extremely small vena comitantes, anatomic variation, and limited flap size has avoided its widespread utilization.

The best way to accomplish replacement with glabrous tissue of the defects on the volar surface of the fingers is by microvascular transplantation from the foot [38]. The most proven free flaps to provide glabrous skin on a consistent vascular pedicle are the free medialis pedis flap, free MPAP flap, and great toe pulp and second toe pulp NVI flaps.

Free medialis pedis flap and free MPAP flap are interconnected and share anatomy and some properties. But the former's use, even though it can be used for small repairs, is usually discouraged for fingertip lesions since it is not a sensory flap. The latter, despite its anatomical proximity to the medialis pedis flap, possesses several positive differences: It is thicker, providing adequate cushioning surface; donor site can be closed primarily if flap width is less than 2 cm; and it can be sensate including the cutaneous branch of the medial plantar nerve or saphenous nerve for anastomosing to the digital nerve [41]. However, though it is a sensate flap, some lack of 2PD recovery must be expected [45].

Of all the free flaps utilized for digital pulp reconstruction, the free NVI toe flap provides the most efficient solution for loss of cutaneous substance [46, 47]. It not only restores the finger with a solid and well-cushioned cover but also with a dense population of specific sensory end organs attached to flap [45]. The two major indications for this flap are the acute loss of the fingertip pad in the thumb and index finger and the posttraumatic distal insensibility, with pulp atrophy, and distal neuroma, without any possibility of nerve anastomosis [47]. Its variable anatomy, the donor-site morbidity, the sacrifice of a major artery, and surgical technical demands are its main drawbacks, but the excellent results make them worth it.

In addition, the free NVI toe flap admits a significant number of modifications that can increase its indications. The second toe pulp NVI

flap, the next best choice for pulp reconstruction after the great toe, is one of these modifications. It is used for small pulp defects, especially in fingers other than the thumb. Another modification is the first web space flap, which is usually indicated for larger defects than pulp.

In our opinion, although classically the free NVI toe flap has been typecast in literature as ideal and an almost exclusive indication for patients with high-demanding professions, its indications should be expanded for any patient when preserving functional and aesthetic appearance of the injured digit is the priority and the size of the defect contraindicates the use of local flaps, since in those terms this flap is shown to be unrivaled.

References

- Lee DH, Mignemi ME, Crosby SN. Fingertip Injuries: an update on management. *J Am Acad Orthop Surg.* 2013;21:756–66.
- Rosenthal EA. Treatment of fingertip and nailbed injuries. *Orthop Clin North Am.* 1983;14:675–97.
- Foucher G, Boulas HJ, Braga Da Silva J. The use of flaps in the treatment of fingertip injuries. *World J Surg.* 1991;15(4):458–62.
- Atasoy E, Iokimidis E, Kasden ML, Kutz JE, Kleinert HE. Reconstruction of the amputated fingertip with a triangular volar flap: A new surgical procedure. *J Bone J Surg.* 1979;52A(5):921–6.
- Kutler W. A new method for fingertip amputation. *JAMA.* 1947;133:29–30.
- Moberg E. Aspects of sensation in reconstructive surgery of the upper extremity. *J Bone Joint Surg.* 1964;46A:817.
- Han SK, Lee BI, Kim WK. The reverse digital artery island flap: clinical experience in 120 fingers. *Plast Reconstr Surg.* 1998;101:1006–13.
- Lim GJS, Yam AKT, Lee JYL, Lam-Chuan T. The spiral flap for fingertip resurfacing: short-term and long-term results. *J Hand Surg.* 2008;33A:340–7.
- Lawson R, Levin LS. Principles of free tissue transfer in orthopaedic practice. *J Am Orthop Surg.* 2007;15:290–9.
- Levin LS. Principles of definitive soft tissue coverage with flaps. *J Orthop Trauma.* 2008;22:S161–6.
- Foucher G, Braun JB. A new island flap transfer from the dorsum of the index to the thumb. *Plast Reconstr Surg.* 1979;63:344–9.
- Venkataswami R, Subramanian N. Oblique triangular flap: A new method of repair for oblique amputations of the fingertip and thumb. *Plast Reconstr Surg.* 1980;66:296–300.
- Sokol AB, Berggren RB. Finger tip amputations. Review of procedures and applications. *Calif Med.* 1973;119:22–8.
- De Lorenzi F van der Hulst RR den Dunnen WF Vranckx JJ Van-denhof B Francois C Boeckx WD. Arterialized venous free flaps for soft-tissue reconstruction of digits: a 40-case series. *J Reconstr Microsurg.* 2002;18:569–74; discussion 575–567.
- Huang SH, Wu SH, Lai CH, Chang CH, Wangchen H, Lai CS, Lin SD, Chang KP. Free medial plantar artery perforator flap for finger pulp reconstruction: report of a series of 10 cases. *Microsurgery.* 2010;30:118–24.
- Tsai TM, Sabapathy SR, Martin D. Revascularization of a finger with a thenar mini-free flap. *J Hand Surg Am.* 1991;16:604–6.
- Omokawa S, Ryu J, Tang JB, et al. Vascular and neural anatomy of the thenar area of the hand: its surgical applications. *Plast Reconstr Surg.* 1997;99:116–21.
- Kamei K, Ide Y, Kimura T. A new free thenar flap. *Plast Reconstr Surg.* 1993;92:1380–4.
- Sassu P, Lin CH, Lin YT, Lin CH. Fourteen cases of free thenar flap. A rare indication in digital reconstruction. *Ann Plast Surg.* 2008;60:260–6.
- Barbato BD, Guelmi K, Romano SJ, et al. Thenar flap rehabilitated: a review of 20 cases. *Ann Plast Surg.* 1996;37:135–9.
- Sakai S. Free Flap from the flexor aspect of the wrist for resurfacing defects of the hand and fingers. *Plast Reconstr Surg.* 2003;111(4):1412–20.
- Ishikura N, Helshiki T, Tsukada S. The use of a free medial pedis flap for resurfacing skin defects of the hand and digits: results in five cases. *Plast. Reconstr. Surg.* 1995;95(1):100–7.
- Yan H, Brooks D, Ladner R, Jackson WD, Gao W, Angel MF. Arterialized venous flaps: a review of the literature. *Microsurgery* 2010;30(6): 472–478.
- Yan H, Zhang F, Akdemir O, Songcharoen S, Jones NI, Angel M, Brook D. Clinical applications of venous flaps in the reconstruction of hands and fingers. *Arch Orthop Trauma Surg.* 2011;131(1):65–74.
- Thatte MR, Thatte RL. Venous flaps. *Plast Reconstr Surg.* 1993;91:747–51.
- Woo SH, Kim KC, Lee GJ, Ha SH, Kim KH, Dhawan V, Lee KS. A retrospective analysis of 154 arterialized venous flaps for hand reconstruction: an 11-year experience. *Plast Reconstr Surg.* 2007;119(6):1823–38.
- Inoue G, Maeda N. Arterialized venous flap coverage for skin defects of the hand or foot. *J Reconstr Microsurg.* 1988;4:259–66.
- Iwasawa M, Ohtsuka Y, Kushima H, Kiyono M. Arterialized venous flaps from the thenar and hypothenar regions for repairing finger pulp tissue losses. *Plast Reconstr Surg.* 1997;99:1765–70.
- Kakinoki R, Ikeguchi R, Nankaku M, Nakamura T. Factors affecting the success of arterialised venous flaps in the hand. *Injury.* 2008;39(Suppl 4):18–24.
- Takeuchi M, Sakurai H, Sasaki K, Nozaki M. Treatment of finger avulsion injuries with innervated arterialized venous flaps. *Plast Reconstr Surg.* 2000;106(4):881–5.

31. Nakazawa H, Nozaki M, Sasaki K, Sakurai H. Utility of arterialized venous flap for the reconstruction of soft tissue defects of the finger tip. *Jpn J Plast Reconstr Surg.* 1999;41:1011.
32. Wada M, Fujino T, Terashima T. Anatomic description of the free retroauricular flap. *J Microsurg.* 1979;1:108–13.
33. Hsieh JH, Wu YC, Chen HC, YB Chen. Posterior auricular artery sensate flap for finger pulp reconstruction. *J Trauma.* 2009;67(2):E48–50.
34. Kobayashi S, Nagase T, Ohmori K. Color Doppler flow imaging of postauricular arteries and veins. *Br J Plast Surg.* 1997;50:172–5.
35. Costa H, Pinto A, Zenha H. The posterior interosseous flap, a prime technique in hand reconstruction. The experience of 100 anatomical dissections and 102 clinical cases. *J Plast Reconstr Aesthet Surg.* 2007;60:740–7.
36. Hirase Y, Kojima T, Bang HH. Secondary reconstruction by temporoparietal free fascial flap for ring avulsion injury. *Ann Plast Surg.* 1990;25:312.
37. Halbert CF, Wei FC. Neurosensory free flaps. *Hand Clinics.* 1997;13(2):251–62.
38. Buncke GM, Buntic RF. Glabrous skin flaps. In: Wei FC and, Mardini S, editors. *Flaps and reconstructive surgery.* Taipei: Elsevier Inc.; 2009. p. 457–472.
39. Masquelet AC, Romana MC. The medialis pedis flap: a new fascio-cutaneous flap. *Plast Reconstr Surg.* 1990;85:765–72.
40. Huang SH, Wu SH, Lai CH, Chang CH, Wangchen H, Lai CH, Lin SD, Chang KP. Free medial plantar artery perforator flap for finger pulp reconstruction: report of a series of 10 cases. *Microsurgery.* 2010;30:118–24.
41. Lee HB, Tark KC, Rah DK, Shin KS. Pulp Reconstruction of fingers with very small sensate medial plantar free flap. *Plast Reconstr Surg.* 1998;101(4):999–1005.
42. Hidalgo DA, Shaw WW. Anatomic basis of plantar flap design. *Plast Reconstr Surg.* 1986;78:627.
43. Mir y Mir L. Functional graft of the heel. *Br J Plast Surg.* 1954;14:444.
44. Inoue T, Kobayashi M, Harashina T. Finger pulp reconstruction with a free sensory medial plantar flap. *Br J Plast Surg.* 1988;41:657.
45. Gu JX, Pan JB, Liu HJ, Zhang NC, Tian H, Zhang WZ, Xu Tao, Feng SH, Wang JC. Aesthetic and sensory reconstruction of finger pulp defects using free toe flaps. *Aesth Plast Surg.* 2014;38:156–63.
46. Buncke HJ, Rose EH. Free toe-to-fingertip neurovascular flaps. *Plast Reconstr Surg.* 1979;63(5):607–12.
47. Foucher G, Merle M, Maneaud M, Michon J. Microsurgical free partial toe transfer in hand reconstruction: a report of 12 cases. *Plast Reconstr Surg.* 1980;65(5):616–27.
48. Gillies H, Millard DR. *The principles and art of plastic surgery.* Boston: Little, Brown; 1957.
49. Southwood WFW. The thickness of the skin. *Plast Reconstr Surg.* 1955;15:423.
50. Barron JN. The structure and function of the skin of the hand. *Hand.* 1970;2:93.
51. Wei FC, Carver N, Lee YH, Chuang DCC, Chen SL. Sensory recovery and Meissner corpuscle number after toe-to-hand transplantation. *Plast Reconstr Surg.* 2000;105:2405.
52. Littler JW. Neurovascular pedicle transfer of tissue in reconstructive surgery of the hand. *J Bone Joint Surg.* 1956;38A:917.
53. Lee DC, Kim JS, Ki SH, Roh SY, Yang JW, Chung KC. Partial second toe pulp free flap for fingertip reconstruction. *Plast Reconstr Surg.* 2008;121(3):899–907.
54. Yan H, Ouyang Y, Chi Z, Gao W, Zhang F, Fan C. Digital pulp reconstruction with free neurovascular toe flaps. *Aesth Plast Surg.* 2012;36:1186–93.
55. Poirier P, Charpy A. *Traité d'anatomie humaine.* Paris: Masson; 1899.
56. Sarrafian SK, Kelikian AS. *Angiology.* In: Kelikian AS, Sarrafian SK, editors. *Sarrafian's anatomy of the foot and ankle: descriptive, topographic, functional (3rd ed).* Philadelphia: Lippincott Williams & Wilkins. 2011;302–380.
57. Gilbert A. In Tubiana R, ed. *Chirurgie de la main.* Paris; Masson et Cie; 1976.
58. May JW Jr, Chait LA, Cohen BE, Ó'Brien BMcC. Free neurovascular flap from the first web of the foot in hand reconstruction. *J Hand Surg.* 1977;2(5):387–93.
59. Murakami T. On the position and course of the deep plantar arteries, with a special reference to the so-called plantar metatarsal arteries. *Okajimas Folia Anat Jpn.* 1971;48:295.
60. Leung PC, Wong WL. The vessels of the first metatarsal web space. *J Bone Joint Surg Am.* 1983;65(2):235.
61. Sun W, Wang Z, Qiu S, Li S, Guan S, Hu Y, Zhu L. Communicating branch of toe web veins as a venous return pathway in free toe pulp flaps. *Plast Reconstr Surg.* 2010;126(5):268e–9e.
62. Woo SH, Choi BC, Oh SJ, Seul JH. Classification of the first web space free flap of the foot and its applications in reconstruction of the hand. *Plast Reconstr Surg.* 1999;103:508.
63. Deglise B, Botta Y. Microsurgical free toe pulp transfer for digital reconstruction. *An Plast Surg.* 1991;266(4):341–6.
64. Morrison WA, Ó'Brien B, Hamilton RB. Neurovascular free foot flaps in reconstruction of the mutilated hand. *Clin Plast Surg.* 1978;5(2):265–72.