Plastic Neurosurgery

Opening and Closing Neurosurgical Doors in Adults and Children

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This book is dedicated to my wife Susan Huba Winston, who supported me in my professional endeavors, encouraged me when I was down, tolerated my idiosyncrasies, and enriched my life immeasurably. The book is also dedicated to the neurosurgical residents from whom I learned so much.

Preface

In a serendipitous encounter in 1963, with Dr. Eustace Semmes, professor of neurosurgery at the University of Tennessee, he queried me, a senior medical student, on lumbar nerve syndromes, and said, as I was departing was, that I should consider becoming a neurosurgeon. I gave little thought to this and only recalled it years later. After considering a career in neurology, completing a medical internship, and spending 2 years in the US Public Health Service, first assigned as a psychiatrist in a US Public Health Hospital for narcotic addicts, 5 months on a ship surveying the northern Pacific Ocean floor, and 7 months in a general medical and leprosy clinic, I decided to become a neurosurgeon. Those who had strong guiding influences in my professional career and growth included Professor Keasley Welch, my neurosurgical mentor, and Professors Joseph Murray and Paul Tessier, who introduced me to plastic surgery and to the world of craniofacial surgery. During my conversational and surgical experiences with these surgeons, I was profoundly impressed and humbled by their professionalism, depth of knowledge, pursuit of perfection, attention to details, and how much they enjoyed helping people.

I too enjoyed my practice of neurosurgery and almost never felt that I was working. I love the science, art, and history of neurosurgery, and I have experienced no greater pleasure than getting to know patients and their families. Patients have shared intimate and often convoluted histories of suffering, fascinating tales of adventure, success, misfortune, crime, and painful-to-hear violence. I strove to understand and relieve their suffering and improve the quality of their lives. My life as a neurosurgeon has been and continues to be an immensely rewarding and enthusiastically enjoyed adventure—well, not every minute!

During years of participation in and supervision of neurosurgical mortality and morbidity (M&M) conferences, I became progressively more aware that many avoidable complications have their roots in the opening and reconstruction phases of neurosurgical interventions. A large proportion of these complications arise from lack of attention to the detailed management of skin, bone, and dura. Over several decades, I repeatedly revised an ever-changing and expanding outline of information and ideas that I thought would be beneficial to trainees, practitioners of neurosurgery, and especially their patients. Professor Kevin Lillehei encouraged me to write or edit a book on these concepts.

Because of the routineness and perceived simplicity of the opening and closing of neurosurgical operations, plastic surgical components receive little directed attention in standard neurosurgical training. Often, the neurosurgical opening may be efficiently executed by the attending surgeon, and the reconstruction and closure by a trusted but less experienced member of the surgical team.

All neurosurgeons, particularly in the formative years of their residencies and fellowships, should learn and never forget not only the *what* and *how* but also the *why* of the plastic components of neurosurgery. Much but not all of this information exists in written form that is scattered through decades of texts and journals on neurosurgery, plastic surgery, basic science, and general surgery. This information is apparently thought to be self-evident or trivial, and because there exists no neurosurgical text or journal that is devoted to or significantly inclusive of this subset of neurosurgical knowledge, it is not always specifically taught or well learned. Many of the practical details and nuances exist as psychomotor skills possessed by experienced expert practitioners.

The execution of plastic neurosurgery is generally uniform around the world, but there is variation among experts with regard to details, as some will recognize in this book. These variations reflect well-reasoned steps that have sound physiologic bases and, like those described in this text, have proven to be successful in the hands of these surgeons. A junior trainee may occasionally attempt to improve an established routine or technique by altering or omitting a component. The consequence is often a complication. The most dangerous surgeon is an "innovative" junior resident.

The surgery of nonneural tissues receives almost no focused attention in the training of neurosurgeons, beyond what may be discussed during surgeries and in M&M conferences. Surgical ideas and skills—good and not so good—have been informally passed along over millennia by observing, interacting with, and imitating experienced practitioners. Similarly, trainees today learn the opening and closing phases of neurosurgery from mentors, which include academic neurosurgeons, fellows, and more senior residents, through a regimen of observation, interaction, imitation, and gradually released responsibility. The nitty-gritty details of the opening and closing of doors for neurosurgery tend to be learned by rote. The levels of understanding and technical expertise among mentors vary with respect to technical details, healing, and cosmesis.

Clearly, there is a need for a neurosurgical source that is focused on the details of the opening and closing phases of operations, rather unlike existing excellent neurosurgical journals, texts, and atlases, which are scholarly weighted on the management of neural tissues.

The management of disorders of the central and peripheral nervous tissues has vastly improved, especially in the most recent 50 years, as a result of advancements in the understanding of physiology and pathology, better diagnostic and surgical tools, and improved techniques. The neurosurgical management of skin, bone, dura, and muscle has undergone slower evolution across the same span of time.

This book is both descriptive and prescriptive of skills and techniques with the recognition that all attempts to achieve perfection or to set specific surgical techniques are doomed before the printer's ink dries, due to the unpredictability, magnitude of force, and benefit of relentless change. Surgeons, in executing operations, teaching, and writing, should be humbled by two fundamental rules of human nature: mistakes are inevitable and we cannot escape our biases, particularly the most dangerous ones which are those we do not recognize [1]. It is important that neurosurgeons do their best for each patient, continually strive to improve, be good teachers, and pay attention to details.

The great Finnish architect, Eliel Saarinen, like many artists at the turn of the nineteenth century, felt that work, art, and life should be an indivisible whole [2]. Never may a surgeon who does not embody these characteristics and who does not enjoy what he or she does perform surgery on me or any member of my family.

1. Michael Lewis. *The Undoing Project.* WW Norton & Company; 1999
2. Hausen M, Mikkola K, Amberg A-L, Valto T. *Eliel Saarinen: Projects 1896–1923.* First MIT ed. Cambridge MA,: MIT Press; 1990

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I gratefully acknowledge the help of my daughter Helena Winston, psychiatrist, for her encouragement and editorial assistance and my son Benjamin Winston, orthopedic surgeon, who provided critical assistance regarding the healing of bone.

I also acknowledge Dr. Kevin Lillehei, professor and chairman of the department of neurosurgery, who encouraged me to compose my ideas on neurosurgical techniques and approaches in the form of a book.

Introduction

This book describes the crucial and undertreated intersection of neurosurgery and plastic surgery and is co-edited by a neurosurgeon and a plastic surgeon with over 75 years of combined experience. It is a topically organized treatise that is both descriptive and prescriptive and is intended as a guidance for residents, fellows, and practitioners in all neurosurgical subspecialties.

Every non-radiosurgical procedure has three distinct phases. Phase one consists of opening a door to a neurosurgical target, which always requires the infliction of damage to nonneural, usually healthy tissues. Phase two is the execution of the surgical mission and involves neural tissue. The third or restorative phase consists of closing the surgical door by repairing the damage done in phase one, with attention to wound healing, prevention of complications, and cosmesis. Neurosurgery thus has two distinctly different major components: (a) phases one and three, which are confined to surgery on nonneural tissues, and (b) phase two, which is surgery on neural tissues. The knowledge base, skill set, surgical techniques, and many of the instruments required for the opening and closing phases are vastly different from those required in phase two. In addition, the risks and types of complications for phases one and three differ greatly from those of the middle phase.

The opening and reconstructive closing phases require detailed knowledge of the micro- and macro-characteristics of nonneural tissues and their masterful handling. These phases are totally plastic (*Greek: capable of being molded*) in nature and therefore are most descriptively and conceptually designated as **plastic neurosurgery**. Plastic neurosurgery, like the specialty of plastic surgery, has two cardinal components: *reconstruction*, which deals with abnormal or damaged tissue, whether iatrogenic in origin or caused by disease or trauma, and *cosmesis*, which is concerned with preservation or improvement of physical appearance, i.e., aesthetics.

Surgical understanding and skills, both good and bad, have been informally passed along over millennia to trainees by observation of, interaction with, and imitation of experienced practitioners combined with gradually increasing independent responsibility. Today, all three phases of neurosurgery are learned from mentors, attending neurosurgeons, fellows, and more senior trainees. The understanding of what constitutes expert neurosurgery or just acceptable practice is not uniform, and technical expertise among mentors varies with respect to attention to detail and knowledge of the physiology of healing. The details of the opening and closing of doors for phase two neurosurgery are too often learned by rote (defined by

Merriam-Webster as "mechanical or unthinking routine or repetition" and by Collins English Dictionary as "learning things by repeating them without thinking about them or trying to understand them). This is not necessarily the best way to teach or learn. Neurosurgeons learn in the formative years of their residencies and fellowships the *what* and *how* of plastic neurosurgery. It is important that they also learn the *why*.

The many details of plastic neurosurgery are strewn across decades of journals on varying subjects. However, many practical details and nuances exist only in the knowledge base of experienced expert practitioners. This latter subset of neurosurgical lore has minimal representation in the literature, perhaps because it has been thought to be too trivial or self-evident to be recorded. The absence of a dedicated source on the plastic components of neurosurgery has been an unrecognized impediment to teaching, learning, and practice of neurosurgical opening and closing skills. Plastic neurosurgery is and always will be the alpha and the omega of *all* surgeries on the nervous system.

Part I: Foundational Information for Plastic Neurosurgery

Detailed knowledge of the anatomy, healing, and handling of the tissues that encase the central nervous system is required for planning and execution of all neurosurgical approaches, restoration of tissues, treatment of neurotrauma, and management of complications. These tissues receive a paucity of attention in neurosurgical literature. It is the ability of these tissues to heal that makes neurosurgery possible and prevents complications if the tissues are handled appropriately.

The surgery of these encasing tissues, particularly skin, receives minimal focused teaching in the course of neurosurgical training. This was appropriate when neurosurgical training began after one or more years of meaningful general surgical experience, but neurosurgery residents now begin their training with only the knowledge and technical skills learned in medical school. The consequences of this difference in the initial experience can pass with little recognition, through residency and fellowship, and have career-long effects on the suboptimal techniques that can lead to infection, scarring, and patient dissatisfaction or poor outcomes. Successful completion of neurosurgical residency is not currently conducive to understanding surgical management of skin, bone, and dura.

Surgery of fascia and muscle is not commonly discussed among neurosurgeons, and focused descriptions on techniques are nearly nonexistent in neurosurgical literature; yet their surgical disruption and need for reconstruction are important components of most neurosurgical operations. Fascia overlying muscles of the temporal fossa, posterior fossa, and spine is commonly incised and must be repaired. The surgical management of muscle too often includes unnecessarily destructive incisions and suboptimal restoration. Chapters Part I address skin management and include discussion of dressings, bandaging, postsurgical management of neurosurgical wounds, and discussions of fascia and muscle.

The gross surgery of cranial bone and dura is often mentioned in neurosurgical literature, but the finer points of hemostasis and optimization of healing receive much less attention. Complications related to bone include suboptimal intracranial exposure, imprecise alignment of fragments, nonunions, cranial defects, infections, and cosmetic defects. The first of these, although well known, is not often categorized as a complication, unless severe. Dura mater has an important role in the growth and healing of cranial bone and in providing a constraining envelope for the central nervous system and cerebrospinal fluid (CSF), particularly in children. The surgical management of dura is important in optimizing surgical exposure and preventing CSF leakage, infection, and pulsatile cranial defects. Techniques for the management of disruptions of cranial bone and dura are reviewed.

Part II: Opening and Closing Neurosurgical Doors

The opening and closing of neurosurgical doors—phases one and three of plastic neurosurgery—are described for a variety of representative neurosurgical approaches. These are presented in three groups: intracranial, spinal, and peripheral nerve surgery. The optimization of surgical exposures and the reconstruction of bone and soft tissues are described with appropriate citations. Minimal attention is given in this book to surgery on neural tissues—i.e., phase two of neurosurgery. The plastic neurosurgical components of neurosurgery vary greatly in complexity from simple (e.g., making a twist drill hole for inserting a pressure monitor) to complex (e.g., the transfrontal-subcranial approach for removal of a tumor).

Detailed descriptions for intracranial approaches to supratentorial, posterior fossa, and subfrontal sites are described. The ideas expressed reflect the individual authors' experiences combined with information gleaned from written neurosurgical, plastic surgical, and other sources, in addition to opinions of plastic surgical colleagues and various trainees. Plastic neurosurgical approaches for spinal surgery are detailed; however, surgery on vertebrae, being another major but separate subspecialty of both neurosurgery and orthopedic surgery, is not included. Plastic neurosurgical approaches for the exposure of the peripheral nerves are described and illustrated.

Many if not most avoidable neurosurgical complications, including hematomas, CSF leakage, surgical site infections, dehiscences, and problematic bone flaps, have their roots in problems with the opening or closing of neurosurgical doors. Less often recognized as complications are intraoperative struggles caused by suboptimal exposures, which increase the risk of complications in the second phase of surgery. However, not all neurosurgical complications/adverse outcomes are avoidable. It is important to distinguish the avoidable from the unavoidable and not self-criticize or ascribe guilt for the unavoidable. That said, it is notable that too often complications are often conveniently interpreted as unavoidable.

Belief that cosmesis is of little importance, except on areas of skin that are visible in a mirror or apparent to others—e.g., face, neck, and arms—is erroneous. Patients, spouses, and parents of children universally dislike scars, and not just the unsightly ones. All surfaces of the body are important to patients. Lay persons commonly associate the appearance of surgical wounds with the perceived attention given to tissues beneath the skin. Neurosurgeons also notice and privately opine on the appearance of surgical wounds. Avoidable cosmetic deformities are complications; however, unless severe, they are very often understood to be unavoidable collateral damage and are almost never mentioned in M&M conferences, tabulations of complications, or neurosurgical writings. Nevertheless, cosmesis is of great importance to patients and should be to their surgeons.

Part III: Plastic Neurosurgery for Cranial and Craniofacial Disorders

Surgeries for corrections of nonsyndromic craniosynostoses and other disorders of the cranial vault are major components of pediatric neurosurgery and, depending on the neurosurgeon's experience, may be done with a craniofacial surgeon. These surgeries consist almost totally of an opening, remodeling of bone, and reconstruction with attention to cosmesis—i.e., phases one and three of plastic neurosurgery. Neurosurgeons often participate in the planning and execution of surgeries, particularly of the osseous and dural components, for correction of syndromic craniofacial disorders. It is essential for neurosurgeons who are involved in the management of all cranial and craniofacial disorders to have a broad understanding of these disorders and *never* accept the role of technician for only making designated burr holes and osteotomies.

Unlike most indications for surgery, decision-making regarding patients with craniofacial disorders is strongly influenced by aesthetic concerns and can be a focal point for plastic surgeons. Still, the management may require relief of intracranial hypertension by neurosurgeons. Although there can be no definitively correct aesthetic opinion, surgeons are the authoritative sources on risk and realistic expectation. Intuition and experience with non-craniofacial disorders are not sufficient for these patients and can lead to avoidable complications. Many techniques developed for craniofacial disorders have applications in neurosurgical approaches to the cranial vault, thereby making familiarity with craniofacial techniques applicable for many elective cranial approaches and reconstructions following trauma in patients of all ages.

A small but significant component of pediatric neurosurgical practice consists of involvement in the treatment of rare disorders, for which there is no universally accepted surgical procedure or approach. Often, neurosurgery is near totally plastic in nature, is technically challenging, and has high risks for the child. The neurosurgeon is unlikely to be comfortable in making confident decisions on many of these cases because of lack of in-depth knowledge and experience. Most encephaloceles, for example, are repaired by pediatric neurosurgeons; however, the skills of a craniofacial surgeon may be required for lesions that are in frontal or frontonasal locations. Reduction cranioplasties and repair of some expanding fractures are challenging undertakings for the experienced neurosurgeon and have significant risks. The extremely complex and high-risk multispecialty management of composite-type aplasia cutis congenita and the separation of craniopagi are briefly summarized for neurosurgeons who need a source of reliable information when consulted or questioned on these subjects. Familiarity with various plastic techniques is very beneficial for appropriate and successful neurosurgical treatment.

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Part I

Foundational Information for Plastic Neurosurgery

Skin: Anatomy and Healing

1

Ken Rose Winston, Brooke French, and Lawrence L. Ketch

Structure of Skin

Epidermis is derived from ectoderm and is approximately 75–150 μm in thickness over most of the body [1]. Epidermis is constantly renewed at a variable rate, but complete renewal occurs over 36–75 days. The epidermis has five layers: *stratum corneum*, *stratum lucidum*, *stratum granulosum*, *stratum spinosum*, and *stratum basale*. The outermost of these, the stratum corneum, consists of dead squamous cells, which slough spontaneously approximately every 2 weeks or in response to abrasive action such as scratching, contact with clothing, during scrubbing of the skin, or drying with a towel. Squames are anuclear cells, most of which are filled with an insoluble protein called keratin, giving rise to the name keratinocytes. Stratum corneum also contains lipids, which contribute to the protective properties of this layer of the epidermis. The stratum lucidum, stratum granulosum, and stratum spinosum are histologically recognizable layers through which cells arising in stratum basale must migrate to reach the stratum corneum. The innermost layer of the epidermis, the stratum basale (*stratum germinativum*), is a glucose-utilizing, mitotically active layer of single cell thickness and its glucose utilization is comparable to muscle. Cells born in this layer move outward, over approximately 2 weeks, through the overlying layers to the stratum corneum and then through that layer over

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the next 2 weeks. The undersurface of epidermis is not flat, but has ridges and pegs which protrude downward into the dermis and contribute to the anchoring of epidermis to dermis. There are no blood vessels or lymphatic channels in the epidermis. The basement membrane zone is a very thin layer that contributes to the anchoring of epidermis to dermis and plays an important role in blister formation.

Melanocytes are dendritic cells which are originally derived from the neural crest. Melanin within melanosomes is transported into the dendrites of these cells and then, by a poorly understood process, but possibly consisting of release and endocytosis, enters keratinocytes of the stratum basale [2]. The density of melanocytes is approximately constant for all colors of skin. Differences in skin color are primarily influenced by the size, number, and distribution of melanosomes. Carotene is also present and contributes to the yellow component of skin color [3]. At least 150 genes affect skin color. Albino skin has melanocytes, but no melanin.

Dermis is derived from mesoderm, and it is much thicker than epidermis, typically 2–4 mm in thickness. This layer is much less densely populated with cells than is epidermis and contains blood vessels and nerves. There are substantial amounts of collagen, elastin, and ground substance, the latter of which is involved in the binding of water and hence influences the volume and turgor of skin. Outwardly directed ridges and pegs of dermis, called papillae, interdigitate with the inwardly directed pegs and ridges of the epidermis. Vascular loops extend outward into the papillae of the dermis and are supplied by a horizontally distributed plexus of vessels immediately below the vascular loops. There are lymphatic channels within the dermis, and these are thought to play a role in interstitial fluid pressure.

The tensile strength of skin is provided by collagen, predominantly type I, within the dermis. This protein is produced by fibroblasts and accounts for about a quarter of the skin's weight. The elastic recoil of skin is made possible by elastin, a protein that forms strands in the form of tufts, sometimes called coils, within the dermis. This protein is at risk for injury from ultraviolet light, particularly in light-skinned people. Other exogenous factors from the environment, such as certain pollutants, negatively impact elastin by the formation of free radicals and contribute to accelerated aging and formation of rhytids (wrinkles).

Hypodermis, the subcutaneous layer of skin, is the layer composed predominantly of adipose tissue which lies beneath the dermis and contributes to the skin's mobility, contour, cushioning effect, and insulation. The adipocytes release leptin, which regulates fat storage by signaling the brain to reduce the intake of food [4]. Sweat glands and hair follicles extend down into this layer [5]. There are also mast cells, macrophages, and lymphocytes in this layer that contribute to the skin's immune system.

Hair

Hair of the scalp provides homeothermic protection from heat, cold, ultraviolet radiation to the scalp and neck, unless the scalp is bald or has very thin hair, and it also provides a small amount of protection from mechanical injury. Hair of the scalp is also beneficial in camouflaging surgical scars. Eyelashes and eyebrows provide important protection of the eyes. The location of the parietal whorl is related to brain and skull development. The presence and characteristics of hair of the scalp have great psychosocial importance for men, women, and children, and several professions are devoted to the management of hair. Its psychosocial importance to patients could hardly be overstated.

Hair derives from epidermis and the portion of a hair protruding from skin is composed of dead keratinized epithelial cells. The characteristics of hair vary greatly with site on the body. Hair follicles in the scalp are arranged in follicular units, each of which has one to four terminal hairs with one or two vellus hairs, and a sebaceous gland is associated with an arrector pili muscle. The tiny vellus hair covers much of the body. Each hair is a single shaft of keratin measuring 60–80 μm in diameter and is covered with flat scales that are imbricated and pointing away from the follicle toward the end of the hair [6]. Hair follicles have three functional zones. The base of the follicle, the matrix, is the germination center for hair growth. Cells progress through the keratogenous zone above the base. Finally, the hair shaft dehydrates and the cells cornify. The diameter of hairs of the scalp increases until approximately 12 years of age and then remains generally constant. Most often each hair of the scalp grows at approximately 1 cm per month for 3–7 years, remains static for a variable number of years, and then becomes disengaged, but some people's scalp hair grows for much longer periods, thereby allowing much greater length. After a few months, a new hair begins to grow from the same follicle. The hair growth cycle is characterized by three stages. The anagen phase is marked by growth and an increase in metabolic activity. The catagen phase is a transitional phase marked by a decrease in cell division. The telogen phase is a resting period during which the shaft is retained in the follicular canal but eventually becomes detached. A more detailed discussion of the biology of hair can be found in *Hair Growth and Disorders* [7].

Sweat Glands

Sweat glands, also known as sudoriferous glands, occur in two types, *eccrine* and *apocrine*. Most sweat glands have their secretory coil or base located in the lower part of the dermis or hypodermis and are surrounded by adipose tissue and capillaries. Each gland has a secretory base and a duct to conduct sweat to the surface of the skin. The secretory coils of both types of sweat glands are surrounded by myoepithelial cells, innervated by fibers of the sympathetic nervous system.

Eccrine sweat glands are distributed over almost the entire body and open directly onto the surface of skin. They produce a clear odorless, salty tasting material called sensible perspiration, which is mostly water (99–99.5%) and sodium chloride (35–65 mmol/L), but also small amounts of urea, fatty material, lactic acid, citric acid, and ascorbic acid. (Some of the lactic acid on skin is produced by bacteria.) The density of eccrine sweat glands decreases with advancing age. Using evaporative cooling, eccrine sweat glands play an important role in thermoregulation and the excretion of water and electrolytes. Eccrine sweat is important in maintaining an acidic surface for the skin which is thought to assist in minimizing colonization by pathogenic organisms. The pH of eccrine sweat varies between 4.0 and 6.8.

Apocrine sweat glands are much larger than eccrine glands, occur in skin of the axilla, areolae, and perianal area, and have their openings into the canals of hair follicles, not directly on the surface of skin. Specialized apocrine sweat glands include the ceruminous glands which occur in the meibomian glands of the eyelids, in the ear where they produce cerumen, and in mammary glands where they produce milk. They remain functionless until puberty when hormonal changes result in their activation. Apocrine sweat is an oily, cloudy, viscous material containing proteins, carbohydrates, and lipids resulting in a pH of between 6.0 and 7.5. Apocrine sweat also contains a pheromone-like substance which is different in males and females. The activity of these glands is greatest during stress and sexual excitement. Apocrine sweat coats the hair and does not evaporate. Meibum is a lipid secreted by the meibomian glands in the rims of the eyelids which impedes evaporation of tears. The sweat from apocrine glands plays no role in temperature regulation of the body.

Apocrine sweat serves as a nutrient for bacteria on the surface of skin and is initially odorless but, after decomposition by bacteria, takes on an acrid odor. Bacteria in the axilla, particularly *Staphylococcus hominis, convert odorless 3M3SH secreted by apocrine glands to a malodorous thioalcohol* [8]. The volatilization of the thioalcohol and hence the spread of odor is facilitated by the watery eccrine sweat.

Lines and Creases

The orientation of incisions in skin of the scalp, face, and elsewhere influences the cosmetic impact of incisions. Many patterns of lines in skin have been described as guides for camouflaging surgical incisions, and there is disagreement regarding which is best. Although much is written on Langer lines, it is preferable for neurosurgeons to design incisions based on relaxed tension lines and naturally occurring rhytids (wrinkles).

Relaxed Skin Tension (RST) Lines

The elastin component of skins tends to be aligned according to tension within skin, and the pull of nearby muscles causes the formation of crease lines which are common in adults. The relaxed skin tension (RST) lines are caused primarily by the constant pull and stretch of underlying muscles attached to skin, within the context of ligamentous adhesions between skin and bone. RST lines are usually not apparent on inspection, but can be most easily and accurately identified by pinching the skin and observing the resulting furrows and ridges [9]. Rhytids, or crease lines, reflect the lines of tension in skin that are of most clinical value. RST lines vary little among individuals, but their number varies. RST lines are not identical to Langer lines (see Fig. 1.1).

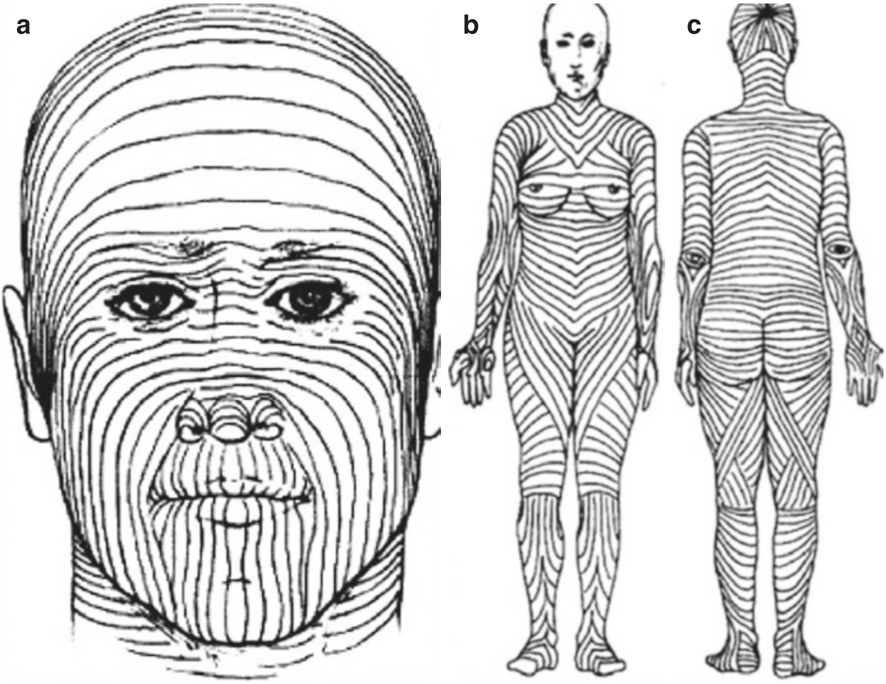

Fig. 1.1 Relaxed skin tension (RST) lines: (**a**) face and neck; (**b**) chest and abdomen; (**c**) back. (Reproduced with permission from Paul SP. Biodynamic excisional skin tension lines for surgical excisions: untangling the science. *Ann R Coll Surg Engl.* 2018;100(4):330–337. https://doi.org/10.1308/rcsann.2018.0038, Fig. 1)

Langer Lines (Cleavage Lines)

These lines correspond to the long axis of elliptical holes produced in the skin of human cadavers when punctured with a round spike. The resulting holes form a topographical pattern when drawn on an outline of a human body [10]. They course generally perpendicular to the long axis of underlying musculature and correspond to the direction of minimal extensibility [10]. Langer lines closely follow the crease lines on the surface of overlying skin, but can be difficult to identify over the scalp because of hair and the tautness and thickness of scalp. In other areas of the body, these lines can usually be identified by inspection alone, but compression of skin may make them more apparent [10, 11].

Anatomy of Scalp

Scalp is 3–9 mm thick in most adults and has the thickest epidermis of the body. It extends over the cranial vault from the superior nuchal line posteriorly to the supraciliary line of the eyebrows anteriorly. Laterally, the scalp extends down to the ear and zygomatic arches. Most of the scalp is composed of hair-bearing skin and is thicker than most other skin, except palms and soles. Occipital scalp is thicker than frontal or temporal scalp. Scalp typically contains very many sebaceous glands and hair follicles, the density of which varies with age, gender, ethnicity, and hormonal influence [12–14].

A mnemonic, **SCALP**, is commonly used to recall the layers of the scalp: **S**kin, ***C***onnective tissue, galea ***A***poneurotica, ***L***oose areolar tissue, and ***P***ericranium. The scalp is most mobile in the parietal regions where temporal parietal fascia overlies the temporalis muscle. The scalp is least mobile in the lateral frontal region due to temporal ligamentous adhesions (see Anatomy of *Temporal Scalp* below.)

The connective tissue layer is composed of fibro-fatty tissue which rigidly attaches skin layer to the galea aponeurotica. The fat of the scalp exists in lobules which are bound by dense fibrous septa, through which course nerves and blood vessels.

The galea aponeurotica is a broad thin tendon attached anteriorly to the frontalis muscle and posteriorly to the occipitalis muscle. It extends across the superior temporal line posteriorly from the superior nuchal line to the occipitalis muscle. Laterally, it is a continuous sheet overlying the temporal fascia and becoming indistinct over the zygomatic arches.

The loose areolar tissue in the subaponeurotic space connects the galea to the pericranium and temporalis fascia. This space extends anteriorly to the supraorbital rims and laterally to the zygomatic arch. The subaponeurotic space is relatively avascular, but may contain a few emissary veins connecting within the cranium to veins of the scalp. This is the layer through which traumatic avulsion (degloving) injuries typically occur.

Pericranium (cranial periosteum) covers the outer surface of the skull and consists of a specialized continuous fibrous membrane having two layers. The outermost layer is composed almost exclusively of collagenous tissue and the inner layer is dominated by elastic fibers. The innermost layer of infants contains many osteoblasts, but adults have fewer of these cells. Pericranium plays an important osteogenic role in the developing skull and in repair of fractures in young children, in the same way as does the periosteum of long bones. This layer is less active in this role in adulthood, probably because of having fewer osteoblasts. Pericranium contains blood vessels and nerves but, unlike periosteum surrounding long bones, pericranium supplies little blood to the convexity of the skull. However, a richer vascularity for cranial bone is thought to occur at the sites of attachment of muscles to the skull. Pericranium is most strongly attached to cranial bone along the suture lines where it is continuous with the periosteal layer of dura, until the suture becomes ossified.

Pericranium is firmly attached to bone in an arc along the superior temporal line, down the lateral surface of the frontozygomatic process, and across the medial surface of the zygomatic arch. The pericranium below the superior temporal line is continuous with two layers of tissue, a deep one beneath the temporal muscle and in contact with the temporal bone and a more superficial layer, the temporal fascia, which covers the temporalis muscle and divides into a superficial and deep lamina, between which lies the superficial temporal fat pad. There is another fat pad, of variable thickness, lying between the temporalis muscle and the fascia, and containing nerves and vessels.

Temporal Scalp [15]

The naming of the layers of the temporoparietal scalp has been inconsistent and therefore confusing. For surgical purposes, the temporal region of the scalp can be viewed as having four identifiable layers: (1) *superficial temporal fascia*, which is a direct extension of the galea and is securely attached to an overlying subcutaneous layer of tissue; (2) *subgaleal fascia* within which reside the frontal branch of the facial nerve and the anterior and posterior branches of the superficial temporal artery which penetrate this fascial layer and can be injured during surgery; (3) *superficial temporal fat pad* with several moderately large veins; (4) and *deep temporal fascia which* covers and is attached to the temporalis muscle, merges with the pericranium along the superior temporal line, and is attached to the lower edge of the zygomatic arch.

Muscles of Scalp

The occipitofrontalis or epicranius (*Latin: on top of + cranium*) muscle can be thought of as being a single muscle in the middle of which lies the galea aponeurotica or thought of as two separate muscles, the frontalis and occipitalis, each of which is attached to the galea aponeurotica. The posterior edge is attached along the highest nuchal line, which is a few mm above the superior nuchal line. The frontalis muscle originates from the scalp of the forehead and, to a lesser extent, to the superior edge of the superficial fascia of the upper eyelids. Both muscles are innervated by branches of the facial nerve (VII), the occipitalis muscle via the posterior auricular nerve and the frontalis muscle via the frontal nerve. The temporalis muscle is not attached to scalp and, being a muscle of mastication, is innervated by the trigeminal nerve (V).

Vasculature of Scalp

Arteries

Five arteries supply each side of the scalp and have an extensive anastomotic network. The superficial temporal artery is the major artery of the scalp [16]. It is a branch of the external carotid artery, beginning within or just below the parotid gland behind the ramus of the mandible, and passes over the posterior part of the zygomatic arch and beneath the auricularis anterior muscle and a dense fascial band. It is usually accompanied posteriorly by the auriculotemporal nerve and is crossed by the temporal and zygomatic branches of the facial nerve and by a few veins. It usually divides above the zygomatic arch into anterior and posterior branches, often of unequal size. This division occurs above the arch, by as much as 5 cm in 74% of autopsies, but directly over the arch in 22%. Above the level of the zygoma, the superficial temporal artery and vein lie within the superficial temporoparietal fascia and within the subcutaneous plane superficial to the galea, directly anterior to the nerve. The anterior or frontal branch supplies skin and muscles and anastomoses with branches of the supratrochlear and supraorbital arteries. The larger posterior or parietal branch of the superficial temporal artery courses superiorly and posteriorly, passing superficial to the temporal fascia and making anastomotic connections with the ipsilateral frontal branch, posterior auricular artery, occipital artery, and over the vertex with the contralateral posterior branch. This anastomotic network tends to decrease after the sixth decade of life.

The posterior auricular artery courses posterior to the mandible, below the parotid gland, and ascends posterior to the ear. It supplies blood to the ear and scalp behind the ear. The posterior branch of this vessel supplies the occipitalis muscle and the overlying scalp above and behind the pinna. It anastomoses with the posterior branch of the superficial temporal artery and with the occipital artery. The auricular branch of this artery ascends behind the auricula, supplying blood to its posterior surface and part of its anterior surface.

The occipital artery is a branch of the external carotid artery and passes below the posterior belly of the digastric muscle. It courses posteriorly past the internal carotid artery, internal jugular vein, vagus nerve, and spinal accessory nerve and then ascends and continues posteriorly across the occipital bone, typically in a groove in that bone, and beneath the muscles. It supplies blood to the sternocleidomastoid muscle and then pierces the fascia above the superior nuchal line to supply blood to the occipital scalp and vertex, with anastomotic connections to the posterior auricular artery, superficial temporal artery, and its contralateral partner. The scalp below the superior nuchal line receives arterial supply from small perforators from the trapezius and splenius muscles.

The supratrochlear artery is a branch of the ophthalmic artery which begins in the orbit just behind the trochlea. It leaves the orbit at a medial angle and courses over the forehead, supplying skin, muscle, and pericranium, anastomosing with the supraorbital artery and with its partner on the opposite side. Its cutaneous branch typically begins about 1 cm above the orbital rim and occasionally there is no muscular branch. It tends to course medial to the medial canthus in females and lateral to the medial canthus in males.

The supraorbital artery is a branch of the ophthalmic artery and, accompanied by the supraorbital nerve, passes within the orbit above the levator palpebrae superioris muscle and enters the supraorbital notch, or foramen, and divides near there into a superficial and deep branch. Its branches anastomose with branches of the temporal and supratrochlear arteries. It supplies blood to the levator palpebrae superioris muscle, the skin of the forehead, upper eyelid, and frontal sinus. This is said to be missing in 10–20% of individuals.

Veins

Veins of the scalp follow the arteries and tend to have the same names but are less numerous and have connections with the diploic veins of the skull, meningeal veins, and with the pterygoid plexus. The supraorbital and supratrochlear veins drain the anterior scalp from the vertex down to the superciliary arches into the ophthalmic vein within the orbit and then into the angular vein which is the upper tributary of the facial vein. The superficial temporal vein drains the lateral scalp into the retromandibular vein. The posterior auricular vein drains the scalp posterior and above the ear, also into the retromandibular vein. The occipital vein drains the posterior scalp into the deep veins in the posterior cervical triangle.

Lymphatics of Scalp

Lymphatic drainage from the posterior half of the scalp flows into the occipital and posterior auricular nodes and from the anterior scalp into the parotid lymph nodes. Lymphatic flow eventually reaches the deep cervical and submandibular nodes.

Nerves of Scalp [17]

The scalp, by way of its sensory innervation, sends information on touch, vibration, and temperature to the brain and is therefore important for protection and for pleasure. The sensory nerve distributions or dermatomes of the skin of the head and neck have appreciable overlap. This is true for the trigeminal dermatomes and the distributions of C1–3 nerves. The first cervical spinal nerve (C1) carries predominantly motor fibers, but occasionally a small branch that supplies sensation to dura around the foramen magnum. The C2 dermatome supplies the occipital scalp, neck, and submental region. The C3 dermatome spans the skin from lower edge of mandible and ear to the clavicle.

The mnemonic Z-GLASS has been used for assisting memory of the sensory innervation of the scalp: Zygomaticotemporal nerve, Greater occipital nerve, Lesser occipital nerve, Auriculotemporal nerve, Supratrochlear nerve, and Supraorbital nerve; however, this mnemonic does not include the third occipital nerve.

The zygomaticotemporal nerve arises from the maxillary division of the trigeminal nerve (V-2) and passes through the zygomaticotemporal foramen, temporalis muscle, and fascia. It then penetrates the temporal fascia approximately 10 mm posterior to the frontozygomatic suture and 22 mm above the zygomatic arch to supply a small lateral portion of the forehead and temporal region.

The greater occipital nerve originates from the medial branch of spinal nerve C2 and supplies innervation to most of the posterior scalp. After piercing the musculature, the nerve runs immediately lateral to the occipital artery.

The lesser occipital nerve originates from spinal nerves C2 and C3, follows the posterior margin of the sternocleidomastoid muscle, and supplies the posterior scalp above the occiput. It passes approximately 2.5 cm lateral to the occipital artery and 7 cm lateral to the external occipital protuberance.

The auriculotemporal nerve is intimately associated with the parotid gland before crossing the zygoma behind the superficial temporal artery. This nerve has five named branches, but the deeper ones will not be described. The anterior auricular branches innervate skin overlying the tragus and adjacent area of the helix. The superficial temporal branches course generally with branches of the superficial temporal arteries and innervate the skin over the temple. The branches to the external auditory meatus innervate the skin of the meatus and the tympanic membrane.

The supraorbital [18, 19] and supratrochlear nerves are terminal branches of the frontal nerve which is a branch of the ophthalmic division of the trigeminal nerve (V-1). The supraorbital nerve passes through the supraorbital notch or foramen and divides into a medial and lateral branch. The supraorbital nerve innervates the medial scalp from the eyebrow and over the vertex, perhaps as far posteriorly as the lambdoid suture of the skull and also innervates much of the upper eyelid, conjunctiva, and mucosa of the frontal sinus.

The supratrochlear nerve [20] leaves the orbit approximately 16 mm lateral to midline and supplies innervation to the lower forehead, lateral conjunctiva, and upper eyelid.

The third occipital nerve [21] originates from the medial branch of spinal nerve C3 and contributes to the skin below the superior nuchal line, which is part of the C3 dermatome. The auriculotemporal nerve [21] arises from the mandibular division of the trigeminal nerve. It supplies parasympathetic innervation to the parotid gland and then innervates the skin of the tragus, anterior portion of the ear, and posterior temporal region. It may wrap around the superficial artery.

The greater auricular nerve arises from the cervical plexus and provides innervation to the skin of the posterior auricular region, external ear, and skin overlying the parotid region.

Nerves of Face [17]

The cutaneous innervation of the face is supplied by the trigeminal nerve. The first branch, the ophthalmic division, often called V-1, is the first branch and carries only sensory fibers. The frontalis branch of the ophthalmic nerve lies in the roof of the orbit and then divides into the supraorbital nerve and supratrochlear nerve. These two nerves supply sensory innervation to the forehead, upper eyelid, conjunctiva, and mucosa of the frontal sinus. The lacrimal nerve is a branch of the ophthalmic nerve that passes through the orbit to the lacrimal gland.

The nasociliary nerve passes through the orbit and sends a medially coursing branch, the anterior ethmoidal nerve, through the anterior ethmoidal foramen and into the cranial cavity, but remains outside of the dura. Here it sends branches to the dura, anterior falx, and dura of the anterior cranial vault. It then enters the nasal cavity via the nasal slit at the side of the cribriform plate of the ethmoid bone and supplies sensation for the mucous membrane of the nasal cavity and ethmoid cells, and then passes between the inferior border of the nasal bone and the nasal cartilage, as the external nasal nerve which innervates the skin of the lower half of the nose.

The maxillary nerve, often called V-2, is the second of the three divisions of the trigeminal nerve and supplies sensory innervation to the nasal and maxillary cavities, palate, upper teeth, and the entire midface, from the palpebral fissure to the angle of the mouth, but not the nose. The ganglion cell bodies reside in the trigeminal ganglion and the maxillary nerve passes anteriorly through the cavernous sinus and foramen rotundum, then crosses the pterygopalatine fossa and enters the orbit. There, where it is known as the infraorbital nerve, it follows the infraorbital fissure and passes through the infraorbital foramen. The maxillary nerve has many named branches in the pterygopalatine fossa, within the infraorbital canal and on the face.

The facial nerve is the seventh cranial nerve and the nerve which innervates the muscles of facial expression. It exits the skull via the stylomastoid foramen and courses and passes through the parotid gland where it divides into five branches [22, 23].

Pitanguy's line may be used to estimate the course of the frontal branch of the facial nerve. This line extends from a point 5 mm below the tragus to a point 15 mm above the lateral end of the eyebrow.

Cervical Plexus

The cervical plexus originates from the ventral rami of the cervical nerves C1–4. Branches from this plexus innervate several deep muscles in the neck and supply cutaneous innervation to the submandibular region, most of the neck and much of the external ear. The great auricular nerve (C2–3) contributes to the innervation of the skin of the external auditory canal and slightly beyond. The transverse cervical nerve (C2–3) supplies the anterior and anterolateral neck from just below the mandible down to the clavicle, with considerable overlap with the mandibular nerve. Its sensory distribution includes the skin overlying the angle of the mandible. The lesser occipital nerve supplies sensory function of the scalp immediately posterior to the ear. The ansa cervicalis loop, with contributions of C1–3, innervates several muscles in the neck. The phrenic nerve comes primarily from C4, but has contributions from C3 and C5 and is the only nerve in the neck which has a lateral to medial course. Other motor and sensory branches of the cervical plexus will not be addressed.

Functions of Skin

Protection

Skin is the interface between the body and the external world. It serves as the essential barrier to and protects from the external environment. The collagen and elastin in the tough fibroelastic tissue of the dermis provide protection against mechanical trauma, chemical injury, microbial invasion, loss of water, and ultraviolet light. Critically, it has tremendous properties for healing and regeneration.

Much of the protection against bacterial invasion and chemicals is provided by the stratum corneum, with assistance by the immune system of skin and by sebum [24, 25]. The squames of the stratum corneum, which contain an insoluble protein, keratin, is shed constantly, thereby steadily renewing the surface of the skin. Sebum, the material secreted by sebaceous glands around hair follicles, impedes the growth of bacteria by providing an oily coating of pH of 4–6.8 (mean 5.5) over the skin [24, 26, 27]. Antimicrobial peptides, such as cathelicidin, are found on skin and impede the proliferation of microbes [28]. Also, some transient bacteria provide bacterial interference [29] (see section "Flora of Skin").

Homeostasis

Skin is an essential organ for maintaining the body's homeostatic environment. It does this by being a barrier to the loss of water and electrolytes, heat, and cold. A normal adult loses about 700 mL of water per day through skin. Skin is highly impermeable to most chemicals, but some molecules with a molecular mass of 500 Da or less can be slowly absorbed.

Thermoregulation

Under normal conditions, body core temperature differs according to location and method of measurement. Both anesthesia and surgery interfere with thermoregulation [30]. A review of the literature found that, in adults, oral temperature was 35.73–37.41 °C, rectal temperature 36.32–37.76 °C, tympanic temperature 35.76–37.52 °C, and axillary 35.01–36.93 °C [31].

Sensation

Skin contains receptors for pain, pressure, touch, and vibration, all of which communicate rapidly with the brain.

Secretion

Sweat of two types are secreted onto the surface of skin (see discussion above of "Sweat Glands").

Synthesis of Vitamin D

Vitamin D is synthesized in the epidermis, when exposed to ultraviolet light [32].

Immunological Surveillance

Langerhans cells, tissue macrophages mast cells, and dermal dendrocytes comprise the cells of the skin immune system, which has both innate and the adaptive immune components [33, 34].

Flora of Skin

Bacteriologically speaking, skin is a culture medium [35] with approximately 10^{12} bacteria on human skin [36, 37]. Organisms causing surgical site infections may have their origin from any part of the body or environment, but organisms from patients' skin are a major source for surgical-site infections. Most neurosurgical interventions include incisions in scalp, face, or along the spine, but some require incisions in extremities, chest, or abdomen. Surgical patients in operating rooms are commonly seminude and have various body parts and orifices exposed or entered. Also, multiple fully dressed surgical personnel are present in operating rooms, all of whom are sources of organisms, which can contaminate surgical wounds. Therefore, the following summary comments on the normal flora will primarily, but not exclusively, address skin and will not be confined to face and scalp.

Many types of microorganisms are present on normal human skin, oral cavities, and potentially the cranial sinuses and these organisms include bacteria, yeast, mites, and viruses, although the latter are not commonly mentioned among normal flora [29]. The adult human has been estimated to have one trillion bacteria on skin, representing over 1000 species from 19 phyla. These numbers are based on data from 16S ribosomal RNA identification of species and far exceed numbers from older data based on identification with culture media [38]. The great majority of these species are unresearched, probably harmless, and almost never identified in clinical cultures [39]. Most are either commensal species, which reside on but do not harm their host, or mutualistic species, which are of benefit to both host and organism. The latter group of organisms express their beneficial effect by impeding the establishment of colonies of transient pathogenic organisms. This is accomplished either by secreting chemicals that impede their growth or competing for nutrients on the skin.

The ecosystem of skin varies greatly and has distinct environments that are "as ecologically dissimilar as rain forests are to deserts" and is influenced by antibiotics, hygiene, and lifestyle [38]. Bacteria of the skin can be considered in two categories, a transient population and a resident population. The transient bacteria vary greatly, are determined by environmental contacts, and are shed by daily activities and bathing. Resident bacteria reside in sebaceous glands and hair follicles, as well as on the stratum corneum of exposed skin, particularly in moist areas such as the axillae and perineum [24].

Resident flora of normal skin include *Staphylococcus*, *Micrococcus*, *Peptococcus*, *Corynebacterium*, *Neisseria*, and *Acinetobacter*, *Brevibacterium*, Demodex, and *Pityrosporum* (yeast). *Staphylococci* and *Corynebacterium* species are the overall most common bacteria on skin, but a single individual likely has only a few of these species [1, 24, 40]. *Corynebacteria* and *Staphylococci* are dominant on moist areas such as axillae, inframammary folds, umbilici, groins, and skin creases. Demodex, a mite, feeds on lining cells of the pilosebaceous unit and possibly on *Propionibacterium* within these sites.

Regional differences in skin favor distinct types of microorganisms. Regions with higher temperature and humidity, such as the axilla and groin, are favorable for the growth of Gram-negative bacilli, coryneforms, and *S. aureus* [4]. The high density of sebaceous glands on the face, chest, and back encourages the growth of lipophilic microorganisms, for example, *Propionibacterium* and *Malassezia*, a fungus [25]. Relatively dry areas, for example, the volar forearm, hypothenar eminence, and buttock have fewer organisms [39]. The spectra of the microbiomes of the external auditory canal and umbilicus are diverse and include organisms uncommonly present on other skin [41, 42]. *Streptococci viridans* is the most common resident bacteria in the upper respiratory tract. The umbilicus contains many bacteria, particularly those that thrive in moist areas, but also *Actinobacteria*, *Clostridiales*, *Bacilli,* and even Archaea, organisms that thrive in extreme environments. Although uncommonly pathogenic, fungi occur over skin surfaces, but oddly the greatest number and diversity occur over the heel [43]. Psoriatic plaques have much higher bacterial counts than unaffected skin [44].

Antimicrobial peptides such as cathelicidins impede the proliferation of microbes on the skin. Cathelicidins occur in many cells including epithelial cells and macrophages, after activation by bacteria, viruses, fungi, or the hormone I,25-D, which is the hormonally active form of vitamin D. Also, the growth of gram-negative bacteria such as *Escherichia*, *Pseudomonas,* and some gram-positive bacteria such as *Staphylococcus aureus* and *Candida albicans* is impeded.

Common Bacteria of Skin

Propionibacterium acnes is a normal commensal inhabitant of skin and predominantly resides in hair follicles and pores of skin where it consumes sebum and cellular debris, but is less commonly on the flatter *surfaces* of skin. It also resides in the gastrointestinal tract. *P. acnes* predominates on skin in sites where there is oily sebum: scalp, face, chest, and back, and it releases free fatty acids onto skin [38, 45]. *Propionibacterium acnes* tends to make the skin an inhospitable environment for *Staphylococcus aureus* and *Streptococcus pyogenes*, but allows less virulent strains of Staphylococci, for example, *Staphylococcus epidermis* and Corynebacteria to grow [39]. It also contributes to the acidic pH of skin which inhibits growth of *Staphylococcus aureus* while favoring growth of coagulase-negative *Staphylococci* [38]. Growth of *P. acnes* is significantly inhibited at pH of 5.5, which is the normal mean pH of skin [26, 46]. This organism is rarely identified on preadolescent skin. Although having a low pathogenic potential, it can produce wound infections and it has a tendency to form a biofilm on implanted hardware [47], for example, Silastic® CSF shunts. There is some evidence that this organism has mutualistic properties that assist in protection of infection by other organisms [48].

Pseudomonas aeruginosa is best known by clinicians for causing serious infection; however, it is a normal inhabitant of the microflora of skin and mouth and is usually harmless. It produces pseudomonic acid (mupirocin), an antimicrobial substance that impedes several fungi including *Candida* and *Aspergillus*, probably in part by quorum-sensing [48, 49]. For this reason, *Pseudomonas* plays an important role in preventing infection by maintaining homeostasis. In infection, *Pseudomonas aerurginosa* secretes a material that protects it from phagocytic killing and from access by antibiotics [50].

Staphylococcus aureus is best known in neurosurgical practices as a pathogen causing wound infections, particularly those involving CSF shunts. However, it is often a transient pathogen on skin, but is a common transient in nasal microflora and, in these locations, is probably a commensal organism. In neurosurgical practice, this organism is best known for wound infections, particularly CSF shunt infections. *S. aureus* resists being killed by phagocytosis and secretes toxins that damage host cells [48].

Staphylococcus epidermidis is the most common organism identified on human skin, accounting for at least 90% of aerobic residents, and is a benign resident in most circumstances. It has a strong tendency to adhere to hydrophobic surfaces, for example, plastic surfaces and Silastic,® and some strains of this organism form biofilms, which provide them protection from antibiotics. This organism produces materials that selectively inhibit such pathogens as *Staphylococcus aureus* and Group A *Streptococcus*. But also is likely a reservoir of genes for antibiotic resistance which it is able to transfer to related more virulent organisms, such as *Staphylococcus aureus* [39]. And there is some evidence that quorum-sensing plays a role in infections from this organism [51]. (Quorum-sensing is extracellular signaling in which bacteria, for example, *Staphylococcus aureus* and *Pseudomonas aeruginosa*, alter gene expression of virulence and other factors, in response to increasing cell density [52].) In neurosurgical practices, *Staphylococcus epidermidis* is the most common organism associated with CSF shunt infections.

Healing of Skin

Surgery would not be possible without the existence of wound healing. Healing is an extremely complex process of extensively overlapping cellular and chemical activities. Much of what is known about wound healing is based on animal experimentation and almost all studies on human wound healing reflect wounds of diverse types on the trunk and extremities of adults with chronic wounds. There are two mechanisms for wound healing: regeneration and scarring. The former is the dominant process in healing of superficial wounds that involve only epidermis and superficial layers of the dermis. Scarring is the dominant method of healing of deeper wounds; however, connective tissue can regenerate. Hair follicles, sweat glands, and sebaceous glands do not regenerate. It is reasonable, however, to believe that the concepts of wound healing derived from these studies can be extrapolated to neurosurgical wounds.

Phases of Wound Healing

Wound healing begins instantly, even as wounding is occurring. The complex physiology of wound healing is commonly explained, for convenience, as consisting of several named phases. However, wound healing consists of multiple interrelated and broadly overlapping activities and not a cascade of sequential discrete steps [53, 54]. Each named phase encompasses many interacting cytological and biochemical activities which extend into other phases [55]. The healing process can adapt for wound type, local conditions, and for bacterial and foreign body contamination. The authors have chosen to describe the continuous process of wound healing in five phases.

Phase 1. Hemostasis *(duration: time of injury to day 4–6)*—A wound which causes bleeding initiates the hemostatic phase. Vasoconstriction of bleeding vessels begins within 2 or 3 s from injury and lasts for 6–8 s. The clotting cascade is activated as blood flows into the wound and contacts the exposed collagen. Vasodilation replaces vasoconstriction and lasts for approximately 20 min, during which there occurs breakdown of platelets and other blood cells and the inflammatory phase of healing begins. Platelets are the most numerous cells in this earliest phase of healing. They stick together and to collagen, and then degranulate with release of various cytokines and platelet-derived growth factor. This activates the coagulation pathway and leads to the formation of a clot composed of fibrin, platelets, and other cells, which provide a protective barrier across the wound. This counters bacterial invasion and provides a scaffold for migrating cells until it is replaced by collagen and becomes a scab. Therefore, within the hemostasis phase, bleeding is halted and the entire process of wound healing begins [53, 56, 57].

Phase 2. Inflammation *(duration: 1–3 days)*. The inflammatory phase begins during the latter hemostasis phase of healing and continues for approximately 5 days. Phagocytic cells begin to enter the wound within the period of vasodilation, which is within minutes of injury [56, 58]. Histamine released by platelets results in vasodilation and increases vascular permeability. Over 6–8 h, polymorphonuclear leukocytes, whose migration is facilitated by TGF-β, enter the wound, followed by an influx of monocytes, which become macrophages. These cells cleanse the wound by phagocytosis. Macrophages release various growth factors which initiate the multiplication of endothelial cells and the sprouting of new blood vessels. A clean incision is usually cleared of debris and bacteria within hours or days [59].

Multiple growth factors continue to be released from platelets and direct the inflammatory process, which continues into the proliferation phase of healing. Plasma proteins leak into the interstitial extravascular space near the wound and raise the local osmotic load. Water drawn into the space by glycosaminoglycans expands the extracellular space and produces edema.

Leucocytes within vessels around the area of injury marginate and release growth factors, vasoactive amines, and prostaglandins. Polymorphonuclear leukocytes arrive within 24–48 h from wounding and are the predominant cell type for about 2 days. These cells, having a life span of about 2 days, decontaminate the wound by killing bacteria with free radicals and by phagocytosing debris. There is an influx of neutrophils which become phagocytic macrophages. These macrophages release various biologic messengers, but also act to prevent infection. Fibroblasts begin entering the wound 2–5 days after injury and become the dominant cell type by 1–2 weeks.

Macrophages, activated by hypoxia, release materials that promote angiogenesis, chemotaxis of fibroblasts, and removal of debris and bacteria by phagocytosis. Macrophages are the most important mediators in this phase of wound healing. They later differentiate into fibroblasts and play an essential role in the next phase.

Granulation tissue appears in open wounds 2–5 days after injury and continues to grow through the proliferation phase of healing and until the wound is completely covered. Granulation tissue is composed of fibroblasts, new blood vessels, epithelial cells, and other materials which form an extracellular matrix. The fibroblasts secrete growth factors and produce collagen type 3 and fibronectin. The fibroblasts undergo apoptosis much later in healing and will be replaced by the stronger Type 1 collagen [60].

The inflammation phase continues for as long as there is debris and the wound remains open. Neutrophils and macrophages diminish steadily as the inflammation phase closes. If the inflammation phase is prolonged, the result is a chronic wound. Prolongation of the inflammatory process increases the likelihood of hyperproliferative scar formation [61, 62].

Phase 3. Proliferation *(duration: 14–21 days, possibly longer)*. The onset of this phase is not discrete, but begins at approximately day 4 (during inflammation phase of healing) and lasts for 2–6 weeks in clean wounds, for example, surgical incisions. The key activities of this phase of healing are epithelialization, neoangiogenesis, and deposition of a collagen matrix [57]. Most of the leucocytes and platelets undergo apoptosis, but some macrophages remain active and release collagenase and elastase. Fibroblasts, which peak around day 7, initiate angiogenesis, epithelialization, and collagen formation [60]. They proliferate and become mobile as they differentiate into myofibroblasts with lamellipodia and advance into the wound, where they contribute to wound contracture.

Collagen synthesis begins on approximately day 3 following injury and continues for 3 or 4 weeks. Fibroblasts migrate into the wound in days 5–7 and deposit collagen types I and III. By the mid-portion of the proliferation stage, 80–90% of collagen in the wound is Type I with the remaining being Type III. Type III collagen predominates in the early stages of wound healing, but is later replaced by type I collagen. Glyco-aminoglycans are produced and form the ground substance of the wound and this is replaced with granulation tissue composed of vascularized extracellular matrix consisting of fibroblasts and endothelial cells. Granulation tissue is not seen in most wound healings by primary intention, but a “healing ridge” can be identified by palpation in the zone of injury [57, 59].

The initial steps of epithelialization begin within 48–72 h of injury with division of peripheral cells and can quickly bridge a simple wound with a thin layer of epithelial cells. Epithelial cells from the edges of the wound and from deeper epidermal appendages, influenced by the hypoxic environment of the wound, migrate inward across the viable tissue in the wound until they contact epithelial cells from the opposite side, thereby forming a protective barrier [59, 63]. Metalloproteinases, which are zinc-dependent, digest basement membrane to facilitate cell migration, proliferation, and angiogenesis [39]. These keratinocytes migrate over granulation tissue and dissolve existing scab. These cells function most efficiently in a moist environment. Contact inhibition causes migration to cease when contact is made with cells advancing from the opposite side. The rate of epithelialization influences the width of the resulting scar, with slow healing producing a broad scar. As hypoxia and lactic acid in the wound diminish, the production of angiographic factors slows and ceases [60]. When the tissue in the wound becomes adequately perfused, migration and proliferation of endothelial cells slow and cease. The cells of blood vessels that are no longer needed undergo apoptosis [60].

Angiogenesis begins with the proliferation of fibroblasts during the proliferation phase of healing. Cells from surrounding capillaries become detached and migrate into the wound to produce new capillaries which self-organize and connect to existing capillaries to produce a new capillary network. The hypoxic and lactic acid environment promote angiogenesis and the fresh ingrowth of capillaries causes the tissue to have a red appearance. Angiogenesis is strongly influenced by FGF-2 and vascular endothelial growth factor (VEGF). Endothelial cells develop from vascular sprouts, thereby resulting in the development of new vascular channels. These processes are more active in wound healings by secondary intention. Angiogenesis slows as the wound becomes less hypoxic [64].

Phase 4. Contraction *(duration: starts around day 7 and last for weeks)*. The contraction phase spans the period in which the edges are pulled toward the middle of the wound and the wound becomes smaller. Sutured clean surgical wound healings by primary intention undergo little or no contraction, but contraction plays a key role in wound healings by secondary intent [56]. Contraction starts approximately a week after injury and can last for weeks, even after reepithelialization ceases. Contraction of a wound occurs from the action of myofibroblasts, which are cells differentiated from fibroblasts and, like smooth muscle cells, contain actin. Hypoxia is thought to impair myofibroblasts and therefore wound contraction [65]. Fibroblasts deposit collagen as the myofibroblasts pull the sides of the wound together. Wounds may contract as rapidly as 0.75 mm per day. When contraction stops, the myofibroblasts undergo apoptosis [60].

Phase 5. Remodeling or maturation *(day 21 to 1 year or longer)*—The remodeling phase of wound healing begins when the synthesis and breakdown of collagen become equal. Remodeling begins by the third week after injury and may continue for years. Collagenase degrades collagen and collagen fibers become cross-linked and more aligned along lines of tension, thereby stabilizing the architecture of the wound. The strength of the wound increases as the proportion of type I collagen increases and type III decreases. The normal basketweave patter of collagen is not reestablished, but fibers tend to align parallel to stress lines of the wound. The processes occurring, particularly in the early portions of the remodeling phase, are strongly influenced or controlled by TGF-β, PDGF, and IL-1. Myofibroblasts, which are specialized fibroblasts that resemble smooth muscle cells, steadily contract the wound. Tensile strength of collagen reaches approximately 20% of its eventual maximum by 3 weeks and 80% by 8 weeks [56, 66]. Two or more years may be required for a wound to reach full maturation, due to differences in the collagen makeup and organization. Slowly, the wound flattens and softens, and erythema fades as the cells of blood vessels undergo apoptosis.

Healing of Wounds

Full-thickness wounds heal by scar formation. Hair follicles, sweat glands, and sebaceous glands within skin do not regenerate [67].

Primary intention healing results from approximation of the edges of a clean wound in which there is little associated tissue damage, for example, a full-thickness surgical incision. Healing occurs rapidly with no visible granulation tissue and minimal scarring. Primary wound closure is the technique of choice and typically results in the most esthetically pleasing scar.

Secondary intention healing (delayed primary wound healing) occurs when a full-thickness wound is not surgically closed, but allowed to heal by formation of scar. Delayed closure is used when primary intention closure is contraindicated due to bacterial contamination, retained foreign bodies, or marginally vascularized tissues. It is preferred for animal bites, wounds with prolonged open exposure prior to presentation, and wounds which cannot be approximated because of swelling or missing tissue. Secondary intention healing can require weeks to months for final closure and require dressing changes and much discomfort [68].

This type of healing is relatively slow and always has microbial contamination. Phagocytosis of contaminated tissue and the healing process are quite active by the fourth day with the beginning of epithelization and deposition of collagen. Foreign materials become walled off by macrophages. There is a more intense inflammatory reaction, with the formation of more granulation tissue than occurs with primary wound healing. Myofibroblasts, which have a key role in wound contraction, have their maximum presence by 10–21 days from wounding. Secondary intention healing involves an inflammatory reaction with formation of granulation tissue and uninhibited contraction due to slow epithelialization typically results in a broad scar with risk for a hypertrophic scar or keloid formation.

Tertiary intention healing occurs when the edges of the wound are brought together after a period of delay. The wound is intentionally left unclosed for several days, to allow a series of dressing changes to decrease contamination, optimize the local bioburden, and allow assessment of tissue viability, thereby diminishing the risk for wound infection. Tertiary intention healing may also be used after a primarily sutured wound dehisces. Phagocytosis of contaminated tissue and the start of epithelialization and deposition of collagen are underway by the fourth day. The time to healing from dehiscence occurs more quickly than does healing after primary closure because the lag phase of inflammation is not repeated.

Reepithelialization is the type of healing that occurs in wounds that involve only epidermis and possibly superficial dermis [57]. This type of healing is regeneration and there is typically no scar formation. There is a brief inflammatory response followed by resurfacing of the epithelium [56]. If there is significant injury to dermis, granulation tissue will form [69]. Epithelial cells migrate, replicate, and move across the wound. Little or no wound contracture occurs. Epithelialization is the dominant phase of wound healing in superficial burns, such as can occur from electrocautery during surgery. This may result in prolonged pigmentary changes which may take years to resolve or may remain permanent [70].

Scab Formation

A scab is a dry, brown crust that forms over a wound in skin within the first hours or day following injury and is a component of the healing process. A scab develops when blood, which contains platelets, fibrin, and several types of blood cells, clots and its outer surface becomes dehydrated. Although it can be thought of as both a biologic dressing and bandage which seals the wound from the entry of contaminants, prevents ongoing dehydration, and provides protection from further injury, it delays wound healing and can predispose to infection. All scabs should be carefully removed, after which the healing surface must be kept moist.

Scar Formation

Scar formation is a normal and important physiologic process. It is the major mechanism of healing of wounds. Scars of face, neck, and bald scalp tend to attract unwanted attention. Scars in hair-bearing scalp are concealed unless the hair is very short or thin. Most scars are not visible in a clothed person, but scars are undesirable to patients, regardless of location.

Scarless Wound Healing

Scarless healing is the term used for healing of full-thickness wounds with no resulting scar, occurs only in fetal tissues and ends at approximately 22–24 weeks gestation [71, 72]. However, healing of partial-thickness wounds, which occurs by reepithelialization, may not result in scar formation. Scarless healing for both surgical incisions and traumatic injuries remains a goal in all surgical practices and has been the subject of continuing extensive research in humans.

Pathologic Scarring

Hypertrophic scars—Hypertrophic scars are raised, wide, firm, and are confined within the borders of the original injury after closure. It typically undergoes a rapid growth phase shortly after healing or following an infectious event. A hypertrophic scar may undergo some regression. Many factors can direct the healing process toward hypertrophic scarring. Healing which occurs in wounds closed under undue tension, in the presence of infection, or retained foreign material will often result in hypertrophy of the scar.

Keloid [Greek: crab's claw] *scars*—Keloid scars are raised, fibrous, often irregular, and extend beyond the borders of original injury. They may appear months to years after healing and do not trend toward regression. Keloids can occur anywhere in the body, but are rare in the scalp. These pathologic scars are hypervascular and have high mesenchymal cell density and thick epidermis. A healed wound may develop into a keloid in patients with keloid elsewhere on the body. There is a genetic predisposition towards hypertrophy or frank keloid formation which often becomes cosmetically worse with significant density of melanin pigmentation in the skin. Keloid scars are characterized by having few macrophages, but many eosinophils, mast cells, lymphocytes and plasma cells.

Keloidization is not well understood and there is no reliable preventive action. There are many treatments for keloid including intra and extra-lesional excision, administration of steroids, cryotherapy, laser, and low-level dermal radiation. The results of all treatments are unpredictable.

Eschar

Eschar is not a type of scab, but is dead tissue covering a full thickness wound, and its development is a normal phase of healing of a wound having a dead piece of skin. Dead tissue covered with intact skin is not eschar. An eschar is usually brown to black, can be hard or leathery, and has discrete edges. It acts as a protective barrier to the entry of bacteria and keeps the wound moist; however, it also delays wound healing by slowing epithelialization and predisposing to infection.

Small eschars which occasionally form along the edges of a surgical wound are the result of tissue being burned by electrocautery, tightly tied sutures, or rough surgical technique, all of which affect blood supply to the affected tissue. Eschar can be the result of prolonged pressure which necroses a section of skin.

Factors That Affect Wound Healing

All healing of skin wounds occurs by the stages discussed above, but varies with age. No drugs or surgical actions have been found which accelerate normal wound healing in healthy individuals; however, many factors can impede or prevent healing. Conditions for normal healing can be optimized and many impediments avoided, hindered, or removed.

Wound-healing problems following neurosurgical interventions are especially problematic and often complex. Reported risk factors for recalcitrant wound healing include the following: CSF leakage, prolonged cortisone application to wound, ongoing chemotherapy or radiation therapy, and multiple failed attempts at closure [73, 74] (see Table 1.1).

Table 1.1 Factors that affect wound healing

Age	Nutrition
Bacterial infection	Obesity
Disease	Oxygen level
Edema	Radiation
Hydration	Surgical technique
Immunosuppression	Temperature
Infection	Tobacco usage
Mechanical force	Vitamins
Moisture/dryness	Wound contamination

Age

Wound healing in the fetus and premature newborn—The dermis of the fetus is typically well developed, but the epidermis, at that age, differs importantly from that of term newborns, being quite thin and having fewer hair follicles and sebaceous glands than does the skin of children. Fetal skin has relatively fewer intercellular connections, and therefore injury to the skin of the fetus by direct impact or firm abrasion is more likely to cause injury, including separation of epidermis from dermis.

A large body of research exists regarding fetal wound healing. Inflammation is minimal throughout early gestation and healing without scarring and is typical in the fetus before 22–24 weeks gestation [75]. Epithelial resurfacing is also rapid. Fetal wound healing is marked by minimal inflammatory response and the deposition of glycosaminoglycans, particularly hyaluronic acid. Collagen is quickly reorganized into seemingly uninjured tissue components with higher levels of type III compared to type I. Mast cells are less mature and are fewer in number. Wounds heal by regeneration instead of repair, until the last trimester of pregnancy at which time in embryonic development healing may result in less favorable scarring. It is postulated that the differences between fetal and postnatal wound healing may be related to differences in endocrine and immune systems, relative hypoxia of the fetus, and the influence of the placenta and amniotic fluid. There are clear distinctions in levels of growth factors and their inhibitors between fetal and adult wounds, such as basic fibroblast growth factor (bFGF). Investigators are more closely examining the relationship of tenascin and extracellular matrix glycoprotein, and whether it is responsible for improved wound healing in utero.

Premature newborns have limited macronutrient stores, and these can quickly deplete in the setting of large wounds. Impaired wound healing in a premature newborn, often manifested by poor granulation or recurrent infection, may be the result of inadequate nutritional intake.

Wound healing in adults—The characteristics of skin and healing change with age. The skin ages by intrinsic and extrinsic factors. Genetic predisposition, oxidative metabolism, and cellular senescence exert intrinsic influence on aging of skin. UV light, nicotine, air pollution, and microorganisms provide extrinsic influence. Extrinsic influence is more notable on exposed skin such as the head, neck, hands, and forearms. Between the second and third decades of life, skin visibly ages due to oxidative stress from reactive oxygen species creating free radicals. These are both naturally made by mitochondrial metabolism and can be made worse by exogenous factors such as smoking, which damages tissue structure and degrades collagen. Extrinsic factors contribute to irregularity of matrix proteins. Clinically, this may ultimately result in wrinkling, atrophy, roughness, hyperpigmentation, sagging, and dry skin. Intrinsic factors may contribute to atrophy of skin and thinning of dermis. This reduces amounts of collagen, elastin, and extracellular matrix.

Wound healing in elderly adults—The skin of elderly people has increased risk of impaired postoperative healing related, in great part, to diminished microcirculation, inadequate growth factors, and thinness. Reepithelialization may be prolonged and there is a diminished proliferative phase of wound healing, which may allow earlier maturation of the wound. Age alone is not a contraindication to complex surgical reconstructive efforts.

Wound healing in the elderly often results in a less exuberant but cosmetically more acceptable scar than in non-elderly patients, probably because of less skin tension and degeneration of elastin [76, 77].

Bacterial Wound Infection

Local infection imparts a negative impact on wound healing. Quantitative cultures demonstrating $>10^5$ bacteria per gram of tissue are associated with inability to heal, including the rejection of skin grafts on a contaminated bed. Elevated bacterial counts contribute to a prolonged inflammatory phase and hypoxia. Local endotoxins release collagenase and interfere with stimulation of phagocytosis. These issues inhibit fibroblast proliferation and collagen maturation. Clearance of infection with debridement, wound care, and appropriate antibiotic therapy is the mainstay of treatment of local wound infection.

Sepsis impairs wound healing through several factors. Septic shock is characterized by increased production and release of inflammatory cytokines and their dysregulation. Systemic inflammatory symptoms of fever, hypotension, poor tissue perfusion, and protein catabolism are common. Immunodeficiency and proinflammatory states have inhibitory effects on wound healing.

Biofilm is an extracellular matrix of polysaccharides in which bacteria, often more than one species, such as *Pseudomonas aeruginosa* or *Propionibacterium acnes*, reside and form a cooperative community with its own homeostatic system [78]. Biofilms have remarkable resistance to host immunity and to antibiotics, including topically applied antibiotics [79]. Organisms of a biofilm can be 500 times more resistant to antibacterial agents than the same organisms in other sites [78]. Quorum sensing, which is the phenomenon in which cell population density regulates gene expression, probably plays a role [52, 73, 74].

Disease

Anemia—Healing can be impaired by decreased oxygen transfer associated with hypovolemic anemia and blood loss from trauma. Mild to moderate normovolemic anemia in a healthy person does not impair wound healing and postsurgical transfusion to address mild to moderate anemia does not improve wound healing; however, at a hematocrit of 20 or less, transfusion is indicated.

Cancer—Patients with metastatic and advanced malignant disease have impaired wound healing. Most neurosurgical practices include patients with malignant neoplasia, both within the central and peripheral nervous systems and spine. Patients with malignant brain tumors commonly have impaired nutritional intake caused by altered brain function, chemotherapy, radiation therapy, and depression. Cancer cachexia is characterized by progressive loss of muscle and fat throughout the body. This differs from starvation in which fat stores are preferentially lost and muscle tends to be preserved. In the presence of malignancy, anorexia is common with diminished appetite and lowered satiety, some of which can be related to depression or pain. Many malignancies are associated, particularly in advanced stages, with a hypermetabolic state and thus an accelerated expenditure of energy. Carbohydrate metabolism may become severely disturbed with an increase in anaerobic glycolysis. Lipid metabolism may increase and result in a reduction or depletion of fat. Catabolism of protein combined with a decrease in production of protein results in reduction of muscle mass throughout the body. Also, multiple cytokines contribute to cachexia in the presence of malignancies. Antineoplastic drugs and steroids administered in close temporal relationship to surgery, either before or after, can significantly delay postsurgical wound healing, particularly if administered concomitantly with radiation therapy.

The problems of wound healing in patients with cancer are most effectively dealt with by eliminating the cancer, but significantly reducing its bulk may be beneficial; however, these goals are often not achievable. The details of addressing the metabolic and nutritional needs of patients with cancer are complex and are best addressed by nutritionists.

Diabetes mellitus—Diabetes mellitus is the most common disease which impairs wound healing. Poor wound healing associated with diabetes is due to the formation of advanced glycosylation end products. A wound in a diabetic patient may have decreased inflammatory response, decreased granulocyte response, and slower epithelialization. After controlling for confounding factors, the contribution of diabetes to the risk of surgical site infection risk is not clear [80]. There is evidence, however, from patients who underwent coronary artery bypass surgery for a significant relationship between elevated levels of HgA1c and the rate of surgical site infection [30]. Also, in the early postoperative period, blood glucose levels >200 mg/dL are associated with increased risk of surgical site infection [81, 82].

Infection—Infection greatly impairs wound healing. The presence of infectious organisms can decrease leucocyte chemotaxis and phagocytosis and also impair angiogenesis and epithelialization. Clearance of infection and consideration of quantitative biopsies to assess bacterial load can be considered to achieve satisfactory healing.

Other Influences on Wound Healing

Edema—Edema (extravascular tissue pressure) reduces blood flow and can thus slow healing.

Hydration—Hypovolemia due to inadequate hydration impairs healing, particularly in the elderly [83, 84].

Immunosuppression—Steroids have a negative impact on wound healing by decreasing the inflammatory infiltrate and ultimately impairing the initial normal wound healing response, resulting in cells that do not produce the necessary growth factors for optimal healing. Steroids inhibit macrophage function, delay angiogenesis, and inhibit wound contraction and epidermal regeneration. Inhibition of fibroblasts interferes with collagen production and therefore wound strength and endurance are impaired [85, 86].

A large study comparing patients who received corticosteroids for at least 30 days before surgery with those who did not found a significantly higher rate of surgical site infections, a two- to fourfold increase in wound dehiscence, and a fourfold increase in mortality in the patients who received steroids [87]. Local administration of vitamin A counters the effects of corticosteroids on wound healing.

Chemotherapeutic agents—These commonly have a negative impact on wound healing by slowing the inflammatory response, impeding angiogenesis, and decreasing fibroblast proliferation and wound contraction. Actinomycin D, bleomycin, and BCNU have been specifically implicated in decreased wound strength. Generally, antimetabolic, cytotoxic, and steroidal agents are immunomodulators and increase risk for infection and failure of tissue repair. It is thought that preoperative chemotherapeutic agents have little or no effect on wound healing, unless received within a few weeks before surgery. However, the administration of chemotherapeutic agents before surgery or thereafter impedes wound healing and strength of healed wounds. The safe time intervals before and after surgery are not clear. Chemotherapy that is started after the proliferation phase of healing is completed, which is approximately 6 weeks, has little or no effect on wound healing.

Mechanical force—Wound trauma and shear forces can disrupt the healing process.

Moisture—A moist wound environment significantly increases the rate of wound healing, epithelization, and time to wound closure. Moisture is thought to shorten the inflammatory phase and speed the proliferative phase. However, a chronically wet wound can lead to maceration of skin and delay in healing.

Nutrition—Malnourishment may lead to impaired wound healing, infectious complications, and prolonged ventilator dependence. Nutrition and wound healing are intimately related. However, routine nutritional assessment should not be done unless there is obvious preexisting deficiency or a chronic clinical course. The most common assessment used for this is the determination of serum albumin or prealbumin, which optimally should be greater than 3.5 mg/dL and greater than 15 mg/dL, respectively. Recommendations for alimentation and supplementation should be tailored to the individual patient. Other biochemical markers such as transferrin (≥200 mg/dL), nitrogen balance, total cholesterol, and creatinine may also provide guidance. For more details on the effect of nutrition on healing, see Molnar's *Nutrition and Wound Healing* [88].

Obesity—The literature on postsurgical wound healing in obese patients is significantly influenced by reports on abdominal surgery, particularly bariatric surgery; however, obesity, particularly in morbidly obese patients, influences all sites of wound healing and predisposes to infection and dehiscence.

Oxygen level—Oxygen levels in injured and healing tissue are of primary importance. The oxygen level and the partial pressure of oxygen must be maintained in the 30–40 mmHg range for optimum healing. This is necessary for fibroblast function and for the formation of collagen. Smoking causes cutaneous hypoxia through vasoconstriction. Increased carbon monoxide levels associated with smoking decreases oxygen-carrying capacity of hemoglobin and impairs healing. Hydrogen cyanide in cigarette smoke inhibits oxygen transport. That is dependent upon not only inspired oxygen concentration, but on the hemoglobin transfer and adequacy of local wound vascularity.

External tissue pressure—High sustained external tissue pressure impairs healing.

Radiation—Radiation adversely affects all living tissue and skin is very vulnerable because of its continuous cellular renewal. Complications from radiation therapy may occur in as high as 60% who have undergone surgery. The early side effects of radiation on skin include erythema, desquamation, hyperpigmentation, hair loss, and delayed or nonhealing of wounds. It has been observed that "… acute radiation may cause erythema at two Gy, cataract at two Gy, permanent epilation at seven Gy, and delayed skin necrosis at 12 Gy" [89].

Ionizing radiation affects all phases of wound healing [90]. Free radicals that damage proteins, DNA, and cell membranes are created. This results in occlusion of vasculature, endothelial edema, and thrombosis. Rapidly dividing cells are damaged and reduced in number. These include keratinocytes, basal cells, endothelial cell, and cells of sebaceous glands and hair follicles. Radiation can also impair fibroblast function which impairs wound healing. The inflammatory phase of healing is slowed with slowing of neovascularization which causes hypoxia and delay of migration of fibroblasts into the wound [57]. The effects of radiation on skin are influenced by dose, energy, size of field irradiated, interval between fractions, concomitant chemotherapy, and biologic modifiers [91]. Also the effects of ionizing radiation are cumulative. Radiation of skin results in reduced microvascularity and thickness, epilation, and reduction in elasticity. It is common for neurosurgical patients who have malignant disease to receive postsurgical radiation therapy, and occasionally surgery is required in patients who have recently received radiation therapy. Also, the effects of radiation on the brain can impair a patient's physical activity and reduce the intake of nutrition.

Presurgical radiation administered to patients, even years before coming to neurosurgical attention, can greatly impair healing; however, generally healthy individuals tend to heal well if the radiation therapy is completed 6–8 weeks before surgery. Irradiated tissue is often significantly fibrotic and thereby can make retraction and dissection of tissues more difficult than normal.

Postsurgical radiation received by normal skin after approximately 6–8 weeks will rarely lead to dehiscence (assuming no prior radiation and excellent wound closure). Radiation that begins 4–6 weeks after surgery usually does not encounter problems. Irradiation of a surgical wound that begins earlier, particularly within 2 weeks, will have greatly impaired healing, and sutures or staples should be left in place for approximately 4 weeks or longer.

Surgical technique—Well-approximated and gently everted wounds heal most favorably in noninfected circumstances. Surgical technique can greatly affect healing of wounds. Cautery should be used precisely to minimize tissue damage and establish hemostasis.

Poor alignment of skin edges raises risk of infection, delays healing, and increases the width of the healed scar. Excessive number of sutures and their excessive tightness delay healing, decrease local vascularity, increase risk of infection, result in poor wound healing, and increase width of the healed scar. Vascular compromise negatively impacts wound healing. Hindrance of microcirculation affects delivery of oxygen, nutrition, and migration of wound healing molecules as well as clearance of phase-specific cells and growth factors.

Temperature—Hypothermia impairs immune function, impairs healing, and probably raises the incidence of wound infection [92]; however, there are reports that intraoperative hypothermia is not significantly associated with surgical site infections (SSI) [93, 94]. Intraoperative and postoperative hypothermia causes vasoconstriction which diminishes local perfusion and wound oxygen tension. Temperatures below 36 ° C are associated with infection, coagulopathy, and prolonged recovery [95–97].

Normothermia should be the goal during surgery. General anesthetics significantly impair normal thermoregulatory control. Anesthesia can significantly affect temperature of the core. A fall of 1–3 °C is common during surgery and often continues into the postoperative period. Skin surface temperature does not reliably reflect core temperature [98]. Peripheral vasoconstriction in response to sympathetic nervous influence lowers skin temperature. In a surgical environment, vasoconstriction may be caused by cold air, blood volume deficit, low core temperature, adrenalin injection, dehydration, and some medications [30, 92, 99, 100].

Tobacco usage—Tobacco usage adversely affects wound healing and secondarily has adverse effects on pulmonary and cardiovascular health which can adversely impact wound healing. The smoking of tobacco delivers nicotine, carbon monoxide, and hydrogen cyanide directly to the lungs where they are absorbed. Nicotine promotes vasoconstriction and platelet aggregation. Smoking causes cutaneous hypoxia through vasoconstriction. Increased carbon monoxide levels with smoking decreases oxygen-carrying capacity of hemoglobin and impairs healing. Hydrogen cyanide in cigarette smoke inhibits oxygen transport. Nicotine delays primary wound healing and increases the risk of surgical site infection. Also, there is a dose-response effect on rhytid (wrinkle) formation [101].

Electronic cigarettes (e-cigs)—These are battery-powered, nicotine-delivery systems with which the user inhales an aerosol containing various combinations of propylene glycol, glycerin, nicotine, and/or flavorings. The use of e-cigarettes, commonly referred to as vaping, is gaining popularity since their introduction in 2004. Smoking and vaping have significantly deleterious effects on wound healing [102–104].

Vitamins and Micronutrients

All vitamins are required for health and healing. In healthy individuals, little if any benefit in healing is derived from administration of vitamins, except for vitamins A and C. Vitamins, particularly A and C, are necessary for collagen production. Many in the lay public and some physicians believe strongly, probably in response to advertising claims, that dietary supplementation with vitamins promotes or accelerates normal wound healing. The evidence for most of these opinions is tenuous, except in patients with severe laboratory documented nutritional deficiency or advanced malignancy. The administration of vitamins and micronutrients in healthy patients does not augment or accelerate the rate of healing beyond normal. A brief overview of the role of vitamins in wound healing is given to address these claims.

Vitamin A

Vitamin A deficiency may result in impaired wound healing. Vitamin A increases macrophages, enhances lysosomal membrane lability, and activates the production of collagen. Deficiency of vitamin A is associated with impaired epithelialization, collagen synthesis, cross-linking of new collagen, wound contraction, and can be associated with impaired wound healing. Vitamin A works synergistically with Vitamin E. Vitamin A is an antagonist of corticosteroids, reversing the anti-inflammatory effects of wound healing. The administration of 25,000 IU/day has been proposed to accelerate the growth of granulation tissue and increase the rate of wound healing for patients on chronic steroids. Excessive intake of vitamin A can be highly toxic [105].

B Vitamins

None of the B vitamins are manufactured in the body and therefore all must be supplied in food. These vitamins interact with one another for energy metabolism and tissue synthesis.

Vitamin B_1 (thiamine)—B_1 deficiency is thought, based on animal studies, to interfere with macrocytic activity in the early phases of wound repair and to have an adverse effect on the breaking strength of wounds.

Vitamin B_2 (riboflavin)—B_2 is involved in all phases of wound healing. Animal studies have demonstrated that vitamin B_2 deficiency is associated with delayed epithelialization, slowed wound contraction, and diminished tensile strength of healing wounds.

Vitamin B_5 (pantothenic acid)—B_5 has been shown in animal studies to increase fibroblast migration rates and thereby may increase the rate of wound healing. Deficiency of this vitamin is extremely rare.

Vitamin B_6 (pyridoxine)—B_6 deficiency is associated in animal studies, with an impaired inflammatory response in skin and with impaired healing of fractured bones, probably related to an effect on osteoblasts and osteoclasts.

Vitamin C

Vitamin C (ascorbic acid) deficiency is thought to be associated with decreased production of collagen, impaired angiogenesis, poor wound healing, bleeding, and a negative impact on bone formation. There is an established relationship to scurvy, in which there is a failure in collagen synthesis and crosslinking. The data on the efficacy of recommending vitamin C to enhance collagen synthesis and wound healing in healthy patients are tenuous.

Vitamin D

The role of vitamin D on wound healing is not clear. Animal studies have demonstrated accelerated wound healing, increase in strength in wounds, and improved epithelialization with topical application. 1,25-Dihydroxyvitamin D_3 is reported to stimulate synthesis of fibronectin, which is important in wound healing, and the activation of macrophages. Patients who may be at risk from Vitamin D deficiency include elderly patients and individuals with malabsorptive disorders, liver disease, long-term corticosteroid administration, as well as patients with burns or chronic wounds. High doses of vitamin D, particularly if ingested for many days or weeks, can be extremely toxic.

Vitamin E

There is no beneficial role for administering vitamin E. There is some evidence that vitamin E may interfere with the wound healing effect of vitamin A. Regardless, many lay people believe that Vitamin E is beneficial. Local application of vitamin E for scar modulation has no benefit and is topically sensitizing in many patients.

Vitamin K

Vitamin K has no direct role in wound healing; however, vitamin K deficiency can impair coagulation which can adversely affect wound healing, particularly in newborns.

Micronutrients

Micronutrients function primarily as cofactors in various biochemical reactions. All micronutrients are required for normal growth and healing, but little if any benefit is derived from dietary supplementation in healthy individuals.

Copper

Copper is a cofactor in cellular proliferation and the production and cross-linking of collagen. Copper deficiency is associated with weak scar formation and predisposes to wound dehiscence.

Iron

Iron is required for the hydroxylation of proline and lysine and it has an essential role in the transport of oxygen. Like other micronutrients, it is necessary for collagen synthesis. *Zinc* deficiency is associated with decreased fibroblast proliferation and collagen synthesis. It has a role in mitosis and proliferation in wound healing. It may be depleted with chronic steroid intake or stress and should be replaced under these conditions. Supplementation in patients with no zinc deficiency does not improve wound healing and can impair phagocytic activity and cause copper deficiency.

Wound Contamination

Traumatic wounds must be debrided of necrotic tissue and foreign materials and irrigated copiously with antibiotic-containing solution. Bacterial colonization $>10^5$ organisms/gram of tissue has risk of wound infection and prolonged healing. Infectious organisms can impair leucocyte chemotaxis, phagocytosis, angiogenesis, and epithelialization. The foreign body burden must be minimized to optimize conditions for wound healing. The presence of foreign material can prolong the inflammatory phase of healing or prevent healing.

Exposed surgically implanted foreign materials, for example, CSF shunts, metal plates, and all synthetic cranioplasty plates, raise the risk of postoperative wound infection. Polymorphonuclear cells in contact with Silastic® have impaired ability to phagocytize and kill bacteria [106].

Intraoperative wound contamination may be recognized when there occur "breaks in sterile surgical technique," unrecognized use of a non-sterile surgical instrument, or the accidental entry of a foreign material or object during surgery.

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2 Preparation for Surgery

Ken Rose Winston and Christopher Ciarallo

Rehearsal

Ken Rose Winston

Rehearsal of surgery increases safety and enhances the efficiency and smooth conduct of the surgery. Rehearsal is therefore beneficial for patient and surgeon and has no associated risk.

Mental Rehearsal

The mental and motoric activities of a specific surgical procedure on a patient can be *visualized and experienced* in a stepwise manner at the speed of thought. This usually requires only a few minutes, but varies with surgical complexity, specific details, and with the surgeon's experience. Mental rehearsal of a surgery is a pre-enactment which has the effect on the surgeon of a stress-free execution of surgery. Therefore, as the live surgery progresses, the surgeon, in an important sense, is executing that surgery for the *second time*. The surgeon will find the anatomy, physiology, pathology, and even the idiosyncrasies of the case more familiar than if not mentally rehearsed. Different surgical incisions can be 'tried', and the details of

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operative procedures *mentally executed*, including the dissection and even direction and force of retraction. Components of a surgical plan can be discovered, during mental rehearsal, to be problematic, in which case alternative plans can be contemplated. Surgical strategies for retreat can be practiced in a non-stressful and absolutely safe setting. Several mental rehearsals may be beneficial in unusual, complex, or high-risk cases.

Events and situations that are unexpected, unlikely, or extremely rare can be 'reacted to' in a manner analogous to that of a pilot mentally practicing the handling of in-flight emergencies in a flight simulator but in a stress-free setting. Mental rehearsal does not limit any action in the operating room. If a situation arises during surgery which was not considered in rehearsal, the surgeon is in the identical situation she/he would have been if no mental rehearsal had occurred. Even familiar surgeries and so-called small surgeries benefit from a quiet moment of contemplative review. Mental rehearsal is best done alone in a quiet setting without mental interruptions, but cannot be done during conversation.

Verbal Rehearsal

A discussion, usually brief, with the surgical assistant, anesthesiologist, circulating nurse, and scrub nurse, is important. Surgeries flow smoother and more safely when all involved persons know 'the big picture' and are aware that others know the same.

Team Rehearsal

All members of the surgical team should be aware of the surgical plan and have freedom to ask questions and make comments. Uncommon and complex surgeries, for example surgeries that will require repositioning (e.g., surgeries accessing both anterior and posterior cervical sites), should be rehearsed or walked through in an operating room if the surgical team is unfamiliar with the surgery. Positioning of patient, requirement for special equipment, large equipment, and positions of scrubbed personnel can be reviewed.

Modern technology has allowed the surgeon access to virtual surgical planning (VSP) and 3D printed models as well as cutting guides for bone. This allows the team to practice the surgery or alternatives with computer-generated imagery in real time via computer teleconference. The printed models may be cut and/or used intraoperatively to increase efficiency and safety. These may be used for teaching and education as well.

Anesthesia

Christopher Ciarallo

In the United States, the anesthesiologist's responsibility for patients of all ages begins with patient assessment and discussion of the anesthetic technique, followed by preoperative informed consent. Their responsibility concludes with handoff and transition of care in the recovery room (or intensive care unit) in stable condition unless there are indwelling neuraxial or perineural catheters for the administration of postoperative analgesia. Many of the perioperative considerations throughout this phase are similar for both adult and pediatric patients, but some pediatric concerns will be acknowledged separately.

Operating Room Considerations

Resuscitation equipment (including a defibrillator, cardiac resuscitative medications, and emergency airway equipment) must be identified and made available prior to transporting a patient to the operating theater. The 2019 *Joint Commission National Patient Safety Goals* underscore the requirement for a formalized "time-out" process to minimize the risk of "wrong site, wrong procedure, wrong person surgery." Patient safety remains a shared responsibility between the surgeon, anesthesia team, and perioperative nurses. Perioperative concerns (including anesthesia induction, intraoperative monitoring, postoperative disposition, and management) can be highly patient and surgeon-specific, and they are an essential component of the "time-out" process. The surgeon should play an active role in the discussion and should never assume that everyone, regardless of assumed responsibility and experience, has the same judgement or situational awareness.

Predictors of Perioperative Adverse Events

The preoperative evaluation of adult and pediatric patients presenting for craniofacial surgery should focus on risk assessment and risk reduction. Some patient-specific risk factors, such as weight and ASA score (American Society of Anesthesiologists) physical status classification, are associated with an increased risk of clinically significant perioperative events, but cannot be optimized [1]. While the elaboration of a complete preanesthetic evaluation is beyond the scope of this text, issues regarding airway management, cardiac pathology, intracranial pressure, and anemia are of particular interest to the surgeon and anesthesiologist. Individuals with craniofacial abnormalities as part of a recognized syndrome are at higher risk than non-syndromic individuals for difficult airway management and obstructive sleep apnea [2]. In the pediatric population, the presence of a craniofacial syndrome is an independent risk factor for a major perioperative complication and prolonged postoperative length of stay [1]. Additionally, craniofacial syndromes are frequently associated with congenital heart disease, and these patients may develop pulmonary arterial hypertension from inadequately treated obstructive sleep apnea. Intracardiac shunts, including an asymptomatic patent foramen ovale, are present in up to 35% of pediatric patients and 20% of adults. Venous air embolism is exceedingly common in craniofacial surgery, and patients with intracardiac shunts are potentially at risk of paradoxical air embolism and acute ischemic stroke. Accordingly, preoperative echocardiography has been recommended for craniofacial surgeries in seated or other head-elevated surgical position [3]. The preoperative evaluation should also include a discussion about intracranial pressure management, as elevated ICP is not uncommon (and may be present in up to 40–70% of patients with syndromic craniosynostosis) [4]. Finally, preoperative anemia should be evaluated and optimized (e.g., iron supplementation or erythropoietin-stimulating agents), as pediatric patients with a preoperative hematocrit above 35% are three times more likely to avoid red blood cell transfusion in cranial vault reconstruction [5].

Monitoring

Most neurosurgical and craniofacial surgeries are performed under general anesthesia, although regional anesthesia (e.g., peripheral nerve blocks) is a consideration for some procedures and regional techniques may be utilized for postoperative analgesia. Intraoperative evoked potential monitoring or nerve stimulation requires modifications to the anesthetic technique and has been summarized elsewhere [6]. Any planned deviation from the supine surgical position must be discussed with the anesthesia team and operating room personnel prior to the patient entering the room to ensure positioning equipment is immediately available.

Anticipated difficult airway management (including the potential for fiberoptic intubation or tracheostomy) should be discussed preoperatively. The final position of the endotracheal tube (e.g., oral, nasal, submental, or tracheostomy) is an important consideration—soft tissue distortion affecting cosmesis may result from securing the tube with tape and osseous/dental malocclusion may result from physical obstruction by the tube. Unintentional endotracheal tube advancement or dislodgement during craniofacial surgery has critical airway implications, and nasal septal suturing of a nasotracheal tube and or interdental wire fixation of an orotracheal tube are recommended. Immobilization of the head with extreme cervical spine flexion is commonly used in posterior fossa surgery. Endotracheal tubes can become soft when warm and sudden severe airway compromise can result from acute folding of the warmed endotracheal tube in the laryngopharynx. As a result, armored or reinforced endotracheal tubes should be considered for any extreme angulations of tube positioning (including submental intubation).

Temperature management is an important component of craniofacial surgery. Significant body heat is lost via the head and face, and the application and evaporation of skin prep solution coupled with vasodilation and disrupted thermoregulation under general anesthesia results in profound patient hypothermia. Consequences of intraoperative hypothermia include: increased blood loss from platelet and coagulation factor dysfunction, increased surgical wound infection rates, reduced drug metabolism, and shivering with resultant elevated metabolic demand and cortisol secretion [7]. The operating room temperature should be increased until the patient is fully draped. Fluid warming devices should be used for both maintenance and resuscitative fluids. Ambient warming lights should be applied to pediatric patients, and towels or foam positioning devices that become saturated should be removed and replaced after surgical prep.

Adequate arterial and venous access is essential during craniofacial reconstruction. While most cases can be safely accomplished with two reliable large-bore peripheral intravenous catheters, central venous access may be necessary when adequate peripheral access cannot be obtained or when infusion of inotropes or vasopressors is anticipated. Central venous pressure monitoring has not been demonstrated to reduce the incidence or duration of hypotension in pediatric craniofacial reconstruction [8]. High-volume centers of pediatric craniofacial reconstruction (those that average >2.7 cases per month) utilize central venous catheters in only 65% of cases, versus 90% of cases at low and middle-volume centers despite increased case complexity [9]. Invasive arterial monitoring is mandatory for complex procedures, as frequent blood sampling and rapid profound changes in blood pressure and volume status can be anticipated. An indwelling urinary catheter should also be placed to assess urine output and allow for the administration of hyperosmolar agents to manage cerebral edema and reduce intracranial pressure.

Preoperative laboratory evaluation (including assessment of blood counts, electrolytes, and coagulation) should be performed prior to major craniofacial surgery. Intraoperative blood salvage should be arranged in advance. Cross-matched red blood cells should be prepared before the induction of anesthesia, as transfusion may be necessary early in the surgery during scalp reflection and bony exposure. Viscoelastic coagulation studies (i.e., thromboelastography or rotational thromboelastometry) should be strongly considered, as they can direct specific coagulation factor replacement and are associated with reduced transfusion requirements in pediatric craniofacial surgery [10].

Intraoperative electrolyte and acid-base management can also be challenging. Hyponatremia is extremely common after pediatric surgical cases, especially when hypotonic intravenous maintenance fluids are administered. Hyperkalemia associated with packed red blood cell transfusion may occur in up to 45% of pediatric craniofacial surgery cases [11]. New (<1 week old) or washed packed red blood cells have much lower potassium levels and should be used in infants and small children. Hypocalcemia occurs in 10% of pediatric craniofacial reconstructions and is principally associated with the transfusion of citrated blood [11]. Metabolic acidosis is the primary acid-base disorder appreciated during craniofacial surgery. Twenty-five percent of pediatric craniofacial surgery patients have an initial arterial base excess of ≤4 mEq/L (normal −2 to +2). The median intraoperative base excess is −9, and 39% of patients demonstrate severe acidosis with a base excess ≤10 [12]. A negative base excess (base deficit) may represent tissue hypoperfusion as a result of lactic acidosis, but it may also be affected by renal disease (unmeasured anions), chronic antiepileptic medication usage (valproic acid, carbamazepine, phenytoin, and topiramate), and hyperchloremia from excessive normal saline administration. Metabolic acidosis should not be unintentionally compounded by respiratory acidosis (i.e., hypoventilation), as the exaggerated acidosis may result in refractory hypotension from reduced myocardial contractility, reduced vascular resistance, and attenuation of vasoconstrictor response to catecholamines.

Loco-regional Anesthesia

Local anesthetics can be useful during craniofacial surgery either as a complete anesthetic, or as a component of postoperative analgesia. Amide local anesthetics (e.g., lidocaine, mepivacaine, bupivacaine, and ropivacaine) are the most frequently utilized local anesthetics in the operating room. The time to onset, peak effect, and clinical effect site duration of lidocaine and mepivacaine are shorter than the more lipid-soluble drugs such as bupivacaine and ropivacaine. Accordingly, lidocaine is frequently utilized to provide shorter duration surgical site *anesthesia*, while bupivacaine is utilized for longer duration (6–8 h) of postoperative *analgesia*.

Topical local anesthetic (e.g., lidocaine or lidocaine/prilocaine cream) may be applied to the scalp or other sites, especially in children, to prevent pain during suture/staple removal or prior to injection of the scalp or spine. The subcutaneous injection of local anesthetic is beneficial for small wound revisions (such as the removal of pins and electrodes), as well as during awake intracranial surgeries during which reliable communication with the patient is required. It is important to inject into and immediately deep to the dermis and not in the subgaleal space, because the dense galea aponeurotica prevents diffusion into the more superficial layers. In addition to procedural anesthesia, the subcutaneous injection of local anesthetics (especially bupivacaine) may be utilized to provide postoperative analgesia as an adjunct to a general anesthetic.

The oral and nasal mucosa can be anesthetized using topical or infiltrative techniques. A topical vasoconstrictor (such as phenylephrine or oxymetazoline) can be used to reduce bleeding from the nasal mucosa and to facilitate examination of the nasal cavity. Tetracaine and cocaine provide reliable mucosal absorption and anesthesia via topical application, while lidocaine must be utilized in higher concentrations (e.g., 2–4%) to achieve more than superficial anesthesia. Topical cocaine (4%) provides a rapid onset of action, and its intrinsic vasoconstrictive properties make it particularly advantageous when used for procedures on highly vascularized mucosa in the nose, mouth, and throat. However, the use of cocaine is not recommended for patients with unstable cardiovascular disease or a history of cardiac arrhythmias.

Lidocaine and to a lesser extent bupivacaine induces vasodilation which increases the rate of absorption, reduces the clinical duration, and increases the risk of systemic toxicity. The addition of epinephrine as a vasoconstrictor at a concentration of 1:100,000 to 1:400,000 can help to reduce cutaneous bleeding and prolong the duration of the local anesthesia. In fact, the concentration of added epinephrine is a more significant predictor of lidocaine duration than local anesthetic concentration [13]. The vasoconstrictive effect of epinephrine 1:200,000 has an onset time of 7 min and a duration of action from 60 to 90 min [14]. If bleeding from the dermis becomes problematic during surgery, additional injection along the exposed dermal edges can be beneficial. The anesthesiologist should be notified before epinephrine is injected and informed of the dose. Premixed solutions of lidocaine with epinephrine are maintained at a very acidic pH (approximately 4–4.5) in order to stabilize the epinephrine component. This lower pH not only reduces the local anesthetic potency, but also results in significant nociceptive pain during injection. Raising the pH of the injectate by the addition of approximately 1 mL of sodium bicarbonate (1 mEq/mL) to each 9 mL of anesthetic solution increases the potency of the anesthetic and significantly reduces the burning sensation without causing precipitation of the solution (as occurs with higher ratios of sodium bicarbonate).

Perineural injections (peripheral nerve blocks) can also be utilized to provide effective anesthesia and analgesia. While an extensive summary of peripheral nerve blocks of the head and face is beyond the scope of this book (can be reviewed in a textbook of regional anesthesia), a few nerve blocks deserve mention. Anesthesia for the branches of the trigeminal nerve can be accomplished with 1–3 mL injections of local anesthetic over the supraorbital, infraorbital, or mental foramina. The supratrochlear nerve can be anesthetized in a similar fashion. The greater and lesser auricular nerves can be anesthetized with a 3 mL superficial injection beginning at the mastoid process following the curve of the posterior auricular sulcus. Finally, the greater occipital nerve may be anesthetized with a 1–3 mL injection along the superior nuchal line approximately 1/3 of the distance from the occipital protuberance to the mastoid (adjacent to the frequently palpable occipital artery).

Infiltrative or perineural injection of local anesthetics should always be preceded by a brief syringe aspiration to avoid vascular puncture and direct intravascular injection. Local anesthetic overdose—either by direct intravascular injection or excessive total dose—can lead to neurotoxicity (tinnitus, dysarthria, altered consciousness, or seizures) or cardiotoxicity (ventricular arrhythmias, hypotension, cardiovascular collapse). Resuscitation from local anesthetic systemic toxicity (LAST) includes benzodiazepines for seizure activity and ACLS (with epinephrine doses reduced to 1 μg/kg) and the administration of 20% lipid as an intravenous bolus of 1.5 mL/kg over 2–3 min followed by an infusion at 0.25 mL/kg/min for cardiotoxicity [15]. Maximum dosages of local anesthetic should be limited to: 5 mg/kg for plain lidocaine, 7 mg/kg for lidocaine with epinephrine, 2.5 mg/kg for bupivacaine, 7 mg/kg for mepivacaine, and 3 mg/kg for ropivacaine. Local anesthetic maximum dosages are assumed to be fractionally proportionate when coadministered, and dosages should be reduced for malnourished patients or extremes of age (less than 4–6 months old or greater than 65 years old).

Postoperative Considerations

Clinically significant cardiopulmonary or hematologic complications occur in up to 15% of pediatric patients undergoing major craniofacial surgery, with an overall mortality of 0.1% [16, 17]. Macroglossia resulting from impaired venous and lymphatic drainage has been described as a cause of post-extubation airway obstruction in both adults and children [18]. In general, most pediatric patients are admitted to an intensive care unit following craniosynostosis repair, although "otherwise healthy patients with non-syndromic craniosynostosis" may be managed on a standard surgical ward after a 4–6 h recovery period in a medium-acuity area (e.g., post anesthetic care unit or step-down unit) [19]. Patient weight less than 10 kg, ASA physical status three or four, intraoperative transfusion of >60 mL/kg PRBC, and the presence of an intraoperative complication are independent predictors of a postoperative cardiac or respiratory event requiring ICU management [17]. Intraoperative management by a dedicated craniofacial team anesthesiologist has been shown to reduce postoperative complications (including earlier tracheal extubation, reduced allogenic blood donor exposures, reduced intensive care length of stay, and reduced hospital length of stay) [20].

Postoperative blood loss following major pediatric craniofacial surgery can be anticipated to approximately equal the intraoperative estimated blood loss [11, 21]. Postoperative coagulopathy is not common unless estimated blood loss exceeds 60–100 mL/kg [17, 22]. Following pediatric craniosynostosis surgery, 11% of patients require hemostatic blood product administration (e.g., plasma, platelets, or cryoprecipitate) and 12.9% have significant postoperative bleeding (>30 mL/kg in 24 h) [17]. In the absence of documented coagulopathy, the initial postoperative hematocrit appears to be the only modifiable intraoperative variable predictive of postoperative red blood cell transfusion. In pediatric craniofacial surgery, the initial postoperative hematocrit target should be greater than 30% in order to minimize the postoperative transfusion risk by 50% (with a transfusion threshold hematocrit of 24%) [23]. Patient weight less than 10 kg, intraoperative transfusion of greater than 60 mL/kg PRBCs, intraoperative coagulation factor replacement, and not administering tranexamic acid are independent risk factors for postoperative severe anemia, clinical coagulopathy, or significant bleeding requiring ICU management [17]. Tranexamic acid is only used in approximately 50% of pediatric cranial vault reconstruction cases despite a documented less than 1% incidence of major complications such as seizure or thrombosis.

Postoperative analgesia is a fundamental consideration after craniofacial surgery. While 50% of patients report moderate-to-severe pain after craniectomy, no standardized management protocols exist [24]. Local anesthetic scalp infiltration is short-lived and does not significantly affect total postoperative opioid use. Seventy-three percent of craniofacial patients receive postoperative opioids—with continuous morphine infusion, patient/nurse-controlled hydromorphone or fentanyl bolus, and intermittent morphine bolus as the most common initial management strategies [24, 25]. Most patients are transitioned to oral oxycodone by postoperative day 1 or 2. Acetaminophen is used in almost all patients, but the route of administration varies from rectal to oral to intravenous. Many patients can be managed with postoperative acetaminophen and NSAIDS without the use of opioid analgesics. However, intravenous dosing may be preferred as this is associated with a significantly lower incidence of nausea and vomiting (3.6% and 14%, respectively) as compared with oral dosing after cranial vault reconstruction [26]. Lastly, dexmedetomidine has shown promise as part of an off-label opioid-sparing strategy when used as a continuous infusion after craniosynostosis [24].

Enhanced recovery after surgery (ERAS) protocols attempt to standardize and optimize some of the perioperative patient and surgical variables, and they have shown improved patient outcomes after colorectal, breast, gynecologic, urologic, and oncologic procedures. The key components include: (1) preoperative patient education, (2) reduced preoperative fasting, (3) minimally invasive techniques when feasible, (4) multimodal analgesia, (5) regional anesthesia techniques, (6) early postoperative nutrition, and (7) early patient mobilization [27]. While ERAS protocols for craniofacial surgery are still in their infancy, a few principles have been shown to reduce blood transfusion, reduce length of stay, and improve postoperative analgesia. Specifically, preoperative optimization of hemoglobin levels (using iron supplementation or preoperative erythropoietin, when appropriate), tranexamic acid consideration, temperature maintenance, *scheduled* NSAID and dexmedetomidine administration intra- and postoperatively, and aggressive postoperative nausea and vomiting (PONV) prophylaxis have shown benefit after pediatric craniofacial surgery [27, 28].

Positioning and Immobilization

Ken Rose Winston

When any type of anesthesia other than general anesthesia or any position of the patient other than prone is required, the anesthesiologist, circulating nurse, and scrub nurse should be informed, before the patient enters the surgical room.

Patient positioning involves more than simple transfer from a gurney to the operating room table. Vulnerable organs such as the eyes, intra-abdominal contents, and genitals must be completely free from compression. The skin must be protected against pressure, friction, and moisture. Attention to positioning and padding over bony prominences is critical in preventing skin breakdown. Pressure ulcers and deep tissue injuries occur by impaired local blood flow to the skin or subcutaneous tissue as a result of excessive external pressure. Normal venous capillary closing pressure is 8–12 mmHg and arterial capillary filling pressure is approximately 32 mmHg. In supine position, the sacrum, heels, and occiput often sustain 40–60 mmHg pressure [29]. In prone position, the chest and knees sustain 50 mmHg, and the ischial tuberosities in seated position may receive almost 100 mmHg pressure. Muscle is susceptible to irreversible ischemia in as little as 2 h, while skin has a low metabolic demand and may tolerate up to 12 h of uninterrupted pressure (unless compressed against unyielding bone.)

It is the responsibility of all members of the operating room team to provide adequate padding and readjustments in positioning depending on the patient position and length of immobilization. Very thin patients have bony prominences that require attentive padding. Similarly, patients with impaired nutritional states are less tolerant of skin compression. Obese patients actually have substantial muscle mass and positioning devices frequently do not accommodate their increased size. Additionally, minor repositioning of obese patients has limited impact on pressure on underlying structures. Prior to draping the patient, the surgeon or an experienced assistant should inspect the position of the patient, remove any tightly folded compressive materials, remove any lines or monitoring cables from underneath the patient, and eliminate any wet towels that could contribute to skin breakdown.

Cervical Rotation

Extreme cervical rotation in normal patients can compromise venous or, less commonly, arterial flow. Also, extreme rotation of an anesthetized and often pharmacologically paralyzed patient can cause mild to moderate subluxations, particularly at C1–2. The authors are aware of no published guidelines for safe limits of passive rotation of the neck when positioning patients for surgery. A preanesthetic check of the rotation tolerated without discomfort has some value in assessing safety, but the same amount of rotation when anesthetized, particularly under rigid immobilization, may result in significant problems.

Regardless of immobilization, the rotation may slowly increase from spontaneous settling of head and trunk into the padding or from pressure exerted against the head by the surgeon.

Some patients undergoing cranial or facial surgery may have significant pathology in the cervical spine, for example, stenosis, metastatic disease, fracture, subluxation, or congenital instability, as in some patients with Down syndrome. Patients with pathology or suspected pathology involving the cervical spine require special attention during positioning. If there is concern regarding alignment of the spine, radiographic or fluoroscopic imaging should be done after the patient is positioned or during positioning.

Immobilization of Head

Crania require at least moderate stability to stabilize the operative field, and some surgeries require rigid immobilization, to optimize the required exposure for surgery and to minimize risks.

Soft Immobilization

Donut pillow—A donut pillow (soft ring of gel) is commonly used to immobilize the head for neurosurgical or craniofacial procedures performed in the supine or near-supine position. This pillow is intuitively easy to use, available in several sizes, reusable, and it provides satisfactory stability for many operations. It protects the scalp by distributing the pressure over a broad area, absorbs little or no water, and does not lose compliance if its surface becomes wet. The donut is usually placed on the firm head-section of the surgical bed. Gel donut pillows are reusable, waterproof, and they distribute pressure better than the disposable foam version. As the donut pillow rests on the standard full-width table headpiece, lateral and posterolateral access to the head is impeded.

Pediatric patients should have appropriately sized donut pillows to ensure that their heads will have support in the center of the donuts. Donut immobilization has few associated risks; however, for positions in which the head is rotated 45° or more with respect to surface of the table, the pinna can be folded and remain so for several hours, resulting in ischemia and possible infarction.

The non-folded position of the pinna against a pillow, regardless of type, should be confirmed during positioning of the head for surgery; folded or compressed pinnae are vulnerable to ischemia and possible infarction. The head-section of the surgical bed, which extends laterally beyond the head, may impede surgical access and thereby be disadvantageous for some surgical approaches.

Horseshoe headrest—(1) *Supine position*—The horseshoe headrest is a U-shaped device that is attached to the surgical table and used to support the head and provide access posteriorly and to both sides of the head. It can be locked in various angles and heights and its width adjusted to accommodate heads of assorted sizes (excluding small infant heads). Although each arm is covered with a gel pad, some surgeons add additional padding to distribute the force more widely against the scalp. The device is adjusted to support the head without allowing it to settle downward between its arms. The width of the horseshoe headrest must be adjusted for head size, *particularly for infants and children*, to prevent the head from becoming progressively displaced downward with tight impingement, which can compromise blood flow to the scalp. (2) *Prone position*—The prone position places the horseshoe in contact with scalp of the forehead, eyebrows, and face, and the downward force of the head can be sufficient to cause infarction of skin in these areas. Most surgeons add additional padding to the arms of the headrest to distribute the force more widely against the face. Placement of one or more pillows beneath the shoulders may reduce the downward force of the head against the headrest. Risks of producing ischemia to the face are increased if the padding over the horseshoe becomes wet during the prep or during surgery. Additional padding before prepping does not prevent this problem. Also, the head must be carefully positioned on the headrest in a manner that avoids pressure on the globes. External globe compression can increase intraocular pressure above pressure in the central retinal artery and cause loss of vision.

Manual head lifts by the surgeon for 15 or more seconds every 10 min throughout the time a patient is prone will allow a brief flow of blood through the compressed facial skin. This maneuver also alleviates any downward impingement of the head between the arms of the horseshoe headrest.

Rigid Immobilization

Rigid cranial immobilization is necessary for many neurosurgical operations, including all operations in which a microscope will be used, most operations done in the posterior fossa, and all stereotactic operations. This can be accomplished with an adjustable C-clamp device, for example the Mayfield head holder, or with a device which surrounds the head, for example devices used in many stereotactic surgeries. Most of these devices allow rigid attachment of the head to the surgical table and provide a frame to which the neurosurgeon can attach various instruments, for example brain retractors.

Mayfield head holder [30]—The Mayfield head-holder is attached to the skull, using three pins, while the patient is supine. The technique for its attachment to the head is intuitive, but there are pitfalls and risks. Although complications associated with its use are uncommon, skull penetration, temporal artery injury, epidural hematoma, and air embolism have occurred [31]. Care must be exercised to avoid placing a pin over a loose bone fragment, recent craniotomy flap, burr hole site, or unfused cranial suture. The majority of complications occur in pediatric patients, and the Mayfield clamp is not recommended for patients less than 3 years of age.

Stereotactic head holder—The stereotactic head holders encircle the head and suspend the head in multiple-pin (usually 4) fixation just below the meridian of the skull. Advantages of the stereotactic holders include rigid immobilization and opportunity for imaging-guided precision. There are multiple manufacturers of stereotactic devices, many having a circular or square configuration. Each is attached to the skull with four or more sharp pins. The points of contact of pins with skull should be a few mm below the meridian of the skull, and this will depend upon the position the head will be during surgery, not at time of placement of the device. Attachment even a few mm above the meridian can often result in slippage during surgery, perhaps with laceration of the scalp or dangerous displacement of attached retractors against brain. The device must be sufficiently tightly clamped to the skull to prevent movement but not so tight as to cause penetration. Most adults and teenagers can safely tolerate 30 psi. Pressure on the pins must be approximately evenly distributed. If one of the pins on the double-pin side of the device is far from the meridian of the skull, the risk of slippage is greatly increased.

Risks of rigid immobilization—Each pin site produces a small scar, but the scar is not noticed in hair-bearing scalp; however, if it is necessary to position a pin on the forehead, the scar can be significant, particularly if the pin slips a few millimeters. A facial pin-scar is least noticeable when it is near the hairline. If it may be necessary to place a pin in the hairless forehead, the small scar will be least noticeable if precisely in the midline. A pin should never be placed on the supraorbital rim because of risk of slippage, in which case the globe could be injured. Placement of a pin over the temporalis muscle may appear initially to be tight and secure, but can become loose during surgery. Also, placement on temporalis muscle, particularly if near the keyhole position, often causes atrophy of the compressed muscle, which will be apparent as a cosmetically undesirable depression as healing occurs.

The pins of the Mayfield head holder can penetrate the skull, dura, and even brain of any age patient in areas of thin bone or if accidently placed over a small cranial defect or patent cranial suture. Bone flaps thought to be firmly healed in place can be displaced inward as the device is tightened. Children are particularly vulnerable to skull penetration because of their thinner bone and the presence of unfused suture lines. This method of immobilization cannot be safely used in most infants because of the risk of penetration.

Protection of Skin from Pressure

Protection of skin requires serious preparatory attention to detail and is the joint responsibilities of the surgeon, anesthesiologist, and nursing staff. Injury of the skin of scalp or face from pressure during surgery can result in severe cosmetic defects and in medicolegal risk. Usually, soft dry padding between scalp and the operating table provides sufficient protection. Scalp that is compromised from prior surgery, radiation, prolonged periods of hypotension, failure to provide adequate padding, or extreme emaciation can result in ischemic injury. However rushed, surgery should never be done without some padding beneath the head and a sheet or towel does not provide padding. Also, padding may become soaked with irrigating fluid or blood during surgery and, although conforming to the contour of the head, provides much less protection from pressure.

The following anatomical sites should be inspected in every patient undergoing general anesthesia and awake patients who cannot perceive discomfort and those who are unable to self-reposition to alleviate pressure sites.

Pinnae: Confirm each pinna has padding between it and OR table and is not folded.

Occiput: Confirm that the occiput has padding between it and OR table.

Elbows: Confirm that the area over the ulnar nerve is well padded. *Hereditary neuropathy with liability* to pressure palsies is a recognized entity that places ulnar nerve injury at risk, likely related to laxness of the nerve, which is a risk associated with anesthesia [32, 33].

Sacrum: Confirm that there is adequate padding between sacrum and surgical table.

Heels: Confirm that the heels have padded and are not lying on a solid surface.

Knees, ankles: If in contact with OR table or other hard object, knees and malleoli require padding. The area just below the lateral surface of the knee, where the common peroneal nerve crosses the fibula, requires careful padding if this area is to be against a surgical table, strap, or other firm object.

Ischial tuberosities: Padding over ischial regions is usually not necessary except in very thin or emaciated patients; however, for patients undergoing surgery in the sitting position, generous padding is important.

Tubes, wires, cables: Padding is required to prevent localized pressure on skin by these materials.

Attention to positioning and padding over bony prominences is necessary to prevent breakdown of skin from pressure. Deep tissue injuries or pressure ulcers may occur from the impairment of local blood flow to an area compromised over time by pressure. Normal venous capillary closing pressure is eight to 12 mmHg and arterial capillary filling pressure is approximately 32 mmHg. Impeding blood flow by pressure over the course of 2 h may result in irreversible injury to underlying muscle. Skin, with its lower metabolic demand, may tolerate up to 12 h of uninterrupted pressure without ischemic damage. By the time a pressure ulcer is recognized on the skin, the extent of the injury has already extended into deeper tissues.

While supine, the sacrum, heels, and occiput often sustain 40–60 mmHg pressure [29]. The prone position can result in 50 mmHg pressure on the chest and knees. The ischial tuberosities receive in the sitting position approximately 100 mmHg pressure. Awake, neurologically intact patients may, without awareness, shift weight and position to relieve these pressures that hugely exceed arterial and venous filling and closing pressures.

It is the responsibility of the surgical team to provide appropriate mattresses, padding and, when appropriate, occasional shifts in position of patient or body part. Some patients and required positions require more attention than others and not every situation can be described in detail. Very thin patients have bony prominences that require extensive padding. Patients with severely impaired nutritional states are less tolerant of skin compression. The skin of obese patients can be challenging to protect, particularly for prolonged operations, because of the high pressure applied to large spans of skin during long surgeries, difficulty in initial positioning, and the impracticability of repositioning.

Prior to draping the patient, the surgeon or an experienced assistant should inspect the position of the patient, with particular attention to padding over bony prominences. Very firm or tightly folded materials beneath a patient can cause focal pressure injuries, especially during long surgeries. Regardless of patient size or nutritional state, folds of very lax skin can result in ischemic damage. Towels and other cloth materials which become wet during the surgical scrub or during surgery conform to bony prominences, but provide almost no cushioning.

The Myth of Surgical Sterility

Ken Rose Winston

Establishing and maintaining surgical sterility is commonly held as the core principle of prevention of SSIs, and questioning its existence is heresy. In the surgical universe, sterile is defined as free from bacteria and other living organisms, *clean* means free of dirt, marks, or stains, and *aseptic* is the condition of being free from pathogenic microorganisms [34–36]. Therefore, a sterile operating room must have *no living microorganisms* or at least not on any exposed surface. It is common to speak of sterile skin, operating rooms, scrub garments, hands, conditions, and techniques.

A patient, upon entering an operating room, is covered with billions of living microorganisms, is often seminude, and soon thereafter multiple orifices which host innumerable bacteria of many genera and species will be entered in preparation for surgery. Fully dressed, scrubbed, and non-scrubbed surgical personnel, whose skins are populated with billions of organisms, enter and leave rooms during surgery, and all breathe, move about, and talk while their loose garments, face masks, and head coverings are rubbing against skin. Air within the room constantly moves, with or without flow-control, across everything in the room, including non-sterile walls, floors, ceilings, cabinets, movable lights, microscopes, anesthetic equipment, and personnel. Some objects may be rendered sterile with chemical agents, autoclaving, or radiation. Regardless of the rigorous attention given, a properly prepared operating room can be made clean and probably aseptic but never sterile.

It is reasonable to believe that minimization of the bacterial population on patients' skin and in the surgical macro and microenvironment will minimize bacterial contamination of a surgical wound and thereby reduce the risk of SSI. The preparation of a patient's skin for surgery, when properly done, accomplishes *near total* elimination of the transient organisms and possibly a significant reduction in the resident population, but does not achieve full-thickness sterility of skin.

As surgery begins, a scalpel that is sterile when its wrap is opened, and probably still sterile (depending on time of exposure to air) when it first contacts skin which has resident bacteria beneath its near-sterile surface, may mechanically redistribute resident bacteria as it glides through tissue. It is unreasonable to believe that no bacteria enter surgical wounds and lodge on their moist surfaces. Therefore, no surgical wound is *reliably* free of bacterial contamination, regardless of adherence to 'sterile technique.'

A clean and aseptic surgical environment and surgical wound are rational, achievable, and important for minimization of SSIs, but the existence of surgical sterility is only a comforting myth.

Preparation of Hair

Ken Rose Winston

Hair is important to patients and families and plays an especially important role in self-image. Whole professions are devoted to the management of hair: shaving, clipping, coloring, electrophoretic removal, and transplantation. Some men and a few women choose for social reasons to have their heads frequently shaved, but this is quite different from giving consent to having hair shaved in preparation for surgery. There is a strong multicultural and traditional belief that all hair is inherently dirty and cannot be cleared of bacteria, but there is no scientific basis for this belief. Hair is a monofilament from which bacteria can be removed with relative ease during prepping and more completely than from skin. Studies have shown that preoperative removal of hair by any means is associated with increased surgical site infection rates [37, 38].

Preoperative shaving is listed as a risk factor for surgical site infection in *Recommendations for Prevention of Surgical Site Infection* from the Center for Disease Control and Infection (CDC) [39]. The **CDC Guideline for Prevention of Surgical Site Infection 1999** includes the following statements, with *Category 1A* evidence (strongly recommended for implementation and supported by well-designed experimental, clinical, or epidemiological studies [39].):

> Do not remove hair preoperatively unless the hair at or around the incision site will interfere with the operation.
>
> If hair is removed, remove immediately before the operation, preferably with electric clippers.

According to the **AST Standards of Practice for Skin Prep of the Surgical Patient**, "… it is recommended that hair removal not be performed" [40].

Shaving

An extensive literature exists comparing the risk of infection in cranial surgeries done with and without shaving, and the evidence supports the position that shaving does not decrease, but likely increases, the rate of infection [38, 41–43]. This is thought to be the result of microscopic injuries (microcuts) in the epidermis, or deeper, followed by oozing of serum, which serves as a medium for bacterial entry and multiplication. Among data from non-neurosurgical operations, shaving the surgical site is associated with a higher risk of surgical site infection than that associated without removal of hair [37, 39, 44].

Shaving immediately before surgery is associated with lower infection (3.1%) than shaving within 24 h preoperatively (7.1%); shaving more than 24 h before operation had an associated surgical site infection that exceeded 20% [45]. Removal of hair in preparation for surgery, particularly by shaving, requires time and there is an associated expense, in terms of material, equipment, and consumption of time in the operating room. In a study on patterns of hair shaving, comparing regional and strip shaving, the regional shaving negatively affected body image [46].

Clipping

The clipping of hair is relatively safe; however, one report on a large surgical series—not restricted to scalp—found a slightly higher rate of infection in patients whose hair was clipped than in those having no hair removal [44]. The explanation for this is not clear but may reflect the occasional nicking of skin by clippers. Clipping immediately before shaving can make shaving easier but probably adds a small risk.

Depilatories

The use of a depilator to remove hair in preparation for surgery has been reported to have a lower risk of surgical site infection than shaving or clipping, but some depilatory agents are associated with hypersensitivity reactions, causing discomfort and predisposing to surgical site infection [45]. Depilatories are now rarely, if ever, used for skin preparation for surgery.

Beard

Facial hair is important to some patients for cosmetic or religious reasons, and therefore removal of facial hair for elective surgeries requires the consent of the patient. Beard impedes, to a variable extent, the surgeon's visualization of the lower face and can present difficulties to the anesthesiologist in obtaining an air-seal for the facemask and in securing an endotracheal tube.

Some craniofacial surgeries, but a few if any neurosurgical procedures, require incisions in hair-bearing facial skin. If incisions will be made in the hair-bearing face, the beard must be prepared as described above for hair of the scalp.

Preparation of Skin

Ken Rose Winston

The practices and customs of maintaining socially and personally acceptable hygiene have only a remote relationship to the skills, actions, and agents required to prepare skin for surgery. There is little reason to attempt the daily removal of bacteria from the skin. Social bathing, with commonly used soaps and other materials, removes unpleasant odors which are mostly due to oils and their breakdown products. Soaps and detergents are surfactants and have their cleaning effect on skin by reducing the surface tension of water with their high molecular polarity. As one end of each molecule of surfactant is attracted to oils, grease, and epidermal cells, the other end of the molecule remains water-soluble. Therefore, the oily materials are surrounded, brought into solution, and can be rinsed away. Also, the amount of friction required to remove debris on skin is decreased.

Soap is a salt of a fatty acid, produced from vegetable oils or animal fats, and is commonly a strong base (pH 9.5–10) [47]. Soaps reduce the cell layers of the stratum corneum, emulsify the lipid on the surface of skin, and remove transient bacteria and some of the resident bacteria [48, 49]. Alcohol and acetone also remove lipids, but cause dehydration of skin, which diminishes the ability of skin to hold water and may reduce its bacterial resistance [48]. The normanl pH of skin, following brief washing with soap, returns to near 5.5 after approximately 45 min, whereas pronged exposure to alkaline soap can require 19 h [50].

Detergents are usually petroleum-based surfactants and can be in either solid or liquid form. Detergents have no nutrients that a vegetable or animal-based soap may contain. The pH of most liquid detergents is neutral or slightly acidic, which is favorable for bacterial growth, and, because of this, detergent-based facial cleansers often contain broad-spectrum preservatives. Detergent-based facial washes commonly contain surfactants, alcohols, and fragrances plus preservatives. The oils and fragrances in many soaps and shampoos can add greatly to the personal satisfaction of bathing, but do not kill bacteria and may impede their removal. Therefore, the soaps or detergents commonly used for bathing are minimally effective at removing bacteria.

When bathing in a tub, bacteria and dislodged epithelial cells surrounded by surfactant molecules from the body enter the water and become extensively redistributed over the wet surface of the body. Bacteria in the perineal region, particularly *E. coli*, gain distribution over the body; however, most of these organisms do not survive for long. Showering tends to remove more bacteria from the body than does tub bathing, but does distribute bacteria from hair of the face, scalp, and axillae over the body.

The use of a washcloth, sponge, or soft brush to abrade the skin is beneficial in removing desiccated cells of epidermis with their attached bacteria. However, much of the benefit of social bathing derives from drying the skin with a towel, which abrades the skin and assists in the removal of the desquamated epidermal surface (stratum corneum). Drying skin with smooth, bedsheet-type cloth, paper towels, or a blow-dryer provides little abrasive effect and therefore removes far fewer squames than does drying with an abrasive towel and does not result in the same "clean feeling." Drying the skin with an abrasive cloth towel accomplishes far more than simply removing water and is an important component of bathing.

Agents for Preparation of Skin

Most postsurgical infections are confined to the surgical site, and the patient's skin is the primary source of pathogens causing surgical-site infection. It is therefore reasonable to believe that meticulous attention to preoperative antisepsis of skin will decrease the occurrence of postoperative wound infections [51]. Many agents have been used in the preparation of skin for surgery and new ones can be expected, but chlorhexidine gluconate, povidone-iodine, and various alcohol-containing products are most commonly used. (See excellent discussion in *Guideline for Prevention of Surgical Site Infection* [39].).

Water

Water is the most important agent in the preparation of skin for surgery because it dissolves salts and is essential for the distribution of various products over skin. Soap and detergents are effective in dissolving oils.

Alcohol

Isopropyl alcohol is the most effective and rapidly acting skin disinfectant and it is inexpensive [39, 52]. It dissolves oils and enters the superficial parts of the hair follicles and sweat glands, but does not consistently reach the bases of these structures. Alcohol evaporates rapidly and hence the persistence of bactericidal effect is quite short. Concentrations of 70–92% have rapid germicidal activity against bacteria, fungi, and viruses but may be less effective against spores than some other agents [39]. Higher concentrations of alcohol are less potent because its effectiveness results from the denaturing of proteins, and some water is necessary for this to occur. According to the FDA, an "alcohol-containing agent" must contain, by volume, either 60–95% ethyl alcohol or 50–91.3% isopropyl alcohol. Alcohol is the standard for surgical hand preparation in several European countries. Many prep solutions are alcohol-based, for example, ChloraPrep® with 70% alcohol [53], and hand rubs, for example, Avagard® with 61% ethyl alcohol. The content of alcohol in oral rinses of 2% chlorhexidine is often 11.6%.

A serious disadvantage of using alcohol in an operating room for preparation of skin is its flammability. Although alcohol rapidly evaporates from flat exposed skin, more time is required for evaporation from hair, from creases in skin, towels, and from pools on padding materials [53]. The flash point, in response to application of an ignition source to an ethanol-water solution that contains 50% alcohol, is 75 °F (24 °C). A mixture of 70% isopropyl alcohol and water has a flash point of 54 °F, (12 °C). The flash point of lower concentrations of alcohol can be reached by higher temperatures, for example a spark from an electrocautery. Pooling of alcohol-containing fluids is particularly dangerous.

Chlorhexidine

Chlorhexidine gluconate is now the most commonly used agent in the preparation of skin for surgery and is superior to povidone-iodine in preventing surgical-site infections [51]. Chlorhexidine is a salt, which dissociates in water, releasing a positively charged ion that binds to the negatively charged surfaces of bacteria, where it has a bactericidal effect [54]. Chlorhexidine gluconate binds to the superficial layers of the epidermis and provides a persistent residual antimicrobial effect that prevents regrowth of microorganisms. Both chlorhexidine and the iodophors have very broad spectra of antimicrobial activity [39, 55], but the greater effectiveness of chlorhexidine-alcohol than povidone iodine probably reflects its more rapid action, persistent activity despite exposure to bodily fluids, and residual effect. [51] Chlorhexidine has bactericidal effect within 20 s of contact and this effect continues for as long as the epithelial cells to which it has adhered remain. Chlorhexidine is not inactivated by exposure to bodily fluids and has persistent effect for at least 48 h [52, 56]. Chlorhexidine gluconate binds strongly to skin and cannot be effectively removed by water, alcohol, or mechanical abrasion, except to the extent to which cells of stratum corneum are removed. This agent is not neutralized by contact with organic material [56].

A chlorhexidine product which contains alcohol is reported to have longer lasting antimicrobial activity than povidone-iodine, perhaps because of deeper penetration into the stratum corneum [57, 58]. There is evidence that preoperative cleansing of skin with chlorhexidine–alcohol is superior to cleansing with povidone–iodine for preventing surgical-site infection after clean and clean-contaminated surgery [51, 59, 60]. Chlorhexidine has rapid action, is not inactivated by exposure to bodily fluids, and has persistent effect for at least 48 h [51].

Chlorhexidine is very toxic to the cornea and middle ear. It can damage the organ of Corti and the mucosal of the tympanic cavity and therefore may lead to loss of hearing and perhaps disturbance of vestibular function. Alcohol-based and aqueous solutions of chlorhexidine have been associated with chemical burns in premature infants and neonates. This risk is thought to be higher in preterm infants, especially those born before 32 weeks' gestation, and within the first 2 weeks of postnatal life. Chlorhexidine is also a contact allergen in some patients.

ChloraPrep™ contains 2% chlorhexidine gluconate in 70% isopropyl alcohol. It effectively, quickly, and persistently reduces a broad spectrum of bacterial organisms. Isopropyl alcohol (70%) immediately kills both transient and resident microorganisms on the stratum corneum. The chlorhexidine component has similar effectiveness in reducing bacteria on skin, but the antibacterial effects are more persistent than alcohol. The combination is thought to have more persistent effect than either component alone. ChloraPrep™ is toxic to the cornea and middle ear and it is flammable.

Povidone-Iodine

Povidone-iodine is effective against bacteria, particularly gram-positive bacteria, and against fungi, and viruses, for as long as the electronegative iodide ions are present [61]. Antimicrobial action begins when the iodine disassociates from the polyvinyl-pyrrolidone, The bactericidal effect is due to damage to microbial proteins and DNA. Iodophors may be inactivated by blood or serum proteins and most of the agent can be removed from skin by water or alcohol [55]. The bactericidal effect begins immediately and is present for approximately 2 h after completion of the surgical scrub. Slowly thereafter, the resident flora in sweat glands and hair follicles begin to emerge. This agent is reported to have superior bactericidal effect against MRSA than chlorhexidine and to be effective against chlorhexidine-resistant and mupirocin-resistant organisms [62]. A few people are allergic to iodophors and can have serious cutaneous blistering. Bacteria do not become resistant to povidone-iodine [63]. Povidone iodine is used in low concentrations in ophthalmological surgeries [64].

Povidone iodine does not impede wound healing, but it can be absorbed through the skin of preterm and low-birthweight infants, with possible serious complications [65]. It has also been reported to cause chemical burns in sites in which drying has not occurred, in pools beneath a body part during surgery, and beneath a tourniquet [66, 67].

DuraPrep™ (iodine povacrylex, having 0.7% available iodine, and 74% isopropyl alcohol) is an effective and popular product for preparing skin for surgery. It is claimed to form a water-resistant film, thereby optimizing persistence of bactericidal effect. It has resistance to removal by saline or blood and does not impair adhesion of drapes.

Preparation of Skin of Neck, Trunk, and Extremities

These areas are typically easy to scrub but may have folds, particularly in the neck of obese adults and infants, which can impair access and interfere with preparation of the skin. Extremities require circumferential scrubbing for some surgeries on peripheral nerves, and this requires special attention to prevent contamination of the undersurface during the process of draping.

Scrub Technique

The satisfactory technique for scrubbing skin for surgery is easily learned, but requires training and a period of supervision for novices, including nurses and doctors. It is importantly different from handwashing and bathing for personal hygiene, and the details of the surgical scrub are often inadequately executed. The area scrubbed should extend several centimeters beyond the proposed surgical incision and the area of draping. The area of the scrub should include all hair within the defined area, which is at risk for entering, intentionally or otherwise, into the surgical field during surgery. A soft gentle scrub with a washcloth that would be appropriate for home bathing or shampooing is not satisfactory for dislodging bacteria and bacteria-laden desquamated skin cells in preparation for surgery. Gentle scrubbing, particularly with a soft brush, removes bacteria, dirt, and squames from skin, particularly in skin creases, and may massage some of the bacterial load from hair follicles and sweat glands. The traditional vigorous scrub, often for 10 min, does not provide greater reduction in SSI and can damage the skin's surface. The optimum duration of scrubbing is unclear, but scrubbing for 3–5 min is likely as effective as the traditional 8–10 min scrub in reducing bacterial colony counts [68, 69]. The scalp is relatively easy to scrub because it overlies smooth convex cranial bone. If there is a large cranial defect, more time is required to prepare the site without injuring the underlying brain. It is important to not leave the head lying in a pool of fluid at the completion of a surgical scrub. The surgeon should pay attention to the scrub process to ensure that no shortcuts in scrub time or technique are taken.

Drying Patient's Skin After Surgical Prep

The drying of skin at the completion of a surgical prep must not be confused with handwashing or bathing for personal hygiene. Much of the benefit of social bathing derives from the act of drying the skin with a towel (see discussion above); however, vigorous drying of an already surgically scrubbed region likely provides no additional benefit. An area of skin that has been prepped should be dried with a dry absorbent cloth towel by pressing the towel firmly against the skin until the skin no longer appears to be wet. Wiping a towel back and forth on the scrubbed skin adds no benefit and is potentially harmful if an edge of a towel passes across an unsterile region and into a sterile region. Wet hair often requires mildly vigorous drying with one or more towels.

Pitfalls/Things to Avoid

Gentle Scrub

Very gentle scrubbing with soapy hands, using skin friction or washcloth, has intuitive appeal, likely based on personal bathing experience or the bathing of children. An important part of scrubbing skin in preparation for surgery is the light abrasion of the epidermis to dislodge bacteria-laden squames, particularly those within creases of the skin. Smooth gentle massaging cannot be relied upon to reduce the bacterial load as effectively as scrubbing.

Vigorous Scrub

Vigorous scrubbing of skin, especially with a stiff brush, often damages the skin's surface and does not provide greater reduction in SSIs than noninjurious less vigorous scrubbing.

Neat (Limited Area) Prep

Limiting the area scrubbed seems reasonable to inexperienced preppers of skin and this is likely based on a desire to "not make a mess." An area much larger than the area expected to be exposed after draping must be prepared for surgery, because it is not uncommon for surgical drapes to become loose and shift a few cm, thereby allowing non-prepped skin to enter the region of surgery. Also, a surgeon may need to extend an incision beyond that which was initially planned. Preparing only the minimal area expected to be necessary increases the risk of contamination of the surgical wound and infection.

Prolonged Contact with Pooled Fluid

Pillows used in surgical suites to support a head or other part of the body have a waterproof surface that is covered with a pillowcase or towel. Fluids of any type can pool in the depression of the pillow. Prolonged soaking of skin, which is usually under pressure, can become macerated during prolonged surgery. Prolonged soaking in solutions of povidone iodine or chlorhexidine can result in blistering or deeper chemical burns.

Special Concerns in Preparation of Scalp and Face

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Protection of Corneas

The corneas must be protected during the surgical preparation and for the duration of surgery. Corneas can be injured during surgery from desiccation, abrasion, or contact with the prep material.

The initial steps for corneal protection are managed by the anesthesiologist. Corneas must be protected during the surgical scrub of scalp from accidental splash or flow of prepping solutions, usually a protective material such as Lacri-lube® applied beneath the eyelids followed by application of a waterproof plastic barrier across the orbits and sealed around its edges to skin with tape. The seal is especially important for surgeries done in the prone position because of possible flow anteriorly around the head. Some scrub materials, especially Chlorhexidine, is *very* toxic to the cornea. Povidone-iodine is an alternative that must be diluted to an appropriate strength with either a balanced salt solution or appropriate dilutant, when prepping around the eyes.

A dry cloth or sponge material should not be used to protect the eyes (corneas), because these materials can come into contact with a cornea, act as a wick, and desiccate the cornea. Also, cloth that remains in contact with the cornea can abrade the cornea.

For the duration of most craniotomies, the protective steps described above will provide protection throughout the surgical procedure. If orbits or eyelids must be exposed or manipulated during the surgery, for example in many surgeries to correct syndromic synostoses, the corneas should be protected with lubrication and either temporary tarsorrhaphies or corneal protectors.

Pinnae and External Auditory Canals

The external auditory canal is not commonly prepped for neurosurgical procedures. The spectrum of the microbiome of the external auditory canal differs from other skin, but does include organisms uncommonly found on skin [70]. Povidone-iodine can be used to prepare the external auditory canal for surgery; however, it must be used in a diluted form and pooling must be prevented. A pinna (auricle) can be cleaned with a swab and fingers, using soap and water, but a swab should not be pushed into the external canal. Chlorhexidine can be very toxic to the ear and may damage hearing if the material gets into the external auditory canal. This may be the result of entry into the middle ear. Significant repositioning of the head during surgery can fold a pinna beneath the weight of the head and, if left folded during surgery, can result in necrosis and significant cosmetic defect.

Nasal Mucosa

Nasal mucosa can be prepared for surgery by swabbing several times with a Betadine® (5%) swab. This material should not be poured into the nares. The cranial air sinuses are often assumed to be sterile and, although usually true, this assumption is not reliable [71, 72]. When sinus mucosa is unexpectedly encountered during surgery, it is reasonable to irrigate the area with an antibiotic-containing solution. If a sinus is known preoperatively to be infected or if purulence in a sinus is unexpectedly encountered, the site must be cultured and irrigated with dilute Betadine® or with Bacitracin solution.

Mouth

Patients may be asked to rinse the mouth with 0.12% chlorhexidine mouthwash two or three times a day for 2 or 3 days before elective surgery. This can cause some yellow-brown discoloration of teeth and oral mucosa if used for several days or weeks.

Umbilicus

The umbilicus commonly has a high bacterial population, and the spectrum of the microbiome differs from other skin and includes organisms not commonly found on skin [73]. Unlike prepping other contaminated sites, the umbilicus should be prepped first, using cotton-tipped swabs soaked with the prep-solution and sponges

[40]. This prevents debris, which is often present in the umbilicus, from being displaced onto the surrounding prepped abdomen.

Dermal Conditions of Special Concern

Abraded Skin (Road Rash)

Abraded skin is often present in patients who require surgery for cranial or craniofacial trauma. The preparation of deeply abraded skin must be done after the patient is anesthetized for surgery. Simple abrasions with no imbedded foreign material require no special attention before undergoing surgery; the area should be washed with water and then prepared with chlorhexidine or povidone-iodine. All imbedded foreign material, for example asphalt, sand, gravel, fragments of glass, and particles from a firearm blast, must be removed before the surgical scrub begins, and this can be quite painful without anesthesia. Brisk irrigation or a mechanical pulsed lavage will remove most foreign material. Scrubbing with a brush may be necessary if the material is imbedded into skin and subcutaneous tissue; however, this may further injure skin and increase scarring. If not removed, permanent tattooing will occur, and delayed removal can be difficult. Deeply imbedded fragments (e.g., glass shard, knife blade, metal, or wooden rod) should not be removed while prepping skin, and care should be taken to minimize movement of the foreign material because of the possibility of causing additional injury. Only after the foreign material is removed should the skin be prepped with chlorhexidine or povidone-iodine.

Infected Wound (Recognized Before Surgery)

If there is an infected wound near the planned surgical incision, it is a contraindication to elective surgery. A large open region of infection anywhere on the body and any site with known MRSA is a contraindication. A small area of skin infection that is remote from the site of planned incision is not a contraindication, but should be covered with an occlusive bandage.

Draining wound (e.g., serum, pus) is a contraindication to elective surgery. Operating through any area that is inflamed or has increased bacterial flora raises the risk of postoperative infection.

Eczema, Acne/Comedones, Folliculitis, Pustules, Nondescript Rashes at or Near Site of Planned Incision

It is best to clear these conditions prior to making an elective incision, when possible, but this is not always possible.

Eschar

Eschar is not an absolute contraindication to elective surgery, unless associated with infection, but should be excised at the beginning of the procedure. Its presence can be an indication for surgery.

Lice

Lice (*Pediculus humanus capitis*) live almost exclusively on human scalp, feed on human blood, and cause severe itching, which induces scratching that can lead to infection of skin. Lice are not agents of wound infection, but can be vectors. Infestation of scalp lice does not affect the risk of surgical outcomes; however, postoperative itching and scratching can be cause for concern for bacterial infection [74]. For nonemergent settings, surgery should be delayed, the scalp treated with permethrin or other agent, and consultation with an infectious disease physician or pediatrician obtained. For surgical emergencies, lindane shampoo can be used for scalp preparation, followed by the usual surgical preparation; however, lindane does not reliably kill all of the lice [75, 76].

Traumatic Open Wounds

Traumatic open wounds should be extensively irrigated with sterile normal saline. A pulsed lavage should be used for large wounds. Severely contaminated tissue and dangling strands of tissue require debridement during or following irrigation [40].

Tar, Asphalt, Chewing Gum in Hair

Tar, asphalt, or chewing gum in the hair should be removed before entering the operating room. Attempts to remove these materials with soap or solvents are time-consuming and commonly end in failure. They are most easily removed by cutting the involved hair with scissors. The solvent WD-40 may assist in removal of these materials. A reported unconventional technique for removal of asphalt that has been ground into skin is the use of kitchen mayonnaise [77].

Preparation of a site having dirt, gravel, or asphalt impeded in skin or deeper tissues requires removal of all apparent debris, first by washing with sterile water and gently massaging with a sponge, soft brush, preferentially, jet lavage irrigation to remove the materials that can be easily dislodged. The site, including wounded tissues, is then scrubbed more firmly with a brush and alcohol-chlorhexidine or povidone iodine for at least 5 min to remove remaining imbedded materials. This may increase oozing or active bleeding, which can be controlled with bipolar coagulation. Infiltration of local anesthetic containing epinephrine greatly limits bleeding, but may increase risk of infection.

Preparation of Contaminated and Infected Sites

Preparation of an open purulent site must be irrigated to remove the visible pus and then all surfaces of the wound should be scrubbed firmly with a sponge or brush and povidone iodine for at least 5 min. If the infected site has only a small drainage site, moderate pressure around the site will express some of the pus during prepping the intact skin, but scrubbing of the deeper tissues must await surgical exposure.

Operating Room Personnel [78]

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Sick or Symptomatic Members of Surgical Team

Members of the surgical team who are ill, as manifested by significant symptoms, fever, or positive cultures of microorganisms, must not participate in activities in the operating suite or preoperative waiting area. The risk of transmitting microorganisms to the surgical wound with resulting surgical site infection may be low, but the risk is not acceptable. In addition, respiratory infections can be transmitted to the patient or to other members of the surgical team. When possible, such individuals should be identified and dismissed before entering the surgical suite. Most hospitals have a policy to exclude ill personnel from an operating suite and, if an ill person does not self-exclude, the surgeon or operating room supervisor should enforce the policy [79]. Surgeons are the most frequent offenders.

Wounds on Surgical Personnel

Personnel with open or visible wounds on hands, forearms, face, or neck should not participate in surgery. Wounds beneath surgical scrub attire should be covered with an occlusive bandage. The presence of MRSA on any site of the body is a contraindication for participating in surgery and for being in an operating room.

Jewelry

Most operating rooms in the United States do not allow surgical team members, whether scrubbed or not, to wear necklaces, bracelets, watches, most finger rings, or earrings; however, some pierced-ear type earrings and wedding bands which cannot be easily removed are usually allowed. The wearing of rings, particularly wedding bands, while scrubbing hands and donning sterile gloves is more commonly allowed in European countries. There have been no reports of a relationship between the wearing of rings and the occurrence of SSIs [80]. Although it seems reasonable to believe that loose jewelry would likely contribute to the dissemination of bacteria about a surgical room and surgical field, the authors are not aware of evidence of a relationship to surgical site infection [80].

Fingernails and Artificial Nails

Subungual areas tend to harbor bacteria, particularly coagulase-negative staphylococci, Gram-negative rods including Pseudomonas, Corynebacteria, and yeasts [81]. Most bacterial growth occurs along the proximal 1 mm of the nail, adjacent to subungual skin, and substantial numbers of potential pathogens often reside in the subungual spaces, even after careful handwashing or surgical scrubs. It is reasonable to use a brush or pick to remove visible debris beneath nails and around cuticles, preferably under running water, but it is not clear whether this reduces the number of CFUs (colony-forming units) on hands [68].

A relationship between nail length and surgical site infection has not been established, but long fingernails, both artificial and natural, easily puncture gloves [82, 83]. Artificial nails may be associated with increased presence of bacteria, particularly gram-negative organisms and fungi, despite hand scrub and should not be worn [84]. Also the wearing of artificial nails is associated with poor hand washing [83]. Natural nails should not exceed 5 mm in length. A relationship between the wearing of nail polish and the number of CFUs identified before and following surgical scrubs supports the avoidance of nail polish [80]. Nail polish can significantly affect oximetry readings [85].

Cosmetics

Cosmetics can inhibit the effectiveness of antiseptic agents used in preparation of skin. Cosmetics and oils or lotions applied to skin should be removed with soap and water, and skin should be dried with a towel before being prepared for surgery.

Antisepsis for Hands and Forearms of Surgical Personnel

Antisepsis is the removal of microflora that can cause infection. Members of the surgical team who have visibly dirty forearms, hands, or fingernails should use a sponge or soft brush to clean these areas before entering operating rooms and before scrubbing for surgical participation. All OR personnel who don scrub suits and will be in a surgical suite should wash hands and forearms, using tap water and soap, immediately before donning scrubs, following restroom visits, after eating meals, and after contact with body fluids from any source. Personnel who work in surgical suites and may enter surgical rooms, for whatever reason, can inadvertently contribute to the distribution of bacteria and therefore to the contamination of surgical wounds.

Members of the surgical team who may have direct contact with the surgical field, instruments used in the surgery, or any item to be implanted must scrub their hands and forearms immediately before donning surgical gowns and gloves. This is done to limit the distribution of bacteria and contamination which can occur if a glove or gown is punctured during the surgical procedure. The first surgical scrub of the day should include cleaning underneath fingernails with a soft brush or nail pick; however, this has been shown to not reduce the CFUs remaining on hands [68]. Dried blood or other visible material requires a repeat scrub.

Antiseptic agents commercially used for scrubbing hands and forearms of surgical team members include chlorhexidine and iodine/iodophors. Alcohol alone is a standard for surgical hand preparation in some European countries, but is uncommonly used alone in the United States, possibly because of concern over flammability. Chlorhexidine gluconate, often with alcohol, and povidone-iodine are commonly the agents of choice of surgical team members in the United States; however, the evidence that one agent is better than others in reducing SSIs is not strong [68]. Tsai, et al. have recommended that the conventional chlorhexidine scrub should be the standard for perioperative hand antisepsis; however, nearly all evidence on decisions regarding hand antisepsis is of "low or very low quality" [86]. Avagard® (1% chlorhexidine with 61% ethyl alcohol w/w) is commonly used for hand antisepsis. Alcoholic chlorhexidine has greater residual antimicrobial activity than other preparations of either chlorhexidine or povidone-iodine, and the use of chlorhexidine gluconate, compared with povidone iodine, results in a greater reduction in CFUs on hands [68, 87]. However, allergies and other factors, such as the brownish discoloration of hands and clothing by residual iodophors, influence surgical team members' preferences on choice of antiseptic. Some alcohol hand-sanitizing gels may inactivate the persistent antibacterial activity of chlorhexidine [88]. Hand soap is not satisfactory for surgical scrubbing. Frequent washing of hands changes the microbiome, which can disturb the skin barrier and may result in skin irritation [89].

Skin Friction Versus Brushing of Hands

Brushes are not recommended for surgical hand scrubbing, according to WHO Guidelines on Hand Hygiene in Health Care [90, 91]. A randomized, controlled clinical trial found that the use of a brush does not add additional antimicrobial effect [92]. Hand rubbing technique is as effective as traditional scrubbing with a brush, causes less skin damage, and is better tolerated [93]. Although scrubbing with a brush increases the shedding of skin cells [94], lower bacterial counts are associated with a brushless surgical scrub than with a scrub done with a brush, when alcohol-based 1% chlorhexidine gluconate is used [91, 92, 95]. Surprisingly, "… vigorous friction scrub is not necessarily advantageous" [74]. A brush may be beneficial in cleaning visibly dirty hands before entering a surgical room.

Duration of Scrubbing Hands

Published information on the optimum duration of initial scrubbing of hands and forearms and subsequent scrubs the same day has very low-quality evidence and is difficult to synthesize. Scrubbing for less than 2 min is inadequate for reducing CFUs and longer than 8 min may injure skin, particularly if a stiff brush is used. Several authors support a scrub duration of 2–5 min [68, 69, 96].

The reappearance of resident bacteria on hands can be detected by 5 h following scrubbing with chlorhexidine-alcohol. For this reason, rescrubbing after 5 h has been recommended [97].

Drying Hands After Scrubbing

After completion of the surgical scrub, hands should be kept up and away from the body with elbows flexed to prevent water from flowing from the elbows and forearms toward the fingers. Drying removes water that can flow on the arms and hands and therefore has value, but there is no evidence that any technique of drying is superior. The following technique is used by author KRW. A sterile towel, folded to have double thickness, is used for dry one hand and forearm (in that order), and then the other end of the double-thickness towel is used to dry the opposite hand and forearm.

Traditionally, it was taught that, after the hands and arms are scrubbed and dried, no surgeon, scrub nurse, or technician should allow hands to drift below that person's waistline at any time before the completion of surgery. The authors are not aware of supporting evidence of benefit for this tradition.

Surgical Attire and Customs [78, 98–101]

Ken Rose Winston

It is important for surgical personnel, particularly surgeons, to know the basis for the near-universal customs, practices, and rituals of operating room behaviors, many of which are mandated for patient safety by some or all of the following: CDC, WHO, AORN, OSHA, and JCAH. These are, with few exceptions, based on expert, consensus-based opinion and supported by available evidence; however, almost all of the supporting evidence is for *reduction in bacteria, not reduction in surgical site infection* [102]. Understanding by physicians and other healthcare personnel of the rational for surgical attire and customs will likely lead to better compliance and fewer complications.

Surgical attire varies little in operating rooms throughout the world, but the supporting rational is heavily influenced, not by published data, but by "it makes sense" and "this is the way it's done." There are guidelines, regulations, recommendations, and strongly held opinions on proper surgical attire; however, data on what constitutes best practices are sometimes contradictory and difficult to synthesize. SSI rates correlate more with perioperative patient wound hygiene and transparency of reported hospital SSI rates than with operating room attire [103]. The authors are not recommending that any of these be ignored.

Evidence that handwashing can reduce infection was introduced by Ignaz Semmelweis and Oliver Wendell Holmes in the 1840s and popularized by Lister about 30 years later [99].

Scrub Suits

Scrub suits protect both patients and wearers. The scrub shirt should cover all underclothing, for example t-shirts, and must always be tucked into the pants to minimize shedding of squames and to prevent billowing and contact with sterile surfaces. Fresh scrub suits must be donned at the beginning of each surgical day, but those worn to work or anywhere outside of the hospital must not be worn into the surgical suite. Scrub suits that are visibly soiled, likely contaminated, or penetrated by blood or other bodily fluids should be changed before even brief entry into an operating room. Fresh scrub suits should be donned on each entry into the restricted surgical area. Surprisingly, there is no convincing evidence that operating room attire, except for sterile gowns and gloves, influences the risk of SSI [99].

Jackets and Lab Coats

Long-sleeve jackets are sometimes worn for warmth by anesthesia personnel, circulating nurses, and various technicians in an operating room. Interestingly, NICE (National Institute for Health and Care Excellence) in the United Kingdom accepts the short-sleeve jackets and "bare below the elbows." These minimize distribution of squames from arms and axillae of wearers; however, a fresh jacket should be worn each day. Long lab coats may be worn outside of the surgical areas to protect surgical scrub suits, but lab coats of any length worn outside the surgical suites must not be worn in restricted surgical areas.

Shoes and Shoe Covers

The wearing of shoe covers has not been demonstrated to reduce the incidence of SSI, but can protect the wearer's shoes from prepping solutions, blood, and other body fluids and can prevent material adherent to shoes from being transferred into or out of an OR. Shoe covers should be removed as the surgeon leaves the OR to prevent tracking of material from the OR floor to other sites. Shoes and shoe protectors with dry blood, dirt, and other materials are very apparent to patients, families, and other surgical personnel and strongly suggest a lack of attention to cleanliness. The presence of such materials on light colored shoes (e.g., white or yellow) is far more obvious than on dark colored, particularly brown, shoes. The wearing of shoe-covers has not been demonstrated to reduce the incidence of surgical site infection, but the absence of evidence does not mean absence of value. Whether noticeable or not, surgical shoes should be frequently scrubbed with a brush. Shoes worn in a surgical suite are rarely cultured but perhaps should be. A few brands are autoclavable. According to CDC Guidelines (Category IB), "Do not wear shoe covers for the prevention of SSI" [39].

Hats and Caps

Controversy exists regarding snug-fitting surgical skullcaps versus bouffant type hats [104, 105]. The snug-fitting cap, which is preferred by most surgeons, holds hair against scalp, may be less permeable to liquids, and may or may not cover ears [105]. A bouffant hat covers ears and the sideburns more completely, does not compress hair against scalp, is more easily displaced, and may be less comfortable. No difference in surgical site infections has been identified [104, 106]. A large study on the impact of imposed strict regulations on operating room attire, including full coverage of ears and facial hair, found no reduction in incisional surgical site infections [107]. There have been no studies providing evidence that hat style influences the risk of SSI or that the covering of hair prevents SSI [107, 108].

Face Masks

Surgical face masks provide a physical barrier to the transmission of bacteria from the nasopharynx and oropharynx to an open surgical wound and it seems intuitively compelling that the wearing of face masks by surgical team members would reduce risk of surgical site infection; however, the wearing of face masks has not been demonstrated to reduce surgical site infections [109]. Also, there is little evidence to support the wearing of face masks by anesthesiologists or other non-scrubbed operating room staff [110, 111]. The wearing of a surgical mask does provide protection for the wearer, particularly from splatter to the face but little or no protection from airborne infectious particles.

Most, if not all, surgeons wear masks during all surgeries, and most hospitals require that a surgical mask that fully covers the mouth and nose be worn by each person entering an operating room, if sterile packs of instruments or other materials are exposed, and when a surgery will soon begin or is underway.

A face mask should fit sufficiently tight to prevent venting at the sides. Tape across the nose can prevent fogging of eyeglasses. The movement of a face mask against skin disrupts squames and therefore may contribute to wound contamination. A loose-fitting mask daintily tied to avoid mussing makeup or hair as a matter of personal preference is not acceptable and may be less safe than wearing no face mask. After a surgical mask is used for a surgical case, it should be removed, discarded, and not reused.

Surgical Gowns

Surgical gowns are worn to protect patient and wearer and should be worn during all except the simplest procedures executed in operating rooms. Surgical gowns must be of a material that resists penetration by water and bodily fluids. Paper gowns that are now in common use are effective against penetration of most liquids encountered during surgery, including blood. Scrub gowns which become punctured or penetrated by blood or other bodily fluids should be changed as soon as noticed.

Stepping briefly out of an OR into a ‘sterile hallway’ while wearing a ‘sterile gown’ is frowned upon and likely causes a small risk of contamination, but this risk has not been assessed.

Gloves

The reduction of surgical infections by the use of surgical gloves was recognized in the 1890s by Joseph C Bloodgood, William Halsted’s resident [99].

Surgical gloves are worn to protect both wearer and patient. The risk of perforation of surgical gloves increases with duration of operative time and occurs more commonly during surgical procedures involving raw bone fragments or the use of surgical wires, for example during some craniofacial surgeries. Perforated gloves must be replaced immediately because of the risk of contamination of the surgical site. Glove perforation is associated with an increase in SSI: however, this association has not been found when antimicrobial prophylaxis is used [112].

When two pairs of gloves are worn (double gloving), significantly fewer perforations occur in the inner glove than occur in single gloves, and therefore the risk of percutaneous injury to the wearer is reduced [113]. Double gloving has not been shown to reduce surgical site infection [114, 115].

Adhesive Drapes

Plastic adhesive incision drapes are used to act as a barrier to the migration of bacteria from the patient's skin into the operative site and are therefore widely used to prevent surgical site infections, but the effectiveness in preventing surgical site infections is controversial. A Cochrane review of randomized controlled studies of over 4000 cases found "There was no evidence from the seven randomized controlled trials that plastic adhesive drapes reduce surgical site infection rates, and some evidence that they increase infection rates" [116]. A related review, in 2018, found no clear evidence of a beneficial effect of iodine-impregnated adhesive drapes [117]. Also, no infections occurred among 581 surgeries for anterior cervical fusion done without iodophor impregnated drapes [118].

Contaminated Surgical Attire and Surgical Barriers

Surgical barriers worn by the surgeon and other members of the surgical team which are penetrated by a surgical instrument or become contaminated or soaked through by blood should be replaced as soon as safely possible. If contamination or penetration of a surgical drape is recognized during their application, the drape should be replaced. If recognized while surgery is in progress, it is best managed by covering the region with a new sterile drape or towel and securing it in place.

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Surgery of Skin: General

3

Ken Rose Winston and Lawrence L. Ketch

Marking Skin

Planned incision lines should be marked before drapes are applied, to prevent wrong-site incisions. Marking is not necessary if the incision will follow either a recent surgical incision or a thin scar; however, the presence of multiple scars can be problematic. Surgeons may choose to mark landmarks that will be important during the surgery. If an incision may require extension during surgery, the initial mark on skin should include that possible extension. Extensions of incisions into unmarked skin can appear, when drapes are removed, to be oddly angled and cosmetically undesirable. Marking after draping can be significantly badly positioned. Drapes applied prematurely—before marking—should be removed to allow reliably accurate marking.

Marking of skin is most commonly done with a surgical pen; however, surgical pens often fail. The author prefers to use methylene blue and mark a thin line with a wooden stick. Ink applied to wet skin will spread (bleed) to produce a wide irregular mark. When making an incision whose precise location is critical, for example on the face, it is important to use an instrument that produces a thin distinct line. Indelible ink should not be used in surgical marking.

Skin should never be marked with the back edge of a scalpel's tip, because this often causes bleeding and may result in scarring or keloid formation and, if the surgeon uses a slightly different site to incise, the scratch will be apparent postoperatively and can be mistakenly interpreted as a surgical error.

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Incising Skin

Neurosurgeons typically choose a skin incision from the repertory of incisions with which they are familiar or learned in residency and not always with consideration for cosmetic impact. Plastic surgeons camouflage incisions within natural creases or between subunits such as on the face. Incisions placed in areas that receive least attention result in the best esthetic result. Before surgery, patients of all ages are concerned about cosmesis, and after surgery they closely and repeatedly scrutinize their scar. A few young men, apparently believing that facial scars are semaphores of toughness, are proud of facial scars.

Elastin that is distributed throughout skin maintains constant tension, but varies by anatomical location. This is apparent when an incision immediately gapes and when a harvested free skin graft immediately contracts. Elastic fibers are arranged along lines of skin tension, and the normal tension and contraction of local muscles account for many of the rhytids (wrinkles), which are apparent in adults. Infants' skin has maximum elasticity and minimum thickness, both of which facilitate the coverage of large defects following surgeries for reconstruction. Elderly patients have skin that is relatively inelastic, but this yields a similar advantage, often resulting in almost undetectable scars.

Relaxed Skin Tension Lines (RSTLs)

Surgical incisions aligned with relaxed skin tension lines (RSTL) minimize tension across the closure, and these wounds heal optimally and with least conspicuous scars. RSTLs are usually not apparent on inspection, but can be most easily and accurately identified by pinching the skin and observing the resulting furrows and ridges [1]. Relaxation of muscle does not relax the overlying skin. When pinching is applied perpendicular to RSTLs, straight furrows extend from each side of the pinch. If the RSTL is curved, several pinches are required to define the curve. Curved furrows and ridges forming an S-pattern indicate that the pinch is obliquely applied on the RSTL [1]. *Langer lines* are useful in planning incisions on the trunk and extremities.

Instruments for Incising Skin

Microneedle Electrocautery

An electrocautery with a microneedle tip can be used to incise skin, including scalp and other soft tissues. It simultaneously cuts and assists with hemostasis by cauterizing small vessels and is commonly used by neurosurgeons [2–4]. The lowest power setting that cuts tissue without significantly distorting or moving it should be chosen. The numerical setting varies by manufacturer and on individual machines, and therefore the surgeon must determine the best setting. Use of too high power may result in thermal injury that will negatively impact healing, follicle survival, and produce more scarring than necessary. The use of low power slows the surgery and can also injure skin by requiring retraction of needle against skin while cauterizing in a small spot. An electrocautery having a standard broad or spatulated tip—i.e., any tip other than a microneedle—causes an unnecessary amount of thermal injury to full-thickness of skin. While power is being applied, it is important to move the cutting tip steadily along the length of the marked incision without pausing in one location. Pausing will cause thermal injury to the epidermis and dermis, with some delay in healing and wider scar at that site. (See *Thermal Injury* below.)

Some surgeons choose to make an initial shallow incision through epidermis and into dermis with one power setting and use a different power setting for cauterization of identified bleeding vessels in skin. Cauterization should never be used along a continuous line of dermis to address oozing or for prophylaxis—called cauterization "to whom it may concern"—resulting in unnecessary and therefore avoidable thermal injury; however, this technique can be useful and acceptable in emergent surgery. Incisions made by electrocautery are reported to result in shorter incision time, less postoperative pain, less blood loss, less distortion of skin while incising, and scar cosmesis that is equivalent to that of scalpel [2, 5–7]. The evidence is controversial regarding scars in scalp from scalpel incisions tending to be wider and have wider scar alopecia than scars made by electrocautery [8–10]. Reported rates of positive cultures of electrocautery needles following clean surgeries have varied widely [11, 12].

Scalpel

Meta-analysis of scalpel versus electrocautery for skin incisions is consistent with the position that the two have similar healing and similar risk for infection [5, 6, 13].

However, some surgeons choose to use an electrocautery instead of a scalpel to avoid needing Raney clips for hemostasis; however, these clips may raise the risk for scar alopecia [8]. The belly of the blade (curved midportion), not the tip, should be used to incise skin and a #10 Bard-Parker® blade is most satisfactory for adults and older children. A #15 blade is more appropriate for precise small and cosmetically important locations and for young children whose skin is significantly less thick. The tip of the blade should be used for initial entry through skin and for precise cutting. The belly of the blade is then moved along the planned line of incision.

Initial penetration of the skin overlying temporalis muscle should be made, except in emergent cases, very cautiously until the temporalis fascia is encountered. Some surgeons then, knowing the depth to temporalis fascia, extend the incision along the ink mark on skin and avoid injury to fascia. Other surgeons insert a broad instrument, for example a periosteal elevator, between galea and temporalis muscle and, using that instrument to protect temporalis fascia and muscle, continue the incision along the marked line on the skin.

Scalpel blades cultured at the conclusion of surgery are reported to be positive in 1.8–2.8% of cases. However, the use of separate knives for skin and deep tissues to minimize contamination of wounds is not supported by evidence.

Laser

Laser is a mnemonic for "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation." A laser emits a beam of coherent light through an optical amplification process. Spatial coherence allows for a laser to be focused to allow for laser cutting. When using high-power lasers of ultraviolet wavelength, chemical bonds can be broken with a relatively small local thermal component to limit injury. As a surgical tool, the laser can cut, vaporize, and facilitate exposure. Many have claimed that there is no convincing evidence to suggest any advantage to laser incision of skin.

Technique for Incising Skin

Incisions in non-hair-bearing skin and skin with sparse distribution of hair should be made perpendicular to the surface. The initial penetration of skin overlying bone should be made with a slow firm insertion of the blade through the full thickness of skin until bone is encountered. The blade should be steadily moved along the inked line on the skin. The length of the initial stroke should be limited by the amount of bleeding. After satisfactory hemostasis is obtained, not necessarily perfect, the incision is extended in a stepwise manner until the planned incision is completed. Alternatively, the surgeon may initially make a superficial incision utilizing the cut option of an electrocautery and then complete the full-thickness incision, as skin edges are gently pulled aside with double skin hooks.

Corner Incisions

Sharp cornered, for example right-angle, incisions should be made by starting at the apex and making a full-thickness incision for several mm away from the apex. The second limb of a corner incision should be made by again starting at the apex and cutting away from the apex.

Curved corners with short radii of curvature are made with a continuous incision. However, the superficial layer of the skin and the flap tend to contract toward the concave side of the incision as deeper layers are cut, often resulting in an incision that can cause difficulty in closure. Cognizance of this phenomenon allows the surgeon to alter the angle of incision through skin by tilting the cutting instrument toward the convex side.

Incisions to Avoid

Attempt should be made to avoid making incisions that cross RSTLs (relaxed skin tension lines), but surgical goals make this not always possible. Although not cosmetically optimal, an incision that must cross an existing scar is rarely a problem unless the new incision will result in compromise of blood supply to a region of scalp. Incisions that would course parallel, or nearly so, to an existing scar should be avoided because of risk of infarction of the intervening strip of skin. It is almost always possible to incise through the existing scar, possibly with an extension, to achieve the necessary exposure.

Incising Skin of Children

The skin of young children is relatively thin and mobile, compared to skin of older children and adults. This relatively loose skin should be manually immobilized as skin incision is made. This assists in cutting along a planned straight or curved line that may have been stretched, distorted, or shifted from its normal location while positioning for surgery. Youthful skin typically has fewer imperfections, such as rhytids, pigmentation, and coarse texture, which can make a scar more obvious.

Incision in Existing Scar

Marking

When a new incision is required in skin that has an existing scar, an attempt should be made to either incise along the existing scar or incorporate that scar into the new incision. The ink used to mark along an existing scar very often bleeds laterally and obscures the edges of the scar, particularly if the old scar is narrow. This can result in the new incision imprecisely following the old scar, making the new scar more noticeable than the original.

Many existing scars are sufficiently visible to require no inking, but some are less apparent. Regardless, the marking of existing scars with ink should be done with small ink dots that will guide the surgeon’s eye along the old scar. Most scars can be safely excised if the blood supply in the region has not been previously compromised.

Incision Versus Excision of Scar

Narrow scars that are cosmetically acceptable can be incised, and they usually heal well with minimal increase in width. Wide scars, particularly those in cosmetically sensitive locations, can usually be safely excised and, if there is no tension on the closure, wound healing can be expected to produce a less noticeable scar. Incision within a wide scar may heal poorly and with an even wider scar. Existing scars from repeat surgeries often present opportunities for cosmetic improvement.

Emergent Incisions

Emergent neurosurgical surgeries occur in a spectrum of clinical settings, ranging from those that allow a small amount of time for planning to those required while CPR is in progress. All incisions in emergent settings should be made in an efficient and deliberate manner. The existence of an emergency is never a satisfactory explanation for *cut first and think later*.

Hemostasis

(See a review of the history of hemostasis in neurosurgery by Chivukula et al. [14])

Hemostasis Along Skin Edges

Care should be taken to minimize injury to skin along the incision. Secure hemostasis should be established with bipolar electrocautery applied to identifiable bleeding sites. This often obviates the need for skin clips, but may minimally increase operative time. The practice of routinely applying electrocautery in a continuous line along the dermis should be avoided because this damages hair follicles, may produce skin necrosis along each side of the dermis, and increases the width of the scar and alopecia.

Some surgeons, while incising with a scalpel, have a surgical assistant apply firm digital compression—four fingers on each side of the marked line—to minimize blood loss as the incision is made. Also, an index finger hooked into each side of an incision to stretch the incision open can be effective in limiting blood loss, but this is esthetically displeasing to some surgeons.

Use of Skin Clips for Hemostasis

Raney clips grip the full thickness of skin and are effective in establishing hemostasis. These spring clips are available in three sizes (light, medium, and heavy) having different closing strengths, with either straight or serrated edges. Their closing force can significantly damage or even infarct the skin edges of infants and young children. For all sizes of Raney clips, the longer they remain attached to skin, the greater the risk of ischemic injury. Regardless of instrument used for incising skin, Raney clips that remain in place for more than 3 h increase the width of alopecia in scalp [9].

Michel clips are steel disposable clips that are used to achieve hemostasis along skin edges and tend to be relatively inexpensive. They are available in several sizes, are easy to apply, and are useful in the thin skin of young children because of the surgeon's control of closing pressure. These are occasionally inadequate for griping thick skin and their small size may increase the risk of their being accidently left in a surgical wound.

Reflecting and Retracting Skin

Reflection of a skin flap consists of separation of full-thickness skin from underlying tissue and is usually easily accomplished by dissecting through relatively loose areolar and adipose tissues. For infants and young children this should be done with a scalpel, as the skin flap is being retracted. Patients of all ages who have had prior surgery or trauma in the area often have relatively fibrotic tissue or even dense scar that must be cut by scalpel, scissors, or electrocautery to reflect the scalp. Occasionally, veins are encountered and require electrocoagulation.

Pitfalls/Things to Avoid

Compromising Blood Supply to Skin

Severe compromise of blood supply to skin, with risk of infection, although rare, occurs in some neurosurgical settings. Settings in which this has occurred include the following: a new incision which, with a preexisting incision, devascularizes an area of skin, incision that is near a prior incision or scar, scalp flaps with very narrow base, and extremely tight closures such as may occur after single-stage cranial expansion or closure of a large myelomeningocele.

Dissecting Fat from Skin

It is important to maintain enough subcutaneous adipose tissue to allow for maintenance of blood supply via the subdermal plexus while dissecting skin. This may be achieved by dissecting either within adipose tissue or over the surface of muscular fascia and periosteum, depending on location—i.e., beneath the adipose tissue.

Accidental Fenestration

This occurs rarely during reflection of normal skin, but its risk of occurrence is greater in very thin skin and when there is densely fibrotic attachment of skin to underlying tissue. Digital palpation over the surface of the skin during sharp subcutaneous dissection can usually guide the depth of dissection and avoid accidental fenestration.

Retraction of Skin

Retraction of skin while making an incision serves two purposes: holds the edges apart to assist the visualization of the planed line of incision and minimizes bleeding from the raw edges of skin. A surgical assistant may use hand-held retractors or digits to achieve both goals while an incision is being extended and during the time needed to establish hemostasis and introduce more secure retraction or as needed. Prolonged manual retraction of skin is rarely if ever necessary. In most neurosurgical procedures, retraction is maintained by skin hooks or self-retaining retractors for more precise control and less risk of causing marginal necrosis.

Self-retaining retractors are commonly available in many sizes and shapes and the surgeon must select one or more to achieve the needed exposure without obstructing the view of the surgical field. Depending on how the retractor is applied, the force against the skin may be primarily against the everted edges of a skin flap or against skin, underlying muscle, and adipose tissue. Usually both arms of a self-retaining retractor are against soft tissue, but the surgeon may place one arm against cranial bone. Unlike manual retractors, self-retaining retractors apply equal force against both sides but not against equal areas. If extremely tightly applied against a skin edge, there can be prolonged ischemia in the edge of epidermis, which can have an adverse cosmetic impact.

Prolonged retraction of skin flaps is commonly achieved by inserting sutures directly into galea or dermis one or more cm from the edge and affixing these sutures to drapes. Retraction sutures can be placed along the edges of a flap or far from the edge, in the site of folding of a skin flap. It is critical that these sutures not encompass local vasculature to the flap. Some surgeons tie these sucurely with square knots or attach the distal ends to drapes with small hemostats. Other surgeons loop these retraction sutures through a staple or towel clip in the drapes and for young children whose skin is significantly less thick and then attach the sutures to drapes with hemostats. The tension of sutures attached to drapes can be easily adjusted at any time after placement.

The raw edges and undersurfaces of skin flaps must be kept moist throughout the surgery. Failure to do this can result in desiccation, contraction, and increased risk of infection. It is impossible to describe the tightness with which a skin can be safely retracted; however, even slight blanching is an indication of excessive tension. Folding, stretching, and crushing of skin must be avoided. The status of retraction should be checked several times during long surgeries. A kinked or sharply folded flap during a long surgical procedure can critically compromise blood supply to the flap. Concern for this problem is the basis for surgeons folding skin flaps over a folded laparotomy pad or stack of Raytecs®.

Desiccation of the edges of a skin flap or its undersurface can be prevented by covering these surfaces with moist Raytecs® and frequent irrigation during the surgical procedure. Cauterization on these surfaces, particularly skin edges, causes desiccation at each spot of application of the cautery and therefore should be minimized. Almost all devascularization of skin flaps can be prevented by careful planning of surgical incisions and attention to precise and delicate surgical technique.

Closing Skin Incisions

All retractors are removed, and the skin flap is inspected and manually returned to its normal location. Actively bleeding sites are controlled with electrocautery. Thorough hemostasis is important and should be achieved with precisely applied electrocautery to identified bleeding sites, encompassing each bleeding vessel. Cauterization of additional tissue should be minimized. Cauterization along a continuous line of the edge of dermis causes unnecessary thermal injury and should not be used. The entire wound, including flap, is vigorously irrigated with antibiotic-containing saline. Some surgeons use one or two galeal sutures to temporarily align wound edges during the early stages of closure.

Closure for Healing by Primary (First) Intention

Almost all lacerations and elective neurosurgical incisions are closed primarily. This is usually a multilayer type closure in which, depending on type and location, the wound is closed with interrupted absorbable sutures. Surgical preference varies but most neurosurgeons close galea with interrupted 2-0 sutures in teens and adults, 3-0 in children and 4-0 in infants. The dermis is most often closed with interrupted 3-0 absorbable sutures, but some surgeons prefer 2-0 sutures. Running suture can be used to approximate dermis, but tends to distribute tension unevenly along the wound and is often applied too tightly, The primary purpose of sutures in dermis is to hold the incision together, but they also assist with alignment of the edges of skin and with hemostasis.

The edges of the wound should be either slightly everted or barely touching. The most popular method for approximating the superficial layer of skin—epidermis, and superficial dermis of the scalp—is with interrupted 3-0 or 4-0 sutures. In areas of greater cosmetic concern, for example face, interrupted technique with smaller sutures should be used. Staples can usually achieve excellent closure along the spine but, if done carelessly, the result can be poor alignment and overlapping edges. Staples must be applied delicately and removed early to avoid excess scar. The size of staples should be commensurate with location, inherent tension, and size of the wound. An assistant may accurately approximate the edges of the wound with skin hooks while staples are applied.

Closure for Healing by Secondary Intention

Secondary intention healing is relatively slow and occurs via the formation of scar. The wound always has microbial contamination. Some wounds that are closed by secondary intention are packed with moist gauze, either because of contamination or to stimulate formation of granulation tissue. The packing must be gradually reduced over time. Healing by secondary intention produces an inflammatory reaction with granulation tissue and results in a more contracted and widened scar than does healing by primary intention and increases the risk for a hypertrophic scar or keloid formation. Secondary intention healing may continue for months, require dressing changes before final closure is achieved, and produce substantially more discomfort compared to primary closure.

Closure for Healing by Tertiary Intention (Delayed Primary Closure)

Tertiary intention healing is used after a primarily sutured wound dehiscences, regardless of reason, and in wounds reopened to drain abscesses. This type of wound will usually heal more quickly than a primary wound because the lag phase of inflammation does not need to repeat. Phagocytosis of contaminated tissue and the start of epithelialization and deposition of collagen are underway by the fourth day.

The wound is left unclosed for several days, to allow a series of bandage changes, including packing, to decrease contamination, optimize the local bioburden, and decrease risk for infection. Closure is achieved by approximating the edges of the wound with sutures or staples several days after being left open. Depending on the depth of the wound, one or more layers of deep absorbable sutures may be required to eliminate dead space, assist in edge approximation, and prevent repeat dehiscence. The dead space must be obliterated to prevent hematoma or the accumulation of serum, which predisposes to dehiscence and infection.

Materials for Repairing Skin

Needles

Cutting type surgical needles usually have a sharp-pointed triangular tip, and each of the three edges is sharp. The more conventional type cutting needle has one of the three cutting edges on the concave side of the needle and therefore may cut through tissue. These are commonly chosen to approximate dermis. Reverse cutting needles have one of the three cutting edges on their convex side and are ideal for suturing skin, particularly in subcuticular closures.

Tapered (round) needles are most useful in suturing soft tissues, for example fascia, muscle, arachnoid mater, dura, and blood vessels. Tapered needles, which pierce tissue without cutting, cause unnecessary trauma when used to close skin because of the force required for penetration and the requirement for grasping the skin very tightly to counter the force of the advancing needle. The 3/8 circle needle is the most common type used in neurosurgical and craniofacial surgeries because it is easy to manipulate in almost all wounds. The ½ circle needle is often more appropriate for use in deep confined wounds.

Sutures [15] (Table 3.1)

The choice of suture is determined by the type of tissue being sutured, size of suture, and the required duration of wound support. (See Tables 3.1 and 3.2). The ideal suture is the smallest suture that will hold tissue together during the healing process with minimal tension and tissue reaction and then be rapidly absorbed. Braided sutures have increased tensile strength for each increase in size, but they create more inflammation. These also increase the risk for wound infection and scaring, particularly in contaminated wounds. Multifilament sutures, for example silk and

Table 3.1 Diameters of surgical sutures

Synthetic absorbable sutures Ethicon® [16, 17]		Surgical wire	
USP size [17, 18]	Minimum diameter[a] mm	American wire size [19]	Diameter mm
# 0	0.35	26	0.40
# 2-0	0.30	28	0.32
# 3-0	0.20	30	0.25
# 4-0	0.15	32	0.20
# 5-0	0.10		
# 6-0	0.07		

[a]Organic absorbable sutures with same USP size designations have slightly larger diameters

Table 3.2 Suture strength and survival of commonly used Ethicon® absorbable sutures [17, 18]

	Wound support	Breaking strength retention in vivo	Complete absorption
Vicryl® violet braided	14–28 days	75% at 2 weeks 50% at 3 weeks 25% at 4 weeks 0% at 5 weeks	56–70 days
Vicryl Rapide®	7–10 days	50% at 5 days 0% at 10–14 days	42 days
Monocryl® undyed	–	60–70% at 1 week 30–40% at 2 weeks 0% at 3 weeks	91–119 days
Plain gut	–	7–10 days	70 days
Chromic gut	10–14 days	21–28 days	90 days
PDS II®	6 weeks	70% at 2 weeks 50% at 4 weeks 25% at 6 weeks	6 months

Mersilene®, have the advantage of being easy to handle and knots can be secured with three throws. Monofilament sutures, for example nylon and Prolene®, glide smoothly through tissues and may have lower association with infection. Because of their tendency to become untied, these sutures should be secured with four or five throws.

Absorbable sutures—Neurosurgeons use absorbable sutures in most circumstances in which the sutures will be buried, particularly in dermis. Vicryl® is excellent for repairing incisions in normal skin. Synthetic absorbable sutures, for example Vicryl® and Monocryl®, are commonly used in neurosurgical and craniofacial surgeries. They undergo breakdown by hydrolysis, as water penetrates the filaments of the suture. Gut sutures are composed of collagen, are associated with more tissue reaction, and less predictable absorption during enzymatic breakdown and phagocytosis. The inflammation associated with absorbable sutures persists until the material is absorbed. All buried sutures should be placed and cut to leave a minimal amount of material in the wound. Repairing hair-bearing skin that has not been shaved or clipped with absorbable sutures does not increase the rate of wound infection [20].

Nonabsorbable sutures—Nonabsorbable synthetic suture, for example 3-0 or 4-0 Nurolon®, Mersilene®, or Prolene®, should be used in incisions for which longer lasting support of aligned skin edges is required, such as that exists in repairing incisions that are under moderate tension or have impaired ability to heal. Subcuticular nonabsorbable pull-out sutures are best for such wounds and may be left in place for an extended time. Examples include irradiated or soon to be irradiated skin, patients receiving chemotherapy, significant malnutrition, and risk of mechanical disruption for any reason. These sutures should be tied with five or six throws. Non-synthetic nonabsorbable sutures, for example silk, cotton, and wire, have little associated tissue reaction. Wire ends must be twisted together, and their tips bent to prevent injury to adjacent tissue.

Barbed sutures—Barbed sutures are monofilaments, and the effective diameters of barbed sutures are reduced by the micro-cuts made along the suture to produce barbs. A typical barbed suture has the approximate strength of the next larger smooth suture and, unlike smooth sutures, maintains its relative uniform distribution of tension along the suture line [21]. When compared to smooth sutures that require knots, absorbable barbed sutures can securely approximate tissues more easily, require less time, have less cost per case, and reduce risk of accidental puncture of surgical personnel because of fewer needles being used [22]. Barbed sutures have been used in neurosurgery, orthopedic, urological, plastic, and obstetric surgery; however, there are reports of increased occurrence of complications with wound closure [22–25].

Layered Closure of Skin

Single-Layer Closure

Single-layer closure is often used to repair short incisions and incisions or lacerations that do not extend through the full-thickness of dermis. This may be done with simple interrupted or running sutural technique; however, tissue adhesives or Steristrips™ are sometimes used. Single-layer closure with large sutures is appropriate in emergent settings, particularly when death is eminent.

Two-Layer Closure

Elective neurosurgical incisions and also lacerations that come to neurosurgical attention are, with few exceptions, closed in two layers—a deep dermal layer or galeal layer and the epidermal layer, which may include superficial dermis. The deep layer is usually closed with single inverted buried sutures of 3-0 Vicryl® (4-0 in infants). The epidermal layer is best closed with 4-0 Vicryl Rapide®, using a simple continuous technique. Some surgeons prefer to use interrupted nonabsorbable sutures or staples.

Techniques for Suturing

Well-approximated and gently everted wounds heal most favorably.

Simple Interrupted Sutures

Placement of interrupted sutures requires more time than placement of continuous sutures and both have a significant risk of producing crosshatched scars (railroad tracking) if left too long or, more importantly, tied too tightly. Interrupted sutures are less prone to impair blood flow and cause edema along the sutured wound, than running sutures, and the surgeon can easily adjust tightness and replace individual sutures. When repairing skin, the number of sutures used should be minimized to the number required to precisely approximate the wound edges, which depends on the inherent local tension. Fascia and galea should be closed with interrupted sutures placed 10–12 mm apart. Sutures used to approximate muscle should usually be tied relatively loosely; however, midline approximation of posterior cervical muscles must be moderately tight to obliterate dead space and minimize risk of CSF leakage.

Placement—Each simple interrupted suture should follow a trapezoidal path, which is counterintuitive to the novice. The course of the needle through skin should enter epidermal surface 4–6 mm from the edge of skin and pass progressively *away from* the raw surface of the incision as it traverses epidermis and superficial dermis—*not obliquely toward the raw surface of the incision*. On the opposite side of the wound, the needle should snag the undersurface of dermis, course obliquely outward, and penetrate the epidermis about 4–6 mm from the edge of the incision. When the suture is tied, the greatest tension will be applied to the deepest surrounded tissue. A suture inserted in the reverse manner applies greatest tension to the epidermis, thereby increasing the likelihood of crosshatched scaring.

Continuous (Running) Percutaneous Suture

Continuous suture technique is simple, rapid, achieves secure closure, and is the most common technique for repairing scalp with sutures. The sutures should be maintained with continuous tension to optimize uniform tension along the approximated suture line. However, a wound may appear to be closed with equal distribution of tension along the suture line, but have very unequal distribution [16]. Differences in tension along the wound can adversely impact healing and predispose to dehiscence. Tight running sutures often cause overlap of the approximated skin edges and, after normal postoperative swelling occurs, result in ischemia along the edges with potential for infection, increased scar formation, and infarction.

Continuous locking suture technique is a variation of the simpler continuous running technique in which each successive suture is passed through the surface loop before the next skin penetration. It is used to improve eversion, compared to simple running sutures, and to distribute tension equally in the loops of the running suture. As each sequential suture is inserted, there is less vulnerability for losing tension along the suture line; however, there is an increased risk of overlap of edges and tissue strangulation.

Continuous (Running) Subcuticular Suture

This technique is used in the closure of wounds in which there is minimal tension, wound edges have approximately equal thickness, and there is no underlying dead space. Tension along the edges of skin is relatively evenly distributed, and the epidermis is penetrated only at the ends of the suture line, thereby resulting in no crosshatching. A running subcuticular suture facilitates epidermal approximation and therefore a favorable cosmetic result, but does not provide reliable strength to the closure. Moderate tension at the line of closure can cause dehiscence of the wound. Some surgeons prefer reverse cutting needles when placing running subcuticular sutures.

Horizontal Mattress Suture

Interrupted horizontal mattress sutures evert the edges of skin and distribute tension along the wound edge. Horizontal mattress sutures can minimize oozing along the edges of skin and are most efficacious when there is concern for dehiscence. If tied tightly, this suture can cause strangulation and skin necrosis [26].

Continuous (running) horizontal mattress sutures tend to result in scars that are flatter than do simple running sutures, but their insertion is more time-consuming. They are often used to prevent inversion, for example in repairing some posterior cervical incisions. A disadvantage is the risk of strangulation if the sutures are tied tightly.

A c*orner suture* is a variation of the horizontal mattress suture and is used to approximate angled skin flaps or corner incisions without compromising blood supply. It is used for closure of a skin flap that has an angle of 90° or less and also wounds having an X or Y shape. The suture must be tied tightly enough to pull the corner into the desired location, but, if tied too tightly, the blood supply to the corner tissue will be compromised, healing will be slowed, and infarction may occur.

Vertical Mattress Suture

Vertical mattress sutures, when correctly used, can approximate both deep and superficial tissues with good alignment and eversion of edges, but their correct insertion is time-consuming. Therefore, this type of suture can be accomplished with a one-layer closure and often requires a two-layer closure. A vertical mattress stitch may be chosen for repairing deep wounds, to counter the tendency for inversion of the edges of thin skin, and any skin edge that tends to invert. Vertical mattress sutures can asymmetrically evert the skin edges and produce an offset in alignment. Therefore, bites should be symmetrical, especially in their depth, to prevent malalignment that will heal with an offset (shelf) along the healed surface. When used for repairing deep wounds, the sutures must be tied snugly to achieve the desired goal and, as a consequence, there is often significant scarring on the surface of skin. The tightness of the suture can be adjusted to achieve the desired amount of opposition and eversion. Vertical mattress sutures should be removed as early as thought to be safe, to limit crosshatching; however, in sites of problematic closures, sutures may be left in place for long periods of time, particularly in areas of less cosmetic concern [27].

Surgical Knots

Monofilament and braided sutures require tying which secures the appropriate approximation of tissues. Barbed sutures do not require knots. The surgical knots are the sites of greatest density of suture material and therefore the sites of greatest foreign material in a surgical wound. The tensile strength of sutures is reduced when thinned and stretched, and therefore the weakest site of a tied suture is the knot and the second weakest site is adjacent to the knot [16]. The normal inflammatory reaction to suture material is greatest at the sites of knots [27]. An extra throw in a knot adds approximately 1.5 times the volume of the knot [27]. Surgeons commonly tie knots unnecessarily tightly to prevent slippage; however, very tightly tied knots are thought to be less favorable for wound healing and strength than more loosely tied knots. Sutures in skin should be tied in a manner that achieves alignment of the edges, with avoidance of excessive tension. Animal studies have shown that wounds that are tied with loose approximation and correct alignment of tissues have greater tensile strength than tightly approximated wounds [28]. Tightly tying sutures with intent to prevent dehiscence or the leakage of CSF or serum should be avoided.

Swelling that occurs in the postoperative hours forces the edges of a wound more snugly together. Sutures that are tied tightly at time of closure will later compress tissue even more tightly, thereby slowing healing and increasing scar formation. The tightness with which skin sutures are tied affects the appearance of the scar. Skin sutures that show evidence of excessive tension or vascular compromise should be released immediately and replaced under less tension or in different locations. The plastic surgical maxim "*Approximate, do not strangulate*" summarizes the above.

Staples [29]

Closure of surgical wounds with staples has less tendency to strangulate tissue and requires less time than closure with sutures. It is not clear whether there are significant differences in cosmesis, patient satisfaction, or risk of infection. However, if not removed early, there will be persistent puncture wound sites adjacent to the scar. The intraoperative use of staples eliminates all risks of needle puncture of healthcare workers. The precise alignment of wound edges, particularly if the sides have different thicknesses, can be difficult and can result in overlapping edges. Staples should not be used in cosmetically sensitive areas, such as the face and neck.

Tissue Adhesive/Glue

Tissue adhesive—e.g., Dermabond®—can be used to close wounds that have little or no tension. This technique is commonly used for repairing short cervical and abdominal incisions made for CSF shunt surgery. Tissue adhesive should not be used to close surgical wounds having significant tension. Incisions larger than 5–10 mm will benefit from deep sutures to supplement adhesive closure. The adhesive should be prevented from flowing into the wound, lest it impair healing. Adhesives typically flake off over 7–10 days, and removal may be facilitated with a petroleum-based ointment.

Steristrips™

Steristrips™ can be used to close wounds of non-hairy skin, which are small (<5–10 cm) and have minimal wound tension. They are easily applied, have no risk of adhesive entering the wound, and are inexpensive. Also, Steristrips™ can be placed across a sutured wound to alleviate or reduce tension across the suture line during the early phase of healing. A small amount of drainage between strips does not dislodge the strips. The adhesion of strips to skin can be strengthened by applying tincture of benzoin or mastic gum adhesive on skin adjacent to the wound edges before application of Steristrips™. Benzoin (marketed under many brand names) prolongs the adherence of Steristrips™, minimizes itching, and protects the skin from allergy of the adhesive material.

Ant or Beetle Pincer Technique (Historical)

The use of the pincers of ants and beetles to close lacerations in skin has been used from antiquity and possibly still used in remote regions of South America and Asia [30].

Handling Skin During Wound Closure

Skin may be handled by grasping the *dermis* with toothed forceps. A strong attempt should be made to avoid grasping epidermis with any type of forceps. Toothed forceps require much less compressive force to grasp tissue than to toothless forceps because of their penetration of tissue. Ideally the teeth of the forceps should be used as a hook against the dermis because any amount of closing pressure causes some injury. Toothless forceps should never be used to grasp or retract skin because of the force required to prevent slippage over the relatively large area of contact.

Timing of Removal of Sutures and Staples

Rapidly absorbing sutures, for example Vicryl Rapide®, do not require removal from children or adults, but should not be used in cosmetically sensitive areas. For best cosmetic result, sutures in healthy scalp that is not under tension, across a joint whose flexion will apply tension, and whose dermal layer is securely closed can be removed in 10–14 days, but sutures in the face and neck are typically removed in 3–7 days. The breaking strength during healing of healthy skin, compared to the breaking strength of never-injured skin, is approximately 3% at one week after closure, 30% at 3 weeks, and 80% at 8 months [31]. Pre-incision breaking strength of never-injured skin is never reached.

Sutures or staples in irradiated skin should be left in place for 14–21 days. If there is concern regarding healing, every second suture can be removed to allow some release of tension without risk of dehiscence, and the remainder removed a week later. After wound dehiscence, particularly multiple dehiscences, closure is usually done with nonabsorbable sutures or staples, and these can't be left in place for 6 weeks.

Drains

Drains can assist wound healing by providing pathways for egress of serous fluid and blood that accumulates within a surgical wound. Drains reduce postoperative edema which produces tension on tissues along a site of closure, but they also add a small risk of wound infection.

Passive Drainage

Passive drainage occurs when pressure within a wound exceeds pressure required to prevent leakage through an incision. Drainage of a small amount of serous material in the few hours after wound closure is unlikely to become problematic. Persistent or increasing drainage is a cause for concern for bacteria gaining entry along the drainage path.

Wick Drains

Wick drains consist of a small strip of fabric or Cottonoid placed in a wound and extending through the incision onto the surface of the skin. They remove fluid by capillary action and delay sealing of the wound, thereby providing a pathway for egress of small volumes of fluid that would otherwise be trapped beneath the skin. A wick drain is appropriate for drainage for only 2–3 days and for no more than a few mL per day. If left in place for more than 3 days, fibrous tissue will grow into the fabric, providing a potential nidus for infection and predisposing to traumatic removal. The removal of wick drains that have become biologically embedded can require surgical debridement. Wick drains require coverage with a bandage of sufficient bulk to absorb the drainage and to prevent displacement of the drain.

Collapsible Passive Drains

Collapsible passive drains are used to maintain a pathway for short-term drainage, either around or through the tube. This type of drain, for example a Penrose drain or a rubber band or strip, is used to facilitate drainage of serous fluid and small to moderate amounts of blood from subgaleal, subcutaneous, and occasionally deeper sites. The drain is laid in the surgical wound before wound closure is completed. If the indication for passive drainage arises in the postoperative period, the drain should be inserted through a separate incision. Sutures and staples used for wound closure must not occlude the drain. Drainage occurs in response to the pressure differential between the vicinity of the buried portion of the tube and external environment.

A snug bandage can secure a collapsible drain in place or, if it is required for more than a day or two, it may be secured to skin with a loose suture to prevent displacement. Collapsible passive drains require coverage with a bandage of sufficient bulk to absorb the drainage.

Non-Collapsible Passive Drains

Non-collapsible passive drains function similarly to collapsible passive drains, but little drainage occurs around them. They must be tethered to the skin with a suture to prevent their accidental removal. These drains are not often used in neurosurgical practice.

CSF (Ventricular, Subdural, Spinal) Drains

CSF drains are passive, and flow occurs when pressure within the compartment exceeds resistance to outflow through the drain, not around it. Outflow resistance can be adjusted by positioning the drip point in the outflow chamber. Spinal drains have a path through muscle before exiting skin a few cm from midline. All CSF drains must be securely fixed to skin in at least one site close to the tube's exit from skin and another site several cm away to reduce the risk of accidental removal. Antibiotic ointment is placed around the exit site and a bandage is frequently applied but probably is not necessary [32].

Active Drainage

Active drainage is commonly used in neurosurgical practice. These drains provide a closed pathway for the egress of fluid from a subcutaneous or deeper space, allowing flow to occur in response to suction. Drainage occurs through the lumen of a non-collapsible tube, for example Jackson-Pratt drain, in response to bulb suction, while the entire system remains closed and sterile. These drains typically have multiple holes in their proximal portion. This type of drainage is useful in surgical wounds in which spontaneous flow cannot be depended upon for the removal of existing or anticipated accumulation of fluid because of insufficient pressure within the fluid compartment or due to the viscosity of the fluid. Vacuum drains should not be used in wounds in which suction may threaten the closure, for example near a microvascular anastomosis. These drains must periodically be milked to maintain flow, because the viscosity of the fluid can cause occlusion. Non-collapsible tubes of various sizes are available to drain wounds. Selection of size is based on surgeon's preference. (French gauge of these drains is three times the diameter in mm.)

Active drainage tubes that are uniformly round must be secured to skin with a suture. The Jackson-Pratt drains that are used in neurosurgical wounds have round tube extending through skin to a wider flat section lying within the wound and having multiple holes. This configuration impedes but does not prevent accidental removal. However, a health care worker can manually remove the tube with traction.

Scar

All surgical scars are collateral damage and consideration should be given to their impact on patients' quality-of-life. Scar formation is a normal and unavoidable physiologic process of healing. Surgery could not be done without the ability to form scar. However, body image and appearance are important to all people including surgeons. Patients often equate the appearance of the scar with the skill of the surgeon and attention likely given to details during surgery; other surgeons may make the same assumption for poorly closed incisions. Much scaring is determined by genetic constitution, and patients with identical incisions and closures may demonstrate a spectrum of scar formation ranging from the nearly imperceptible to keloidal and every permutation between. A well-healed scar is never as structurally strong as intact skin.

Assessing a Scar

The opinions of patients and parents of children may differ significantly from those of healthcare workers. SCAR-Q has been developed for adults and children and is a patient-reported assessment of scar appearance (size, color, contour, and visibility), symptoms (pain, tightness, and itching), and psychosocial impact (self-consciousness and happiness) [33]. *Patient and Observer Scar Assessment Scale*, which includes assessment of vascularity, pigmentation, thickness, pliability, pain, and itching, is a useful and reliable tool for evaluating linear scars [34]. Preoperative discussion of surgical scars with patients and parents of children is important.

Cosmetically Undesirable Scars

Repeat incision at the site of a cosmetically undesirable scar is an opportunity to revise or reduce the scar and thereby achieve cosmetic benefit. Scars that are interfering with normal function due to contraction of important structures, for example eyelid, nose, mouth, or neck, should be dealt with by a plastic surgeon. Not all scars need to be revised or can be easily revised, and revision of some scars may result in no significant cosmetic benefit. Most surgeries to revise a scar for cosmesis *alone* should be done by a plastic surgeon.

Factors that Influence Cosmesis of Scars

Nature of Wound

The nature of a wound, for example abrasion, laceration, surgical incision, or elective linear incision, strongly influences healing. The greater the tissue injury and disruption, whether from surgery or trauma, the poorer the resulting scar will be. Obviously scar length affects cosmetic impact.

Orientation

Wounds heal optimally and with a less conspicuous scar when they follow RSTLs. If these lines are not easily apparent, they may be easily identified by gently pinching the skin and observing the creases and ridges [1]. (See discussion above.) Incisions that do not follow relaxed skin tension lines, so called anti-tension lines, are occasionally necessary and predictably heal with more conspicuous scars. Incisions that must cross RSTLs are best camouflaged if made in a nonlinear manner. The result is a scar that will have accordion-like elasticity without a bowstring effect [35].

Location

The location of a scar has a significant effect on later visibility. Scars that cross convexities may stretch widely. Scars near concavities, such as some cervical regions and the medial canthal hollow, may contract and bowstring. Scars aligned with or parallel to RSTLs or crease lines tend to have favorable appearances. Scars that cross RSTLs have a poor esthetic prognosis. The variability of skin properties and tension (thickness or pigmentation) by anatomical location influences scaring.

Characteristics of Skin

The laxity of skin in elderly patients results in almost undetectable scars. The pigmentation of normal skin varies among individuals, ethnicity, and skin tone, affecting the appearance of a healed scar. The favorable synergism of blood supply to extensible skin in the scalp tends to produce optimal scar in patients of all ages. Skin tension decreases with age as elastin degenerates.

Surgical Technique

Surgical technique has a strong impact on healing and scar formation and therefore on cosmetic impact. Scar can be minimized by appropriate repair technique and with meticulous intraoperative and postoperative attention to detail. A scar can often be made less noticeable by beveling incisions to correspond to hair follicles; however, severely beveled cuts tend to cause bulging of the superficial side of the bevel and heal with a ridge as contraction occurs. Oblique and semicircular incisions or lacerations cause edematous bulging with a so-called *pincushion* or *biscuit* effect resulting from a combination of contraction and compromise of fluid egress from the contained area. Poor results can be the result of large, tightly tied multiple sutures, and leaving sutures in place too long. Scar that causes mobile skin to adhere to deep structures may cause concavity and depression. Likewise, wound edges that are opposed inaccurately or *stair stepped* heal poorly. Deep dermal injuries and avulsions are predictably problematic. Some straight scars contract longitudinally and produce a *bowstring*. All use of cautery on skin should be judicious and exacting to minimize damage. Failure to obtain secure hemostasis, leaving persistent oozing of the wound, and hematoma formation predispose to an undesirable scar and sometimes need for additional surgical attention.

Trauma to Surgical Wound

Repeated trauma to a wound after closure impairs healing and may result in a chronically unstable scar. The trauma of previous surgical incisions can contribute to poor healing due to decreased vascularity, venous stasis, and lymphedema.

Contamination of Wound

Contamination from retained foreign body secondary to ineffective intraoperative irrigation and debridement of skin can result in *tattooing*. This can be prevented by painstaking attention to the removal of all foreign particles, fine debridement of necrotic tissue, and extensive irrigation. Infection exacerbates scar formation, particularly if the wound must be opened to drain sequestered suppuration.

Some bacterial contamination is present in all wounds, but is more extensive in some. This is best managed with a dose of preoperative antibiotics, copious irrigation of the wound with an antibiotic solution, followed by 24 h of postoperative antibiotics. In heavily contaminated wounds, jet lavage should be used, because the pressure will dislodge foreign material better than syringe irrigation.

Surgical Management of Scar

Many patients take steps to conceal cosmetically undesirable scars in visible locations. Scars that are cosmetically undesirable should be, when possible, revised at time of a subsequent neurosurgical intervention. Excision of a wide, imbricated, or hypertrophic scar from prior craniotomy or shunt surgery will often improve wound healing and achieve cosmetic benefit. Most undesirable scars in the line of a planned new neurosurgical incision can be safely excised with an expected good result; however, not all scars need to be or can be easily and safely revised. Most cosmetically undesirable scars, regardless of location on the body, can be significantly improved by a plastic surgeon; however, it is important that patients understand that surgery to improve a scar does not erase its existence. Scars that are the only indication for surgery and scars on the face should be addressed by a plastic surgeon.

It is reasonable for a scar within the line of planned incision to be excised if it is relatively wide, imbricated, or hypertrophic. However, attempt by the neurosurgeon to improve a narrow innocuous scar in response to a patient's or family's request is likely to result in dissatisfaction. A relatively small undesirable scar in the line of planned incision can be simple to excise with an expected good result. Revision of a scar before its maturity is more likely to give a poor cosmetic result. Better results are obtained if scar revision is done when the scar is inactive, as assessed by amount of redness, induration, edema, and itching, but delay is not always possible in neurosurgical practice [36, 37].

Linear scars that correspond roughly to relaxed skin tension lines should be excised with a fusiform, not elliptical, incision. The incision should be made perpendicular to skin surface, except in hair-bearing scalp in which the plane of incision should be tilted to correspond to hair follicles. It is usually not possible to follow an RSTL. The initial cut should begin a few mm or cm from an end and course steadily toward the other end. Incision should be made approximately 2 mm from the edge of the scar. The skin should be held snugly against bone, if possible, to ensure that the incision will be perpendicular to the surface of the skin and should be made through epidermis and dermis. If incision is required through deeper tissues, this is done with another stroke of the scalpel. It is usually best to not complete the full thickness cut along one side of the planned excision before starting the incision on the opposite side. After one end of the scar is freed, the free tip of the scar can be grasped with a forceps or hemostat and gentle traction is applied. If this is not done, the contraction of intact tissue will make further incision difficult with resulting non-vertical margins. Intact tissue should be handled in an atraumatic manner with skin hooks or fine-toothed forceps and hemostasis obtained with minimal and judicious use of electrocautery.

The skin should be undermined in the subdermal plane to disconnect it from underlying tissue and to allow approximation of the fresh edges with minimal tension. Dermis is closed with 3-0 absorbable sutures (4-0 in newborns and infants). This is the layer that maintains closure during the early stages of healing, but also assists in hemostasis. The primary purpose in approximating the epidermal layer is the accurate approximation of the edges of epidermis and not to provide strength to the closure. The edges of skin are approximated with 4-0 Vicryl Rapide® or tissue adhesive. Ideally the skin edges should be slightly everted. Relatively long Steristrips™ across the wound can minimize the tension during the early stages of healing and may minimize the width of the mature scar. Liner scar that cross a RSTL—i.e., anti-tension line—is best managed by a plastic surgeon using a Z or W-plasty [1].

Imbricated Scar

Imbrication of wound edges may occur during healing of any incision, and is especially problematic when repairing a previously operated incision. Imbrication is caused by fibrosis and contraction of subcutaneous tissue following prior surgeries. Infolded skin edges should not be ignored. If the imbricated edges are simply pulled together with sutures, there will be poor abutment of vascularized tissue, which will result in slow healing, worsening of imbrication, and increased risk of infection. Mildly infolded edges can be managed with vertical mattress sutures. More severely infolded edges require that the scar and a few mm of the imbricated skin be excised. It is important to not excise all the infolded skin as this is not necessary, and the reduction in skin can make closure difficult. After the scar is resected, each edge of scalp is everted with forceps and a linear incision is made into the undersurface at five to eight mm from the wound margin, being cautious to not fenestrate the overlying skin. These incisions may be made parallel to the wound or in a radial fashion to allow the skin to lie more flatly when the deep layer is closed. After snug closure of the deeper layer, the dermal and epidermal layers are closed with vertical mattress sutures to ensure alignment of edges and prevent subsequent imbrication. Staples may be used to assist in closure and alignment. Sutures and staples should be left in place for at least 10 days and perhaps longer.

Keloid

Keloids never present primarily to a neurosurgeon, but come to attention when they develop after a neurosurgical operation. Keloids rarely occur in scalp. Treatments that have been used for keloid include intra- and extra-lesional excision, steroid administration, 5-flurouracil injection, dermal radiation, and laser. The results of treatment are unpredictable, but simple excision is consistently followed by regrowth. Keloids that are of cosmetic concern should be managed by a plastic surgeon. When a neurosurgeon must make an incision through keloid, for example for CSF shunt revision, the keloid should be excised.

Pigmented Scar

Hypopigmentation or hyperpigmentation, relative to surrounding skin, can influence the prominence of a scar and is frequently related to the Fitzpatrick skin type [38, 39]. Prolonged inflammation, infection, or sun exposure may result in permanent hyperpigmentation. Hypopigmentation is amenable to tattooing, and certain types of bleaching cream may improve hyperpigmentation.

Problematic Wound Closure

Striving for Perfection

A surgeon who is driven to achieve a perfect or near perfect wound closure may exceed safe limits, for example: ignoring signs of compromised vasculature of skin, traumatizing skin with repeated failed attempts, or repairing a wound that should not be repaired regardless of reason.

Vascular Compromise Recognized During Wound Closure

Small areas of vascular compromise may occur along suture lines because of tightly tied sutures. Sutures that are snugly tied during surgical closure often become excessively tight in the following hours due to normal swelling that occurs in incised skin. This causes vascular compromise along the edges of the wound that delays healing, increases risk of infection, and results in wider scar formation. Cyanotic skin flaps and blanched-white skin flaps are rare occurrences in neurosurgical practice. When any type of vascular compromise is recognized during wound closure, the offending sutures should be replaced.

Standing Cone (Dog-Ear, Pucker, Pleat)

A standing cone is a local redundancy of skin appearing at time of closure of a surgical incision as a protruding fold. Standing cones most often occur from a difference in spacing of galeal sutures on the opposing sides of a wound that is not recognized until the near completion of wound closure, but also occur when one side of an incision is longer than the other, for example after rotating a skin flap. This is seen often in closure of long incisions, for example in peripheral nerve surgery, spinal surgery, and closure of a myelomeningocele. When, during wound closure, it becomes apparent that a standing cone will appear, many or most of the dermal sutures should be removed and replaced with sutures that are equally spaced along each sides of the incision—i.e., *not* equally spaced along the opposing sides. In some settings, dog-ears are expected and cannot be avoided, for example in some scalp flap rotations and closures of myelomeningoceles.

Most standing cones, particularly those in infants and small children, diminish in size over a few months and never require surgical attention, especially in scalp. If a significant cosmetic issue remains, this can be addressed later. At the time of primary wound closure, dog-ears in infants and young children, even relatively large ones, should not be managed by extending the incision or resecting the puckered skin because these will flatten greatly over 1–2 years due to growth and often never requiring correction. If surgical correction is required at a later date, the final scar following delayed repair will be longer but cosmetically better. Too often an inexperienced surgeon elects to maximize the immediate cosmetic appearance of an incision by resecting a standing cone, often with an extension of the incision or excision of the triangular excess, thereby ensuring a longer scar [40–42]. A standing cone at the point of rotation of a flap should never be excised primarily due to the risk of partial or complete necrosis of the flap.

Difficult Approximation of Wound Edges

Settings in which wound closure is problematic include irradiated tissue, multiple prior surgeries, excessive resection of skin, malnutrition, and steroids usage. Very tight wound closures are at risk for dehiscence. Too few sutures in dermis will predispose to dehiscence and excessive numbers of sutures will impede healing and can result in infarction of edges of skin.

When there is difficulty in approximating wound edges, a series of sutures can be inserted 8–10 mm apart without initially tying them. The surgeon then sequentially ties each suture, as an assistant presses the edges of the wound together. It is important to not tear the dermis by repeatedly trying to close the wound without success. Each failed attempt damages tissue, increases the difficulty in achieving closure, and raises the risk of later wound dehiscence.

Wounds that Cannot Be Closed

Wounds may be left open because of structural impossibility of being closed or because of contraindications, such as wound contamination, known tenuous local blood supply, or history of repeated dehiscence. Repeated failed attempts to approximate dermis or galea, regardless of reason, can cause extensive damage to tissue and diminish the likelihood of success. After a few unsuccessful intraoperative endeavors to approximate a wound, attempts should be abandoned, and the wound managed by packing or negative pressure wound therapy and then closed by secondary intention, tertiary intention, or closure may require plastic surgical expertise with a local or regional flap, tissue expansion, or free tissue transfer.

Packing of Wound

Packing is rarely required in neurosurgical wounds, but is occasionally appropriate for wounds that cannot be closed primarily because of insufficient tissue, swelling, dehiscence, or infection. Severely infected purulent wounds of the spine may require packing. Most wounds that require packing can be managed with one or more Raytec® sponges, but large wounds can require packing with laparotomy pads, Kerlex™, or roller gauze. The packing material should fill the entire wound-space without being tightly packed. A bayonet forcep is used to gently push the packing material into contact with all surfaces of the wound, including all pockets and tunnels. The packing material should be gently put into the open wound. The packed wound is then covered with Ioban™ or Tegaderm™ to keep the packing in place and protect the site. If the packed wound is large and overlying the spine, it can be expected to require repeated replacement of packing, and therefore Montgomery straps should be applied. If more than one piece of material is packed into a wound, this should be recorded. The packing material should be replaced every 1 or 2 days until the surface of the wound appears granulated. The wound can then undergo secondary or tertiary closure.

Negative Pressure Wound Therapy (NPWT)

This technique, also called vacuum assisted closure (VAC), can be valuable for assisting the healing of large defects in scalp and dehisced wounds of the spine, particularly if tissue has been irradiated and primary closure has repeatedly failed [43]. NPWT has also been used in complex craniofacial and cervical wounds [44–46]. NPWT removes exudate, maintains a moist environment, and protects the wound from further contamination. It aids healing by reducing the size of the wound, reducing edema, and probably improving perfusion of tissue, stimulating angiogenesis, formation of granulation tissue, and wound contraction [47]. Dehisced wounds requiring NPWT require involvement, if not total care, by a plastic surgeon.

The prophylactic use of NPWT on closed clean surgical wounds has been reported to decrease the incidence of wound infection and seromas, compared to standard wound management; however, the evidence for this is weak [43, 48].

Closely Parallel Incisions

Closely parallel fresh incisions are never surgically necessary, and the resulting inadequately vascularized strip of skin will necrose. Significant vascularization rarely if ever develops across a scar during healing. Incision closely parallel to an existing scar is probably never intentionally made, but may occur accidentally when a surgeon cuts along a broadly inked line that crudely follows an old scar. The breadth of the inked line hides the scar and the new incision courses imprecisely along the old scar. Less often, a surgeon fails to accurately incise precisely within an existing scar.

Incisions Across or near Implanted Hardware

The most common incisions near or across hardware that are made by neurosurgeons are related to CSF shunts and are often necessary, but occasionally incisions must be made near other implanted hardware. When done, the postoperative risk of dehiscence of the wound with exposure of underlying hardware is significant, but these sites of incision are sometimes unavoidable; also, exposure of implanted hardware when the surgeon is unaware of the exact location of hardware.

Improper Suture Tension

Tightly tied skin sutures can delay healing, increase scarring and, in severe cases, infarct skin edges. Loosely tied sutures are less common but can also have adverse consequences, which include progressive drainage, entry of bacteria, and wound infection.

Poor Edge Alignment

Overlapping, inverted, and everted abutment of skin edges are almost always caused by lack of attention to detail. Inspection of the incision immediately following completion of closure can easily identify such problems in time for correction under anesthesia. However, some severely damaged edges of skin can be difficult or impossible to align properly. Freshening of the edges or debridement of devitalized/irregular lacerations may be required for closure, including the need for local tissue realignment to accommodate skin loss of skin.

Dehiscence [49]

Dehiscence *(Latin: gape or break open)* is the spontaneous opening of a wound along the site of closure. This usually occurs within the first 2 weeks after closure but can occur later. Causes include infection, poor surgical closure, irradiated tissue, wound hypoxia, mechanical trauma, steroid administration, and chemotherapy. Factors that increase the risk of dehiscence include age over 65, incisional edema, use of tobacco products, malnutrition, prior dehiscence, and obesity. Dehiscence may involve only skin or all deeper layers of a surgical wound. Not all dehisced wounds are infected, but a dehisced wound immediately becomes contaminated and may become infected. The Sandy grading system for dehisced wounds is based on depth of dehiscence and presence of infection and it includes three grades. The World Union of Wound Healing Societies Consensus Document adds a fourth grade [31].

Management of Dehisced Wound

Early dehisced wounds with no evidence of infection may be irrigated and undergo secure early closure. Dehiscence in which there is suspicion of infection must be irrigated and debrided to bleeding tissue. If quantitative cultures are $<10^5$ organisms per cm^3, the wound may then be closed by tertiary intention. Secondary intention healing can be extremely slow and may be accelerated by NPWT.

Whether closed immediately or by tertiary intention, the edges of the wound must be debrided to bleeding tissue. Local tissue rearrangement or flap coverage may be required at time of closure. Wide debridement increases the likelihood of healing, but is not always possible. Dehisced wounds must be closed with staples or nonabsorbable sutures that remain in place for 4–6 weeks. A dehisced wound is at substantial risk for repeat dehiscence. Repeated dehiscence of a wound may require debridement, depending on the clinical scenario, but may require NPWT (negative pressure wound therapy) or local/distal flap closure.

Components of CSF shunts exposed by dehiscence should be removed. Primary closure over newly dehisced shunt hardware is doomed to failure. Some wounds with exposed spinal rods can be managed successfully with NPWT; however, if there is a biofilm on the rods, the rods must be removed [47, 50]. Recently infected shunt sites can, after clearance of infection, be safely reused [51].

Abnormalities of Skin

Tattoo in Line of Planned Incision

Tattoos in the path of a required neurosurgical incision are occasionally encountered in adults undergoing spinal surgery or on the abdomen when undergoing CSF shunt surgery. Often these tattoos are valuable to the patient and, when possible, should be preserved [49]. Incision across a tattoo will result in a scar that will significantly alter the post-healing appearance of the tattoo. Depending on size and location of a tattoo, it is usually possible to make the required incision along its side, but it is sometimes necessary to incise across a tattoo. When repairing tattooed skin, it is important to realign the components of the tattoo as best possible. Patients, other physicians, and nurses notice postoperative malalignment [49].

Patients may request removal of tattoos while anesthetized for elective surgeries. This is an issue for plastic surgeons and, with few exceptions, should be addressed separately from neurosurgical intervention. All tattoos develop a fuzzy appearance with age, because of migration of phagocytes that have engulfed implanted pigment. Removal of a tattoo is usually achieved with lasers and black is the easiest color to remove. It is not possible to restore tattooed skin to its normal pre-tattoo appearance. The details of tattoo removal are beyond the scope of this text [52].

Irradiated Skin

Incision

Irradiated skin is always less vascular than normal skin, and narrow skin flaps are at greater risk for infarction than broad flaps. Incisions in irradiated skin should be made with a scalpel, not electrocautery, because the later will cause more injury to the edges of irradiated tissue. Also, the amount of cauterization used for hemostasis should be minimized to prevent further vascular compromise.

Repairing Irradiated Skin

Repairing irradiated skin can be difficult because of its thinness, lack of elasticity, fibrosis, and tightness, particularly over the cranium. Sutures should be placed in the dermis unless the skin is too thin to hold sutures, in which case a one-layer closure is necessary. The skin layer should be closed with nonabsorbable sutures, for example nylon or staples, and these must not be removed for 2–3 weeks, and occasionally longer.

Healing of Irradiated Skin

Healing of all irradiated tissues occurs more slowly than normal because the DNA responsible for production of wound-healing factors has been damaged. The final tensile strength is poor.

Dehiscence of Irradiated Skin

Dehiscence of irradiated wounds may occur in the absence of infection as a result of slow healing. Reclosure of an irradiated wound has a high failure rate and can result in a persistent large area of ulceration that may require a skin flap.

Skin Lesions in or near Line of Planned Incision

Surgery exclusively for excision of skin lesions should be done by a plastic surgeon. However, small lipomas or nevi, particularly on forehead, are occasionally present in patients undergoing neurosurgical procedures. If not directly in a line of incision or very nearby, nevi and lipomas should be ignored unless the patient requests and *signs consent* for excision. Some nevi and lipomas are important to a patient's self-image. If the lesion is to be excised, the incision should be designed as a fusiform extension around the lesion. An incision should not be made directly through a lipoma, or nevus. Skin over small lipomas usually has normal appearance, but the adipose tissue often involves the hypodermis. Therefore, excision affects the overlying skin, and the postoperative surface often has a concave or noticeably irregular contour.

Surgical Site Infection

Surgical site infection (SSI) occurs in 2–5% of patients who undergo inpatient surgery and account for 20% of all hospital acquired infections. Pathogens associated with surgical site infection include but are not limited to *Staphylococcus aureus*, coagulase negative *Staphylococcus*, *Enterococcus* species, and *Escherichia coli*. An increase in resistant pathogens such as methicillin-resistant *Staphylococcus aureus* and *Candida albicans* has been observed [53]. Commonly used classifications and terminologies for types of SSIs are based on depth of infection (Table 3.3) and extent of bacterial contamination (Table 3.4) [31, 55].

Factors that Influence Risk of Surgical Site Infection [57]

The CDC (Centers for Disease Control), in *Guidelines for Prevention of Surgical Site Infection*, lists the following characteristics that may influence the risk of

Table 3.3 Types of surgical site infection according to United States Centers for Disease Control and Prevention—National Healthcare Safety Network [54]

Type of SSI	Description
Superficial incisional	Infection occurs within 30 days after any operative procedure (day 1 = procedure date) or 1 year if implant is in place and involves only skin and subcutaneous tissue of the incision
Deep incisional	Infection occurs within 30–90 days after the procedure (day 1 is procedure date) and involves deep soft tissues of the incision (e.g., fascial and muscle layers)
Organ space	Infection occurs within 30–90 days after the procedure (day 1 is procedure date) and infection involves any part of the body deeper than the fascia/muscle layers, which was opened or manipulated during the operative procedure

Table 3.4 CDC classification of surgical wounds with respect to bacterial contamination [54–56]

Class I *Clean*—An elective operative wound in which there is no infection or apparent inflammation and neither the respiratory, alimentary, genitourinary tract, nor oropharyngeal cavity is entered. These wounds are closed primarily or drained with closed drainage systems when required. Most neurosurgical wounds are in this category
Class II *Clean-Contaminated*—An operative wound in which the respiratory, alimentary, genital, or urinary tract is entered under controlled conditions and without unusual contamination, provided there is no evidence of preexisting infection or major break in surgical technique. Neurosurgical wounds include entry into nasopharynx and frontal sinus
Class III *Contaminated*—Open, fresh, accidental wounds, and operations with major breaks in sterile technique or gross spillage from gastrointestinal tract and incisions in which acute non-purulent inflammation is encountered. Neurosurgical wounds include many surgeries for trauma and puncture of abdominal viscus in shunt surgery
Class IV *Dirty-Infected*—Old or traumatic wounds with clinical infection and containing devitalized tissue and those that involve existing clinical infection or perforated viscera (internal organs or gut). Organisms causing postoperative infection are considered to have been present in the operative field before the operation

surgical site infection: patient age, nutritional status, diabetes, smoking, obesity, coexistent infections at a remote body site, colonization with microorganisms, altered immune response, length of preoperative stay and operation, duration of surgical scrub, skin antisepsis, preoperative shaving, preoperative skin prep, duration of operation, break in surgical technique, antimicrobial prophylaxis, operating room ventilation, inadequate sterilization of instruments, foreign material in the surgical site, surgical drains, surgical technique, poor hemostasis, failure to obliterate dead space, and tissue trauma [53].

The SSI rate in a study of prospectively collected data on 12,021 patients who underwent surgery for intracranial neoplasia was 2.04%, with infection being significantly associated with the following: increased rate of return to the operating, postoperative stay greater than 30 days, operative times greater than 4 hours, and recent chemotherapy [58]. In another report, risk factors for infection in neurosurgical cases included surgical drain, number of previous operations, implantation of foreign material, and ASA (American Society of Anesthesiologists) Score [59].

Length of Preoperative Hospitalization

Prolonged preoperative hospitalization is a risk factor for surgical site infection which is strongly related to diagnosis, preoperative diagnostic testing or therapy, and acquisition of nosocomial organisms [53].

Nares Colonization

The nares of 20–30% of healthy people, including healthcare workers, are colonized by *Staphylococcus aureus* as found on preoperative surveillance cultures in asymptomatic patients [60]. Topical application of mupirocin ointment for approximately 5 days is effective in eradicating *Staphylococcus aureus* from the nares of both healthcare workers and colonized patients. There is some evidence that, regardless of carrier status, preoperative prophylactic application of mupirocin to the nares results in a decreased rate of surgical site infection; however, this practice is thought to have rapidly increased the level of resistance to mupirocin and to other antibiotics [61, 62]. Topical single application of povidone iodine (3M Skin and Nasal Antiseptic) 2 h before surgery has very broad-spectrum antibacterial activity, minimal risk of development of resistance, does not require patient compliance, and is inexpensive [63].

Traffic in Operating Room

There is evidence that the number of individuals in an operating room and the traffic (number of door openings) are directly correlated with the number of airborne particles in an operating room [64, 65]; however, the evidence for a relationship to surgical site infection is weak [66–68]. Nevertheless, most surgeons and infection disease specialists agree that the number of individuals in an operating room and the number of door openings should be limited during surgical procedures [65, 67].

Removal of Hair

The following is a Category IA recommendation in the *CDC Guideline for Prevention of Surgical Site Infection*, "Do not remove hair preoperatively unless the hair at or around the incision site will interfere with the operation." [53]

Hypothermia

Thermoregulation is greatly impaired by general anesthesia, often causing hypothermia of 1–2 °C during surgery. This is caused by diminished heat production and by hypothermia-induced vasoconstriction that reduces perfusion of skin. Perioperative hypothermia is associated with surgical site infection, coagulopathy, and prolonged recovery from anesthesia [69–71]. The standard-of-care is to strive for normothermia during general anesthesia.

Glycemic Control

Preoperative hemoglobin A_{lc} levels of less than 7% (approximate glucose concentration 152 mg/dL) are associated with lower postsurgical infection [72, 73]. Glucose target levels should be below 200 mg/dL [57]. This is particularly important in patients with diabetes.

Hemostasis

Failure to achieve secure hemostasis results in a high likelihood of postoperative hematoma or oozing from the wound. Intraoperative hemostasis that seems satisfactory in the presence of significant systemic hypotension is not reliable.

Perioperative Transfusion

Perioperative transfusion of leucocyte-containing blood has been reported to be a risk factor for postoperative infections including surgical site infection, but this remains controversial [74]. The evidence is not of sufficient strength to withhold blood products.

Irrigation of Wound

All wounds have some bacterial contamination and all should be frequently irrigated during surgery with saline, preferably containing an antibiotic, and very extensively irrigated while repairing the wound. Irrigation flushes unattached surface bacteria from the wound and hence the surgical maxim, "The solution to pollution is dilution." It is preferable, if not using jet lavage, to use an 18 or 20-gauge needle attached to a 10 mL syringe, which produces approximately 15-pound pressure, more efficiently removing contaminants than is accomplished by Asepto syringe irrigation.

Tissue Damage

Damaged tissue, particularly dead tissue, is an excellent culture medium. The greater the extent of tissue damage, the greater the risk of infection. Grasping soft tissue with Kocher forceps or needle holders crushes tissue and should be done only in emergent settings. Prolonged cauterization kills an unnecessary amount of tissue and should be avoided. Tight compression of muscle for extended periods with a self-restraining retractor can damage the muscle. Excessive tissue damage will result in increased scarring.

Antimicrobial Prophylaxis

Systemic Prophylaxis [75]

Surgical antimicrobial prophylaxis refers to a short course of a bactericidal antibiotic delivered shortly before the start of an operation to reduce the risk of postoperative infection resulting from intraoperative microbial contamination or when operating through highly colonized anatomical areas despite adequate prep (axilla, groin, and oral cavity). The prophylactic effect is thought to be due to the presence of antibiotics in blood at time of surgery becoming trapped in the fibrin clot [76]. The CDC recommends surgical antimicrobial prophylaxis for "all operations or classes of operations in which its use has been shown to reduce surgical site infection rates based on evidence from clinical trials or for those operations after which incisional or organ/space surgical site infection would represent a catastrophe."

The timing of administration of antibiotics is important, with administration immediately before and during surgery being optimal [69]. This is thought to allow the development of a bactericidal concentration of the drug in serum and most tissues by the time the skin is incised [77]. The Center for Disease Control (CDC) recommends that the administration of antibiotics for prophylaxis begins one hour prior to incision (2 h for vancomycin and fluoroquinolones) [69]. This recommendation applies only to clean wounds and clean-contaminated wounds and not to contaminated or dirty wounds, most of which are receiving antibiotics before surgery.

Antibiotic microbial prophylaxis is indicated for most if not all neurosurgical operations, particularly those in which synthetic material is to be permanently implanted, for example CSF shunts, cranioplasty with synthetic materials and deep brain stimulating electrodes, and for operations in which materials are temporarily implanted (e.g., subdural recording grids and depth recording electrodes).

Cephalosporins that are effective against many gram-positive and gram-negative microorganisms are the most commonly used antibiotic agents used for prophylaxis by neurosurgeons. Intravenous clindamycin and vancomycin are alternative choices for patients who have allergy to penicillin. Cefazolin is commonly the antibiotic of choice for clean (Class 1) operations and provides satisfactory coverage for many clean-contaminated operations. Alternatives for patients with known or suspected allergy to penicillin or if there is concern for MRSA colonization include clindamycin and vancomycin. A single dose of cefazolin is the most widely used antibiotic by neurosurgeons for systemic prophylaxis; however, vancomycin is most commonly used in surgeries involving CSF shunts.

The concentration in tissue of an antibiotic at various times after start of infusion is variable. For example, cephalosporins have time-dependent duration of action of

3–4 h. Many factors influence the time interval between the start of infusion and the surgical incision, including but not limited to the unpredictability of time of incision, time required for induction of anesthesia, surgical preparation, difficulty in achieving venous access, particularly in young children, uncooperative adults, and urgency for surgery. The chosen prophylactic antibiotic needs to be repeated every 3–4 h during surgery to assure therapeutic levels in both serum and tissues throughout the operation and for a few hours after completion of surgery. A therapeutic dose of cefazolin (1–2 g) is typically given to adult patients not more than 30 min before skin incision [77]. Larger doses are necessary to achieve optimum effect in very obese patients [78]. If a patient is allergic to cephalosporins, it is reasonable to consult an expert in infectious disease for gram-negative coverage. The routine use of vancomycin is not the best choice for prophylaxis unless the presence of methicillin-resistant coagulase-negative Staphylococci has been proven. However, many pediatric neurosurgeons prefer vancomycin for prophylaxis in patients undergoing any type of CSF shunt surgery. Antibiotics administered before, during, or after an operation in patients with a contaminated or dirty wound are therapeutic, not prophylactic. Antibiotics continued beyond 24 h after completion of surgery have no convincing effectiveness for preventing wound infection in clean wounds.

Irrigation with Antibiotic Solution

Most neurosurgeons irrigate surgical wounds with saline in which an antibiotic is dissolved, and the most commonly used antibiotic is bacitracin (50,000 u/L). The presence of definite or suspected allergies and the sensitivity of known or identified bacteria should influence the choice of antimicrobial agent. There is no convincing evidence that irrigating class I wounds with antimicrobial solutions results in lower incidence of SSI, although most neurosurgeons, including the author, do so.

Topical Antimicrobial Prophylaxis

The most effective protection in the early hours after wound closure is provided by covering of the wound with an ointment; an antibiotic-containing ointment is applied to almost all neurosurgical wounds. This protects the wound from bacteria of the nearby microenvironment that include resident bacteria of skin and the surrounding biosphere. The oily properties of the ointment adhere to skin and provide a physical barrier, and a moist environment promotes healing and may improve scaring. These protective effects of an antibiotic-containing ointment are likely more important than the antibiotic component of the ointment. The application of topical antibiotics is not among the recommendations of the CDC for prevention of surgical site infection [61]. There is no conclusive (Class I or Class II) evidence supporting topical antibiotic prophylaxis in neurosurgical procedures [79].

Management of Surgical Site Infection

Most wound infections can be managed outside of an operating room; however, purulent wounds with deep extension and superficial wounds requiring extensive exploration, debridement, and irrigation are best managed in an operating room. Operating rooms have excellent lighting, surgical instruments, materials for packing and bandaging, drains, and skilled nursing assistance that are not available on hospital wards or in outpatient settings.

Infected wounds must be opened widely with removal of all sutures. The full depth and lateral extensions of the wound should be explored and copiously irrigated with antibiotics. Missing even a small purulent site can be expected to likely result in continuation of active infection and another trip to the operating room. Although living tissue must be treated with gentleness, infected wound surfaces always require debridement. All loose or ragged tissue should be removed. Vascularized bone surfaces must be scrubbed firmly. Avascular bone flaps and bone fragments must be removed and, contrary to traditional practice, can be scrubbed vigorously and returned to their anatomical sites, followed by a course intravenous antibiotics. Traditional practice requires permanent removal of all contaminated bone fragments.

Almost all infected neurosurgical wounds involving the head or face are managed by exploration, debridement, and copious irrigation with antibiotic-containing solution, occasional insertion of drains, followed by primary closure and a course of intravenous antibiotics. Open packing followed by secondary or tertiary intention closure is very uncommon and used only for severely infected wounds. Wound infections following spinal surgery are managed the same way, but severely infected wounds and purulent wounds that require repeat exploration may require open packing or vacuum-assisted (VAC / NPWT) closure followed by secondary or tertiary closure, particularly if the site has received radiation therapy. (See above discussion of packing of *Wounds that cannot be closed*.) Wounds requiring this type of wound management require involvement, if not total care, by a plastic surgeon.

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4 Surgery of Scalp and Face

Lawrence L. Ketch and Ken Rose Winston

Scalp

Planning Incisions

Opinions on the location, shape, and size of incisions in scalp required for a given intracranial intervention vary among neurosurgeons. The cosmetic impact of scars should be considered, and certainly large scars are more undesirable than small ones. Incisions that follow **RSTL**s (**R**elaxed **S**kin **T**ension **L**ine) produce the best results in bald scalp, but, in hair-bearing scalp these lines are difficult or impossible to identify, and their identification is less important than in non-hair bearing sites (see diagram in Chap. 2).

Decisions on location of incisions in scalp must also take into consideration implanted foreign materials, such as CSF shunts. cranioplasty materials, and possible future surgeries. Scalp incisions should, when reasonably possible, skirt implanted materials. It is best that a new incision intersects an existing scar at a near-right angle and not course alongside a scar or an implanted object. This reduces the risks of injuring implanted material and later wound dehiscence.

Incisions in Hair-Bearing Scalp

Short hair and thin hair, when dried, do not significantly interfere with marking on the scalp. It is acceptable to use K-Y™ jelly, rubber bands, or hemostats to secure

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the hair away from the incision line, but K-Y jelly can blur the ink line. Long hair is easy to deal with and very short hair can be ignored when marking. Hair of medium or long length can be parted with a comb or hemostat and tufts of hair can be secured with rubber bands or hemostats to expose the planned line of incision, which should then be marked with ink. Scalp covered with dense hair of 3–4 cm length, particularly if curly or dark in color, can be difficult to mark, but it is usually possible to make a series of ink dots on scalp to guide the incision. If impossible to mark with ink, some surgeons choose to clip a narrow band of hair along the planned incision line and other surgeons forego identifying a definite line of incision and simply cut through hair and scalp with a scalpel. All incisions in unshaven scalp will cut some hairs, which can be then easily plucked from the wound.

Technique for Incising Scalp

Initial Penetration of Scalp

Initial penetration of scalp overlying temporalis muscle should be made, except in emergent cases, cautiously and usually with several short strokes of the scalpel, until temporalis fascia is encountered. Some surgeons, cognizant of the depth to temporalis fascia, extend the incision freehand along the ink mark on the scalp in a manner that avoids injury to fascia. Other surgeons insert a broad instrument, for example a periosteal elevator, between galea and temporalis fascia and, using that instrument to protect temporalis fascia and muscle, continue the full-thickness incision along the ink mark on the scalp. A Doppler can be helpful in identifying arteries, for example superficial temporal artery, to assure inclusion within the base of a flap and to protect the artery for possible usefulness in a future surgery.

The initial penetration of scalp overlying bone should be made with a slow firm insertion of the blade through the full thickness until bone is encountered. The blade should be tilted to correspond to the perceived orientation of hair follicles and moved along the inked line on the scalp. The length of the initial stroke should be limited by the amount of bleeding. After satisfactory hemostasis is obtained, not necessarily perfect at this time, the incision is extended. This process is repeated stepwise until the planned incision is completed. Alternatively, the surgeon may use the scalpel to cut into the dermis and use the cutting option of the electrocautery to complete the full-thickness incision of scalp.

Beveled Incision

The hair follicles in scalp are often not perpendicular to the surface, and therefore not all incisions in-hair-bearing scalp should be made perpendicular to the surface. A perpendicular incision will destroy more hair follicles than necessary and thereby increase the width alopecia along the hairless scar. A beveled incision that courses parallel to the hair follicles destroys fewer hair follicles, and some injured follicles will likely generate new hairs through the overlying scar and contribute to the limitation of scar alopecia [1]. A beveled incision requires only a few seconds of forethought and no significant increase in expenditure of surgical time or energy.

There are many ethnic variations in patterns of hair growth over the scalp, and therefore no generalization can be made for a consistently correct angle of incision which will minimize injury to hair follicles. Often the optimal angle of incision in scalp needs to change along the course of a long or curved incision. The angulation of hair follicles strongly influences—probably dictates—the *fall line* of hair of most scalps. It may be impossible to identify a fall line in scalp with curly hair and people who have hair follicles that are predominantly perpendicular to the surface. Observation of a fall-line, when apparent, assists the surgeon in recognizing the orientation of the parent hair follicles.

Consequences of Ignoring Fall Line of Hair

Ignoring the fall line when making an incision in hair-bearing scalp often results in hair that parts along the scar, attracting attention to its location. Wide scars, whether from injury to hair follicles at time of incision, excess tension at closure, or poor healing, are associated with an increased amount of cicatricial alopecia. Wide scars in scalp are less thick than adjacent scalp, and this can impart a step-off, which will be cosmetically unacceptable for the patient and will be more vulnerable to sun exposure.

Corner Incisions

Sharp cornered, for example right-angle, incisions should be made by starting at the apex and making a full thickness cut for several mm away from the apex. The second limb of a corner incision should be made by again starting at the apex and cutting away from the apex.

Curved corners with short radii of curvature are made with a continuous incision. However, the superficial layer of the scalp tends to contract more toward the concave side of incision, as deeper layers are cut, often resulting in an incision that can be difficult to close. Cognizance of this phenomenon allows the surgeon to alter the angle of incision through scalp by tilting the cutting instrument toward the convex side.

Hemostasis

Secure hemostasis should be established with bipolar electrocautery applied to identifiable bleeding sites. This often obviates the need for skin clips, but may minimally increase operative time. The practice of applying monopolar electrocautery in a continuous line along the dermis for prophylaxis against bleeding or to control ooze—sometimes designated as "cauterization to whom it may concern"—should never be done, except possibly in the presence of severe coagulopathy, because this action produces thermal injury to hair follicles, and may cause small amounts of necrosis along the side of the incision, and increase in the width of scar and of alopecia. This manerver may obviate the need for Raney clips but rarely shortens the operative time.

Some surgeons, while incising with a scalpel, have a surgical assistant apply firm digital pressure—four fingers on each side of the incision—to reduce blood loss as the incision is being made. Also, an index finger hooked into each side of an incision to stretch open the incision can be effective in limiting blood loss, but this is esthetically displeasing to some surgeons.

Skin Clips for Hemostasis

Raney clips grip the full thickness of scalp and are effective in establishing hemostasis along fresh edges of incised scalp. These spring clips are available in three sizes (light, medium, and heavy) having different closing strengths, with either straight or serrated edges. The heavy (large) clips can significantly damage or infarct the scalp edges of infants and young children. For all size Raney clips, the longer they remain gripped to scalp, the greater the width of scar and peri-incisional alopecia (<3 h 4.1 mm vs >3 h 5.2 mm), independent of technique of incision [2]. Steel Raney clips (perhaps no longer available) can cause infarction along the edges of scalp and should not be used.

Michel clips are stainless + steel disposable clips which are effective in achieving hemostasis along scalp edges and are relatively inexpensive. They are available in several sizes, easy to apply, and are useful in the thin scalp of young children because of the surgeon's control of closing pressure. These are occasionally unable to adequately grip thick scalp, and their small size may increase the risk of being left in a surgical wound.

Minimizing Width of Scar and Para-Incisional Alopecia

The noticeability of a scar in hair-bearing scalp is determined by its location, its dimensions (particularly width), and the width of peri-incisional alopecia. Wide scars in scalp are less thick than adjacent scalp, and this can impart a 'step-off' that will be cosmetically unacceptable. Incisions in scalp, whether made with cold steel scalpel, electrocautery, or Colorado microdissection needle, heal well, but there is disagreement as on scar widths. The mean width of alopecia along bicoronal scalp incisions made with scalpel is reported by Kadakia et al. to be 2.8 mm without use of Raney clips and 3.5 with Raney clips, compared to incisions made with microsurgical Colorado needle of 4.9 and 5.9 mm respectively [3]. Scars and alopecia are wider when Raney clips are left in place for 3 h or longer. Electrocautery is associated with shorter incision time, less postoperative pain, and less blood loss, but equivalent cosmesis. The scar from a scalpel incision is reported to result in wider para-incisional alopecia than that of electrocautery with microdissection needle [2, 4].

The destruction of hair follicles at time of incision, regardless of cause, increases the scar's noticeability and cosmetic undesirability, particularly when hair is wet, and lessens protection from UV light from sun exposure. According to Kdalia et al., the width of para-incisional alopecia in coronal scars following scalp incision with cold steel was 0–4 mm without Raney clips and 1–5 mm with Raney clips. When the same measurements for incisions are made with the Colorado monopolar cautery for both skin and subcutaneous tissue, the para-incisional alopecia was 4.9 mm and 5.9 mm respectively [2].

Para-incisional alopecia is not present at time of closure of a scalp incision, but becomes apparent as the width of alopecia increases during healing. After healing, hair tends to part along a scar, thus making its presence more obvious, and the wider the alopecia, the greater its noticeability.

Surgical incisions which course parallel to the axes of hair follicles minimize damage to hair follicles. The orientation of hair follicles is different in each person's scalp and varies widely among individuals and ethnic groups. Hair follicles can be destroyed or damaged by the cutting instrument (knife or cautery needle), heat from cauterization for hemostasis, and possibly by scar formation during normal healing. Therefore, the angle of incision in scalp, with respect to its surface, influences the extent of destruction of hair follicles and hence the width of postoperative cicatricial para-incisional alopecia. Because of the variations in patterns of hair follicles over the scalp, the tilt of the incising instrument must be beveled to minimize injury to hair follicles and the bevel must change along the course of both straight and curved incisions.

The fall line of hair reflects the orientation of hair follicles in the scalp. It is difficult or impossible to identify the fall line in a shaved scalp. Identification of the fall-line assists the surgeon in recognizing the orientation of the hair follicles. Ignoring the fall line often results in an unnecessarily wide strip of alopecia. The cosmetically best incision in hair-bearing scalp courses parallel to the angle of hair follicles and perpendicular to the fall line of hair.

Common Scalp Incisions

Straight and cruciate incisions centered over the surgical target were the standards for intracranial surgery until Victor Horsley, the father of modern neurosurgery, popularized curved incisions in the late nineteenth century.

Straight Incision

A straight incision can be safely made in any location and orientation over hair-bearing scalp; however, direction, location, and length affect cosmesis. Incisions that lie in the fall-line of hair are less cosmetically acceptable. Straight incisions in the midline of the scalp and long straight incisions tend to be cosmetically undesirable. It is almost always possible to achieve the same exposure with a curved incision that avoids the fall-line of hair and results in a cosmetically better scar. Exceptions include bald scalps, scalps with very thin hair distribution, and individuals who choose to have their hair cut short or shaved. Most patients take steps to conceal undesirable scars in their scalps.

Cruciate incisions in scalp are still in use, often provide good exposure, and their scars can be used cosmetically acceptable if none of the incision lies in the fall line of hair. However, these incisions can present problems in approximating the apices of the four flaps, which usually meet directly over the surgical target.

Curved Incision

Special attention is required while making a curved incision, particularly one with a short radius of curvature—e.g., curved corner. (See Corner Incisions above.) Mobile scalp, particularly in young children, is often distorted by the force applied to the cutting instrument thereby and this can altering the intended course of an incision while marking with ink. This can be prevented by being cognizant of the phenomenon and adjusting the direction of both marking pen and scalpel.

Sigmoid (S-Shaped) Incision

A sigmoid incision can provide the same exposure as a straight or slightly curved incision but with a less noticeable but longer scar. The axis of the incision (tip to tip) can be in any direction. The center of the sigma should cross the approximate center of the surgical target. Closure of a sigmoid incision is straightforward and easy. The cosmetic result tends to be much better than that of a straight or slightly curved incision because much of the scar will not correspond to the fall-line of scalp hair.

U-Shaped (Horseshoe) Incision

The U-shaped incision may have either a curved or flat top. Both have parallel or near parallel straight sides. The horizontal component of the incision may be curved or flat-toped. An incision with a curved top is most appropriate for trephinations. A flat-top incision is used for most craniotomies. It has a straight upper side, two curved corners, and is rectangular in shape, unlike the shape of a horseshoe. A rectangular shape provides more efficient exposure for a rectangular craniotomy. The hinged side of the U-shaped incision should be away from the cranial vertex to allow downward reflection of the flap with preservation of vascular supply and innervation (see exception below). However, the vasculature of the scalp with its extensive anastomotic connections makes most horseshoe incisions safe with respect to blood supply, regardless of direction of reflection. Infarction of the distal portion of the flap often occurs if the flap is very narrow. As a rule of thumb, the height of a U-shaped flap should not exceed twice the width of its base, but it can be longer if an artery can be clearly identified (best done with Doppler) within the flap.

U-shaped scars in hair-bearing scalp can be cosmetically undesirable, and many patients take steps to conceal them. Very often the vertical arms of a horseshoe incision lie in the fall line of scalp hair and the resulting scars are apparent, particularly in patients with very thin or closely cut hair. If these vertical arms are angled by approximately 20° from the fall line of hair, the scars tend to be less apparent.

Intentionally Denervating Scalp Incision

This incision allows painless punctures of a Rickham or Omaya reservoir in patients who require repeated sampling of CSF or injection of drugs. The flap has a U-shape with its base near the frontal midline. It can be used in patients of any age, but is most commonly used in young children. The extensive anastomotic vascular network of scalp supplies the flap, but the width of the flap at the base should be at least as wide as its height and must have no edge overlying an implanted reservoir.

Straight Coronal (Bucket Handle) Incision

This is a common incision in scalp used by neurosurgeons. It passes across the vertex of the head to a point near the insertion of the pinna or continues along a preauricular or postauricular course. A preauricular incision may extend to a point just above the zygomatic arch or lower. This incision allows sufficient forward reflection of scalp to accommodate many vertex, parietal, frontal, and craniofacial exposures. It is commonly used for bifrontal approaches to the anterior cranial fossa and for cranial decompressions. Although not commonly so used, the posterior scalp flap can be reflected below the external occipital protuberance for bilateral parieto-occipital exposures and, in infants, exposure down to the foramen magnum. As the straight coronal incision came into common use approximately 80 years ago, the straight vertical and oblique incisions became less common.

A straight coronal incision over the mid-vertex results in a scar that corresponds in most patients to the fall-line of the hair and therefore the scar commonly remains permanently apparent and undesirable. It is least noticeable in the few days following wound closure, but becomes more noticeable because of the para-incisional alopecia that develops during healing. A coronal scar is most noticeable when the hair is wet. A posteriorly positioned coronal incision may be less likely to correspond to the fall line of hair [5], and also a receding hairline will unlikely expose the scar and will be less noticeable in bald scalps. Also, a far posteriorly positioned coronal incision is unlikely to cross an implanted CSF shunt [5]. Many patients may take steps to camouflage the scar for the remainder of their lives. These steps include special hair styles, wearing a hairpiece, head scarf, or hat.

Zigzag (Sawtooth, Stealth) or Wavy Coronal Incision

A zigzag coronal incision follows a coronal course in scalp down to a few mm above the pinna. The incision producing the least noticeable coronal scar follows a zigzag path over the vertex and sides of the head, resulting in 7–12 interdigitating triangular teeth of scalp [6, 7]. The preauricular course should be straight and always in non-hair bearing scalp. A postauricular extension can be either straight or curved. Each triangle or small flap should be 2–2.5 cm in depth. The zigzag incision provides better camouflage than a wavy sinusoidal; however, some surgeons prefer the sinusoidal incision over the zigzag, perhaps because it requires a little less time [8]. (See “Preauricular and Postauricular Extensions of Scalp Incisions” below.)

For both zigzag and wavy sinusoidal incisions, there is a tendency to make too few triangular or curved flaps and to make them too shallow. The result is a scar that is minimally better than a straight coronal scar but less well-camouflaged. However, the cosmetic result of a wavy sinusoidal incision approaches that of a zigzag incision, if it has the same number of flaps of similar depth. Both zigzag and wavy sinusoidal incisions have the advantage of not following the fall-line of hair.

Eroteme (Question Mark) Incision

The eroteme (*Latin: to ask*) incision is most commonly used for approaches to the middle fossa and low lateral frontal fossa. The lower end of the incision is just above or directly over the posterior part of the zygomatic arch, courses upward in proximity to the tragus, and then anteriorly to a few mm above the insertion of the pinna. The first few mm of the incision above the zygoma should be tilted forward by 30–45° to avoid the superficial temporal artery. The incision then arcs posteriorly above the pinna for 1–3 cm and then upward and anteriorly toward the hairline of the ipsilateral forehead. It is important to avoid injury to the nerve to frontalis muscle (see discussion below) and to avoid disrupting the superficial temporal artery. A Doppler can be helpful in identifying and confirming the present location of this artery.

Preauricular and Postauricular Extensions of Scalp Incisions

A coronal incision can be extended downward along a preauricular or postauricular course. A preauricular extension of either a frontotemporal or coronal incision should pass anterior to the edge of the ear cartilage and ideally pass inside the tragus (rarely done by neurosurgeons). If it is to approach the zygoma, its terminal 5–7 mm should angle 30–45° anteriorly and should be made cautiously and not incising full thickness in one stroke. This lessens the risk of injury to the superficial temporal artery. More anteriorly positioned incisions extending to the upper edge of the zygoma risk severing the nerve to frontalis muscle.

Preauricular extension onto or below zygomatic arch by as much as 1.5 cm is required in some variations of frontotemporal approaches, craniofacial surgeries, and operations for resection of tumors. The superficial temporal artery should be protected.

The postauricular extension may result in a less noticeable scar than a preauricular extension, but does not allow exposure of the zygoma or low exposure in the middle fossa. It can be extended downward onto the mastoid process, if necessary, course arcs behind the ear in hair-bearing scalp.

Pretrichial Forehead Incision

This incision is a curved incision that follows the hairline across the forehead. It is made a few mm anterior to the hairline in normal scalp; however, some surgeons shave about 2 cm of scalp and make the incision in hair-baring scalp a few mm behind the hairline. A pretrichial incision placed slightly behind the line of demarcation is less noticeable than an incision placed precisely along the line.

Approximately two thirds of men develop a receding hairline, starting at about 18 years of age and progressing with increasing age. Pretrichial incisions may remain adequately concealed in children and young men, but often become noticeable and undesirable after a few decades. Its scar remains moderately well concealed in men who never develop a receding hair line or male pattern baldness. The scar becomes apparent in women when their hair is pulled tightly backward.

Incisions in Bald Scalp

Baldness does not affect wound healing; however, a surgical scar in a bald scalp can present cosmetic issues. A coronal incision that arcs very far posteriorly, ideally into hair-bearing scalp, results in a scar that is less apparent than a scar across the bald frontal or parietal scalp.

An incision for bald scalp preferred by plastic surgeons passes along the line where, at a younger age, normal hair-bearing scalp once met normal hairless forehead scalp—i.e., a pretrichial type incision without the presence of hair. This line can usually be identified by the change in texture of scalp and often a slight difference in pigmentation. A pretrichial incision misnomer in bald scalp, if placed precisely in the line of demarcation between the hairless forehead and the slightly different scalp, that in younger adult life had been hair-bearing, has been used, with the resulting scar that is less noticeable than a more posterior scar across bald scalp.

Incisions in Forehead Scalp

Elective incisions in forehead should not be made but, if necessary, should be made in the existing horizontal creases. Closure is done in the standard two-layer technique. Optimum cosmesis is achieved with a subcuticular pull-out suture.

Incisions in Scalp of Children

The scalp of young children is quite mobile and usually needs to be manually immobilized if an incision of more than about 2 cm is to be made. This not only assists in cutting along a marked line, but also prevents accidently cutting through dura if the mobile scalp becomes shifted over a fontanelle or open suture. Newborns and infants have open sutures and fontanelles, and some have bony lacunae, most commonly in parietal bones, A scalpel pressed against bone as scalp is being incised may cut through dura and even into brain. This risk can be minimized by palpating scalp along the marked line for areas of danger and by inserting an instrument beneath the scalp and keeping the scalpel in firm contact with the cutting instrument as the incision is made.

Incisions near or over Implanted Hardware (Including Silastic™)

The most common scalp incisions that must cross or lie near implanted hardware are related to CSF shunts, but are occasionally across the implanted hardware. The postoperative risk of dehiscence of the closed wound with exposure of hardware is considerable. Occasionally shunt hardware is damaged if the surgeon is unaware of its existence or exact site of Silastic™ tubes. Also, incision over or near implanted hardware has risk of wound dehiscence and exposure of hardware. Also, wound healing may be impaired because of scarring and devascularization from multiple surgeries, for example shunt revisions in that vicinity.

These sites for incision should be avoided when reasonably possible, but are occasionally unavoidable. An incision for craniotomy or cranial vault expansion may be required, thus necessitating an incision across a CSF shunt, the valve, or a portion of tubing . It is usually possible to incorporate a portion of an existing scar into the new incision. If this is not practical choice, the surgeon should consider planning an incision that crosses the shunt in a near perpendicular orientation. In extreme cases, the shunt may have to be relocated.

An incision across a cranioplasty plate is relatively safe, but an incision across an implanted cable, for example one in use for deep brain stimulation or the monitoring or treatment of epilepsy, has significant risk of damaging the implant. An incision into a CSF valve or tubing necessitates immediate repair, and a severed cable requires replacement. Cables are small and often not identifiable by palpation. Meticulous attention must be given to their identification and protection. These complications occur most commonly when the surgeon is unaware of the presence or location of hardware.

Emergent Scalp Incisions

Emergent neurosurgical operations occur in a spectrum of clinical settings, ranging from those that allow a small amount of time for planning to those done while CPR is in progress. The presence of one or more lacerations may strongly influence the location and design of an emergent incision. There is always time to plan a surgical incision, but this may be limited to a minute or less. The existence of an emergency is never a satisfactory explanation for cutting and then thinking.

Festina Lente (Latin: Make Haste Slowly)

Hastily made incisions are often far from ideal and *never* reflect surgical thoughtfulness or, competence, even in emergent settings. All scalp incisions in emergent settings should be made in a thoughtful, efficient, and deliberate manner, preferably while an assistant is attending to hemostasis. Manual pressure of scalp against skull can greatly limit blood loss until clips can be applied. It may be necessary to tolerate more blood loss than would be acceptable in an elective operation; however, actively bleeding vessels in scalp and often temporalis muscle, if ignored, can result in unacceptable—even critical—loss of blood and therefore must be controlled.

Protection of Important Structures

Frontotemporal Branch of Facial Nerve [9–15]

The temporal branch of the facial nerve innervates the frontalis muscle, corrugator supercilii, and upper half of the orbicularis oculi muscles. Paralysis of these three muscles causes significant facial deformity. The nerve to frontalis muscle is often in two or three branches as it passes over the zygoma at approximately 1.5 cm from the posterior end of the arch.

The temporal branch of the facial nerve must be reflected with the scalp flap. It is important to *not* use unipolar or bipolar electrocautery near the expected course of the nerve to frontalis muscle on the undersurface of a reflected frontotemporal scalp flap. *Pitanguy's line*, which extends from 5 mm below the tragus to a point 1.5 cm above and lateral to the lateral tail of the eyebrow, roughly indicates the course of the nerve. Incisions in scalp that extend down to or across the zygoma should not be made anterior to one cm from the posterior end of the zygomatic arch.

There are three techniques for avoiding injury to the temporal branch of the facial nerve: interfascial dissection, subfascial dissection, and submuscular dissection. The *interfascial dissection* is in the plane of areolar tissue which separates the temporoparietal fascia from the superficial temporalis fascia and elevates the interfascial fat pad with scalp. *Subfascial dissection* is directly over temporalis muscle fibers, and both superficial and deep temporalis fasciae are elevated [10]. If this dissection is continued down to the zygoma, nerve branches to the muscles supplied by the frontalis nerve will be injured or severed; however, dissection can be continued subperiosteally across the zygoma. *Submuscular dissection* is between temporalis muscle and bone, which allows the temporalis muscle to be reflected with scalp. This dissection provides less exposure, and satisfactory reattachment of muscle to bone can be difficult. The author favors the interfascial technique.

Superficial Temporal Artery

The superficial temporal artery courses over the root of the zygomatic arch and then upward to supply much of the lateral scalp. This vessel is occasionally disrupted by a preauricular incision [16]. Because of the extensive anastomotic connections in scalp, there is rarely any adverse consequence from loss of this vessel; however, it should be preserved when possible, for potential future use in a superficial temporal artery to middle temporal artery (ST-MC) anastomosis or for encephalo-duro-myo-synangiosis, in patients with moyamoya or for free flap reconstruction in some craniofacial deformities. A Doppler may be used to localize the artery and its branches. Also, scalp flaps that have been repeatedly reflected and possibly irradiated may have become dependent on a superficial temporal artery. The superficial temporal artery can usually be reanastomosed, with expectation of a high liklihood of patency [16].

Supraorbital Nerve [1, 14]

The supraorbital nerve, a branch of the ophthalmic division of the facial nerve, courses upward from the orbit, through the supraorbital notch or foramen, to supply sensation to the scalp. This nerve can be crushed or transected when the scalp and pericranium are dissected from the supraorbital ridge. If there is a supraorbital notch, the nerve must be gently freed from soft tissue attachments to allow its safe reflection with scalp. If there is a supraorbital foramen, it must be identified and opened in V-fashion with a small osteotome to release the nerve and allow its safe dissection and reflection with scalp.

Incision in Compromised Scalp

Irradiated Scalp

Incisions in irradiated scalp should be made perpendicular to the surface. Beveled incisions may heal poorly. It is best to make incisions with a scalpel and not electrocautery because of its less compromise of vascularity. Bleeding from scalp edges is usually less than from normal scalp but hemostasis can be difficult, in part due to poor contraction of arteries and arterioles. The use of electrocautery should be minimized and applied to specific bleeding sites. Irradiated scalp can be of normal thickness or quite thin, relatively immobile, and it often resists retraction. Tight retraction with Weitlaner retractors or other devises can greatly compromise blood supply to an irradiated flap.

Infected Wounds

Surgeons are occasionally required to deal with dirty wounds, and urgent surgeries are sometimes required in approaching to some deep pathology, through a wound known or suspected to be infected. Rarely, evidence of infection is unexpectedly encountered in the course of putative clean surgery. This is usually sufficient reason to abort the planned surgery and address the infection, which includes wound culture, wound debridement, irrigation with antibiotic-containing saline, insertion of a passive drain, and closure of the wound.

Undesirable Scalp Incisions

Undesirable Incisions for Vascular Reasons

The vascular supply of scalp is replete with extensive anastomoses and therefore infarction from surgical incision is quite rare. However, one or more incisions can result in a circular or near-circular disruption of blood to a region of scalp. Also, embolization of lesions of scalp or underlying tumor can significantly compromise blood supply to a region of scalp, and a subsequent U-shaped incision may devascularize a region of scalp [17].

Circular incisions result in immediate devascularization and difficulty in wound closure. (Small lesions should be excised with a fusiform incision.) A circular incision may occasionally be necessary for excision of a lesion, but should only be done with a preoperative plan for wound closure—often with a plastic surgeon. Rarely, a surgeon may accidently devascularize a section of scalp, for example when the ends of a new curved incision intersect a preexisting scar. This often requires repair by a plastic surgeon with a flap or tissue expansion.

Closely adjacent incisions occur most often when a surgeon makes an incision along a broadly inked line that crudely traced an existing scar. The breadth of the inked line conceals the actual scar, and the new incision may follow a serpentine course along the existing scar, thereby devascularizing small strips of scalp. Less often, a surgeon fails to recognize or give adequate attention to a preexisting scar.

If an incision is made near or across an existing scar, it is imperative that there be ancillary vascular supply distal to tissue from a different direction. Vascularity does not extend across mature scar. A scar from a new incision will have increased undesirability in cosmetically sensitive areas if it courses parallel to or across a preexisting scar. Closely parallel adjacent incisions are contraindicated.

Incision in a sideburn, particularly if vertical, results in an extremely noticeable scar and never provides better surgical exposure than a vertical incision in the non-hair-bearing scalp posterior to the sideburn. This is apparently counterintuitive for many surgeons. A vertical incision anterior to the sideburn and a few mm inside the tragus produces a much less cosmetically undesirable scar, but is not popular among neurosurgeons. It is rarely if ever necessary to electively make a vertical incision in a sideburn. This is true for men, women, and children.

Incisions perpendicular to or obliquely crossing RSTLs, particularly on the forehead, cause unnecessarily noticeable scars and should not be used. These can always be avoided in elective incisions, but often not in cases of trauma, in which case they may require plastic surgical revisions.

Reflection of Scalp

Reflection of a scalp flap consists of separation of galea from pericranium, which is usually easily accomplished by dissecting through the loose areolar tissue at that location. For infants and young children, this can be done easily with traction on the scalp flap assisted by a blunt instrument and index finger, but in older children and adults, it is usually necessary to use a scalpel to disrupt the areolar tissue as the flap is retracted. Patients of all ages who have had prior surgery in the area and those who have had significant trauma or irradiation to the head often have relatively fibrotic areolar tissue or even dense scar, which must be cut with scalpel, scissors, or electrocautery. Occasionally, a prominent emissary vein is encountered and requires electrocoagulation.

Pitfalls/Things to Avoid

Compromising blood supply to scalp flap—This can occur from making a deep narrow scalp flap, making an incision in scalp that has been compromised by prior surgical incisions, and endovascular embolization of tumor via an artery of the scalp [17].

Fenestration of scalp flap—This occurs rarely during reflection of normal scalp, but can occur during reflection of scalp if there are densely fibrotic attachments to pericranium or the scalp is very thin.

Retraction of Scalp

Retraction of scalp during incision of scalp serves two purposes: minimizes bleeding from raw edges of scalp and holds the edges apart to assist the visualization of the planned line of incision. A surgical assistant may use one or two digits or a handheld retractor to achieve both goals while an incision is being extended and then during the time needed to introduce more secure, longer-lasting retraction. Prolonged manual retraction of scalp and other soft tissues is rarely necessary in most cranial neurosurgical procedures.

Self-retaining retractors are commonly available in many sizes and shapes and the surgeon must select one or more to achieve the needed exposure without obstructing the view of the surgical field. Depending on how the retractor is applied, the force against the scalp may be applied primarily against the edges of scalp or against the folded edge of a scalp flap. Usually both arms of a self-retaining retractor are against soft tissue, usually scalp, or the surgeon may place one retractor arm against an edge of bone. Self-retracting retractors apply equal force against the two sides of retraction. If extremely tightly applied against a scalp edge for a prolonged time, there can be ischemia in the edge of epidermis which can cause poor wound healing or necrosis.

Retraction of scalp flaps or facial tissues is commonly achieved by directly inserting sutures into galea or dermis and affixing these sutures to drapes. Retraction sutures can be placed along the edges of a scalp flap or near the site of folding of a scalp flap. Some surgeons tie these securely to drapes with square knots or attach the distal ends to drapes with hemostats. Other surgeons loop these retraction sutures through a towel clip or staple in the drapes and then grasp the ends with hemostats. The retraction sutures attached with hemostats can have their tension easily adjusted at any time after placement

The entire undersurface and all surrounding raw edges of scalp must be kept moist throughout the surgery. Failure to do this will result in dehydration, eventual desiccation, contraction of the flap, and increased risk of infection. The status of retraction and its moisture should be checked periodically during surgery and irrigated as necessary.

Repairing Scalp Incisions

All retractors are removed, and the flap is inspected to ensure hemostasis and manually returned to its normal location. Actively bleeding sites are controlled with electrocautery. The entire wound is vigorously irrigated with antibiotic-containing saline while being gently massaged manually with a gauze sponge. Secure coverage of cranial vault with vascularized scalp is necessary. Some surgeons place one or two temporary retraction sutures in the galea to facilitate correct anatomical alignment while suturing galea.

The value of placing an active or passive drain in the subgaleal space is controversial. Some surgeons, including the author, routinely place an active drain, for example Jackson-Pratt type, in almost every closure of a scalp flap. However, many surgeons, fearing that a drain could predispose to infection, rarely use subgaleal drainage. Subgaleal drains should exit through a separate puncture wound of the scalp and not through the incision line.

Two-Layer Closure

Full-thickness scalp incisions should be closed in two layers, for healing by primary intention. The galeal layer of adults and teenagers can be securely closed with 2-0 absorbable sutures, children with 3-0, and infants and newborns with 4-0. These sutures should be placed approximately 8 mm apart with attention to approximate the sides of the wound in a manner that optimizes alignment of skin edges. For patients of all ages, the epidermal layer, if not under tension and having no known compromise in healing, can usually be safely, securely, and accurately approximated with 4-0 Vicryl Rapide®, using a running technique; however, some surgeons prefer to use nonabsorbable interrupted sutures or staples.

Incisions in which there may be impairment of healing require nonabsorbable sutures or staples for the epidermal layer. These situations include the following: tension across the suture line, concern for leakage of CSF through the incision line, prior or anticipated early radiation, or chemotherapy.

Single-Layer Closure

A single-layer closure can be useful in extreme emergencies to pull scalp edges together and minimize hemorrhage until a patient can be brought into an operating room. This is often done with 2-0 or larger nonabsorbable sutures, or with large staples.

One-layer closure may be the only practical choice for severely damaged scalp in which its layers are severely mangled and indistinguishable. An attempt should be made to align edges of epidermis as best possible, but optimal alignment may be impossible. Subsequent surgery may be required to deal with an unacceptable scar.

When death seems imminent and nothing further can be done, scalp should be rapidly closed in one layer with tightly tied 2-0 simple sutures, mattress sutures, or staples.

Repairing Unshaven Scalp (Management of Hair)

The technique for repairing unshaven scalp is identical to that for shaved or clipped scalp, but the presence of hair can be distracting, especially to the less experienced practitioner. The hair is pushed aside and the galea is closed in the usual manner. Scalp is closed with either absorbable sutures, for example Vicryl Rapide®, or staples. Hair that has been caught in a suture, whether single or tufts, are easily pulled out. The closure line should be reviewed at the completion of closure to ensure there is satisfactory edge alignment and to remove any hairs trapped in the suture line. Hairs identified postoperatively in the suture line are easily removed with forceps, and the risk of infection is extremely low.

Techniques for Suturing Scalp

Closing Galea

The galea is most commonly approximated with interrupted sutures. A continuous running suture can be used but must be kept continuously taut until tied to achieve a satisfactorily snug approximation. Placement of interrupted sutures requires more time than placement of continuous sutures and the surgeon can easily adjust tightness and replace individual sutures. The number of interrupted sutures used should be limited to the number required to snugly approximate the wound edges, which depends on the inherent local tension. Sutures used in closing galea are most commonly 2-0 absorbable type in teenagers and adults, 3-0 in subteens and older infants, and 4-0 in newborns and young infants. If the galea is intact, tight approximation of edges of galea rarely if ever compromises blood supply to overlying uncompromised scalp.

The surface layer of scalp is most often closed with interrupted sutures or staples. It is important to carefully align scalp edges and have no overlapping or inverted edges. Opinions vary regarding choice of sutures; however, nonabsorbable sutures require removal after healing. For this reason, the author prefers a continuous use of 4-0 Vicryl Rapide® suture for all closures of scalp in which there is little or no requirement for tension to achieve edge alignment.

Knotless barbed sutures have been used instead of continuous sutures and staples in the closure of scalp wounds following craniotomies with results reported to be equivalent to those of non-barbed absorbable sutures [18, 19].

Difficult Scalp Approximation

Mattress sutures may be required for closure of scalp in which strong force is required to achieve approximation. Interrupted horizontal mattress sutures evert the edges of scalp and distribute tension along the wound edge. There are several types of mattress sutures, with various advantages and disadvantages. Vertical mattress sutures can approximate both deep and superficial tissues with good alignment and eversion of edges, but correct insertion is time-consuming. However, this type of suture can achieve a one-layer full-thickness closure, but without specific layer approximation. A vertical mattress stitch may be chosen to counter a tendency for inversion of the edges of thin scalp. Bites should be symmetrical, especially in their depth, to prevent malalignment that will heal with an offset (shelf) along the healed surface. In sites of problematic closures, vertical mattress sutures may be left in place for long periods of time. If tied too tightly, this suture can strangulate scalp and cause necrosis [20].

Closure of Corners

A corner suture is a variation of the horizontal mattress suture and is used to approximate angled scalp flaps or corners, without compromising blood supply. It is used for closure of a scalp flap that has an angle of 90° or less and also wounds having an X or Y shape. The suture must be tied tightly enough to pull the convex surface into the desired location but, if tied too tightly, the blood supply to the corner tissue will be compromised, healing will be slowed, and infarction may occur.

Surgical Knots

Sutures in scalp should be tied in a manner that achieves alignment of the edges, with avoidance of excessive tension. Animal studies have shown that wounds that are tied with loose approximation and correct alignment of tissues have greater tensile strength than tightly approximated wounds [21]. Tightly tying sutures with intent to prevent dehiscence or the leakage of CSF or serum should be avoided.

Swelling that occurs in the postoperative hours forces the edges of the wound more snugly together. Sutures that are tied tightly at time of closure will later compress tissue even more tightly, thereby slowing healing and increasing scar formation. Scalp sutures that show evidence of excessive tension or vascular compromise should be released and replaced under less tension or in different locations.

Staples [22]

Closure of scalp wounds with staples has less tendency to strangulate tissue and requires less time than closure with sutures. The intraoperative use of staples eliminates all risks of needle puncture of healthcare workers. The precise alignment of wound edges, particularly if the sides have different thicknesses, can be difficult and can result in overlapping edges. Staples are especially useful on hair-bearing scalp. Staples are not used in cosmetically sensitive areas, such as forehead.

Tying Strands of Hair

This technique has been used almost exclusively in repairing scalp lacerations in emergency departments. It is applicable for patients of any age, but they must have relatively long hair [18, 23]. A few strands of hair directly at the edges of each side of the wound are twisted to form a strand. K-Y™ jelly may be used to keep adjacent hair out of the way. The hair strands are tied across the wound with sufficient tension to approximate the edges of the wound. If there is concern about slippage of the knots, each can be secured with a tiny drop of cyanoacrylate glue [19]. After the hair grows a few mm, the knotted hair strands can be cut by the patient or health care worker. This technique is simple, painless, quick, cheap, and does not require suture removal.

Surgical Wound Closure When Death Is Imminent

Imminent intraoperative death may become evident during surgery in a variety of settings, for example emergent surgery for cranial trauma and massive unexpected intracranial hemorrhage during elective surgery. The edges of the scalp should be approximated in one layer with 2-0 sutures of any type or with staples. Ongoing massive herniation of brain can make approximation of wound edges difficult; this is of no importance in this setting.

Scars and Scalp Lesions

Neurosurgeons occasionally are asked to resect a scalp lesion, while a patient is anesthetized for other surgery. A lesion on forehead should not be removed without the patient's consent. A plan for closure of the scalp should be decided upon before making an incision to excise a lesion. During resection, the edges of intact scalp retract as the incision progresses, giving the appearance of a larger excision than planned. Excisions of 10–12 mm, in shortest diameter, should be excised via a fusiform, not elliptical, incision. Depending on laxity of the scalp, some larger excisions may be managed similarly. Excisions of scalp of 2 cm or less, in shortest dimension, can usually be closed primarily but if rotations are required, this should be done by a plastic surgeon. Attempts to primarily close defects of 2.5 cm will be very taut and prone to dehiscence or not be achievable. (See sections below on "Tight Closure of Scalp" and "Management of Insufficient or Missing Scalp".)

Cosmetically Undesirable Scars

Scars in hair-bearing scalp are rarely cause for cosmetic concern; however, wide scars and hypertrophic scars can be problematic. Most scars in scalp which are of cosmetic concern can be significantly improved by a plastic surgeon; however, vertical scars in sideburns and very tight scalp can be difficult or impossible to cosmetically improve. Scars that are the only indication for surgery should be addressed by a plastic surgeon.

Scars that are a source of concern at time of a subsequent neurosurgical intervention can and should be revised. Excision of a wide, imbricated, or hypertrophic scar from prior craniotomy or shunt surgery will often improve wound healing and often achieve cosmetic benefit. Most undesirable scars in the line of a planned new incision can be safely excised by a neurosurgeon with expected good result; however, not all scars need to be or can be easily and safely revised.

Revision of Scar in Scalp

The technique for revision of scars in scalp is similar to that described for *Surgical management of scar* in Surgery of Scalp; however, scalp is less mobile than most other scalp, particularly so following surgery. Therefore, undermining at the level of the galea along the sides of an incision can, depending on extent of scarring and amount of tissue excised, be difficult and may require galeal cross hatching. The ability to approximate scalp edges after excision of a scar must be considered when excising a scar.

Managing Benign Lesion in or near Planned Incision

Any surgical incision in the scalp that will expend across or near a mole or small lipoma usually presents an option for relatively easy excision, but these should not be excised without approval by the patient. Often patients are pleased to be able to get rid of these blemishes, but occasionally these are important to the patient's self-image and therefore should not be removed without consent.

An incision should not be made directly through a lesion—e.g., mole, or small lipoma. The removal of a mole or skin tag in the line of incision requires a small fusiform incision around the lesion and should introduce no new cosmetic defect.

Small lipomas of scalp, particularly on forehead or occipital scalp, are occasionally present in patients undergoing neurosurgical procedures. Postoperatively, the scalp overlying the site of excision occasionally may have a concave contour and, if on the forehead, can be less cosmetically acceptable to the patient than the bulge associated with the lipoma. Most small lipomas have normal appearing overlying scalp, but the adipose tissue of a lipoma often involves the hypodermis. Lipomas that are attached almost exclusively to postoperative surface often has a noticeably irregular or concave contour.

Problems Encountered in Repairing Scalp Incisions

Not all scalp incisions can be closed in two layers. Secure closure of scalp requires snug approximation of the galea aponeurotica and overlying scalp, preferably in two layers but single-layer mattress sutures can often achieve satisfactory closure.

Normal scalp is highly vascular with many arterial anastomoses and therefore ischemia is uncommon but may occur in a flap in which a dominant major arterial supply has been interrupted during surgery or from trauma. Surgical causes of vascular compromise of scalp occur in association with very tight closures of scalp, such as may occur following resection of portions of scalp or cranial vault expansion.

Tight Closure of Scalp

Settings in which tight scalp wound closure can be problematic include the following:

scalp that is fibrotic from repeated surgeries, irradiated scalp, single-stage cranial vault expansion, and closure after aggressive revision of wound edges. Sometimes relatively small defect can be quite challenging. Because of the convex curvature of the calvarium, there is no option for compressing underlying tissue to achieve closure. If the galea can be approximated with a line of sutures, even if considerable force is required, the scalp will usually heal satisfactorily; however, a high-tension closure can result in impaired healing or dehiscence or necrosis along the edges of the wound. Tight approximation of the epidermis is particularly prone to ischemia and necrosis.

Stretching scalp—As soon as it is recognized that there may be difficulty in approximating edges of scalp, a series of galeal sutures should be inserted 8–10 mm apart without initially tying them. An assistant should manually press and hold the edges of the wound together as the surgeon sequentially ties the sutures. It is important to not tear the galea aponeurotica by repeatedly trying to pull wound edges together without success. Each failed attempt that tears galea increases the difficulty in achieving closure.

Expansion of scalp—If the galea cannot be pulled together with galeal stitches, the scalp can be expanded by making multiple parallel incisions in the galea. This technique can usually allow approximately 2–2.5 cm of expansion of a large bifrontal flap. (See *Expansion of scalp*.)

Tight closure of scalp in newborns and infants—Tight closure of scalp in newborns and infants in whom cranial sutures are mobile can cause overlap of cranial sutures, with resulting constriction of brain.

Extreme tight closure of scalp—Sharp towel clips can be used to pull the sides of an incision together as a series of preinserted 2-0 galeal sutures are sequentially tied. However, sharp tips may tear through the edges of the wound, further complicating closure. This unesthetic and unappealing technique will sometimes facilitate a two-layer closure following a too-aggressive resection of wound edges and following one-stage cranial vault expansions. The towel clips are removed after the galeal sutures are tied. This technique rarely significantly compromises blood supply to the scalp; unless the galea has been extensively and deeply cross-hatched; however, each application of the towel clip produces two small scars in the scalp, which, in hair-bearing scalp, do not produce a cosmetic issue. This maneuver can also be used for single layer closure in an emergent setting such as impending death on the operating table.

Vascular Compromise Recognized During Closure of Scalp

The scalp is highly vascular with many arterial anastomoses and therefore ischemia is uncommon, but may occur in a flap in which the dominant major arterial supply is severed during surgery or from traumatic devascularization. The extra-galeal subcutaneous tissue of the scalp, being the layer through which the main vessels course, is very inelastic and therefore severed vessels contract little and bleed freely if hemostasis is not achieved. Due to the extensive anastomoses in scalp, it will remain viable if there exists an axial artery in the base of its pedicle. For this reason, large avulsion flaps that have only one or two surviving arterial supplies will often survive.

Blanched scalp flap—The development of a *blanched appearance* that becomes apparent during closure of the scalp or within minutes thereafter is strongly indicative of arterial compromise. Often the blanched appearance will slowly spontaneously improve over a very few minutes, but if not, the galeal sutures must be removed to facilitate reperfusion of the scalp flap. Mildly blanched scalp flaps often do survive, but there is always concern for infarction. If after 2–3 min the flap remains blanched, it will usually progress to infarction.

Cyanotic scalp flap—A *cyanotic (blueish) discoloration* is highly indicative of sever venous compromise. This is usually caused by stretching of the scalp sufficiently tightly to impair or occlude venous drainage. This can occur during closure, when there has been loss of scalp or following single-stage expansion of the cranial vault. It also may occur during closure of irradiated scalp. The bluish discoloration of a scalp flap may become apparent during suturing of galea, or less often the dermis during a very tight scalp closure. A scalp flap that becomes mildly cyanotic in the postoperative period will usually survive, but possibly with some epilation. A scalp flap that becomes deeply cyanotic in the postoperative period will not survive.

The first intraoperative response should be removal of the galeal sutures. An attempt to replace the sutures in slightly different positions, using less purchase of tissue to achieve closure without cyanosis, is often not successful. If unsuccessful, steps must be taken to expand the flap and perhaps adjacent scalp. (See *Expansion of scalp*.) If a subgaleal drain has been placed, it should be removed because this will gain a small amount of space and the drain cannot be useful, to allow safe closure of the scalp. Only rarely is it possible to reposition a bone flap to reduce the tightness of scalp closure. In some cases of single-stage vault expansion, this may be necessary.

Imbricated Scar

Imbrication of wound edges may occur during the healing of any incision after multiple surgeries at the same site. Imbricated scars are most commonly encountered at time of repeat cranial surgery and become especially problematic when repairing an incision. Imbrication is caused by fibrosis and contraction of subcutaneous tissue following prior surgeries. If the imbricated edges are simply pulled together with sutures, there will be poor abutment of vascularized scalp edges, which will result in slow healing, worsening of imbrication, and increased risk of infection.

Infolded edges of scalp should not be ignored. Mildly infolded edges can be managed with vertical mattress sutures. More severely infolded edges require that the scar and 2–3 mm of the imbricated scalp be excised. It is important to not excise all the infolded scalp as this is not necessary and the reduction in scalp can make closure difficult. After the scar is resected, each edge of scalp is everted with forceps and a linear incision is made into the undersurface a few mm from the wound margin, being cautious to not fenestrate the scalp and damage overlying hair follicles. These incisions may be made parallel to the wound or in a radial fashion. This allows the scalp flap to lie more flatly when the deep layer is closed. After snug closure of deeper layer, the dermal and epidermal layers are closed with vertical mattress sutures to ensure alignment of edges and prevent subsequent imbrication. Staples may also be used to assist in closure and alignment. Sutures and staples should be left in place for at least 10 days and perhaps longer.

Management of Insufficient or Missing Scalp

Settings in which there is insufficient scalp to cover severely herniated brain—e.g., following cranial decompression for trauma, infarction, or infection. This has been managed in adults and children by suturing a silicone sheet to the edges of scalp, producing a sterile pouch to protect the herniated brain until edema resolves and brain returns to its normal domicile and allows definitive closure can be achieved (see fungus cerebri below). Other neurosurgical settings in which there is insufficient scalp to achieve closure include resection of a lesion of the scalp, severely macerated scalp, wounds that have repeatedly dehisced, and wounds with recognized poor blood supply. Birth defects such as aplasia cutis congenita and conjoined twins are addressed in chapters with these names.

Closure of scalp defects whose sides cannot be approximated by the techniques described above requires the expertise of a plastic surgeon and this can usually be anticipated before the problem is encountered. The techniques that may be required include scalp flap rotation, tissue expansion with balloon, skin grafts (partial thickness or full thickness), or free tissue transfer. Negative pressure wound therapy (NPWT), often called vacuum assisted closure (VAC), can be valuable for assisting the healing of large defects of the scalp, particularly if tissue has been irradiated and primary closure has failed [24, 25]. These techniques are rarely required in neurosurgical practices.

Management of Dehisced Wound of Scalp

Dehiscences of a scalp wound is uncommon and often requires involvement by a plastic surgeon. Components of CSF shunts exposed by dehiscence should be removed. Primary closure over exposed shunt hardware is doomed to failure; however, recently infected shunt *sites* can, after clearance of infection, be safely reused [26]. Some wounds with exposed spinal rods can be managed successfully with NPWT [20, 27]. If there is a biofilm on the rods, the rods must be removed.

Expansion of Scalp

Crosshatching (scoring) of galea aponeurotica [21]—The reflected scalp flap is manually stretched to allow visualization of the galeal surface. Multiple galeotomies are made in a parallel or crosshatch pattern. Each cut allows 4–6 mm expansion of the scalp in the direction perpendicular to the incision. The incisions should be separated by 1–1.5 cm and must extend through the full thickness of the galea. A surviving small segment of galea will greatly limit the expansion. Deeper incisions can compromise the vascular supply of the scalp.

Bleeding is rarely a significant problem, but all bleeding sites require control by cauterization. The amount of expansion that can be achieved is dependent on size of scalp flap and extent of crosshatching. A large bifrontal frontal flap in an adult can often be expanded by 2–2.5 cm, but this varies. It is occasionally necessary to extend the incision or laceration in scalp to expose more galea for crosshatching. Crosshatching the galea of scalp that has been irradiated achieves little expansion and may compromise a flap's blood supply and result in its infarction. The expanded scalp should be closed in two layers—galea with 2-0 absorbable sutures and scalp edges with staples.

Expansion with tissue expander [22, 28] is accomplished by implanting Silastic™ balloon in a subgaleal pocked, allowing the wound to heel for 4–6 weeks and then incrementally inflating the balloon with saline until sufficient expansion is achieved. This technique requires at least two surgeries, and the disfiguring bulge of scalp is not always well tolerated by patients. Tissue expansion by this technique should not be used in irradiated scalp and can cause erosion of bone in infants [29, 30].

Scalp rotation can be used to manage many sizes and types of scalp defects and there are multiple techniques and types of scalp rotations used by plastic surgeons. Blood supply and innervation are preserved. Intact pericranium is not required, but will augment vascular supply of the flap if not required for other reconstructive purpose. Neurosurgeons may occasionally use simple scalp rotation to cover relatively small defects, but most scalp rotations should be done by plastic surgeons. The surgical details for scalp rotation are beyond the scope of this text.

Skin Grafts

Neurosurgeons should have a working knowledge on the management of wounds closed with skin grafts, whether split-thickness or full-thickness; however, these wounds are typically followed and managed by plastic surgeons. Questions that arise should be referred to the plastic surgeon or nurse practitioner.

All scalp grafts require preparation of the recipient site and harvesting of the graft. Scalp grafting is done by plastic surgeons and the surgical details are beyond the scope of this text. Full thickness scalp grafts do not require intact pericranium and can be done over avascular bone, but the bone must first be burred to punctate bleeding from the diploe. Split thickness scalp grafts require a vascularized base of pericranium or dura and may also be placed over burred bone.

Skin grafts are typically secured with a Xeroform® (bismuth tribromophenate with petrolatum) bolster or wound VAC atop a dressing, such as Adaptic® nonadherent gauze (cellulose mesh with petrolatum), to facilitate the provision of uniform pressure to the bed. Skin grafts may be secured with sutures, staples, and/or fibrin glue. It is imperative that the dressing remains undisturbed from shearing forces to allow the graft to take. Using saline to moisten the dressings and decrease its adherence to the graft, the outer dressing may be removed gently at day 5–10, depending on location and surgeon preference.

The most common causes of loss of skin grafts are seroma, hematoma, shearing forces, and contamination with bacteria above the level of 10^5 per gram of tissue and an inadequate wound bed. The wound bed must have adequate vascularization with optimized local venous and arterial systems to accept a skin graft. Skin grafts may survive on periosteum, perichondrium, peritoneum, perineurium, or a vascularized wound bed, including granulation tissue. The surgeon may choose to mesh or "pie crust" the graft to widen its surface area and allow fluid to egress from beneath the graft. Skin grafts are usually secured with sutures, staples, and/or fibrin glue.

The choice of split or full thickness skin graft is influenced by several factors. Full thickness grafts may be more resistant to infection than split thickness. Thicker grafts have higher metabolic obligations and a higher incidence of graft failure. Full thickness grafts undergo more initial contraction than do split thickness grafts; however, split thickness skin grafts are contracted more after healing.

Degloved Scalp

Actively bleeding sites should be clamped or coagulated as rapidly as possible, and the reflected or loose scalp flap should be returned and maintained in its approximate normal location. All patients with degloving injuries require plastic surgical consultation and emergent surgery to maximize chance of survival of the flap and minimization of cosmetic defect.

Management of Excess Scalp (Scalp Reduction)

Scalp that buckles with overfolding at time of closure is excess scalp. Loose scalp is not always excess scalp. The management of small areas of outward buckled scalp—i.e., dog-ears—is addressed separately. This problem occurs after surgery done to reduce the size of the cranial vault of children, but can also occur in adults following excision of an extremely large tumor involving the cranium.

The surgeon must decide whether to resect the excess scalp and, if so, how much. Scalp, particularly in children, will spontaneously contract over several weeks after closure and reduce or eliminate the excess scalp. As growing scalp is stretched over an expanding cranial vault or tumor, the distance between hair follicles increases, producing a thin hair distribution. Delaying the resection of redundant scalp to allow its contraction will allow hair follicles to become closer together, thereby increasing the density of hair.

There is no guideline for the optimum amount of scalp to resect, but the surgeon should *intentionally err toward less resection*. Requirement for a second resection is extremely rare. The redundant scalp is typically symmetrically enlarged in all directions. It is therefore usually appropriate to resect a fusiform coronal strip to reduce the anterior-posterior excess and resect two midline hemi-fusiform strips of scalp, one into parietal scalp and one into frontal scalp, to correct the transverse excess.

Face

Neurosurgeons are commonly involved in surgeries for craniofacial trauma, which can include injuries to the forehead and orbits. Also, the need to repair facial lacerations in patients who undergo cranial surgery for trauma may be managed by the neurosurgeon when a plastic surgeon is not available. Elective facial incisions are not commonly required for neurosurgical operations, but are required for eyebrow (supraorbital) cranial approaches and transfacial approaches. Facial incisions required in craniofacial surgeries are usually made by craniofacial surgeons.

Incisions in the face solely for correction deformity should be made by plastic surgeons.

Preparation of Facial Skin

Preparation of facial skin has special aspects because of the protection required for eyes and, depending on the details of planed surgery, attention required for nares and mouth. See discussion in Chap. 2.

Planning an Incision in the Face

Surgeries on the face require that the skin of the face *not be distorted* by an orotracheal or nasotracheal tube or with tape.

RST lines course perpendicular to the long axis of underlying musculature and in the direction of minimal extensibility. Therefore, scars from incisions aligned within or parallel to these crease lines tend to have a favorable outcome, in contrast to scars that cross these lines which tends to have a poor esthetic prognosis due to tension. The synergism of blood supply and extensibility of skin tend to result in a satisfactory scar regardless of age. Some young men are proud of scars on their face, apparently believing that they are semaphores of street toughness.

Marking Incisions

All proposed incisions on facial skin must be done with ink. *Never* scratch a mark with the back edge of a blade or a needle.

Cutting Facial Skin

Very meticulous incisions should be made. A blade with a curved edge should be used to incise skin. A #15 blade is usually satisfactory for adults and children. The belly (curved midportion of the blade, not the tip) should be used for making most facial incisions. The tip of the blade should be used only for precise cutting and for making punctures. The surgeon should apply downward force as the belly of the blade is gently pulled along the planned, preferably marked, incision site.

Raney clips should *never* be used on facial skin. Raney clips, regardless of size or technique of application, compress skin very tightly and can increase the width of the healed incision. Hemostasis along skin edges is achieved with least damage to skin and therefore less scar by gentle cautery to identified bleeding sites. The practice, often as a routine, of applying electrocautery in a continuous line along the dermal edge of a bleeding skin flap should be avoided because this significantly increases the width of the resulting scar.

Incisions in Facial Skin of Children

The thin skin of young children is quite mobile and usually needs to be manually immobilized to control the path and bevel of incision. This not only assists in cutting along a planned line, but also prevents accidentally a misdirected incision.

Incisions in Facial Skin of Elderly People

Elderly patients have relatively inelastic very lax skin, which can result in almost undetectable scars. Scars aligned within or parallel with these crease lines have a favorable outcome. Due to tension, scars that cross these lines have a poor esthetic prognosis. Skin tension decreases with age as elastin degenerates and therefore scar in the elderly can be virtually invisible. The favorable synergism of blood supply and extensible skin, which exists in the scalp, tends to produce good scar regardless of age. Also contour and wrinkle lines are useful in camouflaging elective incisions.

Incision in Existing Facial Scar

When a new incision is required in skin that has an existing scar, an attempt should be made to precisely excise the scar.

Inadvisable Facial Incisions

Attempt should be made to avoid making an *elective incision across RST lines;* however, this is often unavoidable in the repair of trauma. If the resulting scars are cosmetically unsatisfactory, they may require revision by a plastic surgeon at a later time.

Facial Wounds that Cannot or Should Not Be Closed

Wounds of the face that cannot be closed by primary intention are extremely rare but may occur from severe trauma, infection, burns, and war injuries. These require plastic neurosurgical attention and undergo delayed closure.

Resection of Excess Midline Skin for Cosmesis

Excess midline skin may require resection during correction of severe orbital hypertelorism and/ or other craniofacial surgeries. This surgery is usually done by a plastic surgeon; however, excision of excess skin in surgeries to reduce the cranial vault may be done by a neurosurgeon.

Pretrichial Incisions Across Forehead

Pretrichial incisions across the forehead are commonly used by neurosurgeons and tend to be well-concealed in children and many adults; however, they may become noticeable and undesirable with advancing age, particularly in men whose hairlines often recede. (See above description of "Pretrichial Incision".)

Tragal and Pretragal Locations for Preauricular Incisions

Incision in a sideburn consistently results in an unsatisfactory alopecic scar, never provides better surgical exposure than an incision posterior to the sideburn, and is never necessary. This is strongly counterintuitive for some neurosurgeons. The cosmetically best location for a preauricular incision is along the edge of the tragus. Incision in this location is simple to execute, easy to close, and results in a near-invisible scar. This incision is almost never used by neurosurgeons, but is commonly used by plastic surgeons. A preauricular location for incision in front of the sideburn usually results in a cosmetically acceptable scar.

Closely Adjacent Incisions

Closely adjacent incisions are never surgically necessary. If the second incision is made before vascular connections have extended across the initial incision (may never occur), the strip of skin between the scar and the new incision will die. If the second incision is made much later, healing of the strip of skin may survive but the double scar is cosmetically undesirable, and healing may be delayed. These scars occur most often as a result of an incision made along a broadly inked old scar. The breadth of the inked line hides the scar and the new incision courses parallel to the old scar or zigzags across it. Less often, a surgeon fails to accurately incise precisely within the old scar.

Hemostasis in Facial Skin

Hemostasis is especially important in facial incisions. Bipolar cauterization offers advantage in precision. It is extremely important to not produce thermal injury to dermis or epidermis.

Reflection and Retraction of Facial Skin

Reflection of a skin flap consists of separation of skin and subcutaneous tissue from underlying tissues. For infants and young children, this can be done easily with traction on the skin flap assisted by a blunt instrument and index finger, but in older children and adults, it is usually necessary to use a scalpel to cut the areolar tissue as the skin flap is retracted. Patients of all ages who have had prior surgery in the area and those who have had significant past trauma often have relatively fibrotic areolar tissue or even dense scar which must be cut with scalpel, scissors, or electrocautery.

It is rare for an incision in the face or the reflection and retraction of facial skin to significantly compromise blood supply. However, it is possible to injure facial skin by strong retraction or vigorous use of electrocautery. Also, facial skin can be fenestrated during reflection, if there is underlying attachment by scar or tumor and when the skin is very thin. This can almost always be avoided by careful surgical technique.

Retraction or compression of facial skin during incision, always in the direction and manner dictated by the surgeon, minimizes bleeding from raw edges of skin and improves visualization of the line marked for incision. A surgical assistant may use one or two digits or a hand-held retractor to achieve both goals while an incision is being extended and during the time needed to achieve hemostasis and secure, longer-lasting retraction.

Self-retaining retractors are available in many sizes and shapes and the surgeon must select one or more to achieve the needed exposure. Depending on how the retractor is positioned, the force against the facial skin flap may be applied primarily against the edges of skin or against the folded flap of skin. Usually both arms of a self-retaining retractor are against soft tissue, usually the undersurface of a flap, but the surgeon may place one arm against an edge of bone. All such retractors apply equal force against the two sides of retraction. If very tightly applied against skin, there can be prolonged ischemia in the edge of epidermis that may cause cosmetic scarring in the skin of the face.

Retraction of facial skin is commonly done with single or double hook sharp retractors, rake retractors or with sutures attached to dermis and affixed to drapes. Retraction sutures can be placed along the edges of a skin incision or in the deep dermis. Some surgeons tie these surely with square knots or attach the distal ends to drapes with small hemostats. Other surgeons loop these retraction sutures through a staple or towel clip in the drapes and attach the ends to drapes with hemostats. The retraction sutures attached to drapes with hemostats can have their tension easily adjusted at any time after placement.

A skin flap and its surrounding raw edges must be kept moist throughout the surgery. Failure to do this will result in dehydration, contraction, and increased risk of infection.

Check occasionally during surgery?

Pitfalls/Things to Avoid

Kinked or sharply folded facial flap
Prolonged retraction
Desiccation
Devascularization

Repairing Facial Incisions and Lacerations

The repair of most facial incisions and lacerations, particularly complex ones, is done by a plastic surgeon; however, incisions made by a neurosurgeon and small facial lacerations present in patients undergoing surgery for trauma may be repaired by neurosurgeons. Avascular strands must be excised, but it is not always advisable to excise jagged wound edges. Although occasionally these scars must be revised, the result is often cosmetically better than from the initial conversion to a straighter scar.

Facial incisions and lacerations must be closed in multiple layers, using small sutures (5-0 or 6-0) in skin, avoidance of tension on tissue, no tightly tied sutures, and gentle technique. Two-layer closure can usually be accomplished without difficulty. Complex incisions should be closed by a plastic surgeon. Unacceptable scars can be revised by a plastic surgeon.

Avoiding Problems/Minimizing Noticeability of Scars on Face

Use smallest suture commensurate with wound tension.
Establish good edge alignment.
Establish reliable hemostasis.
Never use cautery close to skin edge or in a continuous line along the dermis.
Sutures in skin of the face can be safely removed after 5 days.
Delayed removal increases the risk of scarring and railroading along the suture line.

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Management of Neurosurgical Wounds

5

Lawrence L. Ketch and Ken Rose Winston

Dressings

Early History of Wound Management: The Edwin Smith Papyrus (c. 1600 BCE., Egypt) described several dressings for wounds, including fresh meat, grease, honey, and lint and bandage material of linen [1, 2]. Dressings and bandages for wounds are also described in Homer's Iliad and Odyssey (c. 900–800 BCE), in Sanskrit writings, and in the writings of Sushruta, the father of Hindu surgery (c. 600 BCE), in the writings of Hippocrates (c. 460 BCE), and also in the Bible [2, 3]. Gauze was being used to bandage wounds in the fifth-century BCE [4]. Pasteur's germ theory and Semmelweis' demonstration of the effectiveness of carbolic acid as an antiseptic led Joseph Lister (1827–1912) to pioneer the use of bandages soaked in carbolic acid [5]

Initial Dressing

A dressing is not a bandage [6]. A *dressing* can be any of a range of substances, including ointment, gauze, or a material containing medication, which is applied directly against a wound to promote healing [2, 7]. A dressing applied at the conclusion of surgery can be any of many substances but is usually an antibiotic-containing medication, which is applied directly onto the wound [2, 7]. Neurosurgeons are inconsistent in their use of antibiotic-containing ointment on surgical incisions, but its use today is the dominant practice. Dressings on neurosurgical wounds maintain

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a moist environment, which promotes healing and protects the wound from bacterial access.

Many surgeons, including the authors of this book, apply a small amount of antibiotic-containing dressing, usually Bacitracin or Neosporin (bacitracin, polymyxin B, and neomycin,), to all surgical wounds, unless there is a known allergy to one of the components. This use can also increase drug resistance. Betadine/iodine absorption through the skin of newborns and infants may cause toxicity. Perioperative topical prophylaxis has been shown to be beneficial for several types of procedures [8]. The application of a large amount of ointment may be erroneously perceived as being super-protective, but this provides no more benefit than a thin smear of the ointment. Dressing applied at the end of surgery usually survives in sufficient quantity to serve the required functions for a several days.

Xeroform® gauze (impregnated with a petrolatum and bismuth tribromophenate) provides a moist non-adherent occlusive barrier but has little antimicrobial benefit [9].

Vaseline® (petroleum jelly, petrolatum) on wounds maintains a moist environment, seals the wound from contamination, minimizes or prevents formation of scab, and may minimize pruritis [10, 11]. Allergic responses are rare.

Vitamin E ointment has been shown to have no benefit on healing or scarring and can be highly topically sensitizing.

Dressing on a Draining Wound

Antibiotic ointment applied to an oozing or minimally draining surgical wound or areas of skin abrasion associated with a surgical incision can reduce the likelihood of infection while preventing adherence of overlying bandage. If there is significant continuous drainage of serum, blood, or pus, the application of topical antibiotic will provide little or no benefit, may inhibit drainage, and will complicate care of the wound.

Postoperative Management of Dressings

Dressings in the postoperative setting continue to serve the same purposes as when they were applied at the conclusion of surgery, which are (1) maintenance of a moist environment, which promotes healing; and (2) protection from bacterial access to the wound. Dressing applied before a patient leaves the operating room persists in sufficient quality to serve each of these functions for several days. The addition of additional dressing serves no useful purpose unless there is a persistent raw area or wound edge, evidence of delay in healing, or wound infection. Routine postoperative reapplication of dressing should be avoided. Applications of copious amounts provide no added benefit. A clean surgical wound with well-approximated edges and no drainage is sealed to bacterial invasion by 48–72 h. No proprietary salves or vitamin preparations should be applied to the wound after surgery.

Bandage

A bandage is not a dressing but may contain dressing material [2, 6]. A *bandage* is a material, often but not necessarily a strip of fabric, used to hold a dressing in place or cover a diseased or injured part of the body by binding, wrapping, or adhesion. When the medication is a component of the bandage, this combination may be referred to as a bandage. A bandage can (1) hold dressing material in place, (2) protect a wound from contamination by bacteria and other foreign materials, (3) protect a wound from scratching and digital disruption by the patient or other individuals, (4) absorb exudate from a wound, (5) compress to obliterate dead space and minimize accumulation of fluid beneath skin, (6) stabilize or physically immobilize a wound, (7) minimize bleeding, and (8) sometimes serves an aesthetic purpose [2, 12, 13].

Bandages also conceal wounds, and this may be appreciated by patients and family members but is not desirable to medical caretakers [6]. A report from The Cochrane Library found no evidence that any dressing, (including bandage alone and bandage plus dressing), "… significantly reduced the risk of developing a SSI compared with leaving wounds exposed" or compared with alternative dressings in people who had surgical wounds healing by primary intention." They concluded "… that decisions on wound dressing should be based on dressing costs and the symptom management properties offered by each dressing type e.g., exudate management."

The standard management of all incisional wounds of the scalp has been, for centuries if not millennia, the immediate application of a bandage, which is kept in place several days. This practice is based on tradition with little scientific support. The surgical site infection rate in 662 consecutive clean cranial operations, including pediatric cases, which were managed with no bandaging, was 0.48% (95% CI 0.10–1.39) [14].

Materials for bandaging

Conforming gauze
Adhesive tape and bandages
Elastic wraps
Flexible net dressings
Absorbent bandages

Risks Versus Benefits of Bandaging

The centuries-old traditional post-surgical management of incisional wounds of the integument has been occlusive bandaging for 5–10 days and sometimes for weeks.

Almost all neurosurgical wounds are covered with bandages for reasons of tradition and protection; however, bandaging is not always necessary and is not without risks. Bandages mask inspection and therefore very effectively camouflage oozing of blood, serous drainage, signs of infection, dehiscence, and evidence of poor healing. Wounds without a bandage can be examined easily with minimal inconvenience and little or no discomfort for the patient. Cranial bandages, however applied, can be displaced, or may shift to and fro across a wound, particularly on an agitated or uncooperative patient. Discomfort, including pruritis, can be caused or accentuated by a bandage, and this encourages the patients to scratch or otherwise manipulate their bandages and hence the wound. Movement of a loose bandage can wipe away the dressing applied to an incision and possibly massage the bacteria and other contaminants into the wound. Also the changing or removing of a cranial bandage can be stressful for children and some adults [6, 15].

An initially snug circumferential cranial bandage can become constrictive from normal postoperative swelling of the scalp. This can compromise the blood supply to the scalp and cause pain and possible alopecia or infarction [16–18]. The tightness of all circumferential bandages should be checked frequently. Alert and mentally competent patients will usually report when a dressing that *feels too tight*. If the pinnae are included in the headwrap, they should be padded with cotton to protect them from tight compression and possible segments of infarction. Under no circumstance should a continuous strip of tape pass 360° around a turban or other circumferential cranial.

Most bandaging materials are relatively inexpensive but not free. All of the required materials and instruments have costs. Sterilization of instruments, ordering, purchasing, and shelving of bandaging materials, as well as handling and disposal of contaminated bandages, have associated costs. Time consumed by health care workers in applying and attending to bandages also adds to the expense of medical care. The same is true for the brief prolongation of anesthesia required for postoperative application, however rapidly, of a turban bandage [14].

Types of Bandages

Flat Bandage (Gauze with Tape)

Flat bandages may be used on trunk, neck, and extremities and are easy to apply. Sterile gauze can be applied over wounds in non-hair-bearing skin. Adherence of tape to skin may be improved by applying skin adhesive, such as Mastisol®. Under no circumstance should tape be applied to hair-baring scalp, with or without tissue adhesive.

Most incisions in scalp that do not have a drain can be safely managed with an antibiotic-containing ointment and no bandage. However, young children and poorly cooperative patients may need bandaging for many days to prevent wound contamination and minimize risk of dehiscence from scratching.

Compression Bandage

Compression bandaging may be used to prevent the accumulation of blood and serum and to obliterate subcutaneous dead space. There is a strong tendency to wrap a compression bandage too tightly, and the intended goal is frequently not accomplished. Compression bandaging should not be used to halt bleeding or prevent leakage of CSF.

Wet-to-Dry Bandage

Wet-to-dry bandages are used to achieve non-selective mechanical debridement of open wounds that are healing by second intention, for example, some problematic spinal wounds. A saline-soaked gauze is placed on the raw wound and allowed to dry and become adherent to tissue before being removed. Removal of dry adherent gauze often causes bleeding and is painful. This removal strips away the surface of both necrotic and healthy tissue, thereby slowing healing by prolonging the inflammatory phase and possibly increasing the risk of infection. Wet-to-dry bandages are appropriate for selected wounds, which require superficial debridement. Changes should be continued until granulation tissue is sufficient for closure.

Incision with Drain

Incisions in the scalp, which have a non-suction-type drain, for example, Penrose, require an overlying bandage with sufficient bulk to absorb the drainage. A bandage with full-thickness soaking by serum, blood, or any other liquid should be promptly removed and reapplied. Leakage of CSF should be immediately brought to the attention of the surgeon.

Incisions in the scalp, which have a suction-type drain, require only that an antibiotic-containing ointment be applied around the site of penetration of the drain tube but rarely thereafter.

Management of Scalp Incision Following CSF Shunt Surgery

Incision in the scalp for CSF shunt surgery can be managed with an antibiotic-containing dressing and no bandage; however, some neurosurgeons always use a bandage [15]. The absence of a bandage allows early identification of a CSF leak and any problem with the wound. Some neurosurgeons apply a snug circumferential bandage with the goal of preventing subgaleal collections and leakage of CSF and serum. This practice is, in this author's opinion, rarely if ever successful and delays definitive management of such problems.

Bandaging by Region

Bandaging for Cranial Wounds

A *turban-type cranial bandage* is the most commonly used bandage following craniotomies and other cranial surgeries. It provides excellent coverage of the entire scalp and, when properly applied, is stable in most patients. The technique for application appears to be intuitive, but turban bandages are often poorly applied—too loosely, tightly, or insecurely—by the novice. Proper application requires several supervised practices. The pinnae require special attention to prevent possible infarction, if accidently folded or compressed. Protection is best achieved by positioning generous amounts of cotton beneath and over each pinna as the turban is applied.

Tape can be applied over the turban to secure its configuration and protect it from manual displacement. Under no circumstance should the tape be circumferential because this prevents the bandage from accommodating delayed swelling of the scalp without becoming constrictive. If a turban bandage is too loose or not distributed over the whole head, the turban may shift or become unraveled. If too tight, the vascular supply to the scalp can be compromised, causing epilation or infarction.

Turban bandages require a chinstrap if they must remain in place for several days without significant slipping or accidental removal, as is especially important for patients with subdural recording grids. Chinstraps must never be tightly applied but should be secured with tape to the turban on each. If the turban is loose fitting or the chinstrap is not securely attached to each lower edge of the turban, the chinstrap may slide forward or backward and allow the cranial bandage to become loose or dislodged. A loose turban with a chinstrap, if rotated or partially removed by the patient, can constrict the airway with risk of strangulation, especially in young children.

A circumferential cranial bandage without chinstrap is simpler to apply than a turban and is satisfactory for wounds in low-lying temporal and occipital locations. However, they do tend to shift, become accidently displaced, or removed. There is a tendency for the novice to wrap circumferential bandages excessively tight to ensure stability. A tubular elastic netting (commercially available) may be used to secure dressings to the head with extension around the chin; the resulting bandage does not unravel and has a neat appearance.

Bandages for Facial Wounds

Facial wounds do not often require bandaging except for draining wounds. Most bandages for facial wounds are used for camouflage. A thin layer of antibacterial ointment is usually sufficient. If considered necessary, a light taped gauze can be used as bandage.

Bandaging for Spinal Wounds

Most neurosurgical incisions for spinal surgery are straight incisions on the back and usually midline. It is important to seal these incisions with a dressing of antibacterial ointment, for example, Bacitracin, Neosporin, or with Vaseline. Bandaging with gauze and tape protects the wound and prevents removal of dressing by postoperative contact with bedsheets.

Bandaging for Abdominal Wounds

Abdominal incisions are most commonly surgeries for CSF diversion—i.e., shunt surgery—but are also used for some approaches to the spine. If skin has not been closed with sutures or with a dressing of antibacterial ointment, for example, Bacitracin, Neosporin®, or with Vaseline®, it is important to seal these incisions with either tissue adhesive or a small piece of Tegaderm™. Bandaging with gauze and tape is often used to keep ointment away from clothing and bedsheets.

Assessment and Management of Bandages

Assessment of a Bandage

Visual inspection and palpation are usually satisfactory to determine the intactness of a bandage and whether too loose, too tight, wet, or likely contaminated. Dampness or wetness can occur from drainage of serum, blood, pus, CSF, or from an external source. Wet and seriously damp bandages must be removed to allow wound inspection and possible replacement. Circumferential bandages should be assessed for excessive tightness. It should be easy to insert one or two fingers beneath the turban at mid-forehead or in the preauricular area.

The inexperienced caretaker often attempts to avoid replacing a bandage by "reinforcement" – i.e., applying additional layers of gauze and multiple strips of tape. This should not be done.

Postoperative Management of Bandages

Postoperative bandages can (1) hold dressing material in place, (2) protect a wound from contamination by bacteria and foreign materials, (3) provide protection from digital manipulation and other disruption by the patient or another individual, (4) absorb exudate, (5) compress to obliterate dead space and minimize the accumulation of fluid beneath skin, (6) assist in stabilizing or physically immobilize a wound, and (7) may serve an aesthetic function [12, 13, 19]. Many of these functions are not needed for most postoperative wounds but can be important for problem wounds and in patients unable to protect their wounds.

Postoperative bandages can have adverse effects, including the delay in recognition of wound infection and concealment of CSF leakage. Cranial bandages, however applied, can be displaced or may be shifted back and forth across a wound, particularly in a child or in an agitated or uncooperative patient. Discomfort, including pruritis, can be caused or accentuated by a bandage, and this can encourage the patients to manipulate the bandage and hence the wound. An excessively tight circumferential bandage can compromise blood supply to the scalp with resulting pain and, rarely, alopecia or infarction [16–18]. The changing or removing of a cranial bandage is often stressful for children and some adults [6].

Removal of Dressings and Bandages

Most dressing material can be satisfactorily removed at the time of bandage removal by simply wiping the area with sterile gauze or other clean fabric. More active removal at the time of post-surgical evaluation is rarely necessary. A more common issue is the removal of greasy ointment from hair after discharge from the hospital. Common bathing soaps and shampoos, particularly baby shampoos, are poorly effective for this purpose; however, a drop or two of a detergent used for washing dishes can be effective, particularly in removing ointments from hair and is typically required only once or twice. Detergent is irritating to the eyes, and care with its use is necessary.

Removal of Bandage

Indications for the postoperative removal of a bandage include (1) wound inspection, (2) defective bandage, (3) wet or contaminated bandage, and (4) bandage no longer necessary. Bandages that are no longer effective due to being excessively loose or disintegrating, regardless of cause, and those that are wet or apparently contaminated require removal or replacement.

Bandages secured to skin with adhesive or tape can be removed by gently peeling them from skin. If the bandage is in direct contact with the wound, perhaps the result of little or no use of dressing, it may be adherent to the wound and therefore must be removed slowly to prevent unintended debridement, disruption of the wound, and pain. Soaking with sterile saline for a few minutes will facilitate removal.

Removal of circumferential bandages of the cranium should always be done slowly, and it is usually safe to unwind the layers of gauze. Pouring sterile saline over of an adherent gauze bandage and allowing it to soak for several minutes will aid in a less painful removal and less tissue disruption. If there is confidence that no hair, drainage tube, or recording cable is incorporated in the bandage, a few layers of gauze can be cut at a time. Care must also be taken to avoid cutting the pinnae with scissors. Also, if electrode cables or drainage tubes are seen or known to be passing through a turban bandage, they must be protected as the bandage is unwound or cut.

The surgeon or mid-level practitioner must use knowledge and experience on replacement of cranial bandages, and there are no agreed-upon guidelines for this. Common practice, based on those from decades past, commonly determines the duration of bandaging and safe time for removal. Most bandages do not need replacement if (1) the edges of the wound appear securely adherent and impervious to bacterial entry and (2) the bandage is dry.

Repair of Bandage

Bandages that are loose, unraveling, or in significant disarray should be repaired or replaced, Bandages in need of repair can sometimes be improved sufficiently by application of gauze and a few strips of tape. An inexperienced caretaker often attempts to postpone or avoid repair and replacement,

Expanding a Bandage

Expansion of a circumferential cranial bandage can be achieved with one or two vertical cuts with bandage scissors through the multiple layers of gauze on both sides and then reestablishing the integrity of the bandage by applying a few circumferential layers of gauze, which are then secured with tape. It is safest to cut the bandage vertically on the forehead portion of the bandage. Cutting near an ear risks laceration of the pinna.

Replacement of a Bandage

Replacement of a bandage over most dry surgical wounds provides no benefit beyond the simpler, easier, faster, and cheaper practice of non-replacement [6]. A postoperative bandage should be replaced if an indication exists but not to satisfy a routine. If tradition is the sole basis for replacement, the expense and the associated risks, however small, make non-replacement the rational decision [6]. It is reasonable to replace bandages needed for wound protection in some children and adults who cannot cooperate or cannot suppress the drive to scratch the wound. Replacement bandages rarely need to be thick or bulky, unless needed to absorb drainage.

Pitfalls/Things to Avoid

Tight Bandage

See discussion above.

Loose Bandage

A circumferential cranial bandage that is too loose or not distributed over the whole head may shift, become rotated or unraveled with the result of no longer covering the incision, A mobile bandage can wipe away the dressing applied to an incision and may also massage the bacteria and other contaminants into the wound, Tubular elastic dressing retainers such as Surgent® may be helpful as an alternative to tape in maintaining the integrity of the bandage.

Tight Chinstraps

Chinstraps, as a component of a turban dressing, must never be tight against the chin, and their upper portions must always be secured to the turban on each side. If not secured on each side, a chinstrap may slide forward or backward and allow the cranial bandage to become dislodged. If a loose turban with a chinstrap is rotated or partially removed by the patient, the chinstrap may constrict the airway and cause strangulation.

Packing

Indications for packing an open wound include infection and drainage that is not decreasing. Packing of a wound reduces contamination burden, allows questionably viable tissues to declare themselves, facilitates granulation, and allows closure. Most packed wounds should have the packing removed for inspection and repacking approximately every 2 days. The wound should be snugly repacked, and packing the material should be in contact with the entire raw surface of the wound. Tight packing can compromise blood supply to the surfaces of the wound. The wound should be inspected regularly for need to modify the plan of management. As healing occurs and swelling resides, progressively less packing material will be required. The pack is usually held in place with an overlying dry bandage, which may be taped to the skin. It is important to monitor and protect the skin from damage caused by adhesive materials.

Nasal Packing

Packing material can be inserted into the nasal pharynx to tamponade bleeding. Anterior nasal packing in neurosurgical patients may be required at the conclusion of transnasal approaches to the sella turcica, transfrontal subcranial approaches, and some craniofacial surgeries, for example, midface advancement. Many different materials are commercially available for nasal packing, but neurosurgeons most commonly use long ribbons of Vaseline®-coated gauze. This material is packed into the nasal pharynx with a bayonet forceps. Packing should be snugly, not tightly, inserted. The packing is usually removed after 48–72 h. Tight nasal packing can cause necrosis of the compressed mucosa, and tight upward packing can displace any loose fragments of bone in the floor of the frontal fossa.

Posterior nasal packing is rarely if ever required in neurosurgical or craniofacial patients but, if necessary, should be done by an otolaryngologist or plastic surgeon. These patients require close monitoring.

Throat/Pharyngeal Packing

Packing of the throat around an endotracheal tube is used in some neurosurgical patients to prevent drainage of blood, saliva, and irrigation fluid into the trachea and esophagus during surgeries involving the base of the skull, for example, transclival approaches. This packing must be removed at the conclusion of surgery, but may remain postoperatively, if necessary, for the duration of intubation.

Assessment and Care of Wounds

Care of surgical wounds begins when surgery has been completed and the patient leaves the operating room. The goal of wound care for surgical wounds is to promote and achieve functional integrity of skin and underlying tissues, with cosmetically acceptable appearance. Cosmetically acceptable means near the preoperative state or better. These goals are achieved by optimizing the environment for the healing of each type of wound.

Wound Evaluation and Management: Generalizations

A surgical wound with well-aligned edges in normal healthy skin becomes impervious to the entry of most bacteria by approximately 48–72 h. Unless this seal is disrupted over the following hours and days, there is low risk of bacterial entry and start of infection.

Evaluation of a surgical wound requires knowledge of normal wound healing and the challenges that may be encountered. A specific patient's medical history can greatly influence wound evaluation and management, for example, allergies, immunosuppressive medications, antibiotics, radiation exposure, malnutrition, and history of impaired wound healing. Experience clearly imparts an advantage to assessing wounds, but there are principles that can guide even novice clinicians and non-physicians in the evaluation of surgical wounds.

It is important to assess all primarily closed incisions for apposition of skin edges, amount of edema or fluctuance, drainage, odor, and local erythema. Temperature and sensitivity to gentle palpation will provide information on the status of healing. Information from the assessment of these features can aid in understanding and communicating expectations for healing and guide effective management.

Precise approximation of wound edges is important for optimizing the local inflammatory response, speed of healing, and ultimate appearance of the scar. Wounds that are inadequately approximated require a prolonged period of healing by secondary intention and likely with a wide or hypertrophic scar. Irregularly approximated wounds can result in a poor contour with biscuit-like appearance or step-off deformities. The adage "*Approximate, don't strangulate*" communicates, accurately and importantly, that a tightly sutured wound does not accommodate postoperative swelling and may lead to local ischemia. poor healing, and a broad scar. *Well-approximated and gently everted wounds heal most favorably in non-infected circumstances*.

Assessment of edema or fluctuance is necessary to identify inflammation or infection. Swelling in most postoperative wounds peaks at 48–72 h and improves over subsequent days to months. Most normal swelling will have cleared by 3 weeks, and it is commonly expected that all apparent swelling should have cleared by 3 months. Postoperative edema of surgical wounds typically dissipates in a predictable fashion in the absence of pathology, but remodeling may continue for 2 years. Persistent edema often is associated with prolonged inflammation or evolving infection, Fluctuance, likely reflecting the presence of seroma or hematoma, should raise suspicion for infection. This is characterized by undue swelling, often with a fluid wave indicating pathologic fluid in the vicinity. The presence of erythema, fever, excessive warmth, and tenderness raises further concern for infection.

Depending on the pathology, knowledge of surgical details, presence of drains, and the amount and type of drainage can provide useful information regarding healing. Non-infected primarily closed wounds without undue underlying pressure are largely considered "closed," or impervious, after 2–5 days. Thereafter it is uncommon for large or even moderate amounts of bloody or serous fluid to appear or begin to drain through an incision. Turbid, opaque, or malodorous drainage at any time after closure is strongly suggestive of infection and possible underlying abscess. Sanguineous drainage typically becomes serosanguinous during the first 24–48 h after surgery. It is normal and common to observe some clumping of clotted blood in drains or tubing, but a change to opaque or white/green should raise suspicion for infection. If surgical drains are in use, the quality of the drainage should be evaluated similarly. Drainage should be expected to steadily decrease with time; persistence or an increase warrants suspicion for seroma, hematoma, or infection but can be CSF.

Table 5.1 Safe time for removal ofsutures and staples from normal skin

Anatomic location	Days
Scalp	7–14
Face and ears	3–7
Neck	7–10
Body and extremities	7–10
Hands, feet and across joints	10–14

Immediate post-surgical wounds may temporarily exhibit local hyperemia for several days due to tissue inflammation resulting from surgical manipulation. A mildly pinkish hue along a suture or staple is not uncommon and not a cause for concern. Persistent or expanding redness should prompt concern for cellulitis and infection. Associated warmth, fever, or pain further raises suspicion and warrants workup and possible treatment. The above characteristics of wounds are both simple, and their assessment is quite useful. It is important that the individual evaluating the wounds understands wound healing and, preferably, has experience.

Patients are commonly discharged with instructions to return or call with concerns, but it is up to the surgeon and surgical team to examine post-surgical wounds within 1–14 days to assure uncomplicated healing. Important concerns typically present within this time frame. Wounds that are not covered by a bandage can be inspected daily by the patient or a family member. Surgical wounds that are covered by a bandage should be evaluated between 1 and 3 days, depending on surgeon's preference. Replacement of a bandage depends on the characteristics of the incision and patient factors.

Non-absorbable sutures or staples are removed from the scalp in 10–14 days, from the face in 3–7 days, and from most of the rest of the body in 10–14 days. Dissolvable sutures lingering longer than the above periods are often clipped or encouraged to dissolve by mechanical means, such as gentle cleansing with a washcloth. The timing of removal of sutures requires assessment risk of local balance between strength and opposition of closure versus foreign body burden and risk of scarring from the sutures crossing the incision line, commonly referred to as *train tracking*. See Table 5.1.

Wound Evaluation in Post-anesthesia Care Unit (PACU)

The frequency with which surgical wounds should be examined in the *post-anesthesia care unit* is dependent upon many variables, including size and location of incision, magnitude of the surgery done, concern for bleeding, and the appearance of bandages. Bandaging overlying a surgical wound, or the wound itself if not concealed by a bandage, should be visually examined by a nurse or physician shortly after arrival in the PACU, approximately every 30 min while in that unit and immediately before leaving the unit. Circumferential cranial bandages should be assessed upon arrival in the PACU, approximately every hour while in the PACU and just before leaving the PACU, for excessive tightness. This is done by assessing the resistance to the insertion of one or two fingers beneath the edge of the bandage. If this "feels tight," the bandage must be expanded, removed, or replaced. Concerns regarding the wound or the bandage should be brought to the attention of the surgeon or a member of the surgical team. Increase in drainage or a rapid increase in local swelling should prompt concern for leaking CSF or bleeding and requires urgent attention.

Wound Evaluation in Intensive Care Unit (ICU)
Upon arrival in an intensive care unit, the condition of bandaging, tautness of the bandage, and tautness of the wound itself (if not concealed by bandage) should be visually examined by the responsible nurse. If no problem or concern is apparent, it is reasonable to reevaluate the site once or twice per 8-h nursing shift throughout the stay in that unit, unless a decreased frequency is ordered. Concerns regarding the wound, bandage, or drains should be brought to the attention of the surgeon or a member of the surgical team, and regardless of that person's opinion, the site should be reevaluated at an increased frequency over the next few hours.

Wound Evaluation In-House After Leaving Intensive Care Unit (ICU)
Upon arrival in a hospital room, the bandaging overlying all surgical wounds, or the wound itself if not concealed by bandage, should be visually examined. If no problem or cause for concern is apparent, it is reasonable to reevaluate the site approximately every 8 h throughout the remainder of hospitalization, unless a different frequency is ordered. For as long as a circumferential cranial bandage is present, its status, including tautness, should be checked every 8–12 h. Any concern regarding the wound or the bandage should be brought to the attention of the surgeon or a member of the surgical team, and regardless of that person's opinion, the site should thereafter be reevaluated at an increased frequency during the next few hours. All wounds and bandages should be inspected by a nurse or mid-level provider before transfer to another hospital and immediately before discharge from the hospital.

Wound Evaluation in Outpatient Setting
Wounds are commonly considered "closed" or re-epithelialized after 2–5 days, if primarily closed and uncomplicated healing has ensued. Depending on the location of the wound, a patient may be evaluated in an outpatient setting between 3 and 14 days later, for incision check and removal of sutures and staples. Many of the principles discussed earlier apply to the out-patient evaluation of wounds. (See Table 5.1).

We allow, in most uncomplicated situations, the patient to remove the bandage at day 2 or 3 and gently wash the affected area with soap and water. The patient may then replace the bandage or leave the incision open to air, depending on instructions communicated at the time of discharge by the surgeon or mid-level practitioner. It is advisable to gently wash the incision daily or every other day, to decrease the burden of bacteria and local debris. Patients should not submerge the incision for at least 2 weeks after surgery. In more vulnerable wounds, sterile technique for washing and bandaging in the postoperative period may be required. All wounds should be cleansed daily of exudates and kept moist by the application of ointment.

Postoperative Shower [20, 21]

Postoperative showering is controversial, but in patients with clean and clean-contaminated wounds, after 48 h from surgery, there is evidence that it does not increase the risk of wound infection or other complications, and it improves patients' sense of cleanliness and well-being. Showering does require that bandaging not be present. The flow of water and gentle hand contact across the wound are allowed but with no scrubbing or scratching. Many postoperative neurosurgical patients are sufficiently stable to enter a shower, but those who feel unstable or weak should sit on a stool or chair while in the shower.

Tape and Adhesive Removal

Tape and adhesive bandages should be removed by slowly peeling away from the skin. Least damage to the wound is produced by pulling in a direction that is parallel to the surface of the skin. Solvents sometimes reduce adherence to the skin and facilitate removal; however, these should not be used on neonates.

Suture and Staple Removal

When Should Sutures/Staples Be Removed?

Sutures and staples can be removed as soon as the edges of the surgical wound are reliably adherent—i.e., unlikely to be disrupted by anticipated activities. Patients' activities and rate of wound healing differ, and therefore, no exact number of days can be stated. (See Table 5.1). Factors that influence the timing of removal of sutures or staples include location of wound, material used to close wound, whether deep layers of sutures were placed, tension on deep layers of wound, tautness of skin, cooperativeness of patient, and environmental factors.

Early removal of sutures and staples should be considered if they appear to be causing ischemic insult to the wound. This may occur if sutures have been tied too tightly to accommodate normal postoperative edema. The early removal of sutures may be necessary to allow evacuation of an underlying collection of serum or pus, or if the patient has an allergic response to sutures, which is extremely rare.

Most sutures in the face and pinnae may be removed in 3–7 days, because these areas tend to be under minimal tension from muscular movement, and they heal relatively quickly. If left beyond 7 days, there is risk for local scarring from the sutures crossing the suture line, commonly referred to as "train tracking." Most sutures in the head, neck, trunk, and extremities may be removed in 7–10 days. Most sutures in the hands, feet and across joints may be removed in 10–14 days. These areas are not necessarily less cosmetically important, but these wounds can be under more tension and therefore tend to be more mechanically challenged than wounds in other locations. There is likely benefit from longer presence of these sutures to assure adequate healing. Selecting a time for removal of sutures and staples requires balancing the risk for excess scarring against the time required for adequate healing to keep the wound closed.

Situations/Sites in Which Sutures Should Be Delayed

Most neurosurgical wounds are closed in at least two layers, depending on the location and depth. The deeper sutures theoretically maintain strength after the external sutures are removed in the time frames discussed above. There is a paucity of evidence-based recommendations for conditions that warrant delayed removal of sutures. Depending on the location of the wound and comorbidities, consideration may be given to delaying the removal of sutures in patients who are obese or have any condition that may delay wound healing, such as history of poor wound healing, prior dehiscence, prior irradiation, or anticipated early postoperative irradiation.

Home Instructions

Do not submerge in water.
Showering, including water on scalp, is safe but should be patted dry.
Do not remove scabs (your doctor or nurse may do so for you).
Sunlight exposure should be avoided.
Do not apply ointments, salves, or vitamin E to wound.
Contact your surgeon or nurse for redness, swelling, drainage, worsening pain or fever (oral temperature 38.3 °C/101 °F or greater).

Preparation for Removal of Sutures and Staples

Prior to staple or suture removal, wounds often require cleansing to allow a final inspection and to facilitate safe use of instruments. Patients must remain still during removal, and this requires an assistant for infants, young children, and some emotional or intellectually impaired adults. Jerking movements and general lack of cooperation can put to risk the disruption of an apparently secure wound during removal of sutures or staples. Some patients require sedation or application of a topical anesthetic to minimize discomfort and gain cooperation.

How to Remove Sutures

Sutures in the skin can be cut with scissors and removed with forceps. The wound bed may need to be cleansed of ointment, scabs, or debris prior to removal. This may be accomplished with soap and water, normal saline, alcohol, or rarely, hydrogen peroxide if the exudate is adherent. Vigorous abrasion can disrupt the incision line. Removal of sutures from a well-healing wound requires forceps to sequentially lift and immobilize each targeted suture from the skin and scissors to cut the sutures. Simple horizontal or vertical interrupted sutures may be removed by grasping the knot with the forceps, gently retracting to “tent” the suture, and then cutting the suture with scissors. The suture can then be pulled from the skin with gentle retraction on the knot. Running sutures, often called “whipstitch” sutures, may be removed by similarly clipping each second exposed loop. If permanent material has been used for a running subcuticular suture, this may be removed by grasping the end of the suture, rolling it into the forceps, and applying traction.

Removal of sutures from the skin is most easily and least traumatically accomplished with small sharp-tipped scissors. Trying to make-do with larger instruments increases the discomfort and the risk of dehiscence. Patients have at least some anxiety over anticipated discomfort from the removal of sutures, but most sutures can be removed with little or no pain. However, the removal of deeply imbedded sutures resulting from being tightly tied and causing cross-hatching can be difficult and painful for the patient.

How to Remove Staples

Staples are most easily removed and with least discomfort, with a staple remover. The user should place the double prongs of the staple remover beneath the exposed transverse segment of the staple and gently close the arms of the handle. This buckles the exposed straight portion of the staple into an M shape by rotating and elevating the two ends of the staple while stabilizing its mid-point. The L-shaped ends of the staple are rotated out of the skin, thereby freeing the staple with minimal movement or retraction of the tissue and little or no pain.

Alternatively, staples may be removed with a small, curved hemostat inserted beneath the exposed transverse segment of the staple and then opened. This maneuver applies force to the vertically penetrating portions of the staple and bends them outward. This rotates the buried ends of the staple, releases the tissue, and frees the staple. This technique causes a little more movement of the skin than does removal with a staple remover. Under most circumstances, staples can be more easily and rapidly removed than sutures and, contrary to the expectation of patients, often with little or no discomfort.

Management of Drains

Drains of all types provide a path for bacterial entry through the open portion of the wound, and this risk increases with time. However, most wounds are well tolerated without infection for the time their presence is required.

Exit Sites of Drains

Antibiotic ointment should be applied around the site of exit of all tubes draining CSF at the time of implantation of tubes but rarely thereafter. These drains commonly do not have overlying bandages. It is also reasonable to apply ointment to the site immediately after the tube is removed.

Passive Drains

Wick Drains

Wick drains consist of a small strip of fabric or Cottonoid® placed within a wound and extending through the incision onto the surface of the skin. If left in place for more than 3–4 days, fibrous tissue will grow into the fabric and provide a potential nidus for infection. Removal of a wick drain, which has become attached by ingrowth of fibrous tissue, can be difficult, and its removal can injure the tissue.

Collapsible Passive Drains

Collapsible passive drains are used to maintain a pathway for short-term drainage, which can occur either around or through the tube. This type of drain, for example, a Penrose drain or sterile rubber strip, is usually used for drainage of serous fluid or small amounts of blood from subgaleal, subcutaneous, or occasionally deeper sites. These drains, if expected to be in place for more than a day or two, may have been secured to the skin with a loose suture. These drains require coverage with a bandage of sufficient bulk to absorb the drainage and to prevent dislodgement of the drain if it has not been secured with a suture.

Collapsible drains are usually removed after 1 or 2 days and allowed to heal by secondary intention. Removal of collapsible drains requires only gentle traction. The discomfort or pain associated with removal varies greatly. Rarely a passive collapsible drain will have been accidently tethered by a deep, perhaps galeal, suture and therefore cannot be removed without reopening the wound for a sufficient length to identify and cut the tethering suture. Applying strong traction often fractures the tube instead of the tethering suture.

Non-collapsible Passive Drains

Non-collapsible passive drains are uncommonly used in neurosurgical practice—excluding CSF drains. When used, they are usually tethered to the skin with a non-absorbable suture, which is easily cut, thereby allowing the tube to easily slide out.

Active Drains

Active drains are usually secured to the skin with non-absorbable sutures, but this is not always necessary if the drain, for example, Jackson-Pratt type, has a snug fit through a puncture-type incision in the scalp. These drains may remain functional for several days. Their removal requires steady manual traction, and this may cause a brief sharp pain. Some neurosurgeons always close the residual hole in the scalp with a suture, and others do this only if there is persistent drainage. Most often an antibiotic ointment is applied around the penetration site, usually with no overlying bandage.

CSF Drains (Ventricular, Lumbar)

CSF drains are often required for days or weeks, but regardless of time and anatomical location, they must be fixed to the scalp in one or more places to prevent accidental removal. Post-surgical evaluation of tubes draining CSF should be done at least every 8 h, to (1) assure patency, (2) confirm that the outflow resistance (usually determined by the position of the drip point of the closed system) is at the position prescribed by the surgeon, (3) confirm that the drainage tube remains securely attached to the skin, and (4) look for leakage of CSF around the tube, which would indicate obstruction. All other identified problems must be brought immediately to the attention of the responsible surgeon or mid-level practitioner. [Details of management of CSF drains will not be discussed.]

Special Wounds

Granulating Wounds

Most wounds that cannot be approximated without excessive tension should be left open to close by secondary intention. Dehisced wounds often must be managed in this way (see "Problem Wounds" below.)

Negative-Pressure Wound Therapy (NPWT)

Wounds that cannot be closed due to tension, contamination, tenuous blood supply, or history of repeated dehiscence may be managed by open packing or negative-pressure wound therapy (NPWT), also called vacuum-assisted closure (VAC). This has been used successfully for problem wounds of the thoracic and lumbar spine.

Grafted Wounds

Partial-thickness and full-thickness skin grafts may be used in some surgeries to close myelomeningoceles and rarely defects in the scalp. The required dressings and bandages are managed by plastic surgeons.

Skin grafts are typically secured with a Xeroform® (bismuth tribromophenate) bolster or wound VAC atop a non-adherent dressing, such as Adaptic™ gauze (knitted cellulose acetate mesh-impregnated petrolatum emulsion), to facilitate the provision of uniform pressure to the bed. Skin grafts may be secured with sutures or staples. It is imperative that the dressing remain undisturbed from shearing forces to allow the graft to take. Using saline to moisten the dressings and decrease its adherence to the graft, the outer dressing may be removed gently at day 5–10, depending on the location and surgeon's preference.

The most common causes of loss of skin grafts are seroma, hematoma, a shearing force, contamination with bacteria above 10^5 per gram of the tissue, and an inadequate wound bed. The wound bed must have adequate vascularization with optimized local venous and arterial systems to accept a skin graft, Skin grafts may survive on the periosteum, perichondrium, peritoneum, perineurium, or a vascularized wound bed, including the granulation tissue. The surgeon may choose to mesh or “pie crust” the graft to widen its surface area and allow fluid to egress from beneath the graft.

The choice of split- or full-thickness skin graft is influenced by several factors. Full-thickness grafts may be more resistant to infection than split thickness. Thicker grafts have higher metabolic obligations and a higher incidence of graft failure. Full-thickness skin grafts undergo more initial contraction than do split-thickness grafts; however, split-thickness skin grafts contract while healing. Split-thickness skin grafts trend toward hyperpigmentation or hypopigmentation, depending on the Fitzpatrick skin type and donor site.

After the first dressing change, dressings are typically replaced with a non-adherent gauze dressing, such as Xeroform® or Adaptic™. Thereafter the dressing may be changed every 3–7 days until full healing has occurred, often requiring 2–3 weeks. If a hematoma is discovered beneath the graft. a small incision must be made atop the graft to allow drainage lest it impair take of the graft. Reduction in fluid burden may help apposition of healing tissues and improve healing time.

Scab

A scab is the dry, medium-dark brown crust that forms within 24 h after injury over most injuries to the skin of sufficient depth to bleed. Its formation begins when blood clots within a wound and develops into a scab as the outer surface of a clot, composed of platelets, fibrin and blood cells becomes dehydrated. Scab seals the wound from dehydration, provides protection from further contamination and bacterial infection, provides protection from physical injury, and therefore can be thought of as a biologic dressing and bandage. A scab requires no treatment or manipulation. A scab must not be confused with an eschar.

Eschar

Eschar is a full-thickness area of dead tissue within a wound of the skin, and it must not be confused with a scab. It is usually brown to black, can be hard or leathery, and has discrete edges. An eschar acts as a natural protective barrier to the entry of bacteria into a wound and keeps the wound moist; however, it also delays wound healing by slowing epithelialization. Small eschars along the edges of a surgical wound result from having been burned by electrocautery, which were not apparent at the time of closure. An eschar that becomes edematous, oozing, or draining serous material or pus should be debrided or removed.

Infarction of Skin Flap

The scalp usually tolerates considerable compromise of its vascular supply without infarction because it is well vascularized and has an extensive anastomotic network; however, toleration has limits. Infarction of a skin flap in other sites rarely if ever occurs. The most common setting for infarction is a horseshoe-shaped scalp flap with a narrow base, which does not straddle a moderately large artery. A scalp flap that is acutely reflected and left in that position through a long surgical procedure has risk of infarction. A rare cause of scalp infarction results from an incision in the scalp that has undergone embolization of a blood vessel within the scalp that was supplying a meningioma [22].

In a flap with severe venous congestion or absent arterial circulation, a plastic surgeon should be consulted. Infarcted scalp must be totally excised, and the defect is repaired. Excision must be done promptly after diagnosis, but this is not an emergency unless there is infection. The margins of required resection are clear along the sides of the flap and nearly as distinct across the base of the flap. Resection must extend into the tissue with normal appearing vascularity. If a free flap is to be used for closure of the defect, failure to resect the infarction into well-vascularized scalp will impair wound healing and possibly lead to failure of the free flap survival.

Not all infarctions of scalp flap are full-thickness, and partial-thickness infarction requires only the removal of the infarcted tissue.

Problematic Wounds

Wound Pruritis (Itch) [23–25]

Pruritoceptive itching—i.e., originating in the skin and not of systemic or psychogenic origin—is normal in a healing wound. Its intensity and toleration by patients vary greatly and therefore can strongly affect the quality of life. Pruritis lasting less than 6 weeks is considered to be acute but, if persisting for longer, to be chronic. Both pruritis and pain are noxious but are quite different entities having different sensations and different neurophysiological bases. Pruritis-specific neurons reside in the dorsal root ganglia and are not involved in the perception of pain. Unlike pain, pruritis does not evoke a spinal reflex. The itch-scratch reflex is transmitted via the contralateral spinothalamic tract to the thalamus and eventually to the somatosensory and cingulate cortices.

A pruritic stimulus elicits a response of protection and removal of the cause, usually by scratching. Cold, heat, and scratching can often reduce the perceived intensity of itching. Scratching, noxious heat, and noxious cold significantly reduce patients' ratings of intensity of pruritis [25]. However, the stimulation of scratching over or near a surgical wound can provoke and prolong itching, which can lead to more scratching and injury to the skin, wound dehiscence, and infection. A cold compress or snug bandage may diminish the intensity of pruritis. A bandage can provide only limited protection from injury from scratching.

Dehisced Wound

Wound dehiscence occurs because of impaired healing or when force separating the edges of a wound exceeds the force holding the edges together. Sutures in the various layers initially hold the edges of the wound together, but their effect progressively diminishes and disappears as sutures are removed and absorbed. Many factors, including mechanical forces, infection, metabolic issues, and radiation, can independently or concurrently compromise wound healing. Externally applied mechanical forces and forces originating from beneath the skin, for example, an expanding fluid compartment or tissue swelling, can cause dehiscence. Also slow wound healing that extends beyond the effective life of the sutures can result from poor nutritional state, steroids exposure, recent, ongoing or prior irradiation, multiple failed attempts at wound closure, and chemotherapeutic agents [26]. Wound dehiscence can occur several months after a wound appears to be healed in sites that have undergone several elective operations, repeated failed attempts at closure, history of having been irradiated, and in patients who have received or are receiving an anti-angiogenic drug such as bevacizumab [26].

Most delayed wound dehiscences, with or without exposure of cranial bone, should be considered related to contamination, although long delayed dehiscence after irradiation may not be related to infection. If the dehiscence occurred within the first 3 days following wound closure, and if there is no evidence of active infection, the wound can be scrubbed and re-sutured. For deep dehiscence with separation of fascia or wide separation of galea, it is usually best to scrub well, pack the gap with appropriate dressings, and allow closure by tertiary intention with continued dressing changes. Closure may be managed with a vacuum-assisted closure device. Antibiotics may be given in the perioperative period if the wound is to be re-closed.

Dehiscence with exposure of avascular bone is a more serious matter because of the absence of natural defense mechanisms in the exposed bone, and the contamination often extends beneath the bone into the epidural space. The traditional approach has been to remove and discard the entire fragment of avascular bone. This is usually not necessary unless there is obvious active infection extending into the structure of the avascular bone—i.e., osteomyelitis. All exposed bone must be scrubbed, and this may require some extension of the wound.

Exposed Silastic®, for example a component of a CSF shunt, must be removed to clear the infection and achieve wound healing. Exposed metal, for example, a titanium plate or rod, does not always have to be removed to achieve healing; however, the greatest difficulty in these cases is achieving a closure that will not readily dehisce. Dehiscence that occurred from infection or excessive tension should not be simply re-sutured.

Red Wound

A small amount of pinkness along each side of a surgical wound is common, not cause for concern, and will usually clear within 3–5 days from surgery or after suture/staple removal. Pinkness or redness that is expanding or becoming more intense is a cause for concern regarding infection. It is important to examine the patient and look for other indications of infection, such as fever, worsening incisional pain, swelling, drainage, dehiscence, presence of pus in the incision line, and a rising peripheral WBC.

Draining Wound

Irrigation fluid that was flushed into the wound before closure and incompletely evacuated may drain in the early postoperative period. This fluid may accumulate immediately beneath the skin, particularly if there are relatively large skin flaps, but can be in a deeper space. During the contraction of muscles and possible swelling of deep tissues in the hours after wound closure, the irrigation fluid becomes apparent as drainage or as a fluctuant swelling beneath the flap. It does not increase in volume after surgery, and it does not predispose to infection. It rarely is of sufficient volume to require intervention, but if there is persistent fluctuance, aspiration may be appropriate for diagnostic confirmation of being not infected.

Serous fluid originates from a raw surface of living tissue, and it is common in the first 12–24 h after surgery, for small amounts to ooze or drain through a closed non-infected wound or accumulate beneath the flap. The volume of serous fluid that accumulates tends to correlate roughly with the surface area of tissue exposed during surgery and with the amount of trauma (cutting, retracting, suturing) these tissues received during surgery. If an accumulation of serous fluid does not appear to be resolving to the surgeon's satisfaction or if its expansion is threatening the integrity of the incision, it may need to be aspirated or drained.

Oversewing of draining wounds is contraindicated. Indications to aspirate subcutaneous fluid and/or insert a drain include infection, suspicion of infection, impending dehiscence, and avoidance of an organizing hematoma (cosmetic problem). If a large pocket of serous fluid remains for several days or weeks, the surface of the pocket may have become epithelialized. This will prevent resolution, and therefore, after the fluid is aspirated or drained, the epithelium *must* be excised.

CSF drainage through a surgical wound is a serious problem because of the inevitable bacterial contamination that occurs with elevated risk of infection and progression to ventriculitis. Leakage of CSF from a recent cranial or spinal surgical site may be the result of insecure wound closure or of high intracranial pressure.

Leakage of CSF must be addressed immediately and must always be considered to have bacterial contamination. If a bandage is present, it must be removed to identify the leaking site and halt the leakage of CSF. The site of leakage must be identified, and the cause is addressed immediately.

Leakage of CSF from a wound following CSF shunt surgery indicates that CSF is exiting along a pathway that has lower outflow resistance than that of the shunt system. This is most often caused by obstruction of the shunt but can also be via a pathway unrelated to the shunt. Delay in halting the leak increases the risk of infection, and therefore, immediate action is required. The leak must be brought immediately to the attention of the neurosurgeon, resident, or mid-level practitioner. *Purulent drainage* from a surgical wound is an ominous sign and should always be interpreted as evidence of infection, even if culture reports are negative.

Prevention of Postoperative Wound Infection

The most effective protection in the early hours after closure of a wound is provided by covering the wound with an antibiotic-containing ointment. This protects the wound from the bacteria of the nearby microenvironment, which includes resident and transient bacteria of the skin and from the nearby biosphere. Ointments adhere to the skin and provide a physical barrier and a moist environment, which promotes healing. These protective effects are probably more important than the antibiotic component of the ointment. A surgical wound having well-aligned edges becomes impervious to the entry of most bacteria by approximately 72 h. Unless the healing process is disrupted over the following hours and days, there is minimal risk of bacterial entry and infection.

Risk factors for postoperative infections for neurosurgical procedures include an ASA score of II or greater, wound drains, CSF leakage, surgery lasting longer than 2 h, diabetes, preoperative contamination, presence of foreign material, repeat or additional procedures, previous infection, CSF shunt, and emergency procedures.

Disruption of a sealed wound, regardless of cause or timing, restarts the period of postoperative risk of infection, which lasts until the wound is again sealed. It is therefore important to protect wounds from all forces that may cause disruption. Bandages provide important but imperfect protection against the adverse mechanical effects of abrasion against various materials and from scratching by the patient.

If a surgical wound becomes contaminated, whether by clothing, food, dirt from the external environment, or feces, the wound should be immediately washed gently with soap and water. Contamination with urine is a cause for concern, but the risk of causing infection is less so than commonly believed because normal urine is sterile. After a wound becomes sealed, personal hygiene and a clean environment are usually effective in preventing infection, unless the wound becomes reopened. Wound contaminations *without disruption*, particularly those occurring after 24 h from surgery, although disturbing to patients and health care workers, do not result in SSI. Wound infections first recognized days following surgery are more likely related to bacterial inoculation that occurred during surgery or in the early hours after wound closure than from wound contamination that occurred beyond 24 h following surgery.

Prophylactic Intravenous Antibiotics

Antibiotics should usually be discontinued within 24 h after surgery, but at the discretion of the surgeon. There is little to no convincing evidence that longer administration is useful in preventing infection of clean wounds. Longer administration of antibiotics after surgery increases risk for the appearance of resistant microbes and raises expense. The use of topical antibiotic-containing ointment in preventing wound infection is discussed in another section.

Pitfalls/Things to Avoid

Cursive Wound Evaluation

A cursive evaluation of post-surgical wounds can delay or miss the recognition of problems that would benefit from attention. It cannot be safely assumed that a wound is in good condition and healing well, regardless of simplicity of surgery, the appearance of a wound at time of closure, or reliability of assessments by patients, families, or other non-professionals.

Infected Wounds

Wounds in Which Infection Is Suspected

Spreading redness, increasing redness, swelling, appearance of drainage, or fever should raise suspicion of infection. The appropriate response for wounds about which there is concern for infection but no convincing supportive evidence is increased frequency of close visual inspection and palpation. Mild suspicion alone is not a sufficient indication for open exploration of the wound or for starting parenchymal antibiotics.

Unexpected Positive Culture of Wound or CSF

An unexpected positive report on a culture obtained as a matter of routine, for example, the surface of cryopreserved autologous bone, occasionally occurs. These reports are often false positives, but assuming false positivity is dangerous and can have serious medicolegal consequences. The possibility that an unexpectedly positive culture report represents infection must always be seriously considered. Wounds should be examined with increased concern for infection. Ventricular fluid should be re-cultured; and, if negative, this is evidence that the earlier culture was probably, not definitely, a false positive. However, some organisms, for example, *Propionibacterium acnes*, may avoid identification across multiple negative cultures, and concern for infection cannot be totally dismissed. A subsequent unexpectedly positive report, even years later, makes it much more likely that low-grade infection is present.

Stitch Abscess

A stitch abscess is the small amount of purulence at the site of penetration of a suture or staple. This becomes apparent during the removal of sutures or staples, and multiple stitch abscess may be present. If there is no associated edema or redness in the region, no treatment is required beyond wiping the area clean with an alcohol prep pad and applying antibiotic ointment. If a suture knot is visible, it should be grasped, clipped with scissors, and removed.

Visibly Purulent Wound

These wounds must be opened for exploration, cleaning, and debridement, followed by a course of intravenous antibiotics.

Wound Infection Overlying Intact Bone

Redness, swelling, increasing tenderness perhaps accompanied by fever and a rising peripheral WBC count over intact bone are strongly suggestive of wound infection. An intact non-suppurating postoperative wound that has evidence of infection confined to soft tissues should be treated with intravenous antibiotics. If there is drainage of pus or suspicion of underlying purulence, the recommendation is for washout. CT or MRI can provide useful information on the existence of infection within bone—i.e., osteomyelitis—and biopsy for culture may be necessary. If the suspicion for osteomyelitis is low, the bone should remain undisturbed but closely followed.

Wound Infection Overlying De-vascularized Bone

A postoperative soft-tissue infection that is overlying de-vascularized bone, for example, recent free bone flap, should be treated with antibiotics alone unless there is drainage or visible purulence. In the latter situation, the wound must be cultured, the bone flap should be removed, scrubbed vigorously, and all soft tissues that were in contact with the bone should be scrubbed, being careful not to injure underlying brain or penetrate the dura. The scrubbed bone flap can then be re-secured in place, the wound closed, and the patient treated with intravenous antibiotics [27]. The existence of pus on the surface of a recently free bone flap is not diagnostic of osteomyelitis and is *not* an indication for discarding the bone.

Postoperative Incisional Pain

Management of postoperative incisional pain reduces patient suffering, improves patient satisfaction, enhances recovery, and improves rehabilitation. It may also shorten hospitalization and thereby reduce hospital cost. Pain following cranial surgeries is less intense than intuitively believed by many physicians and nurses, leading to the common excessive administration of opiates, which increases their risks. The length of a scalp incision and extent of cranial osteotomies are not reliable indicators of pain or gauges for dosing of analgesic medications. Facial edema following craniofacial surgery is not an indication of pain, but it is extremely annoying for patients, particularly periorbital swelling that impairs children from opening their eyes. This contributes significantly to postoperative fussiness and crying, which can be falsely interpreted as caused by pain. The details of management of postoperative incisional pain are not within the scope of this text. However, the neurosurgeon must be aware of the common over-administration of opiates.

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6 Muscle, Fascia, and Mucosa

Ken Rose Winston

Muscle

The word muscle (*Latin musculus: little mouse*) was so named because the movement of muscle brought to mind the movement of a mouse beneath some material.

Healing of Muscle [1, 2]

Muscle heals by regeneration and formation of scar, in three overlapping phases; however, individual muscle cells are post-mitotic and cannot divide.

1. Destruction Phase (Degeneration or Inflammation Phase)
   This phase begins with the disruption of muscle fibers and small blood vessels in the muscle, caused by stretching, cutting, or tearing. Bleeding occurs in the site of injury, myofibrils necrose, and inflammatory cells infiltrate the site.
2. Repair Phase (Regeneration Phase)
   Macrophages arrive and phagocytize necrotic tissue and blood. Satellite cells (resident myogenic stem cells) are undifferentiated cells lying beneath the basal lamina of each myofibril since embryonic development, proliferate in response to trauma, differentiate, and then fuse into multinucleated myofibrils. Fibroblasts become interspersed with myoblasts and muscle fibers in an apparently random tangle of cells, as capillaries grow into the healing site. Several factors released during this phase have important roles in guiding regeneration, and these include hepatocyte growth factor, fibroblast growth factors, transforming growth factor-β,

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insulin-like growth factor, and tumor necrosis factor α. The repair phase reaches maximum activity approximately 14 days from injury.

Drugs that neutralize the expression of TGF-β1, for example, Losartan and Suramin, have been shown in experimental models to inhibit the formation of scar tissue and improve healing in the skeletal muscle [3]. Dexamethasone has been shown in animal studies to slow the inflammatory and repair phases of healing of muscle [4].

3. Remodeling Phase

   Muscle cells mature and, with fibroblasts, take on a linear orientation corresponding roughly to that of intact nearby muscle fibers. It has been shown in animal studies that, when muscle fibers are transected, both ends of the cells often survive and are pulled together by contracting scar to form apparently permanent tendon–muscle–scar–muscle units. Interestingly, axon sprouts penetrate the scar tissue in the site and new neuromuscular junctions form on the denervated muscle fiber stumps [5]. It has not been shown that transected muscle fibers eventually reunite, but it appears that the restoration of myofiber continuity is possible [6, 7].

Surgery of Muscle: General

Muscle should be protected to the extent that is possible and compatible with achievement of the goal of surgery. The functional and cosmetic complications of postoperative muscular atrophy can be severe, and most are avoidable. Muscle can be significantly injured as a result of mechanical trauma, denervation, interruption of blood supply, and from inadequate reattachment to bone. Trauma from surgical dissection, cauterization for hemostasis, and extensive or prolonged muscle retraction can produce necrosis and fibrosis, followed by atrophy.

Surgery on muscles requires surgery on fascia. Incisions in fascia should be straight and parallel to underlying muscle fibers. Survival of muscle fibers and their ability to function require not only protection of bulk but also the preservation of innervation and vascular supply [8]. Extensive dissection of the fascia over the muscles can damage the muscle fibers, disrupt vascular supply, and denervate the muscle. When exposure through a muscle is necessary, blunt dissection/separation of muscle fibers with little or no cutting of muscle fibers—i.e., splitting muscle—minimizes the injury. Gentle hemostasis with bipolar cautery will be required. If incision across muscle fibers is required, it should be made close to the fascial insertion on the bone and therefore perpendicular to the muscle fibers. There is rarely a neurosurgical indication for a transverse or oblique incision across the belly of a muscle.

Muscle tolerates suturing poorly. Muscle that has been separated along a plane parallel to its fibers will be brought snugly together when the fascia is closed, requiring no sutures; however, if there will be an apparent dead space, a few sutures of gut or Vicryl® can be used to obliterate the space. Sutures that tightly encircle muscle fibers cause ischemia and infarction and should be avoided.

Temporalis Muscle

The bipennate temporalis muscle fills the temporal fossa and originates along the inferior temporal line of the frontal and parietal bones. It passes beneath the zygomatic arch and is inserted on the coronoid process of the mandible. This muscle is innervated by branches of the mandibular division of the trigeminal nerve (V3) as they course within the medial aspect of the muscle [9]. The blood supply to the temporalis muscle comes from the deep and middle temporal arteries, which are branches of the maxillary artery. The deep temporal arteries lie superficial to the periosteum and supply blood to the medial side of the anterior and middle regions of the muscle. The middle temporal artery and a branch of the superficial temporal artery pass through the superficial temporal fascia and supply blood to the posterolateral region of the muscle [8, 10].

Surgery of Temporalis Muscle

Plastic Neurosurgical Concerns

- Minimize damage of muscle, its blood supply, and innervation
- Hemostasis
- Restoration of fascia and muscle
- Prevent temporal hollowing

Incision and Reflection

Neurosurgeons should be aware of the undesirable cosmetic and functional outcomes that can follow incision and disconnection of the temporalis muscle from bone, particularly in frontotemporal craniotomies. Many neurosurgical approaches require disconnection of the temporalis fascia and muscle from the bone, leaving a myofascial cuff for closure. This too often results in functional and cosmetic problems due to fibrosis and atrophy to the muscle [8].

A simple longitudinal incision provides exposure of the bone beneath the temporalis muscle for emergent placement of burr holes and a few other indications. A full-thickness vertical incision through the fascia, muscle, and temporalis tendon is made with a single stroke, and a self-retaining retractor is inserted to hold the muscle aside and expose the bone. Closure is relatively simple, consisting of only approximation of the temporalis fascia with 3-0 absorbable sutures.

Reflection of temporalis muscle—Temporalis muscle can be reflected via subgaleal dissection, or the muscle can be reflected with the scalp. Reflecting scalp as an independent layer has some risk of injury to frontal branches of the facial nerve [8, 10, 11]. Other techniques include interfascial and subfascial dissections, both of which include risk of injury to branches of the facial nerve (VII) and require dissection on both the medial and lateral sides of the temporalis muscle and the leaving of a myofascial cuff (see below). Subfascial dissection increases the risk of injury to the lateral surface of the muscle [12] and produces some intramuscular bleeding. A myocutaneous flap, which requires dissection only on the medial side of the temporalis muscle, preserves the frontal branches of the facial nerve but may provide suboptimal exposure.

Unless the entire temporalis muscle is to be reflected (an uncommon requirement), the reflection of temporalis fascia and muscle requires two actions. The first is an incision coursing vertically through fascia and muscle, and the second is disconnection of the upper end of the fascial and muscular origins from the bone.

The v*ertical myotomy* is made at the posterior extent of the required surgical exposure of the bone and extends from the superior temporal line down to the zygomatic arch in a plane parallel to muscle fibers. This incision injures some muscle fibers and can cause partial denervation; however, oblique myotomies are much more destructive [9].

Disconnecting Edge of Temporalis Muscle

Technique 1
The upper edge of the junction of temporalis fascia to the bone and pericranium is severed, using a microneedle cautery and periosteal elevator, along the superior temporal line. This does not require the incision of the muscle whose attachment begins at the inferior temporal line and does not leave a myofascial cuff. This is the author's preferred technique, but restoration is more complex than that required for technique 2.

Technique 2
The temporalis fascia and temporalis muscle are incised in a curved line 10–12 mm below the superior temporal line, leaving a myofascial cuff attached to the bone [13]. This is the most popular technique, but the surviving myofascial cuff too often has insufficient strength to allow secure approximation and alignment. It often results in suboptimal cosmetic restoration, delayed separation, and temporal hollowing, especially over the keyhole region.

Technique 3
The temporalis fascia and temporalis muscle are incised transversely across the belly of the muscle. Transverse incision across the temporalis muscle a few centimeters below its insertion does make closure easier but will denervate and partially devascularize the muscle above the incision and result in its atrophy. Strong consideration should be given to avoiding this incision.

Disconnecting Muscle from Underlying Bone
Disconnection of the temporalis muscle from the underlying bone is relatively easily accomplished with a periosteal elevator, but the way in which this is done has cosmetic consequences. This is usually done by dissection from the upper edge of the muscle down toward the zygoma, but retrograde dissection of the temporalis muscle beginning is reported to cause less damage to the muscle and therefore less postoperative atrophy [14].

Disconnecting Fascia and Muscle from Lateral Rim of Orbit
The temporalis fascia and muscle are separated anteriorly from the orbital rim with microneedle electrocautery. Because some of the muscle in this location has an

overlying rim of the bone, it may be tempting to incise through the muscle. This temptation should be avoided because the disconnected muscle will undergo atrophy. The lowest power setting of the cautery that efficiently accomplishes the task should be used. High-power settings with a flat cautery tip may allow more rapid dissection with almost no bleeding but cause unnecessary and unacceptable damage to the muscle.

Retraction

After being separated from its bony origin, the temporalis muscle is retracted firmly downward, Lengthy periods of tight compression or retraction over the zygoma will damage the muscle and cause postoperative atrophy. Retraction along a straight vertical myotomy, for example, for placement of a burr hole, requires only separation of muscle fibers with a self-retaining retractor.

Restoration

Satisfactory reconstruction requires that the defect in the bone, including the burr hole, has been closed with no significant residual deformity. The techniques for incising and reflecting the temporalis muscle strongly influence restoration. Temporalis muscle, if left unattached or poorly restored, contracts downward following surgery, causing visible postoperative depression below the inferior temporal line and protrusion in the supra-zygomatic region of the temporal fossa, which is more apparent during mastication and can impair wearing of glasses. Cosmetic defect following restoration after frontotemporal (pterional) craniotomy has been recognized for many years as problematic, and there is not a consistently reliably technique for its avoidance. Optimum restoration requires survival of the nerves, arteries, and muscle fibers followed by reliable reattachment of the muscle to the bone. Several techniques have been described, and none are consistently satisfactory.

Alignment of the temporalis muscle with reestablishment of approximately normal tension is an essential component of reconstruction of temporalis muscle, particularly after pterional craniotomy [15]. The flap of the temporalis muscle and fascia is returned to its normal position and sutured to the musculofascial cuff if present and will hold sutures. It is important that the upper edge of the temporalis muscle be included in these sutures to prevent downward drift of the muscle during healing. If the fascial cuff across the intact frontotemporal bone is not present or insufficient to hold sutures, the muscle must be directly attached to the bone [8]. This requires that four or five pairs of holes be obliquely drilled along the superior temporal line and used to secure the temporalis fascia and muscle with 2-0 absorbable sutures [16]. If the patient will soon receive chemotherapy or radiation, nonabsorbable sutures should be used [11]. Another technique for securing muscle requires the placement of several partially advanced microscrews 6–8 mm below the superior temporal line and suturing the flap to these screws; however, these screws may become palpable or visible cosmetic defects after swelling subsides [17].

The anterior edge of the temporalis muscle must be brought against the rim of the orbit, and this often requires two or more sutures through small holes drilled in the orbital rim. After reattachment of the fascia and muscle as far anteriorly as possible along the temporal lines, the anterior edge of the temporalis muscle, depending on extent of surgical separation of the muscle from the bone, may not lie against the lateral orbital rim or may not have correct edge alignment. The temporal fascia with some muscle fibers must be snugly attached to the edge of the orbit, and this requires drilling of two or three small holes in the bone for passage of 3-0 Vicryl® sutures.

Dealing with Insufficient Temporalis Muscle

If there is insufficient temporalis muscle at the time of closure to provide sound coverage of the keyhole area, whether resulting from recent surgery, prior craniotomy, radiation, or advanced age, coverage can be accomplished by shifting the attachment of the temporalis muscle forward by 1–2 cm. This requires making a vertical incision in the temporalis muscle, if not already existing, in a line parallel to its fibers, beginning 4–6 cm from the anterior edge of the muscle and extending the incision downward near the zygomatic arch. When this flap of muscle is shifted anteriorly and secured along its upper edge, there will be a gap in the muscle at the site of the vertical myotomy, but no attempt should be made to stretch these edges of muscle together. Ignoring this gap does not cause a significant functional or cosmetic defect [16]. If the muscle is not advanced or poorly attached to the bone, there will be significant hollowing in the temporal region after healing occurs and edema recedes.

Closure of Longitudinal Fasciotomy/Myotomy

If anterior advancement of the temporal muscle is not required, the muscle fibers from the vertical myotomy are usually in close approximation and require no sutures after reattachment of the fascia and muscle along the superior temporal line. The lower 1.5–2 cm of the temporalis tendon, which is in the center of the bipennate muscle, can be approximated with a few interrupted sutures. This is nowadays rarely done. The edges of the vertical faciotomy should be approximated with interrupted 3-0 (4-0 in infants) Vicryl® sutures, but attempt should be made to encircle little if any muscle fibers.

Temporalis Muscle Hernia

This is an uncommon postoperative complication resulting from a gap, usually vertical, in the temporalis fascia overlying the belly of the temporalis muscle. Chewing causes the muscle to repeatedly bulge through the fascial defect, causing local pain on mastication. The site of the herniated muscle can usually be identified by palpation as the patient contracts the temporalis muscle. The pain can be alleviated by repair of the fascial defect.

Platysma Muscle

The platysma muscle is a thin broad superficial muscle of the anterior neck, with innervation from the cervical branch of the facial nerve. It is attached inferiorly to the fascia over the pectoralis and deltoid muscles and to the subcutaneous tissue. Superiorly it is inserted into the cheek, facial modiolus, orbicularis oris, and the lower border of the mandible. It is innervated by the cervical branch of the facial nerve (VII) and is one of the muscles of facial expression.

Surgery of Platysma Muscle

Plastic Neurosurgical Concerns

- Linear splitting and retraction
- Minimize damage to muscle
- Restoration

Incision

A muscle splitting incision with undermining on each side usually provides satisfactory exposure and allows preservation of platysma.

The platysma can be very thin in older adults, and care must be taken to prevent unintended transection or damage during skin incision and dissection. It is rarely necessary to transversely cut this muscle to acquire surgical exposure. Transverse and oblique incisions through muscle damage and denervate that portion of the muscle that lies caudal to the transection. Some surgeons routinely cut the platysma muscle transversely or obliquely for anterior surgical approaches. This causes unnecessary cosmetic abnormality, and most, if not all, of these surgeries can be done with preservation of platysma.

Restoration

A longitudinal incision in the platysma muscle is easily repaired with minimal denervation or injury of vascular supply and therefore minimal loss of bulk or function. The edges of an incised platysma muscle should be approximated with interrupted 3-0 or 4-0 absorbable sutures.

Posterior Cervical Muscles

Occipital muscles are attached to the squamous occipital bone over the nuchal planum (area below the superior nuchal line) and include the semispinalis capitis, rectus capitis posterior minor and major, and several smaller muscles. The splenius capitis, trapezius, and occipitalis muscles are attached along the superior nuchal line. These muscles are surgically managed as a group, and most are not individually identified in surgical approaches. Semispinalis capitis is innervated by the greater occipital nerve, the suboccipital muscles by the suboccipital nerve, and the trapezius muscle by the spinal accessory nerve (XI).

The *superior nuchal line* extends laterally along a ridge from the external occipital protuberance and is the site of attachment of trapezius and sternocleidomastoid muscles. Occipitalis muscle is attached a few millimeters higher to the highest nuchal line, whose ridge is not always distinguishable from the *superior nuchal line*.

The *posterior nuchal ligament* is attached superiorly to the occipital bone from the external occipital protuberance and down along its midline of the occipital bone to the posterior tubercle of the atlas and attached inferiorly to the spinous processes of the cervical vertebrae down to C7, thereby forming a fibrous midline septum between the posterior cervical muscles [18].

Surgery of Posterior Cervical Fascia and Muscle

Plastic Neurosurgical Concerns

- Disconnection of the fascia and muscle from bone
- Minimize damage to the muscle and fascia
- Hemostasis in the muscle
- Restoration of the fascia and muscle

Incision and Reflection

Midline incision—Starting just below the superior temporal line, a midline incision is made with a scalpel through fascia and muscle, along the nuchal ligament. This incision is made through the full thickness of the muscle to the median nuchal ridge on the occipital bone and extends downward across the posterior arch of C1 vertebra. Depending on required exposure, this incision is often along the sides of the posterior processes of C1–3.

Occipital muscles are separated in the midline along the posterior nuchal ligament and retracted laterally with self-retaining retractors. Often the fascial connection of the muscles to the occipital bone becomes disconnected by the force of lateral retraction or by surgical incision of the fascia.

Transverse incision along or below superior line—A transverse incision, beginning 8–10 mm below the superior nuchal line, is made through fascia and a small amount of the muscle or the fascial and muscular attachments may together be separated from bone, using a periosteal elevator. For most midline surgical approaches, only 2–4 cm of separation from the bone is required.

Paramedian muscle splitting incision—A full-thickness vertical incision, beginning near, or possibly above, the superior nuchal line is made downward over the occipital bone toward the posterior-lateral edge of the foramen magnum. Some surgical exposures require further downward extension; however, care must be exercised to avoid injury to the vertebral artery. If exposure is required into the upper posterior fossa or above the tentorium, it will be necessary to separate the musculofascial attachments along the superior nuchal line, using a periosteal elevator.

Restoration

Restoration of the posterior cervical muscles after surgery in the posterior fossa or high cervical spine is important to reestablish normal function, for cosmesis, and to assist in preventing leakage of CSF from a durotomy. Reattachment of the posterior cervical muscles to the nuchal planum (area below the superior nuchal line) of the occipital bone can be difficult but is necessary to restore normal function and to minimize cosmetic defect. The usual rigid flexion of the neck commonly makes sufficient stretching of muscle impossible. If a myocutaneous cuff is present and there has been less than 1.5 cm of separation along the superior nuchal line, it may be possible to achieve satisfactory approximation of the fascia to the cuff with 2-0 Vicryl® sutures.

If the posterior cervical muscles and fascia cannot be approximated, as commonly the case, it will be necessary to reduce the cervical flexion. This requires that the surgeon firmly hold the head while an assistant goes under the drapes to loosen the head holder and allow the surgeon to extend the neck. The assistant then tightens the head holder. This allows the posterior cervical fascia and muscle to be sutured to the myofascial cuff or to newly drilled holes in the bone.

The posterior cervical muscles will lie in contact across the midline after the fascial closure across the superior temporal line is completed. These muscles must be brought snugly together in three or four layers of 2-0 Vicryl® (3-0 in young children). Posterior cervical fascia must be closed tightly with the same sutures. In almost all closures, there is difficulty in approximating the superior edges of the fascia and muscle, and this is often the site of egress of CSF.

If the surgery included a durotomy, CSF may accumulate beneath the muscle mass, find a path between the two muscle masses, and leak through a seemingly well-closed myotomy-fasciotomy, regardless of the technique for closing the posterior cervical muscle.

Paraspinous Muscles

The paraspinous muscles constitute a large mass extending from the occiput to the sacrum. While their functions are extremely important for erect posture, flexion, extension, rotation, and lateral movements of the spine, their individual identification is rarely mentioned in neurosurgical practice. However, their attachments to the bone, particularly vertebrae and occiput, are often disrupted to achieve surgical exposures.

Surgery of Paraspinous Muscles

Plastic Neurosurgical Concerns

- Linear dissection
- Minimize damage to the muscle
- Hemostasis in the muscle
- Restoration

Incision and Retraction

Incisions in the fascia should, with few exceptions, be made longitudinally in line with the fibers of underlying muscle. Transverse or oblique incisions, should be avoided because of difficult in closure.

Paraspinous muscle fibers have an oblique course that is not precisely parallel to midline and rarely correspond to the required plane of dissection for surgical exposure. An attempt should be made to bluntly dissection in a generally longitudinal direction with respect to muscle fibers and minimize the cutting of muscle; however, it is usually necessary to cut some of the muscle mass when separating the muscle from the bone. Fascia and muscles are retracted aside with self-retractors after their connections to spinous processes and laminae are disconnected.

Restoration

Paraspinous muscles come into contact with spinous processes when retractors are removed or, if spinous processes have been removed, with the contralateral paraspinous muscles. These muscles contracted when they were disconnected from the bone and fascia, but no attempt is made to realign paraspinous muscles to their precise original sites of insertion. Paraspinous muscles must be snugly approximated to contralateral muscles or interspinous ligaments with two or three layers of interrupted 2-0 absorbable sutures (3-0 in infants and subteen children). Practice varies regarding the amount of muscle grasped with each stitch and regarding the tightness of tying. Tightly tied sutures cause infarction and scarring of the encircled muscle. Grasping large amounts of muscle and tying less tightly are thought by many surgeons to assist hemostasis and, if dura has been opened, reduce the risk of CSF leakage. The author prefers to grasp of moderate amounts of muscle with each suture and avoid tightly tying sutures. It is reasonable to believe that all sutured muscle will undergo some swelling in the postoperative period, which will increase the injury to the encircled muscle.

The closure of the dorsal fascia assists in the restoration toward normal paraspinous muscle anatomy and is therefore important.

Other Muscles

Neurosurgeons encounter and retract other muscles during surgeries, for example, the sternocleidomastoid muscle in anterior cervical approaches and various muscles of the extremities in the course of peripheral nerve surgeries; however, these muscles rarely require manipulation beyond retraction and therefore will not be described.

Fascia

Fascia (*Latin: band*) is a sheet of dense connective tissue, composed primarily of elastic collagen. The deep fascia, also known as the investing fascia, envelops, isolates, and supports muscles like an elastic sheath. Deep fascia also provides sheaths for tendons and the origins and insertions of muscles. The support provided to the muscles strongly influences their shape and contributes to the transmission of force [19].

The anatomy of the temporal fascia has special plastic neurosurgical importance. It has dense attachment superiorly to the pericranium along the superior temporal line. Inferiorly it is split into two layers, with the lateral and medial layer attached respectively to the lateral and medial sides of the zygomatic arch.

Healing of Fascia

There exists no clinical scale for healing of fascia; it either heals or does not. Based on animal studies, fascial wounds develop greater fibroblast cellularity and production of collagen than do dermal wounds, and fascial wounds are thought to heal faster [20].

Surgery of Fascia

Plastic Neurosurgical Concerns

- Incise in line parallel to fibers
- Minimize damage
- Repair

Fascia tolerates suturing extremely well; however, incisions should be made in a line parallel to the fibers of the fascia because of ease in closure. Incisions with other orientations can be difficult to close because of the tendency of sutures to tear free.

Dorsal fascia is closed with 2-0 Vicryl® (3-0 in infants and young children). If dorsal fascia has been harvested for repair of the dura, as occasionally required in some surgeries, it may be necessary to leave a portion of the faciotomy unrepaired.

Mucosa [21–30]

Anatomy

Mucosa is a membrane that lines all body cavities and all canals that lead to the outside surface of the body, including the respiratory, digestive, reproductive, and urogenital tracts. Most of the mucosal surface of a human is in the gastrointestinal tract, with its total surface exceeding that of skin (approximately 2 m^2).

Nasal mucosa lines nasal cavities and is adherent to the periosteal and perichondral surfaces [31]. Nasal mucosa is continuous with the skin through the nares and with the mucous membranes of the pharynx, conjunctiva, and the paranasal sinuses. There are two types of nasal epithelium: respiratory and olfactory. Respiratory epithelium has columnar ciliated cells with scattered mucin (goblet) cells, whose ducts are open to the mucosal surface. Basement membrane lies over a layer of fibrous tissue. The olfactory epithelium is yellowish in color and covered by non-ciliated columnar cells. The olfactory cells are bipolar and are distributed through the olfactory epithelium. Each olfactory cell has one superficial process and one thin process (olfactory hair) that extends to the surface of the mucous membrane and a deep process, which is an axon of an olfactory nerve [32].

Oral mucosa is composed of a surface layer of stratified squamous epithelium and a deeper layer, the lamina propria, composed of loose connective tissue. Nonkeratinized mucosa covers the buccal surface, soft palate, floor of the mouth, including the ventral surface of the tongue. The replacement time for surface cells of oral mucosa is approximately 20 days or about twice that of skin.

Functions of Nasal and Oral Mucosa

Mucosa keeps the oral and nasal surfaces moist and warms and humidifies air flowing through the nasal cavity. Goblet cells along the nasal cavity secrete mucous into a watery film onto the epithelial surface where the cilia of the epithelium produce directional flow of fluid over its surface by coordinated beating of the cilia. This removes bacteria and any particles that have become trapped in mucous. Oral mucosa protects the deeper tissues from mechanical injury from chewing and abrasion by hard food particles in the mouth, and also impairs bacterial entry of organisms in the mouth into the underlying tissues.

Flora of Mucosa

The surfaces of the air sinuses in asymptomatic individuals are commonly sterile, but this is not always true [33, 34]. When the sinus mucosa is encountered, it is always reasonable to irrigate with an antibiotic-containing solution.

The normal oral microbiome includes bacteria, fungi, viruses, archaea, and protozoa. There are over 700 species of bacteria, almost half of which are unnamed. Many of the bacteria in the oral cavity are resistant to the host's immune system and potentially virulent. Normal resident organisms of the oral microbiome adhere tightly to the teeth and gingiva, forming a biofilm. Pathogenic species are thereby not allowed to adhere to the oral mucosa [35]. Bacteria of the biofilm are difficult to remove by brushing.

> *Antony van Leeuwenhoek, while examining material from his own mouth in 1665, was the first to observe bacteria and described them as "… little living animalcules, prettily a-moving."* [36]

Paranasal sinuses are usually sterile under normal physiologic conditions; however, a few colonies may be cultured. Fungi are also a component of normal microflora of both the nose and paranasal sinuses. *Staphylococcus aureus* is present in approximately 70% of hospital employees [31].

Healing of Mucosa

The healing of oral mucosa goes through similar stages as does the healing of the skin but occurs much faster and with less scarring [37]. A tissue factor in salivary exosomes strongly accelerates the clotting of blood. Growth factors in saliva, particularly epidermal growth factor, promote the proliferation of epithelial cells, and secretory leucocyte protease inhibitor plays an important role in accelerating the healing process.

Histatin plays an important role in several phases of wound healing, including the promotion of the migration and adhesion of different cell types in both oral mucosa and non-oral tissues. It is histatin-1 that promotes the re-epithelialization phase of healing and thereby increases epithelial and endothelial cell migration [38].

The healing of respiratory mucosa is well summarized by AG Boule [31]. Trauma without disruption of the basal membrane usually heals rapidly, whereas the healing of wounds that include disruption of the basal membrane may require weeks or months [39].

Deep mucosal wounds heal with a variable amount of scar formation. Most healing of respiratory mucosa occurs within 3–6 months, but completion of remodeling may continue for 12 months.

Surgery of Mucosa

Elective incisions in mucosa of the mouth, nasopharynx, or oropharynx are occasionally required in elective neurosurgical and craniofacial surgeries. Mucosal disruptions are also encountered in patients with facial trauma and in some surgical complications.

Plastic Neurosurgical Concerns

- *Minimize* damage
- Hemostasis
- Repair

Anesthesia of Mucosa

See discussion in “Anesthesia” in Chap. 2.

Incising Mucosa

Oral mucosa can be incised with a #15 blade or with needle electrocautery, although the latter may cause more tissue damage.

Closing Mucosa

Intraoral incisions should be primarily closed whenever possible. Small puncture wounds can be left to close secondarily. Resorbable suture such as 3-0 chromic is ideal for closing intraoral mucosa and also for closing intranasal mucosa; these sutures may be allowed to spontaneously slough. Mucosa can be closed with various types of suturing techniques. A traditional running locking suture, mattress sutures, or interrupted sutures may be used. When possible, having a watertight closure is ideal to prevent leakage of saliva into the wound. Knots should be tied with four throws because the frequent automatic massage of the saliva-covered sutures by the tongue and buccal mucosa tends to untie them. Saliva greatly accelerates the failure rate of absorbable sutures [40].

Oral mucosal wounds frequently dehisce. These separations can be managed with oral rinses of Peridex™ (0.12% chlorhexidine gluconate) three times per day, and they usually heal well. Peridex™ can cause yellow staining of the teeth and oral mucosa.

Mucosal Disruption

Mucosal disruptions of neurosurgical concern occur from elective, traumatic, and iatrogenic causes.

Elective Disruption

Some elective neurosurgical approaches require disruption of the nasal and oral mucosae and mucosa of the air sinuses. Examples include fronto-nasal and fronto-ethmoidal approaches for repair of encephaloceles, management of CSF rhinorrhea through the cribiform plate, subcranial craniotomy for tumor in the floor of the frontal fossa and nasal pharynx, trans-sphenoidal approach to the sella turcica, and transoral approach for transclival surgery.

Craniofacial Surgeries—Mucosal disruption occurs from the craniotome in the course of making an osteotomy across the frontal sinus. The mucosa of the frontal sinus is blindly torn by the spinning bit of the osteotome. Most other surgical incisions in mucosa of the nasopharynx are accomplished with a small scalpel, electrocautery with a microneedle, or less often, with the sharp edge of a small osteotome.

Nasal and oral mucosa are encountered during surgeries for midface advancement, orthognathic surgery, and repair of LeFort osteotomies and fractures. Access starts with a transmucosal maxillary vestibular incision, the anterior portion of the maxilla and the piriform aperture are subperiosteally exposed. If orthognathic surgery is required, the nasal mucosa is dissected from the piriform apertures and the floor and lateral wall of the nasal cavity and from both sides of the bony nasal septum. The mucosa along the nasal floor can be repaired with a resorbable suture such as 3-0 chromic. The disrupted mucosa of the maxillary sinus will usually heal without complications.

Postoperative complications related to the maxillary sinuses are primarily limited to infection caused by inadequate drainage or open fistulas. Although many patients experience drainage and some sinus symptoms in the immediate postoperative period, true perioperative infections of the sinus or long-term sinusitis are rare. Between 2 and 6 months after surgery, there will be normalization of the bony and soft tissue structures in most patients. Potential causes of infection in the sinus are the formation and retention of large blood clots, preexisting disease, dental infection secondary to trauma to the teeth, soft tissue ischemia, and debris within the sinus. Materials used during fixation of fractures such as wires, bone plates, or screws are rarely the isolated cause of a sinus infection and do not increase the incidence of infection after panfacial surgery[8 (240–242)].

Complications can occur during open transnasal approaches, similar to endoscopic sinus surgery. CSF leak is a low risk when operating along the ethmoid bone. If recognized intraoperatively, it should be repaired immediately. The most common complication after transnasal surgery is the formation of synechiae, which may be asymptomatic but can result in nasal stenosis and obstruction. Postoperative use of nasal saline spray and decongestants will ameliorate temporary obstruction from edema.

Disruptions of mucosa overlying the surface of the cranial bone, for example, posterior wall of frontal sinus, ethmoid sinuses, roof of the nasal, and oral pharynxes, usually heal well unless widely stripped from bone.

Submental intubation—Submental intubation is an alternative to nasal intubation and tracheostomy and is indicated for intraoperative intermaxillary fixation in the presence of injuries that preclude nasal intubation and, in a situation, where a tracheostomy is not otherwise required. Anterior and middle cranial fossa skull base fractures frequently coexist with facial fractures and are sometimes a contraindication to the use of a nasal tube because of the small but significant risk of intracranial penetration. The presence of a nasal tube can interfere with access to the surgical site particularly when trying to repair fractures of the nasoorbitoethmoidal complex (NOE), intranasal mucosal lacerations, and procedures using a coronal flap when the nasal bones must be exposed.

Iatrogenic Disruption

Esophagus—The esophagus must be carefully protected during surgical procedures in the anterior cervical region, for example, surgeries on the cervical spine, carotid endarterectomy, and implantation of vagus nerve and phrenic nerve stimulators. Accidental penetration of the esophagus during a neurosurgical procedure can occur, and this may not be recognized until hours or even days after surgery. Such delays greatly increase the risk of serious infectious consequences. Consultation by a general surgeon should be requested as soon as penetration is suspected.

Pharynx—The mucosa of the nasal pharynx is electively entered in transsphenoidal surgeries but can also be disrupted by trauma and by tumors penetrating the floor of the frontal fossa. Incision in the mucosa of the oral pharynx may be required in transclival surgery, midface advancement, and facial bipartition.

Intestinal tract—Penetration of the small or large bowel, more often the latter, can occur during a CSF shunt insertion or revision and some anterolateral approaches to the spine. This may not be recognized until hours or even days after surgery. Such delays greatly increase the risk of grave consequences. This complication is at greatest risk during repeat surgeries, when the bowel may be firmly adhered to the anterior wall. Consultation with a general surgeon should be requested immediately when perforation is recognized or suspected.

Penetration of roof of nasal cavity by nasogastric tube—The insertion of a nasogastric tube can penetrate the mucosa of the roof of the nasal cavity, particularly if done forcefully or with a stiff tube in a small nasal passage. This may cause bleeding that will cease spontaneously, and the mucosa will heal with no intervention. A patient who has undergone disruption of the bony roof of the nasal pharynx (floor of anterior fossa) is at risk of penetration of that roof during an attempt to insert a nasogastric tube. This can have grave consequences of brain damage, hemorrhage, and infection, particularly if not recognized early.

The angle of insertion of a nasogastric tube strongly influences both its ease of insertion and the risk of injuring the mucosa of the nasal vault. Directing the tube in a near straight posterior direction along the floor of the nasal cavity is relatively safe, whereas initially passing it upward from the nares brings its tip into direct contact with the roof of the nasal pharynx.

Urinary bladder—The bladder can be accidently entered/punctured during intraperitoneal insertion of a CSF shunt. Consultation by a urologist or general surgeon should be requested immediately when perforation of the bladder is recognized or suspected. Delay in consultation can have grave consequences.

Traumatic Disruption

Frontal and frontonasal fractures—The frontal sinus is typically absent at birth, and its development is complete at about age 15 in most individuals. Therefore, fractures involving the frontal sinus are less common in children. The size and shape of the frontal sinus vary widely. All of the air sinuses are lined with mucosa composed of pseudostratified columnar ciliated respiratory epithelium covered by a layer of mucin. If the nasofrontal duct becomes obstructed as a result of a fracture, a mucocele may develop and act as an expanding mass, and surgery is required. Early complications include epistaxis, CSF leak, frontal sinusitis, meningitis, intracranial hematomas or intracranial abscess, empyema, or cavernous sinus thrombosis. Late complications, which can occur 6 or more months after initial injury, include mucocele, mucopyoceles, late frontal sinusitis, brain abscess secondary to frontal sinus infection, frontal contour defects, or osteomyelitis of the frontal bone. The goal of surgery in the management of fractures of the frontal sinus is to prevent short and long-term complications and to restore facial contour [6].

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Cranial Bone: Anatomy and Healing

7

Ken Rose Winston

Anatomy of Cranial Bone

Bone is a living tissue with many dynamic functions. It is a solid biological material with excellent compressive and tensile strengths, which give rigid support for the body and allow locomotion. The cranial vault and vertebrae surround and provide protection to the central nervous system. Cancellous bone is the site of production of red blood cells. Bone also has a key role in the body's homeostasis, particularly in calcium and phosphate metabolism. Specialized cells, osteoblasts, osteoclasts, and osteocytes influence the formation and contouring of bone throughout life. Normal bone is approximately 20% water by weight, 30–35% organic material, and 65–70% inorganic. The extracellular component of the bone is composed of an organic matrix that is 90% type I collagen, which provides tensile strength, and a calcium-phosphate salt component called hydroxyapatite, which provides compressive strength.

Growth of Bone

Bone does not enlarge or expand by adding to its internal structure but grows by the accretion of a new bone onto the surface of the existing bone. Bone is constantly remodeled throughout life in an ongoing process in which osteoblasts are responsible for the formation of a new bone and osteoclasts for resorption of the existing bone. See excellent summary by Florencio-Silva et al. [1]. Growth of the cranium in the first 2 years of life is primarily development of the bone along the edges of the existing bone at the sites of sutures as they are separated by expansion of the growing brain. After 2 years of age, a great portion of cranial growth occurs from

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appositional growth over the external surface of the bones combined with resorption of the bone on their inner surfaces [2]. This also accounts for the progressive change of their radii of curvature.

Osteoblasts [1]

Osteoblasts are the cells that synthesize bone. They are large cells of mesenchymal stem cell origin that undergo a process of maturation in which several genes influence their differentiation and proliferation. The blood supply of the primitive tissue that will develop into a bone is the probable determinant of whether the primitive tissue will become cartilage-forming chondroblasts or osteoblasts. Osteoblasts exist within the periosteum/pericranium over the surface of the bone. Osteoblasts produce alkaline phosphatase, cross-linked collagen, and several hormones, which bring about the formation of an osteoid. As bone forms from the osteoid, osteoblasts become enclosed in the lacunae and are then known as osteocytes. Osteocytes typically retain contact with one another by way of cytoplasmic processes extending through canaliculi in the bone, and they remain linked via tight and gap junctions. It is thought that clusters of osteoblasts are required to produce bone and that single osteoblasts cannot do so.

Osteoblasts secrete a substance that interferes with differentiation and activation of osteoclasts and therefore also have a role in the regulation of bone resorption. Also, leptin, a hormone produced by adipocytes, binds to osteoblasts and impedes their osteogenic activity.

Osteoclasts [1]

Osteoclasts are large multi-nucleated cells of mesenchymal origin that exist on the surface of the bone, including endosteal surfaces, and actively remodel the bone by resorption. They are thought to derive from the fusion of multiple macrophages, and they move over the surface of the bone in response to chemotaxis. The edges of these large cells fuse to the underlying bone, and their contact surfaces then release hydrogen ions, which acidify and dissolve the underlying mineralized bone. Cathepsin K, a collagenolytic material, is also released on the undersurface of osteoclasts and actively degrades the underlying dense type 1 collagen strands present within the bone. The activity of osteoclasts is significantly influenced by molecules released by nearby osteoblasts and by parathyroid hormone.

Types of Bone

Cortical Bone

Cortical bone, compact or lamellar, exists on the surface of all bones and provides the mechanical strength of the bone. The primary structural units are osteons, which contain Haversian canals within which are blood vessels and nerves.

Cancellous Bone

Cancellous bone or trabecular bone is a relatively loose matrix of low density, surrounded by cortical bone. Trabeculae tend to be perpendicularly oriented to cortical surfaces. This type of bone resides within the middle portion of most bones of the body and is the site of hematopoiesis.

Woven Bone

Woven bone exists during embryonic development and during healing of fractures and will be replaced with either cancellous or cortical-type bone.

Embryology [3]

The craniofacial skeleton can be considered in two parts, the neurocranium and the viscerocranium. The neurocranium is the vault that encases the brain, and the viscerocranium is the bony face. The bones of the craniofacial skeleton are joined by synarthroidal joints, except for the mandible, which is a ginglymoarthrodial joint *(Greek—hinge + gliding)* joint. Sinuses lighten the weight of the skull and contribute to resonance and warming of air flowing through the nose.

Neurocranium

The neurocranium or brain box has two components, a membranous portion formed by *intramembranous ossification*, and a cartilaginous portion, formed by *endochondral ossification*.

Membranous Neurocranium

A process called morphogenic sequencing (intramembranous ossification) forms the flat frontal and parietal bones, squamous parts of the occipital and temporal bones, lacrimal bones, and nasal bones. These bones originate from cranial neural crest cells. Within the connective tissue capsule surrounding the primitive brain and near the center of each of these regions, certain mesenchymal cells cluster, differentiate into osteoblasts, and form centers of ossification. These osteoblasts secrete osteoid, a material that quickly becomes mineralized, and bony spicules then spread outward from each center of ossification. First osteoid and then bone form around small blood vessels, thus accounting for trabeculae throughout the developing bone. Osteoblasts become densely distributed over the outer and, to a lesser extent, inner surfaces of the individual bones, and these regions become progressively more solid with the laminar deposition of bone. Trabeculae persist within the center of the bones, and the vascular tissue in the spaces between the trabeculae becomes bone marrow.

Growth of Neurocranium

Most enlargement of the cranial vault occurs at the cranial sutures and fontanelles in response to centrifugal force against the dural envelope, regardless of the cause but normally in response to growth of brain. Osteoclastic activity over the inner bony surface of the cranium also contributes importantly to expansion and recontouring of the vault. A combination of osteoblastic and osteoclastic activity increases the radius of curvature of the membranous neurocranium and exerts a remodel effect on the chondrocranium. The cranial base grows significantly more slowly after birth than does the cranial vault.

Pericranium

Mesenchyme on the outer surface of newly formed cranial bone condenses to form periosteum, hence pericranium. The inner layer, the cambium, is composed of a looser collagenous tissue with many osteoblasts in contact with the bone. This layer is relatively thick in newborns and infants but becomes progressively thinner with age [4]. The outer layer of the pericranium is composed of collagenous and fibroelastic tissue and contains blood vessels and nerves, which enter the cortical bone via Volkmann canals. Small fibrous bundles, Sharpey's fibers, attach the outer layer of the pericranium to the bone, most prominently at the cranial sutures [5, 6].

Chondrocranium

The base of the skull is formed by *endochondral ossification*, as is true for all other bones in the body, except clavicle. Bones in the floor of the cranial vault include the cribriform plate, sphenoid bone, petrous portion of the temporal bone, and clivus portion of the occipital bone. Cartilage anterior to the sella turcica is derived from neural crest cells, and cartilage posterior to this structure is derived from paraxial mesoderm. Mesenchymal cells in these regions differentiate into chondrocytes, which produce an avascular cartilaginous matrix. Later as this matrix is invaded by vascular tissue, cells differentiate into osteoblasts, which slowly replace the cartilage with bone.

Viscerocranium

The viscerocranium, or skeleton of the face, is derived from embryonic pharyngeal arches and has two components, the *membranous viscerocranium* and the *chondral viscerocranium*. The facial skeleton supports the structures of the face.

Membranous Viscerocranium

The maxilla, zygomatic bone, palatine bone, vomer, and squamous part of the temporal bone are derived from intramembranous ossification of the maxillary (dorsal) part of the first embryonic pharyngeal arch. The central part of the *mandible* is formed from the mandibular (ventral) part of the first pharyngeal arch, also by membranous ossification.

Chondral Viscerocranium (Splanchnocranium)

The first two pairs of embryonic pharyngeal arches give rise to a cartilaginous skeleton that will form the face. The first arch forms the malleus. Bones of the middle ear and styloid process are formed from the second arch. The ossicles are the first fully ossified bones in the body. The mandible develops from both intramembranous and endochondral ossification. The section between the mandibular and mental foramina develops from intramembranous ossification, but the coronoid and condylar processes develop by endochondral ossification. Each arch is associated with a cranial nerve, an artery, muscles, and skeletal structures. Pharyngeal arches 3 through 6 will not be addressed. Derivatives of the first and second pharyngeal (branchial) arches are as follows:

First Pharyngeal Arch (Mandibular) Derivatives

Nerve	maxillary and mandibular division of the trigeminal nerve
Artery	maxillary artery
Muscles	temporalis, masseter, pterygoids, mylohyoid, anterior belly of digastric, tensor veli palatine, and tensor tympani
Bone and cartilage	incus, sphenoid ale, mandibular or Meckel's cartilage, maxilla, zygoma, squamous portion of temporal bone, and mandible

Second Pharyngeal Arch (Hyoid) Derivatives

Nerve	facial nerve
Artery	stapedial artery
Muscles	orbicularis oculi, orbicularis oris, risorius, buccinators, platysma, frontalis, stapedius, posterior belly of digastric muscle, and stylohyoid muscle
Skeleton	stapes, styloid process, stylohyoid ligament, and upper portion of the body of hyoid bone

The face is formed by five mesenchymal processes or prominences produced by the proliferation of neural crest cells that migrate into the pharyngeal arches during the fourth week of gestation. The frontonasal prominence becomes the forehead and bridge of the nose. The lateral nasal prominences form the alae of the nose. Nasal pits develop in the ventrolateral aspects of the frontonasal prominences separating the lateral prominences from the medial nasal prominences. The medial nasal prominences become the midline of the nose, septum, and philtrum (*Greek—love charm*) of the upper lip. The maxillary prominences become the upper cheeks and remainder of the lip. As the maxillary prominences grow toward the midline, they fuse with the lateral prominences forming the nasolacrimal groove, which persist after fusion as the nasolacrimal duct and lacrimal sac. The mandibular prominences become the chin, lower lip, and lower cheeks.

Fontanelles and Sutures

Sutures and fontanelles (also spelled fontanels) are most prominent in the fetus, newborn, and infant. Childbirth through the vaginal canal requires deformation of the neurocranium, and this occurs at the sites of sutures and fontanelles, which act as hinges (Fig. 7.1).

The *meninx primitive* or primordial meninx is the embryonic mesenchymal layer of the tissue and can be thought of as a huge fontanelle covering the head before ossification, but it is never so designated. It gives rise to the dura mater, arachnoid mater, and pia mater. Ossification centers appear in various sites within the meninx primitive and spread outward. As these ossified areas approach one another, the non-ossified areas between ossification centers become apparent and are known as cranial sutures and fontanelles and have been named.

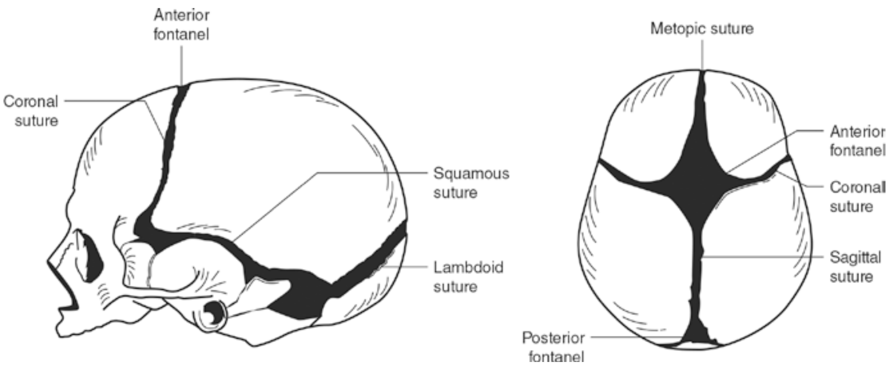

Fig. 7.1 Left lateral and frontal view of fontanels and sutures of a normal newborn child

Fontanelles (Latin: Little Fountains—i.e., Sites of Pulsations)

A fontanelle may be thought of as a wide suture of the cranial vault in which the bony separation, if sufficiently broad, may allow identification by palpation of a non-ossified space, commonly called a *soft spot*. A fontanelle is similar to a cranial suture but with greater bony separation being spanned by the membranous tissue derived from the meninx primitiva. Unlike a suture, a fontanelle is usually situated between more than two bones of the cranial vault and is not spanned by Sharpey's fibers.

When a fontanelle can no longer be identified by palpation, it ceases to be a named entity and is said to be closed, but ossification occurs much later. This is unlike the terminology for closure of cranial sutures, which continue be considered an entity, and hence not closed, until there is an ossified connection across the abutting bones. The timing of closure of a fontanelle is related to closure of adjacent sutures and therefore varies.

The *posterior fontanelle* is triangular and lies at the junction of the two parietal bones and the occipital bone. The *anterior fontanelle* is diamond-shaped and located between the two frontal and two parietal bones. There are two smaller fontanelles on each side of the head. Anteriorly the *sphenoidal* or anterolateral *fontanelle* lies between the sphenoid, parietal, temporal, and frontal bones and is closed by 6 months of age. More posteriorly the *mastoid* or posterolateral *fontanelle* lies between the temporal, occipital, and parietal bones. The usual sequence of closure of fontanelles is as follows: posterior fontanelle, sphenoidal fontanelle, mastoid fontanelle, and anterior fontanelle. The age at closure of fontanelles is quite variable, but has approximate values [7]. See Table 7.1.

Sutures (Latin: Seams) [8]

Cranial sutures are fibrous joints (synarthroses) or soft-tissue connections of the cranial bones by Sharpey's fibers [5, 6]. The tissue between the two edges of endochondral bone is derived from the meninx primitiva and represents the unseparated pericranium and outer or periosteal layer of the dura, in which membranous

Table 7.1 Age at closure of fontanelles. Data from reference # 7

Sequence and range of age for closure of fontanelles	
1. Posterior	2–3 months
2. Sphenoid	6–months
3. Mastoid	6–18 months
4. Anterior	1–3 years

Table 7.2 Approximate age at closure of sutures

Suture	Age at start of fusion	Age at complete fusion
Sagittal	22 months	30–40 years*
Coronal	24 months	30–40 years
Lambdoid	26 months	30–40 years
Squamosal	30 years	40–70 years
Metopic	2 months[a]	3–9 months
Frontosphenoid	22 months	3 months
Mendosal	Near birth[b]	[b]
Temporal- squamosal	35–39 months	40–70 years

Adapted from Table 1 of Ghizoni E, Denadai R, Raposo-Amaral CE, Joaquim AFJ, Tedeschi H, Raposo-Amaral CE. Diagnosis of infant synostotic and nonsynostotic cranial deformities—a review for pediatricians. Rec Paul Pediatr. 2016;34:4–497 [11]. and from text of D'Arco F. A radiological approach to craniosynostosis. Great Ormond Street Hospital for Children; 2015. p. 1–53. D'Arco F [12]

[a]Lower portion may be closed at birth

[b]If persistent into childhood, it usually closes by 6 years but may never completely ossify

ossification occurs [9]. The finger-like edges of the bone along a cranial suture are the advancing fronts of intramembranous bone formation and are modulated by tension [10]. This process requires a steady production of osteoblasts and osteocytes along the edges of bone, but absence for such cells in the membranous tissue between the edges of bone. Sutures, prior to closure, have the unique requirement of remaining unossified while recruiting a new bone into the advancing bone. Bone growth along the edges of cranial sutures is under the influence of various transcription factors, growth factors, and their receptors. The advancing bone fronts have a gradient of growth factors signaling between them. Dura modulates both the sutures and the bone with signals of growth factors and transcription factors acting upon receptors and extracellular matrix components in various stages of development. Unlike enchondral growth, sutures have no intrinsic growth potential but rely on stimuli. Tension at the sutures resulting from intracranial pressure also has important influence on bone formation along the sutures.

Sutures permit movement of the bones of the membranous neurocranium and thereby provide compliance to the cranial vault during parturition and later serve as expansion sites for the cranial vault as the brain grows larger.

There are very many named cranial sutures, but only five are commonly mentioned in neurosurgical practice. (See Table 7.2). These five are important in adult and pediatric practice as anatomical references when describing abnormalities, and as landmarks for neurosurgical operations. In pediatric neurosurgical practice, the sutures are important because of their premature closure (craniosynostosis) and the surgical approaches for dealing with such abnormalities. Usually, all cranial sutures are ossified completely by old age.

Normal Age for Closure of Cranial Sutures

The terms closure of a suture, premature closure of a suture (craniosynostosis), and complete ossification or obliteration of a suture are closely related but not synonymous. Closure or ossification of sutures of the cranial vault is a normal phenomenon; however, most sutures remain unossified until the third decade of life. Long before ossification, most have become closed to palpation and locked together by interdigitating bony extensions along the abutting edges. The normal age for closure of cranial sutures is shown in Table 7.2.

Effect of Age on Bone Thickness

Calvarial bone thickness of adults is reported to increase by a small amount with age. The diploic region of women is reported to expand as the outer cortical layers become thinner [13].

Anthropologic Landmarks on Skull in Common Use

Asterion	meeting point of the occipital, parietal, and temporal bones
Basion	midpoint of anterior inner surface of the foramen magnum, directly opposite opisthion
Bregma	point at which the coronal sutures meet the sagittal suture
Glabella	point in the anterior midline at the lower edge of the frontal bone and between the supraciliary arches
Inion	highest point on external occipital protuberance
Lambda	point at which the lambdoid sutures meet the sagittal suture
Nasion	midpoint of the nasofrontal suture
Opisthion	midpoint of the posterior inner surface of foramen magnum, directly opposite the basion
Pterion	meeting point of four bones, greater wing of sphenoid, temporal bone, frontal bone, and parietal bone. The pterion in infants corresponds to the anterolateral fontanelle [14]

Arterial Supply of Skull

The outer surface of the craniofacial skeleton receives arterial supply from numerous small perforating vessels within the overlying periosteum, which are supplied by the superficial temporal, deep temporal, supraorbital, supratrochlear, and occipital arteries. The major supply to the calvarium, however, is from the meningeal arteries, particularly the middle meningeal artery and its branches. These arteries carry the name “meningeal” because they can be directly visualized on the surface of the dura when the overlying calvarial bones are removed. The dura requires relatively little blood supply, and the major recipient tissue supplied by these vessels is calvarial bone, not dura.

Venous Drainage of Skull [15]

The venous drainage of the skull is through diploic veins, which are thin-walled valveless vessels, that course within the cancellous bone between the inner and outer tables of the skull (Breschet veins or canals) [16]. Few if any diploic veins are present at birth, but they are usually present by 2 years of age. In older patients there are typically four prominent diploic veins on each side of the head, and these empty predominantly into the dural venous sinuses. The frontal diploic vein drains into the superior sagittal sinus and often into the supraorbital vein [15, 16]. The anterior temporal diploic vein courses within the frontal bone and drains into the sphenoparietal sinus, via a small foramen in the greater wing of the sphenoid bone, into a deep temporal vein. The posterior temporal diploic vein courses within the parietal bone, then into the transverse sinus, through a foramen in the mastoid angle of the parietal bone or directly through the mastoid foramen. The occipital diploic vein is the largest of the four diploic veins, and it courses within the occipital bone and drains either externally into the occipital vein or internally into either the transverse sinus or the confluence of the sinuses (torcular Herophili). Emissary veins connect the intracranial venous system to the extracranial veins through small cranial foramina [17].

Abnormal Cranial Bone

Thin Cranial Bone

Mild blunt trauma or even firm digital pressure against the cranial bone in normal newborn children can produce indentations in a manner very analogous to that produced by pressure on a ping-pong ball, hence the name *ping-pong fracture*. These occur most often in the parietal bone and less commonly in frontal bone. Ping-pong fractures are most commonly discovered by parents or other caretakers, and the patient is rushed to medical attention and referred to a neurosurgeon. The indentation is near perfectly round and may be as small as 12 mm or a few centimeters in diameter. The overlying scalp is almost never significantly injured, and there is rarely if ever any identifiable injury to underlying brain. A small amount of edema in the scalp may conceal the indentation from visual inspection, but the indentation is easily identified by palpation. The diagnosis may not be apparent on radiographs of the skull because of the bone being quite thin. The diagnosis is apparent on computed tomography, but this confirmation is rarely needed.

Cranial bone of newborn children and infants up to about 5 months of age may have very thin spots of about 0.5–2 cm in diameter in their cranium, usually in the parietal bone. These appear on neuroimaging as areas of absent of bone. These have clinical importance to the surgeon making an incision in scalp because a knife or electrocautery tip used to cut scalp can easily penetrate the bone and dura and possibly injure the underlying cerebral cortex or a cortical vessel. The associated pericranium and dura are normal, and the very thin bone will develop into normal thickness. Small areas of thin bone may be associated with so-called *venous lakes* in the bone, which are usually prominent venous structures within the dura with very thin overlying bone. These come to clinical attention when neuroimages, particularly plain skull films, are interpreted to show a defect in the cranium. These do not cause clinical problems but have, in the past, been unnecessarily surgically explored.

Macrocephaly in patients with severe intracranial hypertension of long-standing is often associated with cranial bone that is thinner than normal.

De-vascularized Cranial Bone

De-vascularized cranial bone is dead bone and is most commonly the result of elective craniotomy or surgery for trauma. The adjacent edges of healthy living bone and the avascular fragments usually heal solidly, if surgically immobilized, and there is no infection. Occasionally de-vascularized fragments undergo some resorption over their convex surfaces, making them thinner than the abutting living bone. The convexity surfaces of avascular fragments usually become attached to overlying scalp. Surgically de-vascularized cranial bone of newborns and infants may undergo extensive or total replacement by the activity of osteoblasts in the pericranium.

Thick Cranial Bone

Phenytoin Effect

Years of exposure to phenytoin, for the management of epilepsy, causes progressive thickening of the calvarium, which can reach 2.5 cm. The convexity surface remains smooth with normal contour, but the underside slowly develops an irregular knobby surface that is densely adherent to the dura. The combination of very thick bone, knobby internal surface with adherent dura presents serious technical problems for the neurosurgeon, for example, when making burr holes and osteotomies and when separating dura from bone.

The bones of patients who have had prolonged exposure to phenytoin are often golden yellow, but this is not a deposition of phenytoin. A complication of the intake of phenytoin is acne. In past decades, the acne was suppressed with daily doses of tetracycline, and this drug deposited in the bone is the source of the yellow coloration.

Fibrous Dysplasia

Fibrous dysplasia is a genetic osseous disorder in which areas of healthy bone are slowly replaced by fibrous tissue and immature bone. The mutation apparently occurs during early development and is not present in uninvolved tissues of the body; however, it can be a component of the McCune–Albright syndrome.

Fibrous dysplasia most often comes to neurosurgical or plastic surgical attention when it causes bony expansion causing deformity of the face, but may present with headache, sharp pain in the head or face, or with loss of vision or hearing. The frontal bone is most commonly affected. Most patients are 10 years of age or older. The disease is slowly progressive through the teens and commonly stabilizes by the early 20 s; however, it can slowly progress for many years. Fibrous dysplasia may be present in only one bone (monostotic) or more than one (polyostotic) but does not often appear to spread from one bone into another. The expansion of lesions within the cranial vault occurs both outward and inward. Inward expansion can, in extreme cases, compromise intracranial volume. The radiographic appearance is usually diagnostic, but occasionally biopsy is required to confirm the diagnosis. Genetic testing is rarely necessary but is valid only in lesional tissue.

Indications for surgery depend on the extent of cosmetic abnormality and impairment of function, particularly vision. In most patients, the goal of treatment is to achieve an acceptable appearance. Outward cranial expansion can be corrected with a burr, but intracranial expansion requires craniotomy with remodeling of the free bone flaps. In large bony expansions, many prominent venous channels are sometimes present, and hemostasis can be difficult. Blood loss can be a significant problem. Regrowth is unpredictable. In select circumstances, resection of the entire involved bone and its reconstruction can be accomplished and are locally curative, preventing regrowth.

Osteoid Osteoma

An osteoid osteoma is a slowly growing, benign tumor that usually occurs on the flatter bones of the cranium or in bones of the face. They are usually round or oval lesions that can present cosmetic problems or obstruction of air sinuses. There is no malignant potential, and they usually require no surgery.

Osteopetrosis

Osteopetrosis most often comes to the neurosurgical or plastic surgical attention in teenagers and young adult with a cosmetically undesirable bony bulge of some part of the cranium or face but can present with exophthalmos or as unilateral progressive loss of vision or hearing. [Other bones, including vertebrae and long bones, can be affected but will not be addressed here.] Osteopetrosis is a congenital disorder of osteoclasts in which they are unable to secrete acid and thus fail to resorb bone. Bone in the affected areas is very dense and has a radiographic appearance that is usually diagnostic. Cranial nerves can become compressed as involved bony foramina grow smaller.

The adult form, autosomal dominant osteopetrosis, can produce serious cosmetic deformities and nerve compressions but is rarely life-threatening. The diagnosis may be strongly suspected from the appearance of the face and can usually be confirmed by radiography or tomography. Biopsy of bone is rarely necessary.

Cosmetic abnormalities, if relatively minor and not affecting vision, are best followed to determine the eventual course of the disease. Clinically significant cosmetic abnormalities should be addressed before they become extreme. This requires surgical excision of grossly apparent abnormal bone; however, it is commonly impractical to resect some areas. In patients who are losing vision or having progressive evidence on CT of reduction in size of an optic canal, the canal must be decompressed. (The details of this surgery will not be addressed here.)

A malignant form of osteopetrosis occurring in infants, autosomal recessive osteopetrosis, is apparent in the newborn and can come to neurosurgical attention with intracranial hypertension due to craniocerebral disproportion caused by multisutural synostosis. Life expectancy is greatly reduced.

Infants and adults with symptomatic craniocerebral disproportion can greatly benefit from cranial vault expansion by distraction osteogenesis [18]. For children who are severely affected, a bone marrow transplant may be performed to achieve replacement of abnormal osteoclasts with normal ones. This can be a life-saving procedure but does not reverse the existing damage.

Skull Fractures

Most fractures of the skull are caused by slow impact against a blunt object; however, the skull can be fractured by crushing. The crania of newborn children can be fractured by firm pressure and the crania of neonates from birth trauma.

Compound (Open) Fracture

A compound (open) fracture exits when there is full-thickness disruption of the overlying skin, allowing the bone to be visualized or directly touched with an instrument. All compound fractures are contaminated, regardless of appearance or mechanism of injury, and all require surgery to limit further contamination and reduce risk of infection.

Closed Fractures

Closed fractures have intact overlying scalp; however, the scalp or other soft tissues may have suffered injury.

Linear Non-displaced Fracture

A linear non-displaced fracture does not present cosmetic problems but may be associated with underlying pathology, for example, hematoma, cerebral edema, or dural laceration. A long linear fracture with laceration of dura in children under approximately a year of age can result in an expanding fracture. The diagnosis of a linear non-displaced fracture is made by radiologic imaging; however, some large fractures can be strongly suspected by palpation and percussion. Linear non-displaced fractures with the intact overlying skin require no treatment. If there is laceration of the scalp with exposure of the bone, the wound must be debrided, irrigated, and closed in two layers.

Depressed Fracture

A depressed fracture exists when an edge of the fractured bone is displaced inward. Most fractures involve both the inner and outer tables, but it is possible to have an *impacted fracture,* with the outer table depressed into the cancellous diploic space, or a *green stick fracture*. Depressed fractures usually come to neurosurgical attention and may or may not be associated with significant intracranial pathology. (Diagnosis and details of management of intracranial pathology will not be addressed.) A depressed fracture may be either open or closed.

Diagnoses of depressed skull fractures beneath intact scalp can be made by palpation, but when associated with edema or hematoma, palpation can mistakenly identify a linear disruption of galea as a fracture. Plain radiographs or computed tomography is required to confirm the diagnosis and the extent of fracturing. Also computed tomography can identify intracranial pathology. [Diagnosis and management of the later will not be addressed.]

A commonly stated rule-of-thumb is to not recommend surgery for depressed fractures in infants and young children, which do not exceed the thickness of the skull at the site of fracture. Osteoclastic and osteoblastic activity will usually, over a few weeks or months, recontour the bony displacements, and diminish or eliminate the cosmetic impact. Compound depressed fractures of only a few millimeters require surgery for debridement and wound repair but usually not to correct the depression.

This approach is satisfactory for most cranial sites; however, displacements of a skull thickness on the forehead, lateral frontal sites, and regions of baldness can be quite disfiguring and in older children will be permanent. Depressed cranial fractures that cross the supraorbital rim can be permanently visible, rarely if ever improve with time and are unacceptable to patients. Some patients and parents are intolerant of palpable bony depressions.

Most depressions of greater than a skull thickness in older children and adults require surgical correction to elevate and realign fragments. Most of these are associated with significant impingement of bone against or into brain, often with disruption of the dura.

When surgery is required for a depressed fracture, the earlier it is done, regardless of patient's age, the less technical difficulty will be encountered and the greater the likelihood of a satisfactory outcome. Surgery may have to be delayed in patients with severe trauma, but during the delay, edema can increase, fibrotic healing may begin, and in small children there will be remodeling of bone. These occurrences make their surgical repair considerably more difficult.

In the absence of intracranial pathology requiring surgery, a commonly stated rule-of-thumb is to ignore depressions in the cranial bone that do not exceed the thickness of the skull. Osteoclastic and osteoblastic activity will usually, over a few weeks or months, remodel the exposed edges of the bone and diminish or eliminate the cosmetic impact. In patients under about 2 years of age, total recontouring may occur within a few weeks or months. However, if the displaced bone has adult thickness and is in an area without hair, such as forehead, surgical correction is usually appropriate.

Greater displacements of cranial bone fractures require surgery to elevate and realign fragments. Most of these depressions are associated with significant impingement against the brain, with possible disruption of the dura. There will be less technical difficulty and greater likelihood of satisfactory cosmetic outcome if surgery is done shortly after injury, regardless of patient's age. This surgery may have to be delayed in patients with multisystem trauma, but during the delay, edema increases, healing may begin, and in small children, remodeling of bone is quite rapid. These delays can make the delayed surgical repair more difficult.

Fracture that Involves Frontal Sinus

The walls of the frontal sinus are much thinner than most other cranial bone and vary from being paper thin to several mm. Fracture of the wall of the frontal sinus may be produced by direct trauma or from extension of a nearby fracture. A linear non-displaced fracture of the anterior wall of the sinus can be expected to heal with no surgery; however, displacement of the anterior wall typically produces a significant cosmetic deformity, which requires surgery. When extremely thin, the repair can be technically difficult.

Fracture of the posterior wall of the frontal sinus does not produce a cosmetic problem, but the surgery that may be required can be disfiguring. The posterior wall of the frontal sinus may be fractured, with or without displacement, by trauma/against the anterior wall or in association with frontal basilar skull fracture. The latter often results in disruption of the dura and therefore is commonly associated with CSF rhinorrhea. CSF rhinorrhea also occurs when fragments of the posterior wall are displaced more than 5 mm and with extensively comminuted fractures usually. Displacements of fragments of 5 mm or less, with or without CSF rhinorrhea, do not necessarily require surgery unless the rhinorrhea persists [19]. Concern for bacterial entry and resulting meningitis or brain abscess must always be considered. The prophylactic administration of antibiotics is controversial; however, this author does not routinely recommend prophylactic antibiotics.

Fracture of Skull Base

Fractures of the base of the skull do not produce a cosmetic problem but are often seen in association with severe trauma that includes fractures of cranial vault. Often CSF rhinorrhea occurs in association with fractures of base of the frontal fossa and may require surgical intervention to close the site of leakage. CSF otorrhea may occur in patients with fractures of the temporal bone, but these only rarely require surgical intervention.

Expanding (Growing) Fracture

An expanding fracture, also known as a growing fracture, presents with a progressively widening fracture line, through which there is herniation of brain. The same pathophysiology can follow inadequate repair of accidental durotomy in an infant undergoing correction of craniosynostosis [20]. Expanding fractures are most often parietal in location, and over 90% occur in children under 1 year of age (e.g., unrecognized dural disruptions after surgeries for correction of craniosynostosis). There is always a linear laceration of the dura, and by the time of surgical attention, the edges of dura will have retracted far beyond the edges of the defect in the bone. The apparent expansion of the fracture is not simply a progressive separation of the edges of the fracture but is the result of progressive resorption of the bone caused by the pulsating brain as it slowly bulges through the dural laceration. As the dural separation increases, ever more bone is directly exposed to the pulsations and pressure of a normally expanding and herniating brain, which steadily enlarges the defect in the dura. The herniation of the brain results in less need for intracranial space. Expanding fractures rarely occur beyond 12 months of age, occur most commonly in the parietal bone, and rarely in the frontal or occipital bones. If not treated, the resulting defect in the dura with herniation of the brain can become volumetrically huge, resulting in insufficient intracranial space at the time of surgical repair. (See discussion in “Expanding Fracture” in Chap. 18.)

Problematic Bone Flaps

A bone flap may be either healed, meaning there is solid bony union between the flap and intact cranial bone, or free, meaning that the flap does not have solid union to surrounding bone. A free bone flap can be either mobile (loose) or fixed, meaning rigidly immobilized. Fixation does not necessarily imply healing. A bone flap that is fixed by plates, wires, or other means continues to be a free flap until bony union occurs. Bony union usually develops between the edges of living bone surrounding a craniotomy site and the implanted avascular and therefore dead bone flap. All bone flaps, including those replaced following a short surgical procedure, are autologous bone grafts.

The normal healing process will, depending on many factors, establish solid union between 2 and 6 months for most healthy older children and adults. Very thorough application of bone wax along the raw surface of the intact edges of a craniotomy site impairs or prevents bone-to-bone healing and therefore predisposes to non-union of the flap. Newborn children establish bony union by 3–4 weeks. If bony union does not occur, the living bone surrounding the avascular free flap will, during normal healing, develop a cortical-type surface, precluding bony union as the gap fills with scar. A flap that is fixed at the time of surgery may remain free forever and, if bone-to-bone healing does not occur, may become mobile and migrate inward or outward. The normal pulsations of a child’s growing brain or constant intracranial hypertension can loosen screws, wires, or other materials used to fix a flap. In infants or young children, a slightly mobile flap may become less mobile over a few days or weeks, as bony union develops.

Some loose bone flaps slowly migrate inward and eventually heal in a depressed position [21]. If over the forehead or beneath a bald scalp, these present cosmetic problems. Very large and loose flaps can, in response to atmospheric pressure, compress and displace the brain, e.g., sinking skin flap syndrome and syndrome of the trephined [21–23].

Mobile (Loose or Floating) Bone Flap

Visual inspection and palpation are the most reliable ways to identify a mobile bone flap. However, neither physical examination nor plain radiography nor computed tomography can identify, with 100% accuracy, the absence of bony union. If the cranial contour across the flap is normal and there is no visible pulsation of a bone flap, there is rarely if ever a need to determine the extent of bony union of a flap or if bony union exists. A flap that is structurally stable for several months after surgery typically provides satisfactory long-term protection for the brain and therefore is very unlikely to ever require surgical intervention unless there is a significant cosmetic issue.

Causes of a mobile cranial flap include type and/or technique of fixation at the time of elective surgery or cranioplasty, infection, irradiation either before or after flap replacement, and rarely postoperative trauma, which can dislodge a flap that was originally well secured. Close attention to rigid fixation of a free flap, preferably with slight rotation so to maximize bone-to-flap contact in several sites, is the best deterrent. Movement of a mobile bone flap occurs in response to a difference between intracranial and extracranial pressures, and the extent of movement is determined by the tautness of the underlying dura, the fibrous tissue existing between intact cranial bone and bone flap, and by the turgor of overlying scalp. A mobile bone flap, regardless of displacement, can be a cosmetic issue. A flap that is rigidly fixed at the time of surgery can become mobile weeks or months later, if bone-to-bone healing has not occurred.

A mobile bone flap can provide significant but incomplete protection to the underlying brain, from penetrating trauma directly over the flap, but not around the edges. A mobile bone flap does not provide complete protection from penetrating trauma as the surrounding flap is vulnerable to penetration by a sharp object, such as a knife or nail. Blunt trauma to a mobile flap can drive the flap against the brain and cause significant injury to the underlying brain beneath the flap and more diffusely to the intracranial contents. A mobile flap provides limited protection from atmospheric pressure.

Stabilization of a mobile bone flap requires surgical exposure of the entire perimeter of the cranial defect and flap and in most cases the removal of the flap. All fibrous tissue along the concave perimeter of intact cranial bone and around the flap should be removed, and the edge scraped with a curette. An additional maneuver that seems to improve bony union is the making of multiple radial full-thickness osteotomies into the surrounding intact bone of sufficient length to enter the cancellous bone. Bone wax along the raw surface of the structurally intact edges of a craniotomy site will impair bone-to-bone healing and therefore facilitates non-union. If there is a problem with hemostasis, swarf (bone dust), Floseal®, or Avitene™ can be pressed into the site. The mobile bone flap should be placed within the cranial defect with a few degrees of rotation from its original position to maximize the contact between the flap and live cranial bone. The bone flap must then be secured, using more plates than were used in the original immobilization.

A mobile bone flap lying totally beneath a healthy intact temporal muscle usually heals well to the surrounding bone, even if not surgically secured, because the flap is immobilized by the overlying muscle, which insulates it from atmospheric pressure.

A conservative surgical approach to a mobile bone flap commonly fails. Unsuccessful techniques for managing mobile bone flaps include overlaying the flap with a layer of synthetic materials, trying to elevate and fix the flap through a minimal exposure, or by reinforcing the attachment with plates or wire.

The risk of injury to brain from accidental trauma to the mobile flap is low but not zero; however, patients and parents of children often worry. Most loose flaps, particularly slowly settling flaps, are significantly restricted by fibrous tissue, and therefore, movement in response to an externally applied force is limited.

Pulsatile Bone Flap

A pulsating bone flap can be outwardly, inwardly, or normally positioned, but pulsation regardless of position presents as a cosmetic problem. A pulsatile bone flap, particularly if involving the forehead, anterior frontotemporal region, or beneath areas of baldness, attracts unwanted attention and causes patients and families to worry and seek correction. Patients often modify hairstyle or wear caps or scarfs to hide the deformity.

A bone flap, which pulsates with heartbeat and respiration, or which moves in response to gentle manual pressure, will rarely heal to the surrounding cranial bone; however, a slightly mobile flap in infants or young children may become less mobile and heal solidly over a few days or weeks, from ongoing osteoblastic activity.

Settling Bone Flap

A settling or sinking bone flap is a mobile flap that is non-pulsatile and whose surgical fixation has failed, and the fibrous tissue around the flap is insufficient to maintain rigid immobilization [21]. Settling is facilitated by abnormally low intracranial pressure and by extended periods of being in an upright position. Settling of a bone flap often occurs in patients who have lost significant volume of the underlying brain and in children and adults who have CSF shunts with low outflow resistances.

A settling bone flap, particularly if involving the forehead, anterior frontotemporal region, or an area of baldness, is often cosmetically unacceptable to patients and parents, and surgical correction is often desired. Neurosurgeons may downplay the importance of these cosmetic concerns and recommend delaying surgical correction.

Inwardly Displaced Healed Bone Flap

A bone flap that is healed in inward displacement is most often the result of loose or unstable fixation in the setting of low intracranial pressure; however, wound infection, irradiation before or after flap replacement, and postoperative trauma are predisposing causes. Close attention to rigid fixation at the time of repair is the best deterrent. A mobile bone flap in a setting of chronic low intracranial pressure, regardless of cause, results in a depressed position while bone-to-bone healing is occurring.

The treatment of a depressed fixed flap requires freeing the flap of its bony connections to surrounding skull—converting it into a mobile skull flap. The flap is usually removed, but this is not always necessary. The bone flap must then be refixed to the surrounding cranial bone with plates and screws, possibly supplemented with a synthetic material in the gap surrounding the flap. More plates should be used in the correction of failed fixation, and the *screws should not be replaced in their original locations (sites of failure)*.

Outwardly Displaced Healed Bone Flap

A bone flap that is healed in outward displacement may have occurred from malfixation or in response to chronic elevation of intracranial pressure. An intact dural envelope minimal minimizes the risk but does not prevent outward displacement, and most bony displacements occur with an intact dural envelope.

Surgery, which is limited to securing the displaced flap back in its normal location, does not deal with the cause of the problem and will usually be followed by recurrence. If there is intracranial hypertension, this must be addressed before addressing the position of the flap. Treatment should first address the cause of the intracranial hypertension. After the intracranial hypertension has been effectively addressed, the healed bone flap must be cleared of all bony connections to the surrounding cranium and the flap removed. The bulging dura must be reduced to its normal state, either by desiccation or by imbrication with non-absorbable 4-0 sutures. The bone flap is then secured to the cranium with plates, but bone-to-bone is unlikely to occur. If the dura is not been reduced, the repair will likely fail.

Bone Exposed by Wound Dehiscence

Exposure of cranial bone can occur as a consequence of poor wound repair, pressure exerted by a protruding bone fragment against the undersurface of skin, or infarction of the flap from prolonged external pressure over the scalp.

Traumatic Exposure of Bone with Missing Scalp

Normal or near-normal live bone may become exposed from severe damage to a region of the scalp or traumatic avulsion. Regardless of the extent of the exposed bone and the integrity of its pericranium, the exposed bone must be scrubbed vigorously, and the wound closed.

Exposed de-vascularized bone fragments, regardless of size or contamination, can be scrubbed with Betadine or Bacitracin solution and returned to their correct locations. There exists disagreement regarding replacement of obviously contaminated bone fragments with the traditional position being that all contaminated loose bone fragments or flaps must be discarded. This author supports the position that, with very rare exceptions, contaminated bone fragments can be scrubbed and replaced with minimal risk of infection [24, 25].

Bone Flap Overlying Defect in Dura

Disrupted dura beneath the intact normal cranial bone can be the result of surgical replacement of a bone flap over an area recognized to have missing or defective dura, from delayed dehiscence of a durotomy, or as a component of an expanding fracture. Dehiscence of a durotomy, although a common source of worry, is uncommonly a clinical problem.

Beyond 1 year of age, most cranial vaults, in the absence of significant intracranial hypertension, undergo normal bony healing over small dural defects, if the bone flap is well secured. If not well secured, the bone flap in children and even some young adults may become displaced outward by vascular pulsations and growth of the brain.

Aplasia Cutis Congenita

Aplasia cutis congenita is a rare birth defect in which a region of the scalp is missing or severely atretic. The diagnosis is apparent at birth and is often associated with a region of pericranium-covered bone or missing cranial bone and less commonly with an area of missing dura. (See discussion in "Aplasia Cutis Congenita with Cranial Defect" in Chap. 18.)

Healing of Bone

Bone healing is a physiologic process, which occurs in response to bone loss, whether from surgery, other trauma, infection, tumor, or mechanical injury. The bulk of information on the physiology of bone healing is based on studies in animals, most often rats. Most studies on the physiology of healing human bone are clinical studies and tend to be based almost exclusively on long bones, not flat bones, and published in orthopedic journals. It seems reasonable to believe that the healing of the calvarial bone is similar to that of long bones; however, cranial bones are less cancellous, have relatively little marrow, and Wolff's law has little or no role because cranial bones are not significantly weight-bearing. When there is little or no cancellous component, the pericranium and to a lesser extent outer layer of dura contribute greatly to healing by being a source of precursor cells of chondroblasts and osteoblasts. Alternatively, in areas in which there is a significant cancellous component, the endosteum and marrow contribute precursor cells. Healing of bone occurs significantly faster in children, likely related to their thicker periosteum and its robust blood supply [26].

Formation of New Bone

Osteogenesis

Osteogenesis is the formation of new bone and requires the presence of live bone cells, which usually reside in intact bone surrounding a craniotomy, particularly in any exposed cancellous bone; however, not all calvarial bone has a cancellous component. Typically, there are no living osteocytes in a bone graft; however, a few may be present in very fresh bone flaps, but these are thought to rarely if ever survive.

Osteoconduction

Osteoconduction refers to the ability of a material to act as a scaffold, which facilitates the ingrowth of osteogenic precursor cells. Some osteoconductive materials allow cells to attach and proliferate across their non-porous surface, but more porous materials allow cells to attach, differentiate, and migrate to form bone throughout their structure. Cancellous bone autografts, allografts, demineralized bone matrix, and hydroxyapatite have osteoconductive properties.

Osteoinduction

Osteoinduction refers to the ability of a material to induce stem cells to differentiate into osteocytes, which then produce bone. Osteoinductive signals are induced by the release of TGFβ growth factors. Bone grafts, including demineralized bone, and bone morphogenic protein have osteoinductive properties. In some circumstances, osteoinductive signals lead to the formation of bone in extraskeletal tissues, for example muscle, and is referred to as heterotopic ossification.

Physiology of Bone healing [27–29]

Most information on bone healing is based on animal studies and on healing of long bones in humans. Healing mirrors the embryological development of bone. There are two types of healing of bone fractures—primary or direct, and secondary or indirect. The rate of bone healing varies greatly.

Primary (Direct) Bone Healing

Primary healing of bone occurs by *intramembranous healing* if the gap is less than 1 mm and there is sturdy immobilization. This type of healing occurs without callus formation through Haversian remodeling. Osteoclasts remove a small amount of bone leaving tiny cavities in which osteoblasts deposit new bridging bone. Sites of snug bone abutment typically undergo primary healing, as do non-displaced fractures. Interestingly, bone healing during distraction osteogenesis occurs by intramembranous ossification, regardless of whether the bone was originally formed by intramembranous or endochondral ossification [29, 30].

Secondary (Indirect) healing [31]

Secondary healing, also known as *endochondral healing,* is closely related to the embryological development of bone and occurs with callus formation. A small amount of movement at the site stimulates secondary healing, whereas the complete absence of movement—rarely if ever achieved—delays healing or results in non-union. Secondary bone healing has been arbitrarily described in three overlapping stages—inflammatory stage, reparation stage with two phases, and a remodeling stage.

Stage 1. Inflammation (Reactive)

The inflammatory phase begins immediately after fracture and lasts for 2–3 weeks, overlapping the next stage of healing. The solid mineralized component of bone and the strong collagen strands within bone have been disrupted and the extensions of osteocytes torn apart. Immediately after a bone is fractured, bleeding occurs into the site, and shortly thereafter, the injured blood vessels constrict. Hematoma develops within minutes and may expand from additional bleeding over a few hours. Capillaries in the region become increasingly permeable. Most of the cells, excluding fibroblasts, within and adjacent to the hematoma die. Free radicals are released and contribute to additional local breakdown of collagen and bone. Several types of inflammatory cells, which include polymorphonuclear cells, lymphocytes, monocytes, and macrophages, migrate into the area, followed by fibroblasts, which proliferate. Over the first few days, osteoclasts remove 1 or more mm of de-vascularized bone on each side of the fracture and other debris, thereby often making the fracture more apparent on neuroimaging by 7–10 days. With ingrowth of the vascular tissue, granulation tissue appears and receives its supply of oxygen and nutrients from exposed cancellous bone and other adjacent tissues. Pain is characteristic of the inflammatory phase and is particularly prominent in the earliest part.

Stage 2. Reparation

The reparative stage can be viewed in two phases. In the first or phase, soft callus begins to form at approximately 2 weeks and lasts for 4–8 weeks from injury. Fibroblasts continue to migrate into the injured site, and this supports the ongoing vascular ingrowth. Periosteal cells along the edge of the fracture and some of the fibroblasts within the granulation tissue develop into chondroblasts and produce a soft callus of hyaline cartilage. Calvarial bone forms much less callus than long bones, probably because of the small amount of strain at the sites of linear fractures and sites of rigid surgical fixation of bone fragments. Collagen appears in the fracture site, osteoid is secreted, developing into soft callus, which connects the two sides of the fracture. This tissue does not significantly immobilize the adjacent bone and is not apparent on radiographs. Other periosteal cells develop into osteoblasts, and endochondral ossification converts the soft callus into woven-type bone (hard callus). Cancellous bone, which is characteristically a small component of calvarial bone, heals with little callous formation.

The second phase of reparation is the hard callus phase and lasts until 8–12 weeks from injury. The woven bone is replaced with lamellar bone, and the hyaline cartilage undergoes endochondral ossification. As the newly developed bone becomes ossified, small channels develop containing osteoblasts and small vessels. The result is a strong bridge of trabecular bone across the fracture gap. This bony union is apparent on radiographs.

Stage 3. Remodeling

Remodeling begins in the middle of the repair stage—i.e., 8–12 weeks after injury—and may continue for several years. Trabecular bone is slowly absorbed by osteoclasts and replaced by compact bone produced by osteoblasts. The newly formed bone is remodeled by osteoblasts and osteoclasts, and the production of VEGF (vascular endothelial growth factor) leads to an invasion of new vessels. The healing fracture site is restored to its original or near-original contour and structure with approximately normal mechanical strength.

Graft Healing

A bone graft is a fragment of bone, regardless of site of origin or species, which is implanted in contact with viable bone, for the purpose of repairing a defect in the bone or, less commonly, for altering the contour or reinforcing viable bone—i.e., an onlay graft. When a graft is placed in contact with freshly cut living bone, the healing process will occur as described above for healing of a fracture, but the graft contains no surviving cells to contribute to healing.

Autographs

Autographs are bone fragments originating from the same individual, and they have strong osteoinductive and osteoconductive properties. Healing is accomplished by a process called creeping substitution, in which mesenchymal cells differentiate into osteoblasts and deposit osteoid over the dead bone. The dead bone is slowly resorbed and replaced by living bone [32, 33]. This proceeds much faster in cancellous bone than in cortical bone.

A cranial bone flap that is returned to its original or other site, whether minutes, hours, or months following removal, is an autologous bone graft. Autografts have the advantage of having no risk of introducing new disease from a donor. A disadvantage associated with autographs harvested from a site distal to the graft site is the risk of donor site morbidity. A separate surgical incision increases surgical time, blood loss, adds risk of infection from the process of harvesting, and possible cosmetic deformity. In some patients, particularly infants and small children, there is often insufficient bone available for use.

Allografts

Allografts are bone fragments from a different individual of the same species. These are not commonly used for repairing cranial defects but occasionally used in spinal surgery. Allografts are usually quickly available from-the-shelf in numerous sizes and shapes, never require a separate surgical incision, and hence there is no donor site morbidity. Allografts have osteoconductive properties but relatively weak osteoinductive properties, compared to that of autografts. They incorporate with adjacent living bone more slowly than autografts and have higher risks of nonunion. The risk of disease transmission was a grave concern in the past but now is quite low, but not zero.

Xenografts

Xenografts are bone fragments originatiing from another species, usually bovine, and are almost never used to repair cranial or facial defects but are occasionally used in various surgeries for spinal fusion. They are subject to extensive resorption without significant induction of new autologous bone. Neither do they provide efficacious scaffolding, compared to other grafts.

Structural Types of Bone Grafts

Cancellous bone—A cancellous autograph has very large surface area covered with osteocytes, osteoblasts, and osteoclasts. It is much less dense than the cortical bone and therefore has significantly less structural strength. The cancellous construction makes it difficult to secure snugly in place with screws, and its rough surface makes it relatively unsatisfactory for grafting in areas of cosmetic concern. Cancellous bone grafts heal more rapidly than do cortical bone grafts and become progressively stronger during the remodeling phase. Cancellous bone is better for reconstruction because there is more extensive incorporation of a new bone without significant resorption.

Cortical bone—Cortical bone has few osteocytes, osteoblasts, and osteoclasts, is quite dense, and has much greater structural strength than cancellous bone. Ingrowth of vascular tissue is impeded through both reparative and reconstruction phases of healing and is therefore slow. Osteoclastic activity during the remodeling phase of healing is often dominant, and therefore, a site of bony union can become weaker over time. Cortical bone is appropriate for reconstructing defects of the cranium and facial bones for aesthetics. Cortical-to-cortical bone healing is quite slow and generally poor, Cortical-to-cancellous bone healing may occur faster if the smooth cortical surface is "roughed" with a burr but will still proceed slowly. The growth of bone tends to encompass most synthetic materials, including wire and metal plates, with which it is in contact. This is particularly true for titanium.

Factors that Affect Healing of Bone [34]

No dietary supplements, drugs, or surgical actions have been found that accelerate healing beyond the normal rate in healthy individuals; however, LIPUS (low-intensity pulsed ultrasound) and bone stimulators have been shown to accelerate healing [35, 36]. Conditions for normal healing can be optimized and many impediments avoided, hindered, or removed. The rate of healing of bone is important, with rapid healing being superior to slow healing, in osteotomies and fractures of spine and long bones; however, the rapid healing of bones of the cranium and face, although clearly desirable, is less critical for patients' well-being.

Age

Fractures of children, presumably including those of cranium and face, heal more rapidly than those of adults [37]. In adults, particularly the elderly, advancing age has a significant negative impact on healing of bone [38]. Studies of fracture healing in rats have shown that the formation of cartilage and bone and the resorption of cartilage were delayed in elderly animals, and healing continued to decline throughout life. Fractures and osteotomies of vertebrae heal slowly with increasing age [39].

Disease

Diabetes Mellitus

Bone healing is delayed in patients with diabetes mellitus; however, strict control of blood glucose levels reduces the delay [40–42].

Drugs

Anticoagulants

Heparin and warfarin have been shown in animal studies to attenuate the healing of fractures, but this has not been confirmed in humans.

Antineoplastic Drugs

Antineoplastic drugs interfere with bone healing.

Antibiotics

Several antibiotics, including ciprofloxacin, levofloxacin, and topical gentamicin, have been shown to slow bone healing [43–45].

Nonsteroidal *Anti-inflammatory* Drugs (NSAIDs)

Non-steroidal anti-inflammatory drugs inhibit COX-2 activity and thus impede the synthesis of prostaglandins. There is conflicting evidence on the effect on healing of long bones in animals [46, 47].

Selective Serotonin Reuptake Inhibitors (SSRIs)

There is evidence that SSRIs (selective serotonin reuptake inhibitors) inhibit bone healing [48].

Statins

Statins may have an anabolic effect on bone in rats, but the effect of statins on healing of human bone has not been examined. The effect of statins on healing of bone in mice has been shown to be dramatic enhancement [41].

Steroids

The administration of steroids for less than a week probably does not interfere with bone healing [49]. Long-term steroid therapy is detrimental to healing of long bones. Often neurosurgical patients are prescribed several weeks of postoperative steroids, often in high doses. This not only increases the risk for wound infection but also prolongs the healing time of bone [39].

Infection

See “Contamination and Infection of Bone” in Chap. 8.

Mechanical Issues

Repeat surgical manipulation and postoperative trauma to a well-closed wound can dislodge a bone flap.

Nutrition

Most patients who undergo elective neurosurgery on bones or who suffer cranial or spinal fractures do not have nutritional deficiency; however, some patients, particularly the elderly, may have poor nutrition due to dietary deficiencies, and the rare patient may even have cachexia. Nutritional and metabolic requirements increase during fracture healing [39].

The following have been demonstrated in animal studies, but their relevance to healing of bone in humans has not been confirmed:

(a) Rats with protein malnutrition, who underwent tibial fracturing benefited from adequate protein nutrition after the fracture had occurred [50].
(b) Vitamin C is essential for the functions of osteoblasts, including in the setting of fracture repair. Supplementary vitamin C may accelerate fracture healing [51].
(c) Dietary protein. Calcium, phosphorous, and vitamin D are important in healing of fractures [52].

Thermal Injury [53–56]

Heat is produced by friction during the burring or drilling of bone, and 47° is considered the threshold for significantly impairing regeneration. This temperature is reached 1 mm from the burring site of bovine spine bone, at 10 seconds, and at a rotational speed of 45,000 rpm. Irrigation of the site with cool water significantly reduces the temperature of the bone during the drilling process.

Radiation

Total dose of radiation, time elapsed from surgery, and time span of delivery are the most parameters affecting the impact of radiation on wound healing. Radiation reduces the number of osteogenic cells and thereby delays and damages remodeling of bone [57–59]. The sooner radiation is delivered after surgery, the greater the adverse effect on healing [59].

Tobacco Usage [39, 60, 61]

Tobacco usage adversely affects bone healing; however, it may not be the nicotine but other components in cigarette smoke that impair healing [61–63].

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Surgery of Cranial Bone

8

Ken Rose Winston

Surgery of Cranial Bone

The initial plastic neurosurgical concern regarding cranial bone is its removal to safely approach a neurosurgical target with minimum cosmetic damage. In the restoration phase, the protection of brain, structural stability, external contour, and effect on overlying soft tissues is paramount.

Plastic Neurosurgical Concerns in Surgeries of Cranial Bone

- Plan required burr holes and osteotomies
- Prevent of osteonecrosis from high-speed drilling
- Avoid violation of dura
- Hemostasis
- Preservation of bone flaps/fragments
- Secure replacement and alignment of bone flaps/fragments
- Cosmetic management of burr holes

Trephination (Cranial Perforation)

Trephination/trepanation (*Greek trypanon: borer or auger*) refers to the practice of making a hole in a cranial vault or fingernail, by drilling, sawing, or scraping, and this has been done for thousands of years and for many purposes. Trepanning is mentioned in The Edwin Smith Papyrus, from the 17th century BCE [1]. Consider the following from a long influential text of the twelfth century:

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"For mania or melancholy, a cruciate incision is made in the top of the head and the cranium is penetrated, to permit the noxious material to exhale to the outside. The patient is held in chains and the wound is treated" [2].

Twist Drill Hole

A twist drill hole is a small hole, most often made with a drill bit attached to a manually operated drill, sometimes called an eggbeater, and its operation is self-evident. A twist drill hole is *not* a burr hole. Historically, the drill bit was attached to a straight handle, which was manually twisted until penetration of the skull was achieved, thereby producing a "twist drill hole." A twist drill hole in the cranium is usually less than 5 mm in diameter. Its most common indication is for emergent insertion of a ventricular catheter or pressure monitor, but it is also used in elective surgeries, such as biopsy or aspiration of an intracranial lesion and for insertion of recording electrodes. Many emergency departments and neurosurgical hospital units continue to stock these drills. The diameter of the drill bit should be about 2 mm greater than the needle, tube, or electrode to be inserted. If the hole is made to accept a screw, for example, Comino pressure monitor, the diameter of the hole must be slightly smaller than the screw and should be made with the drill bit included in the set.

Penetration of Dura beneath Twist Drill Hole

The drill bit should never be pressed against intact dura because this will strip dura from bone and can cause significant epidural bleeding. The most common technique for opening dura beneath a twist drill hole is using a surgical needle, usually #18, to superficially puncture or "weaken" the dura and allow the penetration of dura by the object to be inserted. The penetrating tip of a sharp needle through dura does not push aside underlying cerebral blood vessels and therefore has the risk of causing subdural of intracerebral hemorrhage. As the blunt smooth tip of a ventricular catheter is inserted against intact pia, the surface of the brain is displaced inward and then suddenly penetrated as the pial surface is broken.

Alternative Technique for Making a Twist Drill Hole (Anecdotally Attributed to Wilder Penfield

The dura and approximately 3–4 mm of cerebrum are penetrated by quick advancement of the rapidly spinning drill bit in a *manually operated* drill. A depth-lock on the bit must be used to prevent excessive penetration. The relatively blunt drill tip, unlike a sharp needle, will usually push aside any underlying blood vessel without disruption. As a blunt ventricular catheter is inserted, the surface of the brain is minimally displaced as the catheter passes smoothly through pia and into brain. Neither this nor any other technique is free of risk of vascular disruption, but it is the author's opinion that this technique is safer than the more common technique.

If a passive drainage catheter will be inserted and tunneled beneath scalp, there is risk of kinking across the right-angle edge of the freshly drilled hole in bone. Therefore, the outer edge of the hole on the side toward which the tunneled catheter will pass should be rounded with the drill bit.

Emergent Twist Drill Hole Under 8 Years of Age

In emergent conditions, for example, cardiorespiratory arrest or near arrest from suspected intracranial hypertension, a large bore (18 gauge or larger) needle can usually be inserted through the scalp, skull, dura, and cerebral mantel into a lateral ventricle. The needle is grasped with a needle holder or hemostat approximately one cm from its tip of and pushed through the scalp. With the needle directly over the coronal suture and carefully aligned toward the lateral ventricle, it is pressed firmly against the coronal suture and rotated back and forth until the cranial vault is punctured. The needle is then advanced in approximately one cm increments by repeatedly grasping with the needle holder or hemostat and pushing until the ventricle is entered. The direction of penetration of skull and cerebral mantel cannot be altered during penetration. This technique has the risk of disruption of a cerebral blood vessel, but in extreme emergencies the risk is justified.

Enlarging a Twist Drill Hole

A twist drill hole may require enlargement for the insertion of a CSF shunt catheter and seating of a Rickham reservoir. This can be difficult to safely accomplish without tearing the dura, particularly after its edges have healed to bone. An attempt to enlarge the hole with a small Rongeur may be used successfully, but this instrument will often snag and tear dura. If the dura can be identified by palpation with a small instrument, for example, #4 Penfield dissector, dura can usually be separated from bone with a nerve hook for a few mm around the hole, and then a small Kerrison rongeur (*French: rodent or gnawer*) can be more safely used to enlarge the bony opening. Also, a burr can be used to cautiously drill directly down the axis of the twist drill hole.

Burr Hole

A burr hole was originally a hole made with a brace and bit and enlarged with a special bit called a burr, hence “burr hole.” Until the introduction of powered instruments, all burr holes were round, and their diameter determined by available bit sizes, which was usually 0.5 in. A burr hole is not a twist drill hole.

A burr hole may vary from approximately eight to 18 mm in diameter, and the shape and size can be tailored for intended use. A burr hole can be made with an electric or gas-driven drill or with a Hudson brace and bit. Burr holes are used for drainage of hematomas and for the insertion of a craniotome at the start of an osteotomy.

Burr Holes Made with Power Tools

The bit used to make a burr hole, when using a powered instrument, is usually described as pear-shaped with sharp-edged spiral flutes around its surface and extending to its tip. The size and shape of a burr hole and its shape are dictated by the intended use and no longer by the available instrumentation or by tradition. Burr holes can now be made with powered instruments in any shape but are often intentionally made to be oval (approximately 4.5 by 9 mm) to accommodate the footplate of a craniotome. A round burr hole is less commonly required. A round hole of 8–10 mm diameter is often best for draining subdural fluid. A larger burr hole, especially if round, can result in a cosmetic defect and is often not ideal for the task.

The drill is held firmly with the fingers of the dominant hand and not in a palmar grasp. The ulnar edge of the surgeon's hand or wrist in firm contact with the patient's head or some object securely attached to the cranium, for example, a Mayfield head holder. It is not safe to make a burr hole with the surgeon's forearm outstretched without support. The spinning of the bit should always start before its tip comes into contact with bone. The surgeon should move the axis of the spinning bit in a circular motion as it is advanced into and through bone. The bit should not be pressed firmly against the bone to hasten the penetration because of the risk of its rapidly spinning tip suddenly passing beyond the inner surface of the cranial, shredding underlying dura, and injuring brain. Knowledge of normal anatomy combined with information obtained from neuroimaging can give the surgeon a rough idea regarding the thickness of cranial bone, but it is difficult for the surgeon to correctly perceive the depth of the spinning bit within the bone. It is therefore important for the surgeon to frequently stop drilling and inspect the hole, looking for a change from cancellous to inner-table cortical bone or a tiny full-thickness opening in the depths. When it is seen that there is full-thickness penetration with a small exposure of dura, the inner edge of bone can be removed with a curette or small Kerrison rongeur. The dust, chips, and curls of bone removed or dislodged during trepanning is the swarf (*Old Norse: file dust*).

Occasionally, a surgeon may desire to make a burr hole whose axis is not perpendicular to the surface. This is most safely accomplished by first making a perpendicularly oriented hole and then asymmetrically modifying the walls of the burr hole with a Kerrison rongeur small cylindrical craniotome bit. Attempts to drill a hole that is significantly nonperpendicular to the external cranial surface may result in dural disruption, as the deeper side of the advancing bit encounters dura before full penetration of bone occurs.

Thermal Osteonecrosis Caused by High-Speed Drilling

Thermal osteonecrosis is the death of bone caused by high temperatures, and high-speed drilling is the cause of thermal bone necrosis. Most information on thermal osteonecrosis caused by drilling is based on reports from orthopedic surgery and dentistry. Bone heated to 47 °C for one minute leads to significantly reduced bone regeneration, and temperatures of 50 °C cause severe damage and impair healing [3]. The temperature at which thermal osteonecrosis occurs in human bone is unclear, but "… 50°C has been defined as the critical value below which bone temperature must be kept" to prevent thermal osteonecrosis [4].

As the feed rate (rate at which the drill or router is advanced against bone) increases, the time required for drilling decreases and less heat is generated. Faster feed rate requires the application of more force during drilling, resulting in a significant *decrease* ($p = 0.001$) in the duration of temperature elevations above 50 °C [5]. Increasing axial force when drilling twist drill holes and burr holes reduces drilling time and time for bone temperature to rise above 50 °C, thereby decreasing the risk for thermal osteonecrosis [5]. The most effective action in the prevention of thermal osteonecrosis while drilling bone is irrigation with saline [6].

Keyholes (Named Burr Holes)

Burr holes are designated by their anatomical locations—e.g., frontal, temporal, and occipital: however, three are named burr holes locations, two of which are eponymous.

The *Dandy burr hole (keyhole)*, also known as the pterional or anatomical burr hole, is made at the pterion and commonly used in orbitozygomatic surgical approaches [7–9]. Pterion overlies the anterior division of the middle meningeal artery in bone that is approximately 4.4 mm thick and therefore the thinnest site of the cranium [10–12]. The location of pterion has been described in the following, not always consistent, ways:

1. The site where the parietal, squamous temporal, and greater wing of the sphenoid bones meet, and their sutures have an H-configuration.
2. Within a one-centimeter circle, 2.6 cm behind and 1.3 cm above the posterolateral margin of the frontozygomatic suture in 68% of adults, and only a few millimeters posteriorly in all others.
3. 2.6 cm behind and 1.3 cm above the posterolateral margin of the frontozygomatic suture.
4. Approximately 39 mm superior to the zygomatic arch and 31 mm posterior to the frontozygomatic suture.
5. The anterior end of the frontozygomatic suture.
6. The midpoint of the frontozygomatic suture.
7. Two finger-widths above the zygomatic arch and a thumb's breadth posterior to the frontal process of the zygomatic bone. [13]
8. Anterior and a few mm below the anterior attachment site of temporalis fascia and muscle to frontal bone.

The *MacCarty keyhole* lies over the frontosphenoidal junction just behind the zygomatic process of the frontal bone which is 5–7 mm above and 5–10 mm behind the frontozygomatic suture. The sides of a MacCarty burr hole enter the orbit and both anterior and middle fossae [14]. This burr–hole is centered approximately 5–10 mm below and anterior to the location of the Dandy burr hole site [9, 15]. Because of its relatively superior location, it requires more attention to cosmesis during closure than the other eponymous burr holes.

The *sphenoid ridge keyhole* is centered over the thickest part of the sphenoid ridge, which is approximately 11 mm posterior and 7 mm inferior to the frontozygomatic suture [7, 16]. The sphenoid ridge is an easily identifiable landmark on the lateral skull surface, located below the location of the McCarty keyhole. When correctly placed, it exposes dura of the frontal and temporal fossa and the periorbita. It is commonly used in pterional and frontotemporal craniotomies.

Burr Holes Made with Brace and Bit [17]

The *Hudson brace* used by neurosurgeons to drill holes in the crania is similar to the brace used for centuries by carpenters to drill holes in wood. It remains available in many operating suites today for use in emergent situations. Its assembly and operation are simple and intuitive; however, its safe use is less intuitive. When improperly used, there is risk of sudden plunge through dura and into brain. The bit's angle of attack, regardless of bit in use, should be perpendicular to the tangent plane of the surface of the skull. The rate of advancement of the bit through bone, as the brace is turned, is determined by the sharpness of the bit, hardness of bone, and the pressure applied to the brace. Frequent visual inspection of the depth of the hole is important.

Perforator bits—There are two types of perforator bits in most instrument sets, a McKenzie and a Cushing. The McKenzie bit has a corkscrew appearance and a tapered profile with spiraled cutting edges around its sides, in contrast to the Cushing bit which has a flat profile with an obtuse triangular tip and two short cutting edges. Immediately after the inner table of the skull is perforated the McKenzie bit typically snags against the edges of bone very soon after the inner table of bone is perforated, thereby producing a tactile signal to the surgeon and reducing the risk accidental plunge through dura. The Cushing bit does not produce a tactile signal when the inner table is perforated, and therefore there is greater risk of plunging through dura and into brain.

Burrs—Special bits, called burrs, are available in several sizes and shaapes and are used to enlarge the burr hole with less risk of plunging through dura. The cutting edges on most burrs are confined to the sides but not across the tip. This reduces the risk of disrupting dura if contact is made. The angle of attack with a burr should be 20–45° from vertical to minimize the risk of plunging or separating dura from bone. Frequent inspection of the depth of the hole is important.

The inner edge of each burr hole can be extended with a Kerrison rongeur in the two directions of planned osteotomies with the Gigli saw.

Burr Holes Made with a Circular Saw (Cookie Cutter)

A circular saw bit on a Hudson handle can be used to make a hole in cranial bone but nowadays this is uncommonly done. Most of these circular bits have a central pin that keeps the axis fixed until the circular kerf is established. Although intuitively simple to use, there is significant risk associated with this technique. Because calvarial bone is not planar, not all sides of the saw achieve full-thickness bony penetration at the same time. Therefore, the circular saw has significant risk of lacerating dura and occasionally brain. If a circular saw is to be used, the surgeon must frequently check the depth of the kerf on all sides, either by direct visualization or palpation with an instrument. The resulting rondelle (*French: washer*) of bone is easily removed.

Hemostasis in a Burr Hole

Venous bleeding from the walls of a burr hole may be encountered. This can be controlled with bone wax applied with a blunt instrument, such as a #4 Penfield dissector. If a site of bleeding site on dura is visible, it can be controlled with electrocautery, but the source is commonly not visible. A small piece of Gelfoam® pressed into the burr hole and secured with a wet Cottonoid® for a minute or more is often successful. Rarely there is arterial bleeding, and this can usually be controlled with Gelfoam® under manual pressure on a Cottonoid® or held in place with bone wax for a few minutes. If the arterial pressure extrudes the wax or if bleeding continues, there is high risk of the arterial pressure dissecting dura from bone. Control of this bleeding requires larger bony exposure for direct visualization of the source.

Burr holes in newborns and infants—A free McKenzie bit—i.e., without Hudson handle—is grasped in one hand, pressed against bone, and rotated back and forth by 60–90°. This technique and can be used in bone up to approximately 4 mm depth with very low risk of violating the dura.

Alternatively, a firmly grasped sharp curette can be used to make an opening in the thin crania of newborns and some infants by scraping the bone with short strokes to produce a full-thickness perforation. This technique is useful in bone under approximately 2.5 mm in thickness. After full-thickness perforation is achieved a Kerrison rongeur can be used to enlarge the opening. If the bone is very thin, this technique is less likely to violate the dura than using a brace and bit. These cranial perforations are usually not called burr holes.

Cranial Osteotomy

An osteotomy is almost always made with an electric or air-driven, craniotome. An entry site is necessary in the form of either a fresh burr hole or a preexisting defect, to allow initiating the use of the craniotome. A cutting bit and nosepiece of selected diameter and length must be chosen. A bit of approximately 2 mm diameter and 12 mm cutting length is satisfactory for most osteotomies in patients older than 5 years. Rarely cranial bone can be 2 cm or more in thickness, for example, in some patients with years of exposure to phenytoin and patients with fibrous dysplasia or osteopetrosis. In such conditions, a longer bit is required.

The tip of the footplate must be held snugly against the undersurface of bone to prevent penetration of dura as an osteotomy is being made. If advancement of the craniotome is halted by a bony irregularity on the inner surface of the cranium, the craniotome should be pushed inward against dura by 2–3 mm and rotated from side to side to separate dura from bone. The craniotome can usually then be advanced along the marked course. A sudden tactile perception of significantly diminished resistance to the advancement of the craniotome is often an indication that the dura has been penetrated. When this occurs, there are three options: (1) remove the craniotome and continue the osteotomy along the marked line, in the opposite direction, (2) make a new burr hole and continue the osteotomy, and (3) slide the craniotome back by about 5–10 mm and alter the path of the craniotome to bypass the dural penetration. Air can be entrained into bone and its veins by the spinning bit of a craniotome, but this rarely causes a clinical problem [18].

Osteotomies in infants and young children are best done with craniotome bits of the smallest available diameter; however, the cranial vault of many newborns can often be cut with curved Mayo scissors, which do not produce a kerf. Cranial openings may be enlarged or have their shape modified with a craniotome or with rongeurs.

Osteotomy with Gigli Saw [19, 20]

There are two indications for use of a Gigli saw to make a craniotomy: (1) craniotomies in patients who may harbor Creutzfeldt-Jakob disease, following which all surgical instruments, must be discarded and (2) extreme emergent settings in which a craniotome is not available. The technique for craniotomy with Gigli saw is described below in "Craniotomy Without Power Tools".

Two burr holes of approximately 12–14 mm diameter are required for each cranial osteotomy made with a Gigli saw, and therefore four holes are required for a quadrilateral craniotomy; more holes are required for a multisided craniotomy. Before passing the saw guide, the dura must be freed for the full distance between each pair of burr holes using Penfield, dissectors. Smaller burr holes may be used in infants and young children in whom the dura is predictably less adherent to bone. Separation of dura from bone can be quite difficult if the dura is very adherent to bone. The flat Gigli saw guide is then passed in the epidural space from one burr hole to an adjacent one and used to pull the end of a Gigli saw (wire) along the same epidural path. The guide is left in place to protect dura. The ends of the saw are attached to the saw handles, which are components of the set, or the ends may be grasped with Kocher forceps. The saw is stretched tightly and pulled back and forth, thereby cutting the bone from inner to outer surface. This routine is repeated for each pair of burr holes. If the saw slips off of the protecting guide in the epidural space, the dura will be shredded, and brain possibly lacerated during the first few glides of the saw. Also, if the saw was passed in the subdural/subarachnoid space, without this errant path being recognized, both dura and brain will be lacerated. These risks can be minimized, but not eliminated, by careful attention to detail. The osteotomy may be beveled, if the surgeon desires, by tilting the angle of the moving Gigli saw as it cuts through bone.

Precautions when Prion Disease Suspected [21]

Extreme caution is essential to avoid accidental distribution of swarf (bone dust) or splash, blood, or other fluids onto surgical personnel. Few neurosurgeons nowadays are familiar with making osteotomies without a craniotome and this unfamiliarity increases the risk of contamination of self or other personnel. A craniotome cannot be used, for two reasons, when prion disease is suspected: (1) a craniotome disperses droplets of body fluids and swarf far from the surgical site and (2) all surgical instruments used in cases of suspected prion disease must either undergo a special sterilization process or be destroyed, and a craniotome cannot be reliably sterilized.

Osteotome/Chisel

Osteotomes and chisels are similar, but the tips of osteotomes are beveled on only one side and the tips of chisels are beveled on both sides. The functional effects also similar, but an osteotome can be observed to advance in a plane corresponding to the nonbeveled side. Osteotomes are more commonly used by neurosurgeons to split or divide bone. Some surgeons believe that chisels may better for removing bone. Either can be used for disrupting a frontal bony keel and in multiple settings of craniofacial surgeries, for example, Le Fort osteotomies and midface mobilization. Neither of these instruments produce a kerf or require a prior burr hole.

Oscillating Saw

An oscillating saw is especially useful in craniofacial surgery because it makes a narrow kerf and removes significantly less bone than does a craniotome. Also, an oscillating saw does not shake the brain as does an osteotome when struck by a mallet.

Osteotomy Across Superior Sagittal Sinus [22]

The classic technique for extending an osteotomy across the superior sagittal sinus begins with placing a small burr hole on each side of the superior sagittal sinus. Dura across the midline can then be separated from attachment to bone with a nerve hook or Penfield dissector, and the bone between the two burr holes is removed with a Kerrison rongeur.

An osteotomy can be extended across the superior sagittal sinus from single burr hole or slot of sufficient size to accommodate the footplate of a craniotome. Dura is separated from bone on the medial side of the burr hole with a nerve hook or other instrument. A craniotome, with tip held firmly upward against bone, is slowly advanced across the sinus. After each 1–2 mm advancement, the craniotome is pushed inward by 2–3 mm and rotated from side to side to separate dura from bone. This process is repeated until the surgeon is confident that the osteotomy has crossed the sinus. In virgin cases, the dura over the large venous sinuses is not tightly adherent to bone, except near the coronal and transverse sinuses and less so along the superior sagittal sinus. Prior cranial surgery in the area raises the likelihood of firm dural attachment to bone.

Preservation of Frontal Sinus

When any part of the frontal sinuses lies in the path of required visualization, the surgeon will need to make an osteotomy across the sinus. Trying to work around the impediment can be dangerous. Frontal sinuses are quite small or absent in young children. The traditional practice has been mandatory cranialization of the sinus; however, this invasive routine is not always necessary [23]. The frontal sinus can be safely preserved in most small traumatic disruptions of the posterior wall of the sinus, small surgical entries, and in many elective osteotomies across the sinus [22].

The craniotome used for making a supraorbital osteotomy is guided across both walls of the frontal sinus to within a few mm from midline, where a bony keel is often encountered. If bifrontal craniotomy is required, an identical osteotomy is made on the contralateral side, leaving a bony midline keel. These osteotomies often require a longer craniotome bit than that being used for single thickness cranial bone. It is usually necessary to disrupt the keel with a narrow osteotome passed through the anterior kerf (see discussion below). Care should be taken to minimize damage to both anterior and posterior walls of the sinus. Preservation of frontal sinuses should not be attempted if there is sinusitis or if the walls of the sinus were shattered during craniotomy, from trauma, or in settings in which tumor has entered the sinus. Most frontal sinuses of asymptomatic adults with normal CTs are sterile [24]. (See description below for “Repair of Frontal Craniotomy with the Preservation of Frontal Sinus”.)

Cranialization of Frontal Sinuses [22, 25, 26]

Cranialization requires a bifrontal craniotomy followed by removal of the entire posterior wall of the frontal sinus thereby expanding the cranial vault. All mucosa of the frontal sinus *must* be removed. Most can be easily striped from the free bone flap and from the remaining intact base of the sinus. A burr is used to remove bits of mucosa lying in bony creases. It is not necessary to do extreme burring of the inner surface of the free frontal bone flap because bits of mucosa having no blood supply over the weeks of cranial bone healing will not survive and cause problems. The nasofrontal ducts must be occluded, with a tiny bone chip or rolled piece of dura or fascia. Cranialization has postoperative risks that include hematoma, infection, new or additional dural disruption, new or persistent CSF rhinorrhea, and mucocele if viable mucosa remains.

Several surgeries have been described to deal with traumatic disruptions of the posterior wall of the frontal sinus. *Obliteration* of the sinus requires a relatively small entry into the sinus to remove all mucosa, occlude the nasofrontal ducts, and completely fill the cavity with an avascular material such as fat, bone, pericranium, hydroxyapatite, or other material, is rarely used today. The following two historical surgeries have been abandoned. *Exeneration* is a disfiguring procedure that includes removal of the anterior and posterior walls of the sinus and often the supraorbital rims. *Osteoneogenesis* is the removal of all mucosa of the sinus, followed by scoring the inner walls of the sinus "to induce the formation of new bone."

Managing Sagittal Keel

A keel of bone of variable thickness and length is often present along the inner surface of the anterior frontal midline bone, particularly the 2–3 cm above the floor of the frontal fossa. This structure blocks the passage of the footplate of the craniotome and persistence with this instrument may cause penetration of dura. Further advancement of the craniotome must be halted and the osteotomy approached from the opposite side until the keel is again encountered. A small osteotome can then disrupt the bony keel without violating the dura.

Osteotomy to Assist Bony Alignment at Closure

Precise bone alignment is required in some neurosurgical and craniofacial procedures, for example, reconstruction of supraorbital rims following transfrontal subcranial approaches, and in various, facial, and orthognathic surgeries. This can be accomplished by attaching two to four small plates that straddle the planed osteotomy, using four screws in each plate. The two screws in the bone that are outside the marked craniotomy and one of the two screws in the planned bone flap are removed, leaving each plate attached to the bone flap by a single screw. The plates are rotated over the planned bone flap. The planned osteotomy is then executed, and bone flap removed. At time of repair, the plates and screws are used to precisely reestablish the original alignment of bones.

Another way to secure precise bony alignment is to make multiple osteotomies along the marked outline of the planned craniotomy, leaving several small bridges. When the osteotomies are completed between these bridges, the bridges are disrupted with an osteotome. The absence a kerf at the sites of the disrupted bridges will greatly assists precise realignment of the flap during closure. This technique is not in common use.

Craniotomy/Craniectomy

Craniotomy is the term for removal of a full-thickness fragment of cranial bone followed by its postoperative replacement or replacement with a different material. Craniectomy is the same, except without replacement—i.e., leaving the cranial opening void. The first step is the marking of the planned craniotomy with ink; however, some surgeons make the first burr before marking, thereby reducing the obliteration of inked lines during irrigation. A single burr hole (see *Trephination* above) is usually sufficient but surgical preference varies. The osteotomies should meet each burr hold at its outside edge to ensure that the holes will lie almost entirely within the bone flap. The osteotomy is made along a roughly circumferential path, followed by removal of the bone flap after it is freed from dural attachments. Nowadays osteotomies are most commonly done with electric or gas-driven craniotomes but may be accomplished with a Gigli saw (see above discussion). The routine use of multiple burr holes is a carry-over from the era of the Gigli saw—i.e., before power-driven craniotome came into common use. A craniotomy site may be enlarged or modified with rongeurs.

Piecemeal Removal of Bone

The piecemeal removal of cranial bone is often required to enlarge or modify the contour of a fresh cranial opening. It is often necessary to remove jagged edges of bone and bone in locations that are impossible or inconvenient for the craniotome, particularly in the setting of trauma. The piecemeal removal of bone is most often done with rongeurs of various types and sizes or with osteotomes, but larger fragments can be removed with a craniotome.

In past centuries, cranial bone was removed in piecemeal fashion, using chisels, rongeurs, and saws of various design. The bone was probably never replaced, as evidenced by surviving drawings and from archeological discoveries of skulls from around the world.

Management of Iatrogenic Entry of Frontal Sinus

The frontal sinus may be accidently entered by a craniotome or drill while working near the sinus. These violations of the frontal sinus are not obligatory indications for cranialization of the sinus or other radical action. Blood which may have entered the sinus is removed with suction and the sinus irrigated with an antibiotic containing solution. The defect in bone should be covered with Gelfoam® or strip of harvested galea. A bone chip can be harvested from the free bone flap or cranial surface and wedged into the bony defect in the sinus, but it not clear that this is necessary. Antibiotics administered for prophylaxis are usually sufficient to cover the risk of infection. Iatrogenic entry of the frontal sinus usually heals without complication. A subgaleal suction drain should be avoided because of the high likelihood of its sucking air from the nasopharynx.

Craniotomy Without Power Tools

Craniotomy without power tools is necessary in two settings: (1) emergencies in which instruments requiring a power source is not available and (2) when brain biopsies are required in patients in whom prion disease, for example, Creutzfeldt-Jacob disease, is suspected (See above discussions of "Burr Holes Made with Hudson Brace and Bit" and "Osteotomy with Gigli Saw".)

Hemostasis in Bone

Normal bone is living tissue with arteries and veins that are most prominent in cancellous type bone. Techniques for hemostasis in cancellous and cortical bone are addressed separately.

Hemostasis in Cancellous Bone

Bleeding from cancellous bone was a major, sometimes life-threatening, source of blood loss in surgeries involving he cranial vault in the early days of elective intracranial surgery An historical technique for hemostasis was to crush the tables of the skull together with various tools designed for this purpose. Surgery often had to be cancelled when this technique was ineffective [27].

Bone Wax

Wax pressed into bleeding cancellous bone is highly effective in achieving hemostasis by producing a mechanical barrier, but it has no chemical hemostatic properties. The wax enters the interstices of cancellous bone where it is not easily displaced by arterial or venous pressures within bone. Bone wax is available in sterile sticks, and it is commonly manually manipulated to soften it before application, but this is not necessary, and some believe that extensive manipulation renders it slightly less effective. Currently available formulations of bone wax vary with manufacturer and may contain beeswax, paraffin, and isopropyl palmitate (Ethicon®) or beeswax with petroleum jelly (Aesculap®).

Bone wax is insoluble and typically remains in place for an extended period, often years but is slowly removed, probably by phagocytosis. Risk associated with bone wax is low, but it can shield a persistent nidus of infection. If wax is pressed into large open venous channels, it can be embolized to heart and lung. There is evidence from noncranial sites and studies in animals that bone wax inhibits osteogenesis and can impair the ability of cancellous bone to clear bacteria [28–31]. Almost a century ago, bone wax was recommended for prevention of healing of bone and to create pseudo-arthroses as a component of arthroplasty [32]. It is reasonable to minimize the amount of bone wax used intraoperatively and, when possible, its use should be avoided on bone in which fusion is important [33].

Several resorbable materials similar to bone wax have been developed. Ostene® is an inert water-soluble mixture of alkylene oxide copolymers which has physical properties similar to those of bone wax and does not inhibit osteogenesis or bone healing [33]. Hemasorb is a putty-like mixture of calcium stearate, vitamin E acetate, and a liquid surfactant. It requires no kneading prior to application and is absorbed within a few days.

Wax of several types was used for centuries to control bleeding from cranial bone [34], but its improved formulation ("7 parts beeswax, 1-part almond oil, and 1% salicylic acid") as "antiseptic wax," by Victor Horsley, the father of neurosurgery, was a landmark advancement. Horsley's wax, as it was known far into the twentieth century, was an excellent agent for achieving hemostasis in bone, did not liquefy at body temperature, did not add to the risk of infection, and, in more recent formulations, continues to be commonly used and is inexpensive [27].

Floseal® consists of powdered thrombin and gelatin granules that, when combined, produce a slurry of material which precipitates clotting and expands volumetrically by 15–20% over 5–10 min following application. The earlier Floseal contained bovine thrombin but Floseal Matrix® contains human thrombin. It is typically applied over the bleeding site via syringe and held in place for a few minutes, commonly by a sucker pressed against a wet Cottonoid®. Irrigation can remove excess material. Other effective materials include Avitene® (microfibrillary collagen with thrombin), Floseal (gelatin granules with human thrombin), and Surgiflo® (porcine gelatin sponge) and held in place with a Cottonoid® for a few seconds will halt most small-vessel bleeding.

Swarf, the bone dust and curls of bone produced by a craniotome, burr, or rongeur can be pressed into raw bleeding bone to assist in hemostasis. This is often quite effective in dealing with low pressure bleeding from bone but not for vigorous osseous bleeding. It is safe, free, and usually instantly available. Bone dust in the subarachnoid space has been associated with aseptic meningeal reaction and therefore should be removed with irrigation, to the extent possible, before dural incision.

Cauterization—Bleeding from cancellous bone can rarely if ever be reliably controlled by cauterization.

Hemostasis on Cortical Bone

Most bleeding from cortical bone is venous and is exiting through smooth-walled choanoid foramina. Bone wax is sometimes effective, but bone wax does not adhere well to the smooth walls of the cortical walls of choanal foramina. Wax pressed into choanoid foramina of cortical bone may halt venous bleeding, but arterial bleeding often displaces the wax, particularly as it warms toward body temperature [35]. Because the axes of these small foramina are often not perpendicular to the cortical surface, the angle at which the wax is pressed against cortical bone can result in either forcing wax into foramina, as intended, or in the unintended removal of wax from foramina. For these same reasons, Floseal® is often ineffective. Tiny bleeding sites on a cortical surface can occasionally be controlled with microelectrode electrocautery, but this is consistently effective.

High-pressure venous bleeding from foramina on cortical surfaces can be impossible to control with bone wax, Gelfoam® plugs, or cautery. Hemostasis can be established with a wedge of bone driven into an oblique osteotomy that crosses the foramen, as shown in Fig. 8.1 [35].

The middle meningeal artery may be avulsed by trauma, during reflection of dura on the floor of the middle fossa, or during resection of tumor, causing vigorous bleeding that cannot be adequately controlled with bone wax. Arterial bleeding from a choanoid foramen, for example, foramen spinosum, can rarely if ever be reliably controlled with bone wax or cautery but can be quickly and securely controlled by forcing a short dowel of wood into the foramen. As shown in Fig. 8.1, a small sliver of cortical bone can be tried but is usually pushed out by the arterial pressure [35].

Hemostasis Along a Kerf

Venous bleeding along a kerf can be stemmed reasonably well with wax and Cottonoids® until the bone flap is removed, the source of bleeding identified, and

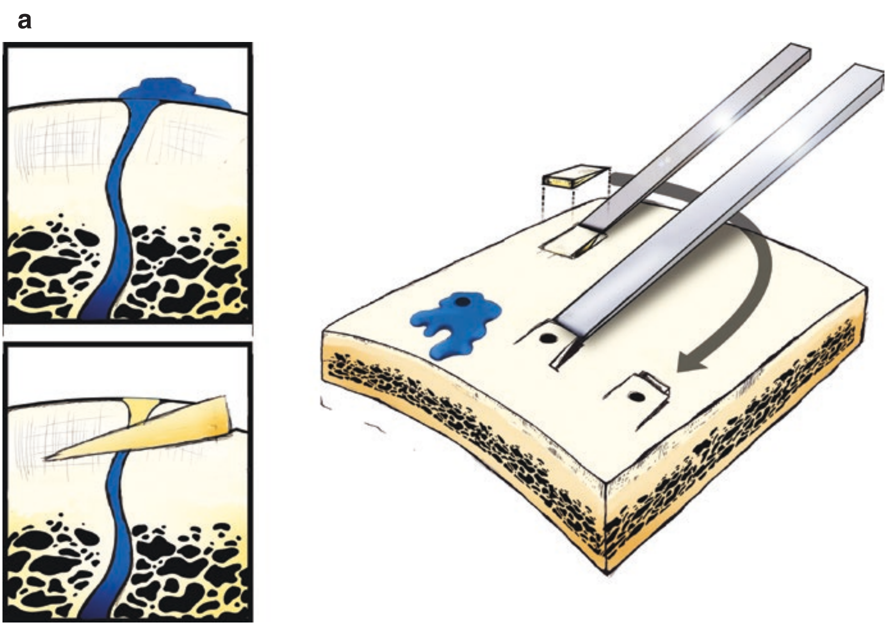

Fig. 8.1 Obtaining hemostasis from choanal cranial foramina: (**a**) Venous; (**b**) Arterial. (Permission obtained from Folzenlogen Z, Winston KR. Techniques for achieving hemostasis from choanoid cranial foramina. *World Neurosurg.* 2017;100:710.e717-e719. https://doi.org/10.1016/j.wneu.2017.01.128)

Fig. 8.1 (continued)

controlled. Venous bleeding from disruption of a large vein in dura, particularly a venous sinus, can be problematic.

Arterial bleeding can be vigorous and is occasionally encountered when the middle meningeal artery is disrupted near the sphenoid wing. In extreme cases of arterial bleeding that cannot be halted, it is necessary to quickly complete the circumferential osteotomy and sequentially press bone wax into the kerf as the craniotome is advanced. After the bone flap is removed the bleeding artery can be visualized and controlled with electrocoagulation or a ligature around the artery. In some cases, additional bone must be removed with a rongeur to identify the arterial source.

Hemostasis Along an Acute Fracture Line

Bleeding from fracture lines in cranial bone is strongly related to the amount of separation of fragments and their angulation. Bleeding from full-thickness fractures, including depressed fragments, is likely to occur, at least partially, into the epidural space and this can be severe and life threatening, if the fracture crosses an artery that is partially or totally encased in bone, for example, the middle meningeal artery.

Bleeding along the edge of a minimally displaced cranial fractures is sometimes seen during neurosurgical operations for trauma, and this can usually be securely controlled with bone wax.

Hemostasis on Undersurface of Intact Cranial Bone

Bleeding into the epidural space commonly occurs around the edge of a fresh craniotomy. This may be initiated by the instruments used to make the osteotomy or by tightly stretching and bowstringing the dura with tenting sutures. The precise site of bleeding cannot be visualized unless it is near the bony edge. The bleeding can be either from vessels on the dura or from bone, but most often the former. Regardless of source, active bleeding into the epidural space must be controlled, and this is most commonly accomplished by dural tenting. If the chief or sole site of epidural bleeding is thought to be from the undersurface of bone, s*mall pieces* of bone wax can be pressed outward against the undersurface of bone with a curved instrument, such as a #3 Penfield dissector, but this is not consistently successful. Dural retraction with sutures is often effective in halting venous bleeding and tiny sites of arterial bleeding. Large chunks of bone wax pressed into the epidural space may halt the *visible* egress of blood but often only conceals the bleeding and allows the epidural bleeding, if arterial, to progressively separate dura from bone. If neither dural retraction sutures nor tenting sutures control the epidural source of bleeding, additional bone must be removed to allow visualization and control.

Protection of Dura

There is no technique that reliably avoids injury of dura while making cranial burr holes or osteotomies; however, its occurrence can be minimized, and its consequences limited, for example, in patients in whom the dense adhesion is secondary to phenytoin usage, neoplastic involvement, or in some elderly patients. It is usually possible to make a burr hole without disrupting the dura if drilling is done slowly, with repeated checks on depth. The separation of dura for a few mm around the burr hole can almost always be safely accomplished with a nerve hook or lip of a Kerrison rongeur and the opening can be safely enlarged with a curette or Kerrison rongeur.

Dural Penetration Beneath a Burr Hole

If dura is intact, its attachment to bone at the edges of the burr hole should be cleared in the directions of planned osteotomies, using a nerve hook. Visual inspection is usually accurate but not 100% reliable. Visualization of CSF or brain is the absolute indication of dural penetration.

If not intact, a decision must be made regarding the likely safe insertion of the tip of the foot plate of a craniotome and shredding dura. If in doubt, the exposed dura should be explored with a surgical instrument, such as a #4 Penfield dissector or nerve hook. If there is a large dural disruption, relative to the size of the burr hole or at the side of the burr hole on which the craniotome will be applied, the burr hole must be enlarged with a Kerrison rongeur or a new hole drilled along the planned osteotomy. Occasionally, it is necessary to repeat this action several times in patients with tightly adherent thin dura. It can be difficult or impossible to reliably detect dural penetration in patients with densely adherent dura and very thick cranial bone, as often the case in elderly patients and those who have had a prolonged exposure to phenytoin.

Vigorous arterial bleeding from a burr hole in the keyhole region is almost always from an injured middle meningeal artery. The hole should be temporarily plugged with bone wax and a new hole drilled.

Dural Penetration During Osteotomy

The risk of disrupting dura with a craniotome can be minimized by advancing the instrument slowly with its axis tilted to keep the tip of the foot plate tightly against bone. When resistance is encountered but the craniotome can still be advanced, back-and-forth rotations of approximately 20° after each few mm of advancement will often sufficiently separate adherent dura to allow continued advancement of the craniotome. If the craniotome suddenly encounters a hard, seemingly impossible obstruction to further advancement, a small amount of wiggling of the craniotome with an inward push of 2–3 mm against intact dura will usually disengage the footplate from a vascular groove in bone and separate the dura for a few mm without disrupting the dura.

Disruption may be signaled by the appearance of CSF or vigorous venous bleeding in the kerf, but neither of these consistently appear. Penetration of dura by the craniotome often occurs when advancement of the craniotome suddenly encounters a hard obstruction followed by sudden disappearance of the obstruction as the craniotome is advanced. A sudden decrease in resistance is strongly suggestive of dural penetration. If there is suspicion that dural penetration has occurred, the surgeon should immediately stop advancing the craniotome and gently push the device inward by a few mm. The tactile distinction between the resistance offered by intact dura versus the resistance of brain or CSF usually allows reliable assessment of the status of the dura. If uncertainty remains, the kerf should be explored with a thin surgical instrument, such as a small nerve hook or freer elevator. When there is confirmation or serious suspicion of dural penetration, the craniotome should be removed from the kerf and a new burr hole made.

After a craniotome penetrates dura, further advancement, shreds dura and blood vessels within the dura. If near the cranial midline, the dural shredding may disrupt veins in the dura, bridging veins to the superior sagittal sinus, or the sinus. If a tear into a sinus is above the heart by a distance exceeding central venous pressure, air will enter the sinus, resulting in air embolism. The head should be lowered to minimize loss of blood.

Dealing with Adherent Dura

It may be necessary in areas of normal dense adhesion, for example, suture lines in children, to use a freer elevator or Penfield dissector to separate dura from bone and allow flap removal. When dura is densely adherent to a free bone flap that has not been removed, it will be necessary to pry one side of the bone flap outward and dissect the dura free with a #2 Penfield dissector, freer elevator or occasionally in large flaps with a periosteal elevator. As one side of the bone flap is pried out, the opposite side of the flap will be displaced inward against the dural envelope and brain. This displacement can be minimized by prying firmly against the opposite side of the flap with a thin instrument as the adherent dura is dissected free.

The separation of densely adherent dura from a bone flap can on rare occasions be impossible, for example, in patients with prolonged exposure to phenytoin whose cranial bone is very thick and has a knobby undersurface. In such extreme cases, particularly if the dura is penetrated several times in attempts at separation, the safest course of action is to forego dural separation and circumferentially disrupt the dura with the craniotome, leaving the inseparably adherent dura attached to the bone flap. Attempts to cut the surrounding dura with a knife or small scissors, may seem less esthetically displeasing but is more dangerous. Following disruption with a craniotome, a dural patch will be necessary for repair, and this will require special attention because of the ragged edge of surrounding dura.

The dura, in patients who have had prior radiation in the surgical field, is often thinner and more adherent to bone than normal, thus increasing the risk for disruption during surgery, but occasionally irradiated is minimally adherent to bone. Regardless, the surgeon should proceed slowly when making burr holes and osteotomies and make frequent checks for intactness of dura. Bleeding from bone is often less than usual but hemostasis can require more attention than expected.

Carpentry and Recontouring of Bone

Remodeling of bone is critically important in craniofacial surgery and is valuable in some neurosurgical procedures. The contour of cranial and facial bone greatly influences the contour of overlying soft tissues and hence cosmetic outcome. Expertise in remodeling of bone is less intuitive than commonly perceived. Surfaces of intact bone can be remodeled by removing unwanted prominences with a burr and by onlaying a bone graft or synthetic material. Free cranial and facial bone fragments can be remodeled by altering their outer and inner surfaces, their curvature, and shape.

Characteristics of Bone Which Affect Remodeling

Most living bone can be remodeled without difficulty, using burrs and osteotomes. Thick bone can be easily remodeled with a burr with small risk of full penetration or fragmentation. Thin bone, for example, that of infants, is usually most safely remodeled by osteotomies or recontouring with bone molding forceps and less use of a burr. Cancellous bone is much more amenable to remodeling without fracturing than is cortical bone. Some bone is, regardless of thickness, brittle and prone to fracturing or shattering during attempts at recontouring. This is true in many elderly people, disorders in which there is little or no cancellous bone, for example, osteopetrosis, and intact appearing cranial bone that has been devascularized by past mechanical or surgical trauma.

Techniques for Remodeling Cranial and Facial Bone Burr

A burr is the most useful instrument for recontouring or remodeling bone. The external surface of intact bone or any surface of free fragments, including undersurfaces, may require remodeling. Large pear-shaped and cylindrical burrs are the most appropriate for this task and produce the best results.

Osteotome

An osteotome can be used to remove bony prominences from intact cranium, and thereby improve contour; however, care must be taken to avoid full-thickness penetration of the cranium. Although appearing simple, considerable skill is required in the use of an osteotome to improve cosmetic appearance.

Craniotome

A craniotome is used to make radial osteotomies, which facilitate the recontouring of a cranial bone flap by facilitating, usually decreasing, its radius of curvature. This is most often required when recontouring fragments removed during correction of craniosynostosis. Also, radial osteotomies around the periphery of an intact craniotomy site facilitate the outward bending or intentional outward fracturing of sections of bone to improve cranial contour without bony disconnection.

Bone Molding Forceps

Bone molding forceps are useful in altering the curvature of free fragments and attached bone strips (see above section). The bone of infants and young children, often mostly cortical, can usually be bent without fracturing. When hard bone of children resists sufficiently molding, it will usually become malleable in response to repeatedly crushing in multiple directions with Tessier bone bending forceps. Brittle bone cannot be bent or made malleable.

Grooves

Grooves in bone made with high-speed drill, usually on undersurface, facilitate bending without fracturing, particularly in infants and young children and occasionally in adults. The grooves must be near full thickness, and most of the bending will then occur in cortical bone. If more than about 15° of bending is desired, the grove must have a broad V-shaped crossection to facilitate the bending, which can be up to 90° in pediatric bone. This technique can also be valuable when bending full-thickness bone grafts during cranioplasty without having to divide the graft into fragments.

Sutures can be placed through paired holes in bone fragments to establish a desired alignment and in bent fragments to maintain the bend during healing. This technique is most useful in infants undergoing corrective surgery for craniosynostosis. Absorbable sutures, for example, 2-0 Vicryl®, serve this purpose quite well. Nonabsorbable sutures add no benefit, and wire sutures for this purpose has fallen into disfavor.

Thin Titanium Plates

Thin titantium plates can be used to reinforce and maintain a desired curvature of bone or alignment of free fragments during postoperative healing. This is commonly required during extensive cranial vault reconstruction; however, in infants and young children titanium plates and screws can migrate partially or totally through growing bone and penetrate dura and even brain, as a result of normal osteoclastic and osteoblastic activity [36]. In older children and adults, plates can be also placed on the undersurface of free bone fragments to maintain curvature before reattaching the construct to the intact skull.

Steel screws or wire should not be used with titanium plates because of possible bony erosion resulting from a slow electrolytic process. Absorbable sutures add no benefit, and wire sutures for this purpose are no longer in common use.

Underlying Reinforcement

Underlying reinforcement with a flat bone graft is often useful in securing alignment and contour of fragments of thin cranial bone fragments that cannot be otherwise reliably stabilized. The graft is usual full thickness infant bone and is secured in place with absorbable sutures. This technique is beneficial in some infants undergoing correction of craniosynostosis.

Cranial Onlay Grafting

Autologous bone or synthetic materials may be used as onlay. Preformed synthetic materials offer a quick precise fit, may be held in place with screws or fibrous tissue and never absorb. However, they are subject to infection, displacement, migration, can cause erosion, and are expensive.

Replacement, Alignment, and Fixation of Bone Fragments

Bone flaps being replaced following elective craniotomies and in the repair of defects from cranial decompressions are, with rare exceptions, returned to their sites of origin with their original orientations. Autologous flaps are always smaller than the cranial opening because of the kerf produced by the craniotome. Stability is enhanced, and healing optimized by firm bony-to-bone contact around the periphery. This is very often best achieved by rotating the flap by a few degrees from its original orientation before rigidly fixing it. This ensures that the bone flap will be in contact with intact cranial bone at three or four sites, and these contact sites will not be limited to one side or corner of the cranial defect. This small rotation rarely if ever has any adverse cosmetic impact; however, flaps on the forehead, particularly if including supraorbital rim should *not* be rotated.

Abutment of Cranial Bone Fragments

Bone-to-bone abutment is achieved when bone flaps are replaced and when bone grafts are implanted in cranial defects during craniofacial reconstructions. Rigid fixation is important. The configuration of the abutting edges influences stability, and the abutment of fresh cancellous bone optimizes bony healing. Stable abutment of bone edges with precise alignment in cosmetically sensitive sites is desirable but not always possible because of the amount of available bone and its shape.

Edge-to-Edge Flat Abutment

This is the best and most common technique used in replacement of bone flaps and repair of cranial defects. For autologous bone flaps, this re-establishes normal cranial contour and can be easily secured by plates or by sutures.

Edge-to-Edge Offset Abutment

This technique can be quite useful for securing external surface alignment of bones of unequal thickness, for example, during cranioplasty with less than full-thickness autologous bone.

Overlapping Abutment

Overlapping abutment can be quite useful in cosmetically sensitive sites, in which case the overlying edge must be very thin. This technique often results in an acceptable contour across the junction of fragments; however, the overlapping edges, which are often cortex-to-cortex, may heal poorly or not at all. If much of the overlying bone resorbs over time, this joint can become palpable unless obscured by scar. This technique is sometimes used in frontal cranial reconstructions during correction of craniosynostoses but can also be useful in surgeries in adults.

Tongue-in-Groove Abutment

This abutment ensures stable alignment and assists fixation; however, it is rarely used. It can be used on only one side of a cranial defect. The tongue and the groove need to be only about 2 mm in thickness to maintain alignment, and it is best for the groove to be slightly deeper than the tongue. Few if any plates are required at the site of tongue-in-grove abutment but are required on other sides.

Snap-in-Place Technique

Snap-in is *not a common* option but can occasionally be used to replace a bone fragment that has been removed, usually in surgeries for trauma, without the fragment or adjacent intact bone being significantly altered. It may be necessary to slightly pry adjacent bone to allow the insertion of the fragment. This technique results in perfect alignment, contour, and usually quite secure fixation, without the use of plates. Occasionally, one side of a fragment can be snapped in place, with the opposite side requiring a plate.

Fixation of Bone Flaps and Fragments

Historically, bone flaps were secured in place with wire or silk sutures, but this technique often did not achieve rigid fixation. Another technique was the use of glazier points (small triangles of tantalum) that were hammered into the living bone surrounding the bone flap. The name is from the technique for securing glass to wooden frames [37].

The purpose of fixation is the immobilization of bone flaps and bone fragments in functionally and cosmetically acceptable alignment until secure healing occurs across the interface with living bone. The materials used for the initial fixation, for example, plates and screws or sutures, cannot be depended upon for maintaining long-term stability of the bone fragments. Small amounts of mobility, allowing movement of a bone flap with each heartbeat and respiration, impairs healing and will often result in a depressed or floating flap. Healing is a slow across gaps in juxtaposed fragments, and the wider the separation of fragments the more time required for fusion to occur. The edges of the avascular bone will be slowly invaded by osteoclasts and *creeping replacement* of bone will begin and continue for months or years. This occurs more rapidly with autologous bone than other types of bone and much more rapidly in children than adults. Regardless of bone-to-bone healing, fibroblasts grow and migrate around avascular materials, for example, around a bone flap or other cranioplasty material and are highly effective in securing the avascular material while bony fusion is occurring.

Titanium Plates and Screws

Plates and screws usually provide reliable rigid immobilization of bone fragments over sufficient time to allow solid fusion to occur; however, after solid bone fusion occurs, plates and screws serve no long-term purpose. After the bone flap is securely fixed, the available swarf, whether bone dust, chips, or curls, should be packed into the surrounding kerf [38]. These materials are now readily available in most neurosurgical operating suites, in a wide variety of shapes and thicknesses. They are intuitively easy to use, relatively safe, but can be expensive.

Plate fixation of cranial and facial bones is most often done with titanium plates and screws. Steel plates and screws are now rarely used. Titanium produces only a small artifact on neuroimaging, whereas ferromagnetic steel produces a large artifact and obscures nearby tissues. Some surgeons prefer absorbable plates and screws because of the obvious advantages of their eventual disappearance and their producing no artifacts on neuroimaging. Disadvantages include an occasional inflammatory response in adjacent soft tissue with weeks for months of swelling. Also, absorbable plates and screw heads are usually thicker than metal counterparts and may be palpable beneath the scalp of infants until they are resorbed.

Most bone flaps can be securely fixed with four plates. There is a tendency for neurosurgeons, particularly the less experienced, to use many more plates and screws than necessary to achieve secure immobilization and alignment of bone fragments. Loosening of a bone flap a few weeks after being securely immobilized with plates and screws is a complication likely related to thermal osteonecrosis.

Manufacturers of metal screws market them in multiple lengths, but the shapes of screw heads are not standardized, and each brand seems to have a differently shaped head, several of which require a unique screwdriver. This can present significant technical problems when reoperations are done, particularly if in a different hospital from that of their implantation. Metal screws used in infants and young children are said to "migrate through bone" due to the simultaneous active deposition of new bone over the cranial convexity by osteoblasts of the pericranium and the resorption of bone by osteoclasts of the endosteal layer of dura. Therefore, many surgeons remove implanted screws in infants and young children after bone is healed. This results in the plates being relatively easy to remove, but the shafts of the screws remain. These protruding metal shafts can often be removed with a heavy needle holder, but often the protruding portions must be removed with a small burr. Whenever metal is removed with a burr, there is a scattering of metallic dust over the nearby exposed raw tissue, over the surgeon's gloves and there is risk of impacting the unprotected corneas of scrubbed personnel. Therefore, wet gauze sponges should be used to cover the exposed tissues before the burr contacts the metal. Surgeons should irrigate their gloves and all personnel should be wearing ocular protection. The metal dust cannot be removed from tissue with irrigation. The distributed titanium dust does not impair healing or produce a significant artifact on MR imaging.

Securing an irradiated bone flap usually proceeds without difficulty, but slow bony union should be anticipated. Therefore, more plates and screws should be used to securely immobilize the flap than required for a healthy flap.

If postsurgical irradiation is anticipated, more plates than usual should be used to immobilize flaps. The healing of bone will proceed normally until irradiation begins and, as radiation is delivered, the healing of bone will become impaired and progress slowly. The longer the delay in start of radiation, the more normal the early stages of healing will progress. Bony nonunion is much more likely to occur in early irradiated bone, and the healing of overlying soft tissues will heal more slowly than normal, resulting in thin, poorly vascularized skin. There is risk of erosion of titanium plates and screws through the scalp of young children and through thin irradiated scalp.

Sutures and Shims

Flap fixation with 2-0 absorbable sutures and bone fragments used as shims achieves structural stability in a keystone configuration over the convex calvarium, with and excellent esthetic results [39, 40]. This technique requires the drilling of pairs of holes in the bone flap and surrounding intact cranial bone. Six to eight sutures are typically required, depending on size of flap and its location. Six to ten small chips of bone are harvested from the undersurface of the free flap for use as shims. The free flap is then returned to its normal position and all sutures tied tightly. The bone chips are pressed or tapped into the surrounding kerf. If not secured tightly with shims, the flap will become loose and either heal in a depressed position or become a mobile flap. Absorbable sutures used for flap fixation without bony shims to immobilize the bone flap will result in either a floating flap or bony fusion in a significantly depressed position.

When used with *snugly placed* bony shims, the result is as satisfactory as that associated with plates and screws, but with none of the associated risks and at far less expense [39, 40]. This technique should not be used for irradiated bone or when postsurgical radiation is anticipated.

Nonabsorbable Sutures

Nonabsorbable sutures of many types—e.g., silk, cotton, and wire—have been used to secure bone flaps in place since the early days of cranial surgery. The short-term result is usually quite satisfactory but too often the flap becomes loose after a few days or weeks, resulting in either inward displacement before bony union occurs or a permanently mobile flap. This delayed loosening is a consequence of stretching of the sutures and resorption of bone beneath the tightly tied sutures combined with the effects of atmospheric and intracranial pressures on the flap.

Silk Sutures

Silk sutures have been used to immobilize bone flaps for over a century. They are not apparent on neuroimaging but when infection is being treated, they can harbor bacteria. In the absence of bony healing, silk sutures do not provide permanent immobilization of bone fragments.

Stainless Steel Wire

Stainless steel wire produces immediate solid immobilization of bone fragments—cranial or spinal—and usually with lasting satisfactory stability, if bony fusion occurs within a few weeks. If healing is delayed, the flap may become loose. This is thought to occur because of resorption of bone or stretching of the wires. Tissue reactivity is low and association with infection is low. The tips of wire sutures occasionally cause sites of tenderness in scalp and require removal. During surgery, the manipulation of wire can snag and penetrate gloves and skin of surgical personnel who are inexperienced with its use.

If wires must be removed, regardless of reason, after bony healing has occurred, this can usually be accomplished by cutting the wire and pulling the wire out. Occasionally, the wire cannot be removed by traction and must be left in place.

In the early twentieth century, wire sutures were used by some neurosurgeons for closure of all layers of tissue, including dura, because of its low tissue reaction and association with infection.

Repair of Frontal Craniotomy with the Preservation of Frontal Sinus [22]

All mucosa on the free flap must be removed and any loose mucosa within the remaining intact sinus must be removed. A burr can be used to remove mucosa from crevices and difficult-to-visualize sites. It is controversial as to whether *all* mucosa attached to intact bone must be removed, but all flaps or loose pieces of mucosa *must* be removed to prevent delayed occlusion of the frontonasal tracts with formation of mucocele. The frontonasal tract on each side must be probed for patency before repair, except in small entries into the frontal sinus. If there is suspicion of compromise of a foramen, it should be enlarged with a narrow osteotome or small bone impactor. The free bone flap is returned to its normal position. If the entry into the sinus was the result of a frontal craniotomy, the free frontal flap should be positioned in firm contact with bone across the upper edge of the intact cranial bone, leaving no kerf. The flap is secured with plates and screws, none of which should enter the frontal sinus.

Harvesting Bone

Freshly harvested autologous bone is the best material for repairing cranial defeats; however, the size availability, lack of experience, time required for harvesting, and risk of compilations are often cited as reasons for not choosing to use autologous bone.

Harvesting Full-Thickness Autologous Cranial Bone [41, 42]

The surgeon chooses a calvarial site that has the desired contour; however, this site may be limited by accessibility, safety for the patient, and by cosmetic concerns. It may be necessary to extend an existing scalp incision or make and incision in a new site. A template of the cranial defect is made, usually with aluminum foil. This template is then placed on the chosen harvest site and its outline is marked with ink. A small slot-shaped burr hole is made and a craniotome just outside one edge of the inked line. The osteotomy is made along the marked line. The bone flap is easily removed.

Splitting a bone flap—The free flap is removed and inspected for suitability to being tangentially split, which requires the presence of a cancellous layer. Calvarial bones of the newborn are unilaminar, but by 3.5–4 years, these bones are usually bilaminar and have a diploic space filled with bone marrow. The presence of a layer of cancellous bone is required for successful tangential splitting. It is impractical and nearly impossible to satisfactorily split cortical bone without severe fragmentation. If the entire full-thickness flap can be split, there will be two flaps of near identical contour but whose convex surfaces vary. Splitting is done with a small mallet and osteotomes, usually two. The process of splitting adult bone can be slow and tedious, and experience is beneficial. Cranial bone of infants can often be manually split with a hand-held osteotome, while carefully protecting the surgeons' palm and fingers [43]. A Tessier bone splitting instrument may be helpful in this maneuver. If splitting is successful, the outer fragment is usually best for repairing the targeted defect and the inner fragment for repairing the harvest site. Sometimes both fragments are used to repair critical defects. If the harvested bone flap cannot be split, for example, solid cortical bone, or if attempts result in only chipping the bone, the entire flap must be used to fill the targeted cranial defect and the harvest site repaired with synthetic material.

Harvesting Cortical (Outer Table) Cranial Bone

Split-thickness cranial bone can be useful in repairing small cranial defects and for onlay grafts. It consists primarily of cortical type bone with little or no cancellous component, and it cannot be split. The proposed graft is marked on the exposed cranium with ink, and an electric drill is used to make a grove around the harvest site. Harvesting is accomplished with an osteotome and mallet. The osteotome is driven at a 45° angle to a depth of about half the cranial thickness or until cancellous bone can be identified, and then the angle of attack is reduced to about 30° and driven for about 4–6 mm. The osteotome is then removed and repositioned to expand the width of the osteotomy and the process repeated. The fragment can be slightly pried outward as the osteotome is driven stepwise forward, but attempt should be made to not crack the fragment. It is difficult to perceive the depth of the advancing osteotome and full-thickness penetration of the skull can disrupt dura. It is difficult to harvest a single fragment of more than 2–2.5 cm length by this technique. When the desired length is reached, as determined by assessing the desired fragment length and depth of penetration of the osteotome, the fragment can be either fractured outward or cut with an osteotome.

If the bone cannot be separated from the intact cranium or if attempts result in only chipping the cortical bone, the attempt must be terminated. Cortical chips may be satisfactory for repairing small cranial defects

Management of Cranial Donor Sites

Hemostasis in full-thickness donor sites is achieved by the same techniques described below for hemostasis in bone. If the graft has been successfully split tangentially, the inner fragment is usually used to repair the harvest site. Because this fragment is approximately half the thickness of the intact bone at the harvest site, alignment of the fragment's surface with that of adjacent bone requires special attention, lest the half-thickness fragment settle inward and result in an unsatisfactory cosmetic depression. If no bone is available for repairing the donor site, it must be repaired with synthetic material.

Bleeding from split-thickness donor sites is easy to control with bone wax, Floseal®, topical thrombin, or Avitene® (See discussion below on "Hemostasis in Cancellous Bone".) Partial-thickness donor-site defects rarely result in cosmetic or functional problems; however, the edges of the donor site should be reduced and made smooth with a burr.

Harvesting Ribs

Ribs can be useful for the repair of cranial defects when sufficient cranial bone is not available. Each rib can be tangentially, and each half easily molded to the desired curvature. Each end must be attached to intact cranial bone and the sides to one another. The exposed appearance has a washboard appearance, but the postoperative cosmetic result of cranioplasty with ribs is usually much better than expected [44–47].

The anesthesiologist must be informed preoperatively that the pleura may be punctured during the dissection. The patient must be initially positioned to facilitate the harvesting of ribs, and this position may not be satisfactory for the cranial surgery. Therefore, preoperative planning must include repositioning while the patient is anesthetized.

Ribs may be harvested from an anterior-lateral or posterior-lateral approach. The posterior approach requires an oblique skin incision just below the scapula of 8–10 cm length. Trapezius muscle can usually be retracted medially, and the latissimus dorsi muscle incised in a line parallel to its fibers. An anterior approach requires a skin incision below the pectoralis muscle in the submammary crease. Muscles should not be transected.

The posterior approach typically allows exposure of ribs 8 through 10 and the anterior approach allows exposure of ribs 4 through 6. No more than two adjacent ribs should be harvested. If three ribs are required, one rib should be left intact between the two-rib harvest site and the site of harvest of a third rib. Although uncommon, bilateral rib harvesting can be done. The length of safe resection of ribs varies with body size but rarely exceeds 10 cm.

After the targeted ribs are exposed, a longitudinal incision is made along the periosteum, and Doyen periosteal elevators (right and left) are used to circumferentially strip the periosteum of each rib. The periosteum should be protected to the extent possible and not transected. Each rib is transected with a rib-cutting instrument at the ends of its intended length. Bleeding from intact bone is managed with the minimum amount of bone wax. The edges of each periosteal sleeve are brought together with a few absorbable sutures to facilitate the regeneration of bone. Throughout the exposure and resection of ribs, care must be exercised to avoid puncture of the parietal pleura. If this occurs, a chest tube will be required. A few sutures are often required to approximate the edges of muscle. Skin is closed in two layers. A chest x-ray should be done either before extubation or in the recovery unit to evaluate for pneumothorax. New ribs may appear within 6 months in teenagers and young adults, if the residual costal periosteum has not been severely damaged. The new ribs are always irregular in contour and may not fill the entire gap but do have approximate normal curvature.

Harvesting Ilium [47]

Iliac bone is commonly used in spinal fusions but only rarely for cranial repair. The ilia of adults can provide a moderately large curved fragment of autologous bone [48, 49]. A curved incision in skin of approximately 12 cm length is made 1.5–2 cm above the iliac crest. Incision directly over the crest is associated with more postoperative pain and may heal more slowly because of pressure along the underlying edge of bone. The fascial attachment of *gluteus medius muscle* along the lateral edge of the iliac crest is cut for 8–10 cm and the gluteal muscles are separated from the lateral surface of the ilium. The attachment of abdominal muscular fascia to the crest of the ilium is divided along the upper edge of the ilium, and the *iliacus muscle* is separated from the inner surface.

There are two techniques for harvesting the bone, the difference being the treatment of the iliac crest. Two osteotomies, approximately 6–8 cm apart, depending on size of ilium, are made with an oscillating saw or osteotome through the iliac crest and each is continued down the iliac bone. Alternatively, the iliac crest can be left intact and an osteotomy made transversely through the ilium approximately 1.5 cm below the crest, and then the two osteotomies approximately 7 cm apart are made downward for the distance required to harvest the required amount of bone. It is particularly important to avoid damaging the acetabulum or extending an osteotomy close to this structure. The inner surface of the ilium can be digitally palpated or frequently explored with an instrument to minimize injury to the iliopsoas muscle. If the two osteotomies do not meet at depth, it may be necessary to connect the two with a short transverse osteotomy. Avitene™ or a minimum amount of bone wax is used to achieve hemostasis, but nonbleeding sites should not be waxed for prophylaxis.

If the iliac crest has been resected, it must be separated from the free fragment, returned to its original position, and securely fixed with wire sutures. The abdominal fascia is sutured to the fascia along the iliac crest. A drain (Penfield drain or closed suction drain) is inserted deep into the wound and passed through a stab wound in skin. The gluteal fascia is closed, and skin is closed in the usual two-layer manner.

Ilia are only rarely harvested in sub-teen children because of the small amount of bone that can be obtained; however this has been done in very young children [50]. Elderly patients tend to not tolerate this routine well and often the fragment obtained is quite thin. Postoperatively, pain can last for many weeks, and this is a significant disadvantage.

Harvesting Tibial Bone

The use of tibial bone for the repair of cranial defects has historical interest but is rarely used nowadays [45, 48]. Tibial grafts have also been used in spinal surgery, for example, in cervical fusion following corpectomy. Longitudinal tibial osteotomies in the midportion of the bone can be made with an oscillating saw but two-thirds or more of the tibial shaft should be left intact. Tibial grafts resist recontouring and are therefore awkward for the repair of cranial defects because of their straight contour and their being predominantly cortical-type bone [51].

Xenografts and Allografts

Allografts have been used for cranioplasty for many years with relatively satisfactory results. Xenografts tend to be quite brittle and remodeling is difficult. Allografts are most useful in filling defects of less than 4 cm in diameter and located on the flatter portions of the cranium. The graft should be rigidly fixed with plates and screws. The graft usually becomes strongly ensconced with scar, but bony integration is slow and quite limited.

Artificial Materials

No ideal artificial bone substitute has been developed, but extensive research continues. Implantation of various matrices infused with bone morphogenetic protein has been used in spinal surgery but this is not recommended.

Storage of Cranial Bone

Bone flaps that are not replaced at the conclusion of cranial surgery are commonly preserved for later implantation (cranioplasty). A review comparing outcome of cryopreservation and subcutaneous storage in 4096 cases of cranioplasty with autologous bone found no statistically significant differences in infection, resorption, or reoperation [52]. Preserved bone flaps have the advantage over harvested bone for the repair of cranial defects of being the correct size and contour, except in young children whose crania may undergo significant change in size and contour before the flap is reimplanted.

The practice of culturing every bone flap immediately before cryopreservation, but not before subcutaneous implantation, and discarding those flaps which are culture positive has intuitive and traditional appeal, but, in the opinion of these authors, this practice leads to unnecessary discarding of bone flaps. All surgical wounds, and hence bone flaps, are exposed to circulating nonsterile air and likely most, if not all, bone flaps would be culture positive if multiple cultures were obtained from their surfaces.

Cryopreservation

Four to 23% of cryopreserved bone flips undergo slow resorption over the months following reimplantation and the cause of this is not clear at the time of this writing [53–56]. Absorption is more common in children and in bone flaps replaced greater than a year from craniectomy [57]. Surgical site infection is reported to occur is 3–26% of cranioplasties in which cryopreserved bone was used and is most likely related to contamination at time of reimplantation, in the opinion of these authors [56, 58].

Subcutaneous Storage

Subcutaneous storage in an abdominal pocket ensures exposure to near ideal physiologic conditions throughout the period of storage [59]. The infection rate and resorption rates are reported to be low [59, 60]. If patients will be transported to other hospitals after removal of a bone flap, for example, in battlefield settings, this storage site ensures that the free flap will not be lost. Subcutaneous storage has the disadvantage of requiring two additional surgeries (implantation and retrieval), often extensive resorption, and/or loss of anatomical contour. *Subgaleal storage* has been used successfully in a young child [61].

Cranioplasty [62]

Job Janszoon van Meekeren, in 1668, reported the case of Butterlijn, a Cossack soldier, who lost of a portion of his skull from a strike with a saber. The army's surgeon repaired the defect by modeling a segment of canine skull to fit the man's cranial defect. The wound healed but, when the army returned to Moscow, the soldier was refused entry into the church and excommunicated on the basis of being not fully human. The surgeon refused to remove the xenograft, apparently because the bone graft was thought to be healed to the patient's skull. The soldier chose to leave Russia [63].

Cranioplasty is the repair of a congenital or acquired defect or deformity in the skull. It protects brain from mechanical trauma, provides esthetic contour, and may alleviate neurological symptoms. Fresh cranial defects are obvious and most cranial defects covered with scalp are apparent from inspection and palpation. Cranial defects may have congenital, surgical, or pathologic origin. Neurosurgical interventions are the most common cause, and these include burr holes, craniectomies, osteotomies done to enlarge craniotomy sites, and craniectomies. There usually exists some information on the existence, site, and type of prior cranial surgeries which can be obtained from the patient, but some patients forget to mention prior surgeries, give incorrect information, or are unable to give any history.

Small Cranial Defects

Small cranial defects are those whose greatest diameter does not exceed approximately 2.5 cm. Visible indentations, whether pulsating or not, are cosmetic defects, particularly if on the forehead, lateral frontal region, and in regions of baldness. These commonly attract unwanted attention. Such defects are often the result of burr holes or gaps adjacent to a replaced bone flap.

Burr Holes

Round holes of eight to 12.5 mm in diameter in cranial bone are most often burr holes from an earlier surgical procedure. Until gas-driven and electric drills came into common use, burr holes were perfectly round and usually one-half inch in diameter.

Among the pathologic causes of cranial defects in adults are metastatic disease and in children are eosinophilic granuloma and neurofibromatosis. Newborns and infants have normal cranial defects in the form of fontanelles, but these are well known and their location predictable.

Parietal Foramina

Small parietal foramina are normal variants and contain an emissary vein. These small foramina may not be identified on radiography but are commonly seen during surgical exposure of a parietal bone. A small foramen is often present in the mid-parietal region approximately 1.5 cm from midline. This is the foramen of Santorini, through which passes the parietal commissary veins (vein of Santorini) veins of Santorini, connection the superior sagittal sinus with a vein on the external surface of the parietal bone. They may enlarge slightly during infancy but are usually stable thereafter and some are pulsatile.

Giant parietal foramina, or Catlin marks, are areas of incomplete ossification present during normal fetal development but usually close before the fifth month of development. There are two different genetic causes of large parietal foramina but no difference in phenotype. Type 1, accounting for 60% of cases, has a mutation in ALX-4, and type 2, accounting for 40%, has a mutation in MSX-2. Both have autosomal dominant inheritance.

These large parietal foramina are circular, occur in the mid high location, are bilaterally symmetric in size and location, and persist throughout life. They range from a few mm to 3 cm in diameter. Giant parietal foramina occasionally come to neurosurgical attention, particularly if pulsatile and, depending on extent of worry by patient and parents, they can be obliterated with cranioplasty. These large bony defects risk accidental penetration by a sharp object.

Other Lesions

Metastatic disease is the most common cause of lesional defects in the crania of adults and are often multiple. Dermoid and epidermoid cysts may occur within the bones of the calvarium, most often in the frontal region and are usually diagnosed in infancy or childhood. These defects are roughly circular in shape and have sclerotic margins. Also, small cranial defects may be associated with a sudoriferous cyst, neurofibroma, and eosinophilic granuloma, the last of which does not have a sclerotic margin—i.e., said to have a *moth-eaten* appearance.

Unrecognized defects in the calvarium are minefields for the inattentive neurosurgeon. Lack of awareness of a cranial defect at the time of scalp incision or as pericranium is reflected can result in accidental penetration of underlying dura. Even a few mm defect in bone can produce dural penetration, brain penetration, and hemorrhage. It is because of unrecognized defects that a surgeon must be cautious in making *every* incision in scalp. Small cranial defects can be congenital, the result of trauma, or prior surgical intervention. If visually apparent as scalp is reflected—i.e., before accidental penetration—previously unrecognized defects can be dealt with safely.

Large Cranial Defects

Large cranial are usually the result of surgical removal of bone for cranial decompression, treatment of infection, or resection of tumor involving bone but can also be the result of postoperative resorption of a bone flap. Large cranial defects can be of any size, shape, and location.

Resorption of Bone Flap

Small amounts of resorption along the edges of a bone flap can be ignored unless it presents a cosmetic concern. The resorption may be more extensive following wound infection or cranial irradiation. The most common setting in which extensive resorption of a bone flap occurs is following the replacement of a cryopreserved bone flap weeks or months after craniectomy for decompression, regardless of cause. The pathophysiology of this phenomenon is not well understood.

Total flap resorption may occur following autoclaving, as has occasionally been done in reaction to a dropped bone flap. An apparent exception to this may occur in infants because osteoblastic activity forms new bone during the likely total resorption of the autoclaved bone.

When flap resorption is first noticed, it is usually present in only one or two small regions. No corrective action should be taken until the resorption runs its course and the site is stable, which usually requires 6–12 months from the time it is first noticed. Repair of a cranial defect resulting from cranial bone resorption is best accomplished with one of the synthetic materials such as PEEK (polyether ether ketone) or acrylic. Autologous bone, whether from cranial sites, ribs or elsewhere, to repair defects which have resulted from bone resorption is often followed by resorption of the newly implanted bone.

Repeated Cranial Surgery

Cranial bone flaps that are replaced at the conclusion of surgery usually undergo bony union with satisfactory contour of the external surface. However, repeat osteotomy at the same site, with removal and replacement of a bone flap, with removal and replacement of a bone flap, often produces significant cosmetic deformity. With each removal and reimplantation, the bone flap undergoes some resorption around its edges and on both the convex and concave surfaces. The healing across the osteotomy site is slower following each surgery and the cortical bone along the surrounding edges of intact cranium are much less conducive to bone-to-bone healing. The result is increased risk of nonunion, often with sinking (settling) of the flap, developmental of a pulsatile flap, and often abnormal appearance.

Indications for Cranioplasty

Cosmesis

Cranial defects may be visible, palpable, or both. Defects that are readily visible directly or in a mirror, for example, those involving forehead or anterior lateral temporal region are commonly repaired at the request of patient or family. Cranial defects that are not readily apparent to an observer, for example, behind the hairline or in the occipital region are often not repaired but some patients and parents of children want these corrected. Decisions regarding cranioplasty for nonfresh cranial defects are influenced by cosmesis, age of patient, size and location of the defect, patient's neurological condition, and the opinions of patient, patient's family, and the surgeon.

Opinions of Patient, Parent, and Surgeon

Decisions regarding need for repair of cranial defects are based almost exclusively on cosmetic concerns and perception of surgical risks. Conversely surgery for defects that are not noticeable is rarely desired by patients. Almost everyone with large defects and severe cosmetically abnormalities want surgical repair but there are exceptions. However, some patients accept of seemingly significant defects; others are extremely risk aversive. Often families of severely neurologically impaired children and adults insist upon surgical repair, particularly if the defect is large or involving face. Interestingly, hospitalized patients with severe facial abnormalities often receive less frequent contact, have fewer visitors, and experience more errors in prescribed care.

Surgeons' opinions *are* based on medical knowledge and experience but have a subjective component. This can differ significantly from that of patient and family. Some neurosurgeons downplay or refuse to address cosmetic concerns, particularly small cranial defects and those camouflaged by hair, whereas plastic surgeons are more likely to accept cosmesis as an important indication for surgical repair.

Size and location of defect—Visible deformity on the forehead, defects that are concave or visibly pulsatile, and those involving the supraorbital rim, regardless of size, are commonly of great cosmetic concern. Not surprisingly large defects are more likely to come to surgical attention than are small ones.

Health status—Surgery to repair cranial defects should not be undertaken in seriously ill patients because of the increased risk of complications.

Syndrome of the Trephined [64, 65]

Patients who have large cranial defects and normal CSF dynamics often experience significant neurological problems when sitting or standing. The absence of cranial bone over a large region allows atmospheric pressure against scalp to displace brain beneath, often with significant midline shift. and this can vary with body position. At the extreme, a patient may experience diminished consciousness and hemiparesis. Symptoms usually diminish or clear seconds or minutes after the patient reclines. Often neuroimaging reveals little or no displacement of brain because scans are done in the supine position. Patients with large cranial defects and CSF shunts are particularly susceptible to this syndrome.

Patients with syndrome of the trephined usually benefit greatly from cranioplasty, which isolates the intracranial contents from atmospheric pressure. However, many patients with large cranial defects have significant neurologic impairment secondary to the pathology for which the craniectomy was done. Regardless, cranioplasty removes the effect of atmospheric pressure and body position.

Timing of Cranioplasty

A cranial defect can be repaired after cerebral edema has resolved [66]. Cranioplasty for large cranial defects through which atmospheric pressure is depressing the brain should not be postponed for completion of rehabilitation but should be repaired as early as medical condition allows. Fresh cranial defects of 12 mm of less and in areas that will be cosmetically undesirable—e.g., burr holes and small craniectomies—can and should be repaired before closure of the wound. If a cranial defect is not repaired within a few days or perhaps weeks following its creation, bony healing will begin producing cortical type bone around the raw edges of intact bone and impair bone-to-bone healing when later repair is done with autologous bone.

Materials for Cranioplasty

Over many centuries, many materials that have been used, with variable success, in the repair of cranial defects. These include various metals (gold, silver, titanium, tantalum, lead, platinum, stainless steel, and the alloy Vitallium), xenografts (dog, ape, goose, rabbit, calf, and eagle), and other substances (hard rubber, plaster-of-Paris, sheet mica, and gum cork) [23, 51, 52]. Autografts have included autologous calvarium, ileum, and tibia and scapula. Autologous cranial bone is the best material for cranioplasty, but this is not always available in sufficient size. In the twenty-first century, the fabrication of custom prostheses by stereolithography (using computerized tomographic images) has become widely accepted; however, titanium mesh and custom titanium prostheses are also in use.

Fixation of Materials Used in Cranioplasty

See above discussion of "Fixation of Bone Flaps and Fragments".

Effect of Intracranial Pressure

Cranial defects that are flat or concave when the patient is lying or upright can be repaired without problems related to intracranial pressure. Preoperative bulging of the site reflects elevated intracranial pressure, and this should be addressed before cranioplasty. Bulging of brain that unexpectedly becomes apparent during surgery is likely caused by some combination of intraoperative overhydration, elevated pCO_2, or high venous pressure and can usually be addressed intraoperatively. Preoperative placement of a lumbar drain to deal with *mildly* bulging sites in patients undergoing cranioplasty can be quite beneficial [67].

Preparation of Recipient Sites for Cranioplasty

The full thickness edges of intact bone surrounding the defect should be meticulously cleared of fibrous tissue to facilitate close abutment of the cranioplasty material to the surrounding intact cranial bone. When autologous bone is to be used for cranioplasty, some surgeons (including the author) expose segments of fresh cancellous surface, to facilitate bone-to-bone healing. This is done by "roughing" the edge of the intact bone with a burr and making a series (6–10) of radial osteotomies of sufficient length to enter cancellous bone.

Cranioplasty for Small Cranial Defects

Normal osteoblastic activity in neonates and infants efficiently closes most bony defects, even large ones. Young children, up to approximately 8 years of age, typically spontaneously close most cranial defects smaller than 2.5 cm in diameter. Beyond that age, osteoblastic activity becomes progressively slower and the ability to reduce or close defects progressively diminishes.

There are no agreed-upon maximum dimensions for a small cranial defect and not all small defects need to be repaired. The undesirable cosmetic impact of burr holes should be anticipated at time of surgery in which they were made, and undesirable cosmetic consequence can be avoided by placing bone chips or a button-shaped autologous graft within or across the defect, covering the opening with a titanium burr hole cover, or filling the defect with bone cement—e.g., HydroSet [68, 69].

If there is a preexisting scar, it should be used, otherwise a U-shaped incision is made in scalp and a full-thickness scalp flap must be elevated. If the pericranium was positioned over the cranial defect at a prior surgery, it may have allowed the pericranium to adhere to dura, in which case some authors have recommended not disrupting this attachment [70]. Cranial defects smaller than about 1.5–2 cm in diameter can be repaired with cortical bone chips harvested from nearby intact cranial bone [69]. Ideally, these should be snugly wedged into the defect to prevent their being displaced during scalp repair.

At the time of repeat craniotomy, small linear cranial defects may have developed during healing can be repaired with alloplastic material. If a defect is recognized at the site of fresh bone flap, it can be addressed with bone chips and swarf. These loose bony materials may have an immediate satisfactory cosmetic appearance but occasionally will be slowly resorbed in the following weeks; however, by that time the narrow defect may have become filled with scar.

Risk Associated with Small Open Cranial Defect

Visible deformity on the forehead, defects that are concave or visibly pulsatile and those involving the supraorbital rim, regardless of size, is commonly of great concern. Not surprisingly, large defects are more likely to come to surgical attention than are small ones. *Health status*: Surgery to repair cranial defects should not be undertaken in seriously ill patients because of the increased risk of complications.

Cranioplasty for Large Cranial Defects

There is controversy regarding the materials and techniques for repairing large cranial defects [71, 72]. Fresh autologous bone is the best material for the repair of all large cranial defects, but its harvest always produces a new defect which requires attention. Sources of autologous bone include full-thickness cranial bone, split-thickness cranial bone, and, less commonly, iliac bone. Cryopreserved autologous bone is also an excellent material and has the correct contour and thickness to match the cranial defect (see discussion later), but it is often not be available. Xenografts can be used and, although usually successful, they never have the desired contour and can be difficult to remodel. Custom prosthetic plates of synthetic materials, for example, PEEK or other materials, are commercially available, have near perfect fit, and none of the problems associated with harvested autologous bone. Methyl methacrylate, either alone or with titanium mesh, has been used for decades to intraoperatively fabricate prostheses, but the process is time consuming, not consistently well executed and therefore is nowadays not commonly used [73, 74]. Large cranial defects, particularly on the front quarter-to-half of the cranial vault or a fronto-parieto-temporal defect, should be repaired with cryopreserved cranial bone but, if not available, with a customized prosthetic plate [75–78].

Cranial Defects that Do Not Require Repair

Few if any small defects in hidden locations require repair, for example, beneath muscle in the lower part of the squama of the temporal or occipital bones, small parietal defects, and those behind the hairline of the frontal convexities.

Risk Associated with Cranioplasty

All cranioplasties have risks, most common of which are infection and unsatisfactory cosmetic result. The risk of postoperative infection is greater than for many other cranial surgeries because avascular bone or synthetic material is implanted. Factors that contribute to bone flap resorption include very young age, smoking, initial dead space, and multiplicity of bone fragments [79, 80]. The risks associated with surgical repair of most cranial defects are low. Neurologic injury is always possible but quite rare.

Contamination and Infection of Bone

Wound Sterility

The existence of wound sterility, in a literal sense, is widely believed and is a comforting myth. All cranial bone fragments exposed during surgery have contamination from organisms moving about in the air. If every mm^2 of surface of a bone flap, without irrigation or immersion in an antibiotic solution, were meticulously cultured, the result would be positive in most if not all patients.

Intraoperative Contamination

Surgeons commonly refer to bone as being contaminated, for example, when purulence is seen, when bone has been dropped on the floor, or a break in sterile technique has occurred. Bone flaps or fragments, which have been dropped onto the floor cause great consternation among personnel at time of occurrence but, surprisingly, this is not often associated with wound infection. The authors recommend immediate immersion in a solution of either Betadine® or Bacitracin and scrubbing the fragment with a brush [81, 82]. It is also reasonable to administer intravenous prophylactic antibiotics for 24–48 h after surgery. The patient or family, if a child, must be informed of this occurrence. The autoclaving of contaminated bone flaps is controversial with regard to the occurrence of resorption of bone [83]. The author believes that total resorption is common in teenagers and adults, and that the apparent nonresorption in infant skulls is the result of replacement of bone by osteoclastic action and osteogenesis.

The near universal use of prophylactic intravenous antibiotics and irrigation with antibiotic-containing solutions of surgical wounds, including bone flaps, greatly reduces the effects of both unrecognized and recognized bacterial contamination and the occurrence of infection.

Breaks in Sterile Technique

This category is too broad for detailed discussion here. It spans a broad array of preoperative preparation of the entire surgical team, preparation of surgical site, and behaviors of all individuals passing through the operating room or having contact with anything that could enter the wound throughout the surgery.

Suspected Wound Contamination

Wound contamination that is only suspected is necessarily vague. Is the suspected contamination small, moderate, almost certain? In the strictest sense, every surgical wound is contaminated, and living skin is never sterile. Air in the operating room contains bacteria and there are live resident bacteria in sweat glands and hair follicles.

Reaction to suspected wound contamination is necessarily at the discretion of the surgeon and will be influenced by the patient's vulnerability for infection and other factors, including the surgeon's experience.

Suspicion that a set of surgical instruments may not have been properly sterilized is clear cause for halting proceedings and obtaining a set that has been through a confirmed proper sterilizing process. Unless there is strong suspicion of contamination, it is probably safe to not administer more antibiotics, larger doses of antibiotics, or take any definitive surgical action such as discarding a bone flap. The risk of infection in immunosuppressed patients is far greater, and it is quite reasonable to have a lower threshold for use of antibiotics.

Contaminated Vascularized Bone

Contamination of vascularized bone, whether intact or fractured, occurs most often from trauma that penetrates the scalp, including pericranium. Depending on severity of injury, the contamination may be limited to the convex cranial surface or, if the bone is fractured, extend into the fracture line. Exposed surfaces must have all foreign material removed and scrubbed with Betadine® or bacitracin solution for several minutes. If there is visible foreign material within a fracture line, it should be removed with a small burr. Intact cortical bone, regardless of severity of contamination, does not require removal or excoriation with a burr unless foreign material is imbedded in the bone. Contaminated cancellous bone into which dirt or debris has been impacted must be debrided with a burr and scrubbed vigorously before replacement.

Vascularized bone can become contaminated in neonates with infected subperiosteal hematomas. Treatment requires drainage of the purulence, irrigation of the space with antibiotic solution, temporary drainage via a small Penrose drain, and a course of intravenous antibiotics.

Contaminated Devascularized Bone (Often Mistakenly Called Infected Bone Flap)

The terms *contaminated devascularized bone flap* and *infected bone flap* are not synonymous. Contamination of devascularized bone occurs in the setting of craniotomy to deal with purulence, for example, epidural or subdural empyema, post-craniotomy wound infection, and for obvious contamination as occurs when a bone fragment is accidently dropped onto the floor [81]. The contamination is on the external cortical surfaces and along the edges of the bone. Unlike osteomyelitis (see below), the contamination is not within the cancellous matrices, except perhaps superficially over freshly osteotomized surfaces. Bacteria are likely impacted onto exposed bony surfaces in compound fractures, and therefore these surfaces must be scrubbed with a brush, using povidone-iodine or Bacitracin solution.

Traditionally, neurosurgeons have managed *all* contaminations of bone flaps and fragments with disposal, debridement of the wound, and a course of intravenous antibiotics, followed weeks later by cranioplasty with an allograft. This requires at least one additional hospitalization and considerable expense, including but not limited to additional CT scans and the harvesting of an allograft or fabrication of a prosthetic replacement. This is usually successful, but the appearance of infection days or weeks later may occur and may or may not be related to the original contamination.

Most contaminated devascularized bone flaps and fragments can be safely salvaged and therefore, in the opinion of the author, rarely if ever need to be discarded. All attached soft tissue must be meticulously removed and the flap scrubbed vigorously with Betadine® or bacitracin-containing solution, using a brush, for several minutes and then rigidly secured in its home site. The same is true for bone flaps accidently contaminated during surgery. Contaminated cancellous bone and cortical bone into which debris (e.g., for example, dirt, gravel, sand, asphalt, or broken glass) has been driven must be debrided with a high-speed burr.

The site from which the bone was removed must also be meticulously cleaned and irrigated with antibiotic-containing solution. If purulence has been present, the surrounding edges of the intact bone must be scrubbed vigorously and possibly abraded with a burr. Postoperative antibiotics should be administered with dosage and duration appropriate for treatment of a wound infection, not prophylaxis. Immediate reimplantation of the scrubbed bone flap avoids a second surgery for cranioplasty with a synthetic material and has a low risk of infection [84, 85].

Infected Craniotomy Site

The term "*infected bone flap*" is commonly applied to all post-craniotomy wound infections, particularly if there is purulence, and to any dehisced wound in which there is postsurgical exposure of devascularized bone. Therefore, this term, as commonly used, is a misnomer. Only rarely in these settings is there any evidence of active infection within the interstices of a contaminated bone flap. If there is active infection within surrounding intact bone, then the diagnosis is cranial osteomyelitis.

Cranial Osteomyelitis

Osteomyelitis is a rare but potentially life-threatening disorder in which there is active infection within bone with viable organisms, by any of a host of bacterial and fungal species, tuberculosis, or syphilis. Bacteria may be directly introduced into bone by extension of infection from frontal sinus, middle ear, mastoid, hematogenous spread from a remote site of infection as a result of penetrating trauma or intravenous injections using contaminated needles and materials. Osteomyelitis of the skull is rare, particularly as a complication of surgical intervention, but does occur in the anterior, middle, or posterior skull base [86]. Osteomyelitis in vertebrae may result from contamination during surgery. Early diagnosis is important and, although osteomyelitis can coexist with epidural empyema, postoperative wound infection, or purulence in contact with bone, none of these is diagnostic of osteomyelitis. Whenever there is suspicion of osteomyelitis, it is appropriate to consult infection disease physicians and obtain tissue for confirmation of the diagnosis, identification of the causative organism, and assessment of drug sensitivities. White blood cell count and sedimentation rate have limited diagnostic value [87].

Areas of osteomyelitis should be aggressively resected; however, sites in the base of the skull may have limited accessibility. The margins of infection are never distinct and therefore the resection should extend beyond the visible and radiographic boundaries of infection. Intravenous antibiotics are commonly required for 2–4 months. It is important to identify the causative organism and to treat with appropriate antibiotics, usually broad-spectrum type. The delivery of antibiotics to infected regions of bone is impaired by the blood supply of nearby normal bone, which can be compromised by the infection. Six to 12 months after the infection is thought to be cleared, the cranial defect requires cranioplasty.

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9 Dura Mater: Anatomy

Ken Rose Winston

Cranial Dura Mater

The dura mater (*Greek: tough mother*) or pachymeninx (*Greek: thick + membrane*), commonly called simply "the dura," is a membranous sac of mesenchymal origin whose outer surface lies in firm contact with the inner surface of the skull and whose inner surface surrounds the arachnoid mater (*Latin: spider + in the image of + mother)* of the cranial vault and spine. (See excellent review by Lopes [1])

Embryology [2, 3]

In early embryogenesis, a layer of mesenchyme, the meninx primitiva *(Greek: membrane + Latin: original)*, composed of neural crest cells and mesenchyme, covers the neural tube. The outermost layer becomes the dura mater, also called the pachymeninges and is entirely of mesenchymal origin. The inner layer of the meninx primitiva, which contains neural crest cells, becomes the leptomeninges (*Greek: thin + membrane*), and this layer develops into two distinct thin layers, the arachnoid mater *(Greek: spider-like + Latin: mother)* and pia mater (*Latin: pious mother*). The latter two will not be addressed. Calvarial bone develops from ossification centers within the meninx primitive.

The outer layer of the cranial dura mater, the *endosteal* layer, is continuous, through foramina with cranial periosteum, and can be thought of as the pericranium of the inner surface of the cranial bones. This layer does not extend beyond the foramen magnum, and therefore, there is no endosteal layer in the spinal dura mater. The endosteal layer of the dura also terminates near the external end of each cranial foramen and fuses with the epineurium of nerves.

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The inner layer of the dura mater, the *meningeal* layer, is a tough fibrous membrane, which is tightly adherent to the endosteal layer of the dura and less tightly adherent to the arachnoid mater. The meningeal layer of the dura mater continues through the foramen magnum to become the spinal dura mater and through the cranial foramina as sheaths to become continuous with the epineurium surrounding the nerves.

Structure [4]

In the cranium, the *dura mater* consists of two layers, the *endosteal layer* and the *meningeal layer*. (See excellent reviews by Yamashima [5] and Seker et al. [6]). The outermost or endosteal layer is the periosteum of the inner surface of the cranial vault and is composed of fibroblasts and osteoblasts with a large amount of collagen [7]. Along the cranial sutures, it is continuous with the periosteum covering the outer surface of the skull and is most densely adherent to the bone near the cranial sutures, at the foramen magnum, and over the base of the skull. It forms sheaths around nerves, including the optic nerve, as they exit the cranial vault. In children, particularly newborns and infants, this endosteal layer has relatively loose attachment to the frontal and parietal bones and the squamous portions of the occipital and temporal bones. The endosteal layer of the dura mater becomes progressively more adherent to the bone with advancing age and can be very adherent over the entire surface in the elderly.

The meningeal layer consists of fibrous and elastic tissue bands having little or no pattern of arrangement and is adherent to the endosteal layer. A layer of flat fibroblasts, the dural border cell layer, exists at the junction of the dura with the arachnoid and has prominent extracellular spaces, no extracellular collagen, and few cell junctions, thereby forming a relatively weak inner structural layer in contact with the arachnoid [8]. The meningeal layer of the dura mater has several double-layered infoldings or processes extending into the cranial vault, and several of these restrict rotary displacement of the brain. These include the falx cerebri, tentorium cerebelli, falx cerebelli, the diaphragm sella, and the roof of Meckel's cave (named for Friedrich Meckel, the Elder). The periosteal layer of the dura mater does not extend into these structures. The meningeal layer also surrounds the venous sinuses of the dura mater. Melanin-containing cells are often present in the dura, particularly around the base of the cranial vault.

The *tentorium cerebelli* (*Latin: tent of the cerebellum*) is a double-layered fold of the dura and separates the supratentorial and infratentorial spaces. The tentorium is fixed laterally to the superior edges of the petrous part of the temporal bones, and anteriorly the tentorium is attached to the anterior clinoid process. The tent shape transfers the weight, and hence downward force, of the cerebral hemispheres laterally toward the walls of the cranium and away from the foramen magnum [9].

The *falx cerebri* (*Greek: scythe of the brain*) is a sickle-shaped extension of the meningeal dura mater continuous with the dura over the midline cranial convexity and is positioned between the two cerebral hemispheres. The narrow anterior end of the sickle is attached to the crista galli and to the dura mater of the floor of the anterior fossa. The much wider posterior portion of the falx is attached along the upper surface of the tentorium cerebelli, straddling the straight sinus. The two layers of the falx cerebri separate to enclose the *superior sagittal sinus* along the inner convexity of the skull. The smaller *inferior sagittal sinus* lies within the lower free edge of the falx cerebri.

The roof of each *Meckel's cave* or trigeminal cave, is a small, arachnoid lined pouch in which lies the trigeminal ganglion surrounded by CSF. It is formed by a double-layered fold of meningeal dura, which is located at the posterior edge of the middle cranial fossa and at the posterolateral extent of the cavernous sinus immediately lateral to the internal carotid artery with its intracranial opening facing the posterior fossa [10].

The *diaphragma sellae (Latin: partition saddle)* is a circular double-layered fold of the meningeal layer of the dura mater, which covers the sella turcica *(Latin: Turkish saddle)* and forms the hypophyseal (pituitary) fossa. The infundibulum of the pituitary gland passes through a round opening in the diaphragma [11, 12].

The *falx cerebelli (Latin: scythe of the small brain)* is a small, sickle-shaped, double-layered sagittal infolding of the meningeal dura. Superiorly it is attached to the tentorium cerebelli, and inferiorly it extends downward in the vallecula cerebelli and posterior cerebellar notch toward the foramen magnum. Its margin contains the *occipital sinus*. The falx cerebelli in most patients is small and may not be identifiable in its lower half. In small children, it occasionally divides inferiorly with an extension for several millimeters to each side of the foramen magnum [7].

The *dura mater of cranial base* has the same structure as that of the convexity but is densely adherent to the bone, except across the floor of the frontal fossa.

The *arachnoid villi* are one-way valves in the paths of egress of CSF from the subarachnoid space into the venous blood, but they do not appear until 7–8 months of age [13, 14]. An arachnoid villus consists of subarachnoid tissue, surrounded by arachnoid membrane projecting into a parasagittal venous lake or into the venous sinus, and is covered by a thin layer of endothelium. The arachnoid villi are soft small protrusions of thin spots of mater, usually near the sagittal sinus but occasionally near a transverse sinus, which act as one-way valves [13]. They are not present in infants and children but are usually present by 7 years of age. Overlying bone is absorbed, probably caused by pressure from the expanding arachnoid against the overlying thin dura mater. This accounts for the extensions of the dura into depressions on the inner surface of the calvarium. As arachnoid mater in these regions expands and penetrates the dura, it comes into direct contact with the vascular endothelium of the dura along the large venous sinuses.

A *subdural space* does not exist in normal meninges, except as being a *potential space*. However, in response to trauma or other pathologic process, a cleavage plane develops near the dura–arachnoid continuum, in the *border cell layer* of the dura and therefore not, in a literal sense, beneath the dura [8].

Arteries of Cranial Dura Mater [3, 15]

The arterial supply of the meninges is almost exclusively concerned with the endosteal layer of the dura mater. Although the middle meningeal artery is the dominant supplier for the supratentorial dura mater, dura requires little supply, and the major end organ supplied by this vessel is the calvarial bone. Arteries in the dura mater have extensive anastomotic connections with one another, particularly near the dura of the falx, tentorium, and parasellar region.

The arterial supply to *dura of the anterior cranial fossa* is from the meningeal branches of the anterior ethmoidal and posterior ethmoidal arteries, the ophthalmic artery, and from a frontal branch of the middle meningeal artery. The arterial supply to *dura mater of the middle cranial fossa* is primarily from the middle meningeal artery, but there is also contribution from the ascending pharyngeal artery and the internal carotid artery.

The dura mater of the posterior cranial fossa receives supply from the meningeal branches of the ascending pharyngeal artery (via hypoglossal canal and jugular foramen) and meningeal arteries from the occipital artery (via jugular or mastoid foramen) and from the vertebral artery (via foramen magnum) [16].

In summary, small branches of the internal carotid artery supply the medial-most dura mater of the anterior and middle cranial fossae and a small amount of the posterior fossa. Branches from the external carotid artery supply the much larger lateral dural territories of all three fossae, and the vertebral arterial system supplies the more medial dura mater of the posterior cranial fossa and the dura mater near the foramen magnum.

Anterior Meningeal Artery (Falx Artery or Anterior Falcine Artery)

The anterior meningeal artery is a branch of the anterior ethmoidal artery, which is a branch from the ophthalmic artery as it accompanies the nasociliary nerve in the orbit and then through the anterior ethmoidal foramen. This anterior meningeal artery supplies a variable area of bone and dura mater of the anterior fossa, including the dura over the cribriform plate. One small branch enters the falx and becomes the anterior falx artery.

Confusingly there is another artery with the name “anterior meningeal artery.” It is a branch of the vertebral artery at the C2 or C3 level and supplies various adjacent structures including the bone and an area of the dura mater at or below the foramen magnum.

Middle Meningeal Artery

The middle meningeal artery is a branch from the retromandibular part of the maxillary artery, which is a branch of the external carotid artery. It runs near and often directly through this nerve and then through the foramen spinosum of the sphenoid bone in the floor of the middle fossa. The middle meningeal artery is the largest of the arteries that supply the cranial bone and meninges and, throughout much of its proximal intracranial course, lies within a groove along the greater wing of the sphenoid bone and on the undersurface of the frontal and parietal bones. It is very often surrounded with bone along the lateral extent of the greater wing of the sphenoid bone and occasionally for several millimeters of the parietal bone. Its branches spread upward to the vertex and backward into the occipital region. The largest branch of the middle meningeal artery is the anterior branch, and it typically lies approximately beneath the pterion. The posterior branch of the middle meningeal artery courses posteriorly along the undersurface of the squamous part of the temporal and parietal bones. There are anastomotic connections through the superior orbital fissure, with the ophthalmic artery and lacrimal artery. Occasionally the ophthalmic artery arises as a branch of the middle meningeal artery or lacrimal artery. Rarely there is an accessory meningeal artery or pterygomeningeal artery, which supplies a small area of the dura mater in the floor of the middle fossa, the trigeminal ganglion, and some muscles before entering the cranium.

The tentorium cerebelli receive arterial supply from the external carotid, internal carotid, posterior cerebral, and vertebral arteries. The meningohypophyseal artery arises from the internal carotid artery and divides into the tentorial artery of Bernasconi and Cassinari and dorsal meningeal arteries. The former courses in the tentorium near its free edge and supplies anterior and lateral portions of the tentorium and often the oculomotor, abducens, and trochlear nerves. The artery of Davidoff and Schechter, a branch of the P2 segment of the posterior cerebral artery, courses beneath the superior cerebellar artery and enters the undersurface of the tentorium cerebelli near the midpoint of the incisura to supply the medial portion of the tentorium cerebelli [17].

Posterior Meningeal Artery

The posterior meningeal artery enters the cranium through the jugular foramen, hypoglossal canal, or foramen magnum. It is usually a branch of the ascending pharyngeal artery but can arise from the occipital artery. It is the largest vessel supplying the bones and dura mater of the posterior fossa.

Veins of Cranial Dura Mater

Meningeal veins course within the endosteal layer of dura mater. The larger of these tend to run near or in contact with the larger arteries in the dura and drain into the pterygoid venous plexus or sphenoparietal sinus. At the site of dural folds, large venous structures, called venous sinuses, develop between the opposing meningeal layers of the dura mater. The venous sinuses drain blood and hence cerebrospinal fluid from the brain into the internal jugular veins. *Bridging veins* connect the veins of the underlying neural tissue with the dural sinuses and therefore lie within the subarachnoid space.

Veins Attached to Arachnoid Mater

Many cerebral veins and bridging veins are attached to the arachnoid mater by fibrous arachnoidal strands. These adhesions must be disrupted while reflecting a dural flap, without disrupting the vessel. This can be done with a small blunt instrument, and others must be cut with a small, pointed knife or with microscissors.

Venous Sinuses

The *superior sagittal sinus* is a large, midline intracranial venous structure coursing along the upper extent of the falx cerebri, from the foramen cecum anteriorly, to the tentorium posteriorly. Its posterior few centimeters usually tilts toward the right at the confluence of sinuses (torcula Herophili) and therefore drains primarily into the right transverse sinus. Valve-like lamellae, the *chordae willisii*, exist within the lumen of the superior sagittal sinus, chiefly in its parietal and occipital sections, and can partially cover entering cerebral veins [18, 19]. Their precise function is not known, but they are thought to influence laminar flow. The two *transverse sinuses* lie in the posterior edges of the tentorium, receive blood from the superior sagittal sinus, and drain into the sigmoid sinuses. The *occipital sinus*, which is prominent in infants but rudimentary or absent in adults, lies along the edge of the falx cerebelli and also drains into the confluence of sinuses.

Lymphatics of Cranial Dura Mater [20–22]

It was long taught that lymphatic vessels did not exist in the dura mater, but there is now a growing literature on a functioning dural lymphatic network, which drains toward the superior sagittal sinus, along the cranial nerves, and through the cribriform plates. These vessels have a role in drainage of CSF.

The lymphatic drainage of the falx cerebri occurs via the meningeal lymphatic vessels, which run parallel to the dural sinuses. These lymphatic vessels drain primarily along a similar path as the dural sinuses, pass through the jugular foramen, and empty into the deep cervical lymph nodes. Lymphatic channels from the falx cerebri drain anteriorly through the cribriform plate into the lymphatic channels of the nasal mucosa. Lymphatic vessels of the meninges have few if any valves [23].

The glymphatic drainage from the brain probably empties into the lymphatic vessels of the dura and falx and then into the extracranial lymphatic system [24]. Details of this system are not within the scope of this book.

Innervation of Cranial Dura Mater

Dura mater of the anterior cranial fossa receives innervation from the ophthalmic division of the trigeminal nerve, through the anterior ethmoidal, posterior ethmoidal, and nasociliary nerves. Dura mater over the middle fossa is innervated by branches from the ophthalmic nerve and some small contributions from the maxillary and mandibular divisions of the trigeminal nerve. The upper surface of the tentorium receives innervation from both the maxillary and mandibular nerves, whose branches course posteriorly along the dura of the cavernous sinus. The undersurface of the tentorium and the dura mater of most of the posterior cranial fossa are innervated by branches of the vagus nerve (X) and glossopharyngeal nerve (IX) with contribution, near the foramen magnum, from cervical nerves C2 and C3. Afferent fibers in the dura mater reside in the trigeminal ganglion and sympathetic fibers are from the superior cervical ganglion. The falx cerebri is innervated by all three branches of the trigeminal nerve [25–27].

Abnormal Cranial Dura Mater

Thin Dura

There are no criteria for what constitutes abnormally thin dura, but nonetheless the designation has clinical usefulness. Dura in neonates and infants is noticeably thin. Dura is often thin in patients who have chronically elevated intracranial pressure. Elderly people are often said to have abnormally thin dura, perhaps because of the difficulty surgeons may encounter when separating the dura from the bone. Little if anything has been published on unusually thin dura.

Very thin dura can be opened with little or no difficulty, but it is easily torn by retraction. It becomes desiccated more quickly than does the normal dura and therefore requires more attention to keeping it moist with wet Cottonoids® and frequent irrigation. The act of suturing can easily tear the dura, and needle puncture sites may stretch larger than expected. Thin dura should be gently closed using 4-0 or 5-0 sutures to achieve continuous approximation of edges.

Thick Dura

Abnormally thick dura occurs in several settings and usually comes to attention as it is being incised, for example, in patients who have undergone prior surgical manipulation, in local regions of plexiform neurofibromatosis, and occasionally in elderly patients with Alzheimer disease. Dura can also be abnormally thick in settings of chronic intracranial hypotension.

Opening abnormally thick dura presents little difficulty unless it is hypervascular, infiltrated with tumor, or adherent to the brain, as can occur following prior surgery (irradiation or infection). Retraction and closing of thick dura rarely present a significant difficulty.

Hypervascular Dura

Hypervascular dura may occur in neurofibromatosis, vascular malformation, or neoplastic involvement and can be occasionally encountered unexpectedly in normal patients. It also may occur in infected dura and in the dura that has had undergone surgery. Hypervascular dura may have normal attachment to bone or can be adherent, making surgical separation difficult, often with significant bleeding from both dura and bone. The opening, retraction, and closing of hypervascular dura must be done slowly with constant attention to hemostasis. Tamponade with Cottonoids® and mild manual pressure is effective for temporary control. Persistent bleeding can be managed with liberal use of bipolar electrocautery, Weck® clips, and multiple ligating sutures. In association with neoplasia, much of the hypervascularity is a component of the lesion and will be excised. Extensive coagulation can cause substantial dural contraction, making closure problematic.

Neoplastic Involvement of Dura

Neoplastic involvement of the dura is commonly associated with meningiomas. Infiltration of the dura also occurs in malignant tumors of the cerebrum and in the cranial base. These may grow through the dura, for example, chordomas of the clivus. Neoplastic infiltration of the dura can result in difficult hemostasis, particularly when the tumor has grown through the dura and into the bone, as occurs with meningiomas, malignant brain tumors, and a few primary tumors of bone such as chordoma, neuroesthesioma, and melanotic progonoma. Melanin-containing cells are often present in the dura, particularly around the base of the cranial vault, and their presence is not always indicative of neoplasia; however, there are several melanin-containing tumors of dura, including melanotic meningioma, melanotic progonoma, and meningeal melanomatosis.

Dura involved with tumor is commonly managed with circumferential resection. Arteries and veins in the surrounding normal appearing dura can be cauterized, but large arteries supplying the lesion will require ligation.

Neurofibromatosis

Hypervascular dura associated with neurofibromatosis type 1 tends to be confined to small regions. Hypervascularity associated with neurofibromatosis type 1 tends to be confined to regions of grossly identifiable abnormality, and hemostasis in the region can be difficult and time-consuming. Dura in patients with plexiform neurofibromatosis, particularly when extending intracranially from the orbit, can be very hypervascular and have a network of vascular channels that respond poorly to electrocoagulation. Compression with multiple hemostats combined with extensive cauterization or placement of sutures around identified bleeding sites may be required. Such measures result in desiccation and contraction of the dura. Hemostasis obtained by packing may achieve temporary success, but bleeding usually starts anew when the packing is removed.

Dense Adherence of Dura to Bone

Dura is densely adherent to the cranial bone along the cranial sutures in normal neonates, infants, and young children and becomes less adherent as the sutures close and generally more adherent over the entire cranial convexity in elderly patients. Dense adherence is also normal at all ages across most of the cranial base, except for the floor of the frontal fossa. Dura along the edges of prior twist drill sites, burr holes, and craniotomy sites is almost always densely adherent. Densely adherent dura can be thinner than normal, in elderly patients, or often appears so to the neurosurgeon when attempt is being made to preserve its integrity. Dura in an irradiated field, as in patients with many types of brain tumors, can be quite adherent to overlying bone or almost unattached. Prolonged intake of phenytoin, as was common in years past in patients with epilepsy, resulted in dense adherence of the dura to the knobby irregular inner surface of the cranial bone, also caused by the drug. These patients are now in midlife or older. Dura that has been irradiated can be very adherent but is occasionally loosely attached.

Adherence of Galea to Brain Through Defect in Bone

If brain parenchyma comes into firm contact with galea, as can occur following craniectomy for decompression in which no intervening barrier was implanted, or through a dural defect resulting from a dehisced durotomy in a setting of high intracranial pressure, the brain parenchyma very commonly becomes fibrotically attached to the galea. At the time any of future surgery in the area, the two can be difficult or impossible to surgically separate without considerable injury to the brain.

Excess Dura

Bulging Dura in Craniotomy Sites

An intact dural envelope, whether overlying brain or over a CSF apace, can displace a bone flap whenever intracranial pressure exceeds atmospheric pressure and then expand into the cranial defect. Early displacement of a flap is more likely to occur when the flap is poorly secured, but chronically elevated pressure may elevate a flap after weeks or months. Also, intact dura occasionally will bulge through a cranial defect following craniectomy or come to attention during surgery for cranioplasty. If the excessive dura is not addressed at the time of subsequent cranioplasty, there is significant risk of delayed displacement of the flap, regardless of the material used. Free fragments of bone immediately conform to the contour of the underlying dural envelope. If overlying bone fragments, bone flap, or synthetic material is used to eliminate the dural bulge by compression, there is significant risk of delayed displacement of the flap and need for repeat surgery.

Dural Bulge in Infants

Normal intact, non-bulging dura lying beneath a postoperative cranial defect of an infant may begin to bulge within a few days or weeks following surgery and cause progressive resorption of bone, similar to that which occurs in an expanding skull fracture. This is most often seen following surgery for correction of craniosynostosis and is not apparently related to elevated intracranial pressure.

Surgical correction is required and must include reduction of the dural bulge by either imbrication or by desiccation of the dura with electrocautery, followed by secure repair of the cranial defect.

Macrocrania Secondary to Hydrocephalus

Within a vault that has functioning cranial sutures, the envelope can steadily expand over months or years in response to intracranial hypertension. Surgery to reduce cranial volume, reduction cranioplasty, is rarely done except in extreme cases and should be understood as being a long and high-risk surgical undertaking. These patients have severe ventriculomegaly, and a thin cerebral mantel. Reduction cranioplasty results in excess dura.

Abnormally Shaped Dural Envelope

Patients with craniosynostosis have abnormally shaped cranial vaults and, consequentially, abnormal dural envelopes. Most surgeries for correction of craniosynostoses alter the cranial vault toward a more spherical configuration. Therefore, less dura is required for enclosure. Some surgeons ignore the dura in these cases, but others, including the author, often use electrocautery to shrink the bulging regions by desiccating multiple spots or lines across the dura. If a bulging region of dura is ignored, it may slowly displace the overlying bone and return to the abnormal cranial shape.

Dural Defects

Adverse Consequences

Adverse consequences of dural defects are influenced by the size and site of the defect, patient's age, intracranial pressure, operant pathologic processes, the integrity of cranial bone and scalp, and by the neurosurgical interventions, which may have produced the defect. Problems associated with dural defects include leakage of CSF, herniation of brain, pneumocephalus, bacterial contamination of the CSF and brain, displacement of bone flaps, and expanding fracture of overlying bone; however, many small defects in dura have no recognizable adverse consequences.

A dural defect is a window through which the brain can herniate whenever centripetal force of intracranial pressure exceeds the opposing force. An intact dural envelope in neonates, infants, and young children has an especially important role of being a restraining envelope within which intracranial pressure is distributed approximately equally in all directions as the brain grows. Most neurosurgical operations that include durotomy, excluding twist drill holes and operations done for decompression, require some form of closure to reestablish a dural envelope. This is particularly important in pediatric patients because the normal growth of the brain produces a steady centrifugal force against the dural envelope, and a large defect in the dura is a region of lesser resistance to expansion of the brain, which will result in slow cerebral herniation. Adults with normal intracranial pressures may tolerate relatively large persistent dural defects beneath a cranial bone flap; however, a dural defect beneath a craniectomy site results in the brain being in contact with the pericranium, to which it commonly adheres. This can cause neurosurgical difficulty if that region needs to be exposed in the future.

Defects in the cranial dura of any size predisposes to CSF leakage and to the herniation of the brain. A large dural defect through which the brain is expanding, for example, a growing brain of a child, or high intracranial pressure may at any age allow herniation of the brain tissue through the opening.

CSF Leakage

Defects in the cranial dura of any size predispose to CSF leakage into the epidural space and beyond. Leakage can occur through any size defects, even tiny ones, but is much more likely to occur in sites where the dura is not in contact with the brain tissue, for example, over cisterns, large cerebral sulci, in sites overlying atrophic brain, and sites of resection of tumor or brain tissue. Needle holes and openings of 1 or 2 mm are usually not problematic but can result in leakage of CSF when CSF pressure significantly exceeds the pressure against which it must flow. High intracranial pressure greatly increases the likelihood of CSF leakage. CSF that leaks through an opening in the cranial dura can accumulate in the epidural space, subgaleal space, through a scalp incision, or any combination of these. CSF drainage requires a space into which to flow, for example, epidural space resulting from postoperative dura not being adherent to the bone. Persistent flow of CSF through a tiny dural defect can impair healing and result in the development and persistence of a pocket of CSF in an epidural or subgaleal space, and the tract can become epithelialized. (The clinical details of CSF leakage, their diagnoses, and management will not be addressed.)

Herniation of Brain at Sites of Dural Defects

Brain not uncommonly bulges progressively through a dural defect resulting from its being intentionally unclosed or in which the dural suture line became disrupted following surgery. A dural defect in which brain is expanding, for example, a growing brain or high intracranial pressure at any age, allows the enclosed brain to herniate through the opening. In older children and adults, this bulging may occur only if there is high intracranial pressure, and the bulge will often be flat or concave in the upright position.

Large dural defects are stretched ever larger by steadily growing brain, thereby allowing progressively worsening herniation. When a large defect is present, the expanding brain, whether from normal growth or pathologic cause, herniates the dural opening and steadily enlarges, and the overlying bone is resorbed. Over several months, the mid portion of the brain can shift. After the first year of life, this risk diminishes, except in settings of elevated intracranial pressure.

Risk of herniation diminishes after the first year of life except in settings of elevated intracranial pressure. However, in children with large dural defects beneath a cranial bone slowly progressive outward expansion of the bone flap can occur. In patients who have undergone craniectomies for decompression with the dura left widely open, the brain parenchyma becomes adherent to the galea and can become difficult or impossible to surgically separate without considerable cortical injury.

Patients who have large cranial defects and normal CSF dynamics often experience significant neurological problems when sitting or standing (syndrome of the trephined).

Fungus Cerebri [28, 29]

Fungus cerebri is a herniation of brain through a defect in scalp at the site of a cranial defect and having a mushroom-like gross appearance. The herniation of brain occurs in response to severe cerebral edema, often but not always following surgery, which is followed by dehiscence of durotomy and scalp; however, instances have occurred into the mastoid and middle ear. Historical treatment included frequent change of dressings, often followed by shaving of slices of brain until the scalp could be securely repaired, uncommonly but not universally followed by death. The entity of fungus cerebri disappeared, with rare exceptions, following the introduction of steroids to reduce cerebral edema, and the evolution of surgical techniques and procedures including decompression craniectomies. The treatment of fungus cerebri requires wide surgical exposure, excision of any herniated necrotic brain tissue, and the secure closure of the dura and scalp. Cranioplasty should probably be delayed because of wound contamination.

Causes of Dural Defects

The most common cause of insufficient dura for primary closure is contraction caused by desiccation, electrocoagulation, or by prolonged intraoperative exposure to air, particularly if the dura has not been tightly retracted during surgery. Some neurosurgical operations require the resection of sections of dura, for example, when there is neoplastic invasion. Iatrogenic injury of dura occurs when a router penetrates the dura and shreds a path along the course of an osteotomy, particularly when the dura is tightly adherent to overlying bone. Traumatic laceration of the dura is common, but avulsion is extremely rare.

Encephalocele

The brain at birth is found to be bulging through an area of missing cranial bone. The dura surrounding an encephalocele is often hypoplastic, and the herniated brain is usually if not always structurally abnormal. These occur in or near the cranial midline, and size can vary from 1 cm to larger than the cranial cavity. Severe dural attenuation and dural defects may exist occur in association with encephaloceles in the floor of the frontal fossa.

Meningocele

This is a CSF-filled outpouching of the dura, often, but not consistently atretic, of the dural envelope. The term is most often used for a congenital abnormality in or near the cranial midline. A meningocele differs from an encephalocele by not containing the brain tissue. Typically, the meningocele has a small communication with the cranial dural envelope. The term is also used for post-surgical outpouching of the dura, regardless of the location.

Surgery for Neoplasia

Most dural defects related to surgery for neoplasia are the result of resection with the tumor. Tumors such as meningioma and neuroesthesioma can grow through the dura of the floor of the frontal fossa.

Aplasia Cutis Congenita

This is a birth defect in which there is one or more regions of missing or severely atretic skin and may occur any part of the body. When involving scalp, there may also be a cranial defect or cranial and dural defect. Defects that include the cranium typically overlie the superior sagittal sinus and, in the hours and days after birth, and if not managed appropriately, desiccation often leads to cracking across the sinus and exsanguination.

Trauma

Trauma to the low forehead or midface is the most common cause of dural disruption in the anterior cranial base and can occur at any age but much more commonly in older children and adults. This may come to attention with the identification of CSF leakage or when directly visualized during surgery. These CSF leaks are often through dural disruptions in the cribriform plate and can be difficult to identify radiographically and only identified at time of surgical reconstruction.

A raw acute edge of fractured cranial bone, when acutely driven inward, can lacerate dura, with significant concomitant injury to the underlying brain. The dural edges immediately contract from the facture line by a few millimeters and, if not treated, will contract by a centimeter or more over the following days.

When the same injury occurs in neonates or infants (usually under 1 year of age), the normal growth of brain will, over weeks and months, stretch the lacerated dura and allow progressive cerebral herniation with resorption of overlying calvarial bone, hence the name expanding or growing fracture. Expanding fractures can also occur from an unrecognized or unrepaired elective durotomy in an infant.

Iatrogenic (Greek: Healer + Produced) Injury

The most common cause of dural defects coming to neurosurgical attention is the contraction of dura caused by desiccation during long neurosurgical procedures, particularly if the dura was not tightly retracted during surgery. A path of injury to the dura can be the result of accidental penetration and shredding by a router while making an osteotomy.

Dural puncture by a drill bit of 3–4 mm diameter, commonly called a twist drill, only rarely causes a problem, which requires neurosurgical attention. Although an artery of the dura can be disrupted but the relatively dull tip and its rotary action as it advances usually stretches and pushes aside arteries directly in the path. Single puncture of the dura with a sharp needle produces a much smaller hole but does not push the vessels aside and therefore may penetrate any vessel in the path of puncture. Multiple needle punctures made to produce a larger hole in the dura or greatly weaken the dura for more easy passage of a larger instrument greatly increases the risk of penetration of a cerebral artery.

Iatrogenic dural injury may occur when a router penetrates the dura and shreds a path beneath the course of an osteotomy, particularly in areas where the dura is tightly adherent to the overlying bone. The path of shredded dura is always several millimeters wider than the diameter of the bit and the osteotomy.

Surgical Resection of Dura

Portions of dura may be resected during neurosurgical operations, for example, resection of meningiomas and vascular malformations of the dura.

Dural Defects by Location

Region of Sella Turcica

Defects in this region present with CSF rhinorrhea following transsphenoidal surgery for tumors (e.g., pituitary adenomas or craniopharyngiomas). Spontaneous CSF leaks in this region are rare but reported and are often associated with an empty sella. Fluid in the sphenoid sinus that is apparent after cranial trauma can be CSF that has leaked through a dural rent associated with a non-displaced fracture, and the fracture can be quite difficult to radiographically identify.

Anterior Cranial Base

Trauma to the low forehead or midface is a common cause of dural disruption in the anterior cranial base and can occur at any age but more commonly in older children and adults. This may be immediately visibly apparent or on early neuroimaging of a victim of trauma, but not uncommonly this may first come to attention with the identification of CSF rhinorrhea hours or days after trauma. Delayed CSF leaks are often through dural disruptions over the cribriform plate or into the frontal sinus. These sites can be difficult to identify radiographically and even at the time of surgical exploration.

Dural defects or severe attenuation of the dura occurs in association with encephaloceles in the floor of the frontal fossa, almost always in or near the midline, and is commonly associated with significant craniofacial abnormality that includes hypertelorism.

Floor of Middle Fossa

Defects in the dura of the floor of the middle fossa are commonly a result of resection of tumors, for example, meningiomas. Many neurosurgeons place an onlay patch of the pericranium or a synthetic material, for example, DuraGen®, over the defect. Others leave these dural defects unrepaired, and adverse consequences are rare. It is difficult to impossible to suture a graft in this location.

Trauma that fractures the temporal bone can disrupt the attached dura and allow CSF to flow into the middle ear. If the tympanic membrane is disrupted, the result is CSF otorrhea, but if the tympanic membrane remains intact, CSF can flow through the Eustachian tube and present with rhinorrhea or as an intermittent salty taste. If the leakage of CSF ceases spontaneously within a few days, no treatment is required, but persistent leakage has significant risk of meningitis. Details of management of rhinorrhea and otorrhea are not within the scope of this book.

Posterior Fossa

Dural defects in the posterior fossa, which come to neurosurgical attention, are almost exclusively post-surgical and are commonly the result of problematic surgical closure. These defects present as post-surgical CSF leaking or accumulation of CSF in the extradural space or within soft tissues. Elevated intracranial pressure greatly increases this risk. Postoperative CSF leaks following surgeries within or near the cerebellopontine angle are usually avoidable.

Which Dural Defects Require Repair?

Elective durotomies are, with a few exceptions, meticulously closed at the end of all intracranial surgeries. It is particularly important in children to close dura and hence reestablish the dural envelope. Most neurosurgeons ignore needle holes and dural openings beneath burr holes unless there is a persistent postoperative CSF leak. Some neurosurgeons do not repair mild to moderately large dural gaps in the floor of the middle fossa. Very large dural openings, such as the stellate durotomies accompanying decompression craniectomies, are intentionally left unrepaired to allow cerebral herniation; however, the dural opening site is usually covered with a synthetic material, such as DuraGen®, to prevent adherence of the brain to the galea.

A strong attempt should be made to achieve a secure closure of all openings in the spinal dura. There are settings, however, in which this may not be safely accomplished, for example, the ventral defect after resection of diastematomyelia, and when surgery was done to decompress unresectable tumor.

Irradiated Dura

Irradiated dura often has a gross appearance of being thin, dry, inelastic, and grayer in color than normal dura, but if intact, its function as an enveloping membrane is normal. It rarely presents a surgical problem when being incised but can be difficult to close.

Spinal Dura Mater [5, 30, 31]

The spinal dura mater is an extension of the meningeal layer of the cranial dura mater, and it is attached firmly to the surrounding bone only at the foramen magnum. The spinal dura mater is structurally similar to the meningeal layer of cranial dura mater; however, its fibrous and elastic tissues are arranged in bands, which generally course parallel with one another in a longitudinal arrangement. Spinal dura is composed of an fibroelastic outer layer, a middle layer, and, like cranial dura, an inner dural border cell layer.

Spinal dura mater has no endosteal layer; however, the spinal representation of the periosteal layer of cranial dura mater exists in the spine as the periosteum of the vertebral canal and is not a component of the spinal dura. There may be small fibrous connections of the posterior side of the spinal dura mater to the C2 and C3 vertebral arches and a few connections to the posterior longitudinal ligament in the mid sacral region. In the lower sacral region, the dura mater is tightly attached to the filum terminale, and this structure is tightly attached to the periosteum of the coccyx.

The tubular compartment formed by spinal dura is the theca (*Greek: box or place to put*) or thecal sac, which surrounds the spinal cord, cauda equina, and CSF.

Vasculature of Spinal Dura Mater

The arterial supply to the spinal dura mater is primarily arises from the anterior and posterior radicular arteries [15, 32]. There is a network of arterial vessels and veins in the epidural space, which have connections to vessels of the dura mater [33]. Veins tend to follow arteries in the dura and drain into segmental veins. A spinal venous sinus has been described near the midline of the dorsal lumbosacral dura [34].

Innervation of Spinal Dura Mater [35]

The spinal innervation of dura mater has two components. The ventral dura mater contains a dense plexus of longitudinally coursing nerves having contributions from *sinuvertebral nerves*, nerve plexus from the posterior longitudinal ligament, and the radicular branches of segmental arteries. Sinuvertebral nerves, also known as meningeal branches of the spinal nerves, recurrent meningeal nerves (sinuvertebral nerves or *recurrent nerves of Luschka*) are small nerves arising from each spinal nerve somewhere near the anterior and posterior rami. They pass through the intervertebral foramina to supply facet joints, posterior longitudinal ligament, posterior-lateral part of the annulus fibrosis, and the ligaments and periosteum within the spinal canal. These nerves may span as many as eight segments, with considerable overlapping. There are fewer nerves in the dorsal portion of spinal dura mater, and they do not form a plexus and may not reach the most medial dorsal region. The dorsal nerves are derived from the ventral dural plexus at the "intersleeval" parts of the dura mater. The curled bundles of nerve fibers allow displacements of the spinal dura mater during normal flexion and extension of the spine.

Abnormal Spinal Dura

Openings in spinal dura, regardless of size, will result in leakage of CSF into epidural space and often beyond. In settings in which the spinal cord is in continuous contact with a durotomy site, the spinal cord can herniate through the opening if the dura is not securely repaired.

Iatrogenic Defects

Persistent CSF leakage following lumbar puncture causes abnormally low intracranial pressure and can be a cause for positional headache and meningeal enhancement on MRI [36].

Unintended surgical disruption of the spinal dura can occur during laminectomy for spinal decompression, particularly lumbar decompressions and in the course of exposing a spinal nerve.

Chiari malformations, lipomyelomeningocele, spinal meningocele, myelomeningocele, and split cord malformation (diastematomyelia).

The dural abnormalities associated with these disorders are addressed individually in Chap. 18.

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Surgery of Dura Mater

10

Ken Rose Winston

Surgery of Supratentorial Dura Mater

Plastic neurosurgical concerns

- Protect dura during its exposure
- Protect venous sinuses and bridging veins
- Prevent desiccation
- Re-establish contour and tautness of dural envelope
- Minimize risk of postoperative CSF leak

Exposing Dura

Supratentorial dura is exposed by removing the overlying bone which requires its separation from bone. In neonates, infants, and young children, unmolested dura is only loosely attached over the frontal and parietal convexities, the squamous portions of the frontal and temporal bones, and floor of frontal fossa making surgical separation easy. Dura is densely attached to bone along suture lines and its separation can be difficult. In young adults and most middle-aged adults, the attachment of bone to dura at these sites becomes more like that in the intersutural regions of the neocranium. Dural adherence seems to correlate inversely with the closure of the cranial sutures. Also, the dura becomes progressively more adherent to bone over its entire surface in elderly patients, often making separation difficult. It can also be difficult to separate dura from bone near the edges of foramina, particularly the foramen magnum, and over the cranial base, except for the floor of the anterior fossa.

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Opening Dura

The preferred technique for initial penetration of cranial dura varies among surgeons, with each neurosurgeon strongly advocating a technique that is perceived to be the *correct, simplest*, or *most comfortable*. Slow deliberate movement under no or low magnification is important. Dura can usually be incised quite safely without dural immobilization, using the curved belly of a #15 blade. Many surgeons prefer to grasp the intact dura with toothed forceps, but this can be difficult because this requires buckling of the taut dura. Others use a sharp dural hook or a small needle whose tip has been acutely bent for this purpose with advancing age. The use of a pointed blade, for example #11, to make initial entry risks injuring underlying vessels or brain parenchyma.

After initial full-thickness incision, the undersurface of dura should be gently explored with a surgical instrument, such as one of the Penfield dissectors, to identify adherence of brain along the proposed line of dural incision. If the path is clear, the edge of dura can be grasped with toothed forceps and slowly cut with scissors. Some surgeons choose Metzenbaum-type scissors and others believe that scissors designed for cutting dura are safer, each with claims of greater safety.

Another common technique for incising dura is to insert a small instrument such as a #4 Penfield dissector for a few mm beneath the dura and press a #15 blade firmly against the dissector. The knife and dissector, while held snugly together, can be advanced as a unit along the proposed incision path. The instrument beneath the dura provides protection for the brain by separating the brain from dura and by preventing the blade from contacting brain. Skill is required to prevent the knife from slipping off the curved surface of the dissector. If dura is adherent to brain, the tip of the advancing #4 Penfield diminishes the risk of disrupting veins or injuring the parenchyma.

Incisions can be safely made in any direction in normal supratentorial dura. Attention is required to avoid disrupting large veins within dura, cerebral veins in contact with its undersurface, and bridging veins along the middle two-thirds of the superior sagittal sinus.

When it is impossible or impractical to separate dura from cranial bone, for example in patients with severely adherent dura over a knobby bone surface, attempts to separate should be abandoned. The dura must be cut circumferentially around the flap, while protecting the brain, bone, and dura removed together. This can be difficult to accomplish. A patch will be required for closure.

Durotomies

U-Shaped (Horseshoe-Shaped) Dural Incision

A U-shaped (horseshoe-shaped) dural incision is commonly used, particularly for surgeries in which the cranial opening is approximately 6 cm or greater in shortest dimension. The orientation of the horseshoe can be in any direction chosen by the surgeon. It is important to consider how the durotomy will be repaired before making an incision in dura. The durotomy must not course less than 5–8 mm from the edge of bone but the termination of the incision can be closer. The surrounding rim of dura can be retracted with sutures to maximize exposure within the cranial opening and to minimize epidural bleeding. The dural flap can be retracted with sutures and these should be inserted near the edge of the flap to fully expand the flap and minimize its contraction.

Sinusoidal (S-Shaped) Dural Incision

A sinusoidal (S-shaped) dural incision has the disadvantage of not taking full advantage of the size of the cranial opening. It can be advantageous in odd-shaped cranial openings, as may be necessary in settings of trauma and operations in which the pathology, for example tumors, may dictate advantage.

Closed Loop Dural Incision

A closed loop dural incision, sometimes called a circular incision, is used only when it is necessary to remove dura that is involved with pathology.

A circular durotomy followed by inversion of the free fragment and suturing it back into the dural defect has been done to ensure complete devascularization of a region of highly vascular dura (anecdotally attributed to Walter Dandy).

Cruciate Dural Incision

A cruciate dural incision is appropriate when the cranial opening is relatively small, for example about 5 cm or less in greatest dimension. In small or nearly flat exposures of dura, an X-shaped incision with four triangular flaps provides maximum exposure. Dural closure can be facilitated by avoiding incisions that produce triangular flaps whose apices meet at one point. A small offset of the dural apices facilitates a better closure.

Radial Dural Incisions

Radial dural incisions are commonly used in surgeries with large craniectomies done for decompression of brain. The number of incisions is dictated by the convexity of the dural surface, and multiple radial incisions are typically required for optimum exposure or decompression. The later closure of dura in these cases may be facilitated if the apices of dural flaps do not meet at one point; however, the contraction of dural flaps which occurs during the days or weeks of decompression often obviates this benefit.

Dashed (Interrupted) Dural Incisions

Dashed (interrupted) dural incisions are rarely used today. The rational for use was to allow, in the presence of intracranial hypertension, dural expansion to occur over a large region and diminish the outward herniation and kinking of brain over the edge of dura as dura was being incised. Its disappearance from use was likely attributable to the introduction of more effective ways to deal with intracranial hypertension, for example osmotic agents, hyperventilation, and steroids.

Hemostasis in Dura

Hemostasis on Exposed Dura

Actively bleeding sites of all sizes on the surface of dura can be isolated with a sucker and almost all can be promptly controlled with bipolar coagulation. Small bleeding arteries or veins along the edges of freshly cut dura can usually be quickly and securely controlled by a few seconds of compression with a needle holder and this technique has the advantage of producing no desiccation or physiologic contraction of dura. The heat from cauterization of a targeted blood vessel spreads circumferentially into dura, causing desiccation and contraction, which can complicate its closure. Arteries crossing a planned durotomy should, depending on size, be coagulated or ligated before being cut. Large vessels in dura, particularly arteries contributing to the supply of vascular malformations or neoplasms (e.g., meningiomas), should be identified, doubly ligated, and cut between the ligands. It is safe to extensively coagulate blood vessels supplying an AVM or tumor and to remove them with the lesion. Single or groups of arteries within dura can be sacrificed with no adverse consequences; however, there are exceptions. Dural arteries which are also supplying brain, as occurs in some patients with moyamoya, must be meticulously protected.

The *Goldilocks principle* of “enough but not too much” should always be applied to the neurosurgical use of cautery in achieving hemostasis and *especially on dura*. If bleeding ceases immediately when the vessel is grasped, only one or perhaps 2 s of current is usually sufficient. Continued cauterization after hemostasis has been achieved adds no additional benefit but increases the region of thermal injury. The use of high-power settings of cautery or prolonged application not only causes unnecessary dural desiccation and shrinkage but can produce thermal injury to underlying brain.

Epidural Hemostasis

The source of bleeding into the epidural space around a craniotomy is usually not visible, unless it is very near the edge of the craniotomy, and therefore, hemostasis must be achieved by indirect means. The bleeding may be from one or more sites on the dura, the undersurface of bone, or both. Active bleeding from vessels on the dural surface beyond the edge of craniotomy can rarely be reliably controlled with bipolar cauterization and attempts to do so are time-consuming and may further separate dura from bone and activate new bleeding sites.

Venous bleeding is best controlled with a few tenting sutures (see description below) straddling the site of egress of blood. A thin strip of Gelfoam® placed in the epidural space before tying the tenting sutures may be beneficial, but a thick pack of Gelfoam® is often ineffective or makes the bleeding worse by extending the separation of dura or by propping the dura away from bone beyond the pack if dural tenting sutures tightly stretch the dura over the mass of Gelfoam®. Slow persistent epidural bleeding—i.e., oozing—can very often be controlled with application of a sealant, such as Floseal® foam, followed by a few seconds or minute of pressure against the undersurface of dura with an instrument. Coagulopathy, even when not severe, can be particularly problematic in achieving epidural hemostasis. Arterial bleeding in the epidural space is particularly dangerous. The site of bleeding must be identified and definitively controlled. Tenuous control is not reliable, and reactivation of bleeding can occur after surgery is completed. Bleeding from branches of the middle meningeal artery, particularly near the lesser wing of the sphenoid wing at the anterior edge of a frontotemporal craniotomy, can be difficult to control and may require removal of additional bone.

Epidural Hematoma

Bleeding into the epidural space can occur in association with fracturing of bones of the lateral cranial convexity but can occur, in infants and young children, in the absence of a cranial fracture. The source of bleeding is most often one or more branches of the middle meningeal artery or a vein coursing with this artery, but bleeding into the epidural space can also occur from disrupted commissary veins near the superior sagittal sinus. As epidural blending continues, the dura is progressively separated from bone. The resulting hematoma compresses underlying brain, and if not surgically evacuated, will damage brain, and become life-threatening. This is a neurosurgical emergency.

Tenting Suture (Hitch Stitch)

Walter Dandy, in the early twentieth century, introduced the practice of tightly suturing dura to the bone around a craniotomy site to obtain epidural hemostasis and also for prophylaxis against postoperative bleeding into the epidural space [1]. These are called tenting sutures or sleeper sutures (referring to reduction in nocturnal arousals of neurosurgeons to deal with postoperative epidural hematomas). Many craniotomy patients were significantly hypotensive at time of wound closure, thus making reliable hemostasis difficult. Tenting sutures were, in Dandy's time and now, almost the only reliable way to control active intraoperative bleeding into the epidural space. Nowadays, it is quite uncommon for patients to be significantly hypotensive at the time of closure of craniotomies, making the appearance of hemostasis much more reliable [2, 3].

Dura is tented by suturing it snugly to either pericranium or to bone via small, angled holes drilled for that purpose. Tenting sutures are especially useful in establishing epidural hemostasis. However, contrary to common belief, these provide little prophylactic benefit and have a small associated risk of causing bleeding by snagging cortical vessels or brain parenchyma or by bowstringing the dura beneath bone. A small amount of epidural hematoma can be seen on neuroimaging after most craniotomies and is usually but not always clinically insignificant. The size of these hematomas is smaller when no tenting sutures are used, in this author's opinion [4].

Most neurosurgeons use at least a few tenting sutures for prophylaxis, but far fewer than were used decades ago, particularly in pediatric neurosurgical practice. Many surgeons use non-absorbable suture, usually silk or Nurolon®, but long-lasting tension is never necessary for maintaining hemostasis and therefore absorbable suture, such as 4–0 polyglycolate, is equally effective without being a long-lasting site for harboring bacteria. When dura is tented, the sutures should be placed as close to the edge of bone as possible to minimize outward traction of dura, which makes closure more difficult. Tenting sutures should be tied snugly to achieve their goal but, if tied extremely tightly, the tension applied to dura can bowstring dura away from bone and thereby cause epidural bleeding while obscuring its occurrence. Slow bleeding may continue at a distance from the bony edge and present postoperatively as an epidural hematoma remote from the craniotomy site; these hematomas are *not* prevented by prophylactic tenting sutures. In summary, tenting sutures are particularly useful for achieving epidural hemostasis, but not for prophylaxis [2–4].

Persistent Epidural Bleeding

If the above-described techniques for hemostasis fail, it is necessary to directly visualize the bleeding source by enlarging the cranial opening. Usually, this is best achieved by removal of a crescent-shaped piece of cranial bone, using a craniotome or rongeur. The tendency to minimize the enlargement by repeatedly removing small amounts of bone often delays the required exposure. All bone fragments should be saved for use in closure.

Hemostasis in Shorenstein's Angle

Shorenstein's angle (origin of term unknown) is known for being a site in which hemostasis can be frustratingly difficult. This is a three-sided pyramidal space which becomes apparent only after removal of much of the lesser wing of the sphenoid bone. It is bounded on two sides by the fold in dura which was wrapped around the lesser wing of the sphenoid bone and on the third side by freshly raw bone. Bleeding into Shorenstein's angle occurs during resection of the lesser wing of the sphenoid bone and the separation of dura from this bone, as commonly required during frontotemporal craniotomies. The arterial and venous bleeding occurs from small foramina on the undersurface of the lesser wing of the sphenoid bone; however, arterial bleeding is usually the dominant type and may be from the trunk or branches of the middle meningeal artery. The trunk is often partially enclosed by bone at this site and therefore may be disrupted while making an osteotomy across the lesser wing of the sphenoid bone or during removal of the lateral wall of the middle fossa. The arterial bleeding in Shorenstein's angle often occurs from both ends of disrupted vessels, one of which is on dura and the other retracted into bone. The precise sites of bleeding on dura and from bone may be difficult to identify because of difficulty in visualization. Retraction of dura from bone to attempt better visualization can disrupt more vessels and increase the bleeding.

All bleeding from arteries in this location must be controlled by cauterization or ligation. Persistent bleeding from veins and dural arterioles in Shorenstein's angle that cannot be visualized can sometimes be controlled with Floseal® held firmly in place by packing with Cottonoids®. Bone wax can be beneficial for halting venous bleeding but is not reliable for arterial hemostasis. Tenting sutures in Shorenstein's angle may occasionally be helpful but more often not, because of difficulty of their insertion and also because of the often-undesirable direction of their tension.

Prolonged use of imprecisely applied cauterization in the "general region" of active bleeding, commonly described as being directed "to whom it may concern," is rarely successful and, if on dura, can cause thermal injury to underlying brain. Bleeding from the epidural space around Shorenstein's angle may reactivate as packed Cottonoids® are removed and the durotomy is being sutured.

Bleeding from Middle Meningeal Artery at Foramen Spinosum

Arterial bleeding from foramen spinosum resulting from avulsion of the middle meningeal artery may be encountered during resection of meningiomas in the floor of the middle fossa and occasionally when evacuating acute epidural hematomas. This bleeding can be difficult to control and may result in considerable loss of blood during failed attempts at hemostasis. Application of bone wax may briefly appear to be successful, but usually fails when the wax warms to body temperature. Coagulation is sometimes successful but repeated failed attempts only cause the end of the artery to retract farther into the bone. An old technique which is not commonly known is reliably effective. A small peg of sterile wood trimmed from a swab stick or tongue blade can be easily pressed firmly or tapped into the foramen and cut flush with the surface of bone. The peg is left permanently in the foramen [5].

Bleeding from Major Venous Sinus

Injury of major venous sinuses may occur from blunt or penetrating trauma, accidental iatrogenic injury during craniotomy, or in the course of resection of tumor which has invaded a venous sinus. Violation of a major venous sinus can cause severe bleeding with massive loss of blood or result in air embolism, and, although the anatomical injury is the same in both, the presentations are totally different. If there is immediate continuous venous bleeding, the pressure in that venous sinus is above atmospheric pressure, and the surgical problem is loss of blood. Air embolism comes to the surgeon's attention when the anesthesiologist recognizes and announces the diagnostic signs.

Injury of Sinus During Osteotomy

Sudden vigorous venous bleeding encountered while making an osteotomy across a venous sinus is usually associated with tight adherence of dura to bone or presence of meningioma and bone usually cannot be quickly removed to expose the bleeding site. Bone wax must be immediately pressed into the kerf. The bleeding rate can be reduced by elevating the head to reduce the intra-sinus pressure but, if intra-sinus pressure becomes lower than venous pressure, the result will be life-threatening air embolism. Completion of the osteotomy along the marked line should be made from the opposite direction to avoid extending the opening in the sinus, and this may require another burr hole. Completion of the osteotomy to allow removal of the bone flap must be done as rapidly as possible.

Bleeding from this source of injury is on the dural convexity surface. As soon as the bleeding site is identified, it must be covered with double-thickness Gelfoam® and held in place with two or more layers of wet Cottonoids® for several minutes. Unless the cranial opening must be enlarged to achieve the required surgical exposure, it is often beneficial to enlarge the cranial opening across the disruption in the sinus. A small piece of muscle or other tissue may be inserted beneath the Gelfoam®. At time of closure, the Cottonoids® are removed, leaving the Gelfoam® in place. Replacement of the bone flap over the tamponade will secure it in place if the defect is confined to the convexity dural surface. Attempts to control this bleeding with sutures usually fail and often enlarge the bleeding site.

Small Bleeding Site Over a Sinus

Bleeding from a small site over a venous sinus may be halted with one or two quick applications of bipolar cauterization but repeated failed attempts will cause centrifugal retraction of the edges of the hole and increase the rate of bleeding. Application of a small piece of Gelfoam® held in place by pressure over a wet Cottonoid® for a few seconds or minutes will halt bleeding. After bleeding ceases, the Gelfoam® and Cottonoid® should be left in place until just before bone replacement, at which time the Cottonoids® are removed. Attempt to control bleeding with a suture usually fails.

Injury of Sinus During Durotomy

These violations of a sinus are almost exclusively in the lateral corner or wall of the sinus and tend to bleed vigorously. Immediate hemostasis can be obtained by pressing a wet Cottonoid® over a small piece of Gelfoam® against the site with a sucker for a minute or two. Placement of a 4–0 suture may be effective, but care must be taken to not compromise flow in the sinus. Coagulation is occasionally beneficial but can enlarge a small effect and make bleeding worse. Bleeding from a torn bridging vein, but not the site of an avulsed vein on the sinus, can usually be controlled by coagulation.

Bleeding During Dissection of Tumor from Sinus

The wall of the superior sagittal sinus may be invaded by meningioma, in which case dissection often results in bleeding along the involved walls of the sinus. Small bleeding sites can be controlled with Gelfoam® and pressure, as described above. Also, the Gelfoam® may be secured in place by a suture spanning site and attached to tissue on each side (hitch stitch) [6]. A tack-up suture from the falx and across Gelfoam® is reported to be an effective maneuver [7]. Extensive invasion of the sinus by tumor may require using a bypass shunt and resection of a section of sinus. This technique is not within the scope of this text.

One transverse sinus, particularly the left one, can be ligated, usually without serious adverse consequences if the contralateral transverse sinus is intact. It is commonly believed, but not universally true, that the superior sagittal sinus can be ligated safely anywhere in its anterior third. Not well known is that sacrifice of the anterior quarter or third of the superior sagittal sinus in patients in whom there exists a more posterior occlusion of the sinus—e.g., by tumor—will often result in bilateral venous infarction of anterior portions of both frontal lobes. *The safety of* *elective occlusion of a sinus at any site is never certain and should be avoided when possible.*

Traumatic Laceration of Venous Sinus

Laceration of a sinus must be suspected whenever a depressed fragment of bone is impinged against a venous sinus, a fracture line crosses, or courses parallel to a sinus. Although CT and 3-D reconstructions are often helpful, the puncture or tear of an impinged sinus may not be apparent before surgical inspection. Absence of hematoma is not diagnostically reliable for non-injury of a venous sinus.

The anesthesiologist must be made aware of possible injury of a venous sinus. Doppler echocardiography, insertion of a central venous line, and availability of blood for transfusion are components of preoperative steps.

Many neurosurgeons, being extremely fearful of the hemorrhage initiated by removing bone impinged against a sinus, delay or avoid removing the critical fragments. The surgeon must be prepared to deal with bleeding from a punctured sinus. This includes mild elevation of the head but not enough to risk air embolism and having blood for transfusion. As the depressed bone fragment is removed, wet Cottonoids® is quickly placed over the bleeding site and held manually or with a sucker. These are then replaced with double-thickness Gelfoam® held firmly in place with two or three layers of Cottonoids®. Attempt to repair the laceration by suturing is often unsuccessful and will reduce the size of the sinus at that location. Coagulation of the site will retract the edges and enlarge the defect. Reflection of a flap of dura across a site of laceration has also been used successfully [8]. A hitch stitch across the sinus can hold the Gelfoam® in place and have been used successfully. As soon as safely possible, the fragments of bone should be returned to their approximate normal locations and secured with plates, leaving the Gelfoam® in place. Single and multiple lacerations of 1 cm or less in length can usually be successfully managed in this manner.

Open injuries of a sinus are often a result of gunshot or shrapnel wounds and are associated with massive blood loss and often exsanguination.

Injury of Occipital Sinus

The occipital sinus, which can be double, is prominent in newborns and infants but rudimentary in most adults. It lies along the base of the falx cerebelli and has prominent connections to the marginal sinus, which lies around the foramen magnum, and to the internal vertebral plexus. The exact location of the occipital sinus and its connecting veins near the foramen magnum cannot usually be visualized and the inexperienced surgeon can be surprised by the volume of blood loss before hemostasis can be obtained. It is important for pediatric neurosurgeons to be knowledgeable of this risk when incising dura across the midline at the foramen magnum. If not anticipated, for example in Chiari decompressions, much blood can be lost before hemostasis is obtained. Coagulation is rarely sufficient in infants. Although awkward, the bleeding site must be grasped with the tips of one or two hemostats or a needle holder and then surrounded with a 4–0 suture.

Pitfalls/Things to Avoid

Excessive Cauterization of Dura

Excessive cauterization of dura can be injurious in several ways. Continued cauterization for more than a very few seconds after hemostasis has been achieved serves no beneficial purpose. The use of high-power settings or prolonged contact with dura can produce contraction of dura and thermal injury to underlying brain.

Failure to Achieve Robust Hemostasis

A small amount of persistent bleeding or reactivation of bleeding, as can occur as dura is stretched to achieve closure, can result in accumulation of blood in the epidural spaces.

Excessively Tight Tenting Sutures

The act of pulling dural tenting sutures very tight can “bowstring” dura from the concave inner surface of cranial bone and activate bleeding into the epidural space beyond the edges of the craniotomy. The tenting sutures can halt visible evidence of epidural bleeding at the edge of the craniotomy while concealing the bleeding and dural displacement beyond the bony edge and therefore be the cause of delayed recognition of postoperative epidural hematoma.

Retraction of Cranial Dura

Retraction of supratentorial dura serves three functions: (1) expands exposure beneath the dura to take full advantage of the cranial opening, (2) assists with hemostasis in the epidural space surrounding the craniotomy, and (3) maintains dural flap under tension to minimize contraction.

Technique

The rim of dura around the edge of the craniotomy requires retraction to take full advantage of the size of the cranial opening, prevent contraction of dura, and control and prevent bleeding from the surrounding epidural space. For each dural incision, there are two edges that require retraction, usually a flap and a surrounding rim of dura. Retraction is accomplished with a few sutures, commonly 4–0 silk or Vicryl®, inserted along both edges to prevent contraction. A hemostat can be used to secure each retraction suture to drapes or each can be sewn to nearby drapes. The former technique allows easier readjustment of direction and force of retraction as needed. These sutures may be temporarily sewn to any convenient nearby material, for example pericranium, galea, drapes, or bone via holes drilled for this purpose. It is important that the dural flap and the surrounding edge of dura be kept moist and under tension until the durotomy is repaired to prevent its retraction, which can greatly hinder dural closure.

Preventing Desiccation

Desiccation of dura causes its contraction, and this can greatly complicate or prevent satisfactory abutment of the edges at time of closure. There are two causes for desiccation associated with surgery—exposure to air having low humidity and cauterization used to achieve hemostasis. Desiccation can be minimized by keeping dura moist with saline-soaked Cottonoids® or gauze sponges throughout the operative procedure, minimization of use of cauterization, and keeping the dura stretched with sutures during surgery. Desiccated dura, even when severe, usually retains the ability to heal.

Repair of Durotomy [9]

Most neurosurgical operations, excluding trephinations, require closure of dura to re-establish their dural envelopes and prevent leaking of CSF. Closure of dura is particularly important in pediatric patients because the normal growth of brain produces a steady centrifugal force against the dural envelope and a large defect in dura is a region of diminished resistance to expansion. The result is stretching of the dural defect and slow progressive herniation of brain. Adults with normal intracranial pressures may tolerate dural defects if covered with cranial bone. A dural defect beneath a cranial defect, with no other interposed layer such as DuraGen®, allows brain to be in contact with pericranium to which it becomes tightly adherent. This can cause great technical difficulty if that region requires surgical exposure in the future.

An incision in normal dura heals well if the edges are brought snugly together by sutures. Many surgeons attempt to achieve maximally tight abutment with closely placed sutures to decrease the risk of CSF leakage but this is not necessary for healing. A rigid attempt to achieve this often results in multiple small tears in dura and stretching of the needle puncture sites. A goal of "watertight" dural closure is often sought but difficult to achieve [10]. The application of a tissue sealant along the suture line may increase the security of the closure; however, a review article, by Kinaci et al. on 3682 surgical procedures found that dural sealants do not diminish the incidence of CSF leaks or pseudomeningocele formation [11]. Factors that interfere with healing of durotomies include elevated intracranial pressure, infection, chemotherapy, and exposure to radiation.

Dura with Ragged Edges

If the dura is disrupted by a craniotome, the edges will be ragged and either aligned with the edge of bone or located 1–3 mm beyond the edge. The raged dural edges cannot be brought into snug contact with simple sutures and the result is a defect whose repair often requires a patch. Regardless of need for patching, the edges of dura must be identified. The peripheral edge of the dura which is consistently retracted to or beyond the edge of bone must be dissected free of bony attachment to prevent its further injury by bone-cutting instruments. It is almost always necessary to remove additional bone to expose enough dura to allow suturing. A craniotome or rongeur is used to remove approximately 7 mm of bone to expose sufficient dura along the length of the dural tear to accept sutures.

Expedient Management of Densely Adherent Dura

Techniques described in this section should be used only when other techniques have failed and primary dural closure must be abandoned due to the inseparability of dura from bone If most of the dura flap has survived, the flap can be tacked to *pericranium* or to surrounding bone using holes drilled for this purpose. A strip of pericranium or DuraGen® is then positioned around the dura-bone junction, followed by replacement and fixation of the bone flap, which will depress the outwardly suspended dural flap and patching material. This technique stretches the flap of dura across most or all of the gap in dura but does not achieve continuous approximation of dural edges.

In patients in which adherent dura has been removed with the bone flap because of its inseparability, the exposed brain can be covered with suturable DuraGen® with its edges tucked beneath the surrounding edges of intact cranium. The bone flap is then secured in place with plates.

Closing Technique

Magnification

Decision on use of magnification during closure of dura is surgeon-specific, but most often supratentorial dura can be safely and easily repaired without magnification. If magnification is preferred, loupes are adequate.

Sutures

Absorbable or non-absorbable sutures can be used to repair durotomies; however, most neurosurgeons use non-absorbable sutures, for example Nurolon® or silk, because of concern that sutures could allow separation of the durotomy if the sutures absorb before healing occurs. The author prefers absorbable sutures in almost cases because it does not provide a long-term haven for bacteria. Absorbable 4–0 polyglycolate sutures function well for almost all dura applications and will disappear within 60–75 days. It is reasonable to choose non-absorbable sutures in patients who have recently received or will soon receive irradiation or chemotherapy. A running suture technique for closing dura is satisfactory and reliable.

Decades ago, it was taught that all durotomies must be repaired with interrupted sutures because of a fear that if a running suture broke or became untied, the entire durotomy would separate. Silk or cotton and occasionally wire was used to repair dura because of its low rate of associated infection. The use of wire to repair dura was abandoned decades ago.

Needles

Non-cutting, taper needles should always be used on dura. Needles with cutting or spatula tips produce a hole in the dura that tears when tension is applied. Needles of 3/8 or occasionally ½ circle configuration seem to function best, but opinions vary. Large needles can be cumbersome when penetrating dura adjacent to bone and they increase the risk of penetration of brain. Small needles can be difficult to manipulate unless closure is being done under a microscope.

Suturing Technique

Opinions vary regarding whether a simple running suture technique or a locking running technique is best for closing dura, with little published evidence on the subject [12]. The traditional closure of dura with simple interrupted sutures is unnecessarily time-consuming and the approximation of dural edges between interrupted sutures is less snug than achieved with running sutures, unless very closely placed. The author prefers the non-locking running technique as it is simpler, requires less time, and implants less foreign material.

Distance from Edge of Dura for Placement of Sutures

The distance of placement of sutures from edge of dura is important. Durotomies in normal supratentorial dura in patients of almost all ages can be repaired with sutures placed approximately 2–3 mm from the edges. Distances of 1.5–2.5 mm may be used in premature and newborn children. Dural edges of most durotomies in supratentorial dura are relatively easy to align and pull together without having sutures tear through the edges. The placement of sutures at greater distance from edges has the effect of reducing the area of dura available for stretching and approximation of edges. This often results in tearing of the edges of dura as the sutures are tied, thereby greatly impairing closure. There is no advantage in buckling the edges of dura in the process of closing.

It is not unusual to notice during the closure of the second half of a U-shaped durotomy that there is insufficient dura for closure. This is commonly the result of an inexperienced surgeon consuming an unnecessarily broad strip on the opposite side by placing sutures far from the edge of the dural flap, apparently believing that greater distance will decrease the risk of tearing. Optimizing the placement of sutures and use of the cheating (see discussion below) usually obviates the for requirement of a dural patch.

Spacing of Dural Sutures

The first and last sutures along a durotomy should be placed within 1–2 mm of its ends. The spacing of sutures should be determined by the required closing tension along the edges. Five to seven mm separation of sutures usually achieves excellent closure. Some surgeons choose closer spacing in attempt to achieve "watertight closure." Though often claimed, durable watertight closure is difficult to achieve with sutures alone in the presence of normal intracranial pressure, and rarely if ever in the presence of high intracranial pressure; however, an application of sealant along the line of dural closure greatly assists this goal. Snug support by a well-secured overlying bone flap is also beneficial in preventing CSF leaks, probably because it restricts pulsation of dura and therefore limits the lateral tension across the sutured durotomy.

Cheating Technique

Cheating is an old and especially useful technique for stretching dura to achieve approximation of edges and avoid requirement for patching. This is accomplished by, starting at one end of the durotomy using a running technique and offset alignment of sutures, as opposed to direct opposite alignment. This technique stretches the shorter appearing, flap-side of dura to match the opposite side. This technique is particularly useful in closing the dura of the posterior fossa.

Gaps in Suture Line

The running suture used to repair dura should be continued across all gaps of approximately 1 cm or less. This maximally expands the available dura, and the spanning sutures prevent the inward sag of an onlay graft. Gaps of about 1.5 mm or less heal well if covered with a small onlay strip of flat Gelfoam®. Gaps in dural approximation up to 1 cm usually heal well if covered with an onlay graft of pericranium that is snugly covered by a well-secured bone flap. Much time can be consumed in closing small gaps of dural edges with tightly sutured patches. The result is often a satisfactory appearing closure that probably does not alter the risk of postoperative CSF egress. Gaps larger than a cm should be repaired with a patch of pericranium or a synthetic material such as DuraGen® (type I bovine collagen).

Tenuous Suture Lines and Attenuated Dura

When dural closure is tenuous, a strip of periosteum may be either sewn snugly over the area of concern with 4–0 polyglycolate sutures or simply placed over the area of attenuated dura and tacked in place with two or three sutures to prevent displacement during irrigation and replacement of bone flap. The author prefers the latter technique in most settings. Rigid support over a tenuous dural closure by bone flap, bone fragments, or solid synthetic material provides protection from postoperative stretching by intracranial pressure and the effects of pulsation on suture lines and thereby diminishing the risk of delayed dehiscence.

Epidural Bleeding Activated During Closure of Dura

Bleeding from the epidural space may be activated or become reactivated as retraction sutures are removed and as the dural edges are pulled together. These activities alter the magnitude and direction of tension on dura and can activate bleeding from sites that had been dormant during surgery. The tension applied to dura while tightly approximating dural edges can occasionally strip dura from bone, either near the edge of bone or centimeters away; this can activate epidural bleeding or, if bleeding is already occurring, this may make it more difficult to control.

Intraoperative Consequences of Unintended Dural Disruption

The instrument making an unintended durotomy, most often a craniotome or an osteotome, usually causes no serious problem; however, there is risk of disruption of a vein, artery, or tearing brain parenchyma. The site of disruption should be inspected for active bleeding. If dural disruption extends into the superior sagittal sinus, confluens sinuses, a transverse sinus, or across bridging veins to the superior sagittal sinus, severe venous bleeding will occur and can be difficult to control.

Duraplasty

Duraplasty is the repair of dura by closing or patching a defect or intentionally altering the shape of the dural envelope.

Small Defects in Dura

[See above discussion of gaps in suture line.] Tiny holes in dura resulting from needle punctures are ignored; however, if overlying a CSF-containing pocket, chronic leakage is possible and closure with another suture and application of a tissue sealant may be required. Defects in dura up to 1 cm in diameter usually heal well if a piece of pericranium is stretched across the defect and overlaid with Surgicel®, to prevent its curling, and then covered by a well-secured bone flap. Much time can be consumed in closing a small defect with tightly sutured patches that result in a satisfying appearance with little or no reduction of the risk of postoperative CSF leakage or brain herniation. Gaps of 3 mm can usually be safely managed with onlay grafts of homologous tissue, such as pericranium. Surgeons in past decades used small pieces of temporalis muscle, but this can significantly damage the muscle and is best avoided.

Large Defects in Dura

There is no agreement of what constitutes a large dural defect but those of 2 or more cm in shortest dimension can be considered large and will require a patch. Defects of 2 cm or larger should be patched with pericranium or a synthetic material such as DuraGen®. This can be secured with 4–0 polyglycolate sutures or simply may be placed over the area of attenuated dura and tacked in place with two or three sutures to prevent displacement during irrigation and placement of bone flap. The author prefers the latter technique in most situations.

Materials for Patching Dura

The material used for a patch should be a water-impermeable sheet, not significantly elastic, but relatively easy to sew in place and not absorbable over time. It must re-establish a snug dural envelope.

Pericranium

Pericranium, which is embryologically closely related to the *endosteal* layer of dura which is the best material for patching dural defects, is often available and is free [13]. Pericranium over the frontal and parietal bones is easily accessed and usually simple to harvest, unless extensively disrupted as the scalp flap is reflected, or if allowed to become desiccated from prolonged exposure to air. Pericranium can be sutured to dura over medium size and large dural defects or used as an onlay graft with few or no sutures for small defects.

Pericranium is often reflected with the scalp flap, but some surgeons choose to initially leave it attached to all or part of the exposed bone. Whether harvested by separating it from the undersurface of reflected scalp or from the cranial surface, it is important to strive to obtain an intact sheet with no holes and the patch (graft) should be a little larger than the size of the defect for which it is to be applied. Multiple pieces of pericranium can be sutured together if necessary but this increases the number of suture lines through which CSF can leak.

Galea

Galea is an excellent homographic material to repair defects in the floor of the frontal fossa and in other locations. It is tougher than pericranium and holds sutures well. More time is required to harvest galea than pericranium and there is more bleeding from the scalp. If the scalp has undergone prior surgery, irradiation, or infection, it can be difficult or impossible to harvest galea without multiple tears. Some surgeons, when dealing with large defects in the floor of the frontal fossa, do not sever the galeal attachment across the supraorbital edge of bone to preserve the galea's blood supply; however, it is not clear that this blood supply survives nor that its survival is necessary to achieve a secure patch in this location.

Fascia Lata

Fascia lata is an excellent material for patching dura. It is very tough and is relatively easy and safe to harvest but does require a vertical incision in the anterolateral thigh [14]. Care must be taken to avoid injuring the lateral femoral cutaneous nerve.

Bovine Pericardium

Bovine pericardium is a satisfactory xenograft for patching dura but is thicker and tougher than normal dura. It seems to be well tolerated.

Lyophilized Human Dura

Lyophilized human dura is structurally an excellent material for patching dura but is no longer used. There were reported cases of transmission of Creutzfeldt–Jacob prions, probably as a consequence of the source being cadavers of mentally impaired individuals [15].

Synthetic Materials

DuraGen® (one example) is available in both a suturable and a non-suturable form. The complication rate for using dural substitutes of all types is reported to be approximately 11% with no significant differences among allografts, xenografts, and synthetic materials, but this rate seems too high in this author's opinion [16].

Materials Useful in Managing Small Dural Defect but not for Patching

Gelfoam® (absorbable compressed gelatin sponge) applied across a dural gap becomes snugly bound to dura and thus prevents or minimizes leakage of CSF as blood and serum enter its matrix. Gelfoam does not develop into a neodura as has been claimed but will eventually be absorbed leaving a thin scar. This thin scar partially or totally spanning the dural defect does not re-establish a dural envelope. For dural gaps of less than about 3 mm which are covered by Gelfoam®, healing often occurs as fibroblasts from the live dura edges apparently bridge the gap. It has not been demonstrated that Gelfoam® plays a role in this healing. Regardless, Gelfoam® does not become a component of the dural envelope and should never be used as a material for patching dura.

Surgicel® (oxidized cellulose polymer) has no role as a patch material for dural defects but can be useful in halting bleeding from small sites on dura. It will be absorbed but does not become a component of the dural envelope itself.

Tissue sealants, for example, DuraSeal® and fibrin glue (Tisseel®, Surgiflo®, and Floseal®), can be helpful in reinforcing dural repairs. Opinions vary as to whether they decrease the risk of CSF leak after or decrease venous bleeding. For some neurosurgeons, the efficacy of augmenting duraplasty with tissue sealant remains controversial [10–12].

Technique for Patching Dura

The first step in patching a dural defect is to identify the edge of dura around the entire perimetry. Freshly cut edges of dura are readily apparent but dural defects related to trauma, remote surgical procedures, or expanding fractures can be difficult to find.

Defects in dura of the cerebral convexity larger than approximately 1 cm in greatest dimension in infants and young children and all defects of 2 cm or larger in older patients should be patched. This is done to re-establish or secure the dural envelope.

Patches for defects over the cerebral convexity that are larger than approximately 1.5 cm diameter should be sutured around their entire periphery. It is usually not possible to suture around the periphery of dural defects in the base of the cranial vault. Attempts to suture small patches in place can result in injury to underlying brain, is never as secure as appearing, and is time-consuming. Small defects can be patched with onlay grafts.

Suturing of Patches

The patching material should be cut to the approximate correct shape and a size and slightly larger than the defect to be repaired. One corner of the patch should be sutured to the dura and then approximately 3 interrupted retraction sutures used to loosely stretch the patch over the defect in the desired orientation. Many surgeons use non-absorbable sutures with a simple running technique; however, the author prefers absorbable sutures.

Materials for Patching

Homologous tissue, for example pericranium, galea, fat, and fascia lata, is usually available for grafting [4, 17, 18]. The use of homologous fat was first used by Harvey Cushing to repair a dural defect and is still commonly used [19, 20]. Neurosurgeons commonly consider pericranium to be the ideal autograft; however, it can be difficult to manipulate because of its relative thinness and its tendency to contract. The harvesting and manipulation of a pericranial patch are reported to be made much easier if tissue sealant is applied to the pericranium before harvesting [21]. Temporalis fascia, because of its intrinsic tissue properties, is also an excellent autologous material for patching dura but harvesting is more difficult [22]. Xenografts have also been used for patching dura. Most of these materials have a smoother side which should be positioned toward the inner surface at the recipient site.

Three or four temporary sutures should be used to roughly stretch and align the patch over the defect. The patch can then be sutured tautly to surrounding intact dura. Homografts, particularly pericranium, are soft, pliable, and easy to manage. All patches over the cranial convexity, particularly in infants and young children, should be sutured tautly to establish a snug dural envelope.

Most neurosurgeons use non-absorbable suture material, usually 4–0 silk or Nurolon® for suturing patches of all types; however, this author prefers absorbable 4–0 suture for all dural closures, unless the region will soon receive radiation therapy or chemotherapy. Sound healing will occur long before the absorbable sutures lose their tensile strength. Rational for absorbable sutures is avoidance of the short-term risk of harboring bacteria.

Patching Dura with Shredded Edges

Dura can be so densely adherent to cranial bone that separation cannot be achieved without severely disrupting dura and risking injury to brain. In such cases, it is occasionally necessary to cut the dura with the craniotome as bone is being cut. This results in a bone flap covered with adherent dura and a cranial defect with a ragged edge of dura around the edge of the cranial defect. Identifying edges of dura would require removal of more bone which would likely further injure the adherent dura and make suturing impossible.

This can be managed with strips of periosteum or Suturable DuraGen® of approximately 1.5 cm width tucked, using half their widths, beneath the ragged dura surrounding the cranial defect, and then placing the bone flap in its home position and securing it with titanium plates. This esthetically unappealing maneuver is usually successful.

Complications of Dural Repair

Complications include CSF leak, pseudomeningocele, and meningitis.

Management of Irradiated Dura

Irradiated dura does not present a surgical problem when being incised but repair can be difficult. Its near absent elasticity impairs approximation of dural edges and, if sutures are pulled tight, the tissue tears. Because of the poor vascularity of irradiated dura, it heals slowly or fails to heal. Small gaps can be managed successfully with an onlay graft of pericranium, muscle, or a synthetic material. Larger grafts require a sutured patch with one of these materials. The bonding with synthetic materials is slow and may not occur. Because of delayed healing, it is reasonable to repair irradiated dura with non-absorbable sutures.

Management of Excess Dura

Dura Outwardly Displaced Through Cranial Defect

Dura that is outwardly expanded by approximately six or more millimeters should be corrected at time of cranioplasty to minimize the risk of delayed displacement of overlying bone. If intracranial hypertension is present, this must be corrected before correcting the dural bulge. Correcting bulging dura by displacing it inward with a firmly secured bone flap or synthetic material gives an immediate appearance of success that is often followed by delayed dislodgment of the bone flap and reappearance of the bulge. A concave cranial defect may be associated with excessive dura but, unless extreme, this can be ignored during cranioplasty.

When dealing with excess dura, it is beneficial but not essential to separate dura from bone around the edge of a cranial defect. If the bulge does not extend beyond the normal external cranial contour, the dura can be shrunk by desiccation with cautery. Greater dural bulging must be reduced by imbricating or excising of one or more fusiform bands of dura with 4–0 Nurolon® or silk sutures.

Dural Bulge Associated with Craniosynostosis

Dural bulges associated with craniosynostoses can usually be sufficiently reduced by desiccation with cautery. Caution must be exercised to avoid thermal injury to brain. Large bulges require imbrication of fusiform bands of dura.

Correction of Shape of Dural Envelope

Methods to correct abnormal contour of the dural envelope include desiccation with cautery, imbrication, resection alone, and resection with patching.

Desiccation

Bipolar coagulation of dura causes desiccation which results in shrinkage of a small area of dura. When applied in a line across exposed dura, the dural envelope is contracted in the direction perpendicular to the line of coagulation. This is a common technique in surgery for craniosynostosis and is generally considered to be safe. However, the coagulation forceps should be continuously moved across the dura and never held still in one place while power is applied. It is reasonable to believe that thermal injury to underlying brain could result from use of high cautery current if the cautery forceps is held still in one place versus moved slowly across the dura. There is no way to visually assess the impact on underlying brain.

Imbrication

A fusiform-shaped section of the dural envelope can be eliminated by buckling or folding the excess dura with a simple running suture line of 4–0 Nurolon® or silk, along a curved course perpendicular to the direction of desired reduction. Non-absorbable sutures should not be used. Usually several lines of imbrication, not necessarily parallel, are required. Care must be taken to avoid snagging underlying brain with the needle and to avoid excessive tightening of the dural envelope.

Resection

When the dura is extremely excessive, for example in patients who undergo reduction cranioplasty, imbrication results in infolding or wading of large areas of normal dura. This situation is best handled with resection of one or more elliptical areas of dura and suturing the raw edges of the surrounding intact dura.

Resection with Patching

Some patients with extreme cranial dysmorphia require reduction of the dural envelope in one direction and expansion in the perpendicular direction. A fusiform section of dura is resected and a perpendicularly oriented durotomy of the same length is made across the site of dural resection. The free fusiform piece of dura is then sutured into the durotomy site and the edges of the resection site are approximated primarily. This technique has minimal effect on the volume of the dural envelope but does alter the shape of the cerebrum.

Surgery of Infratentorial Cranial Dura Mater

Plastic neurosurgical concerns

- Protect dura during its exposure
- Protect venous sinuses

- Hemostasis near foramen magnum
- Prevent desiccation
- Closure of dura
- Minimize risk of postoperative CSF leak

Opening Dura of Posterior Fossa

Most durotomies for lesions in the posterior fossa are U-shaped, often with a vertical midline incision across the dura at the foramen magnum. The initial dural penetration is made with a scalpel starting in the lateral exposure of dura below the transverse sinus. This incision is then extended downward in an arc toward midline but halting 5–7 mm from the midline just above the dura of the foramen magnum. The dura should be incised slowly with microscissors or a knife blade held tightly against a Penfield dissector to allow bleeding sites to be controlled as they are encountered. An identical incision is then made on the opposite side of the exposed dura. Either straight, or slightly curved, vertically oriented incisions in dura of the posterior fossa may be chosen to approach small lesions of the vermis or cerebellar convexity [23].

Significant arterial bleeding is rarely encountered during opening of posterior fossa dura. Bleeding from dural vessels in these lateral durotomies can be controlled by clamping with a needle holder for a few seconds, but occasionally mild cauterization is required. Near the foramen magnum, vigorous venous bleeding should be anticipated while cutting the dura across the midline, especially in newborns and infants, and its control can be frustratingly difficult. The dura here often contains a plexus of veins which predisposes to partial thickness grasping with forceps or scissors which can increase the bleeding. A circular sinus is a prominent feature in newborns and infants but may be present in older patients and can add to the difficulty in hemostasis.

Brief episodes of vigorous bleeding can usually be quickly controlled by tamponade with small Cottonoids® held in place with a sucker. Great care must be taken to avoid compression of medulla. As the durotomy is extended, the stepwise placement of retraction sutures along each edge facilitates hemostasis and assists exposure. Cauterization of these venous sites at the foramen magnum can be tried but is often unsuccessful. Unsuccessful persistence can result in extensive desiccation of dura which will greatly impede and complicate closure. The most successful and efficient technique is to quickly grasp the bleeding site with a thin needle holder or small hemostat and then place 4–0 ligatures or retraction sutures to secure hemostasis. Weck® clips can also be effective but should be removed before closure to prevent artifacts on postoperative neuroimaging. Bleeding into the spinal subarachnoid space may pass unnoticed and result in significant accumulation of blood in the lumbar thecal sac.

Often exposure across the foramen magnum or into the cervical region is required and this is easily accomplished with a vertical durotomy from the above-described U-shaped durotomy. The result is a Y-shaped incision of the cervicomedullary region.

Retraction of Infratentorial Dura

Retraction of infratentorial dura expands exposure to take full advantage of the cranial opening and maintains the dural flap under tension to minimize contraction but does not usually assist significantly with epidural hemostasis which is usually minimal. Very tight lateral retraction of dura can bowstring the dura and separate it from bone, but unless severe this is rarely a significant problem. Lateral tenting of dura is not required.

Tight upward retraction of a dural flap across the transverse sinuses can restrict flow in the sinuses and may avulse bridging veins along the upper edge of the tentorium and therefore must be avoided.

Closing Dura of Posterior Fossa

Straight and mildly curved durotomies in the posterior fossa can usually be repaired with simple approximation using a continuous running technique. Contraction is uncommonly a significant problem with these incisions. Closure of U-shaped or V-shaped durotomies can be frustrating and time-consuming. The dural flap very often appears to be too small for primary closure, thereby leading the inexperienced neurosurgeon to choose to use a patch without first attempting primary closure.

Primary closure of a U-shaped or V-shaped durotomy is usually achievable. This requires (1) beginning the continuous non-locking suturing technique at one end, not in the mid-portion of the durotomy, (2) inserting sutures approximately 2 mm from the dural edges, and (3) using the cheating technique (see description of closure of supratentorial dura) to maximally expand the flap and bring the dural edges together. It is often helpful to have an assistant maintain tension on the suture with a needle holder. Minimizing the distance from edge of dura for placement of sutures is critically important. The initial laxness of the dural flap can seduce the surgeon into inserting sutures several mm from the dural edges, believing this will reduce the likelihood of tearing; however, this (1) prevents the durotomy on the opposite side from being pulled together, (2) increases the likelihood of sutures tearing through the edges of dura, and (3) strongly predisposes to a requirement for a dural patch. Placement of sutures farther from the dural edge usually ensures the need for a patch. Many neurosurgeons use non-absorbable sutures, for example Nurolon®, but the author consistently uses absorbable sutures. A narrow strip of Gelfoam covering the durotomy reduces the risk of CSF leakage; however, covering the entire flap adds no benefit and increases the bulk of foreign material. Closure of dura across the midline at the cervico-medullary junction can be problematic, particularly if the dural flap has contracted in that region as a consequence of steps taken to establish hemostasis there.

Patching Dura of Posterior Fossa

(See above discussion of *gaps in suture line* and *patching dura.*) A need for patching is almost always the result of dural contraction due to desiccation; only rarely has dura of the posterior fossa been resected. Although xenographs and DuraGen® are commonly used and relatively safe, posterior cervical fascia is a handy homograph and, in the author's opinion, results in excellent healing with minimal risk of complications [24]. Pericranium is not readily available unless the incision in scalp is extended several cm. The patching material should be stretched over the defect with temporary sutures to establish and roughly maintain its position and orientation during suturing. Many neurosurgeons use non-absorbable sutures, but the author again consistently uses absorbable sutures. A narrow strip of Gelfoam® covering the durotomy reduces the risk of CSF leakage; however, covering the entire flap adds no benefit and increases the bulk of foreign material. Replacement of a bone provides support and reduces effect of dural pulsation and likelihood of CSF leakage.

Complications following the patching of posterior fossa dura with materials other than a homograph include aseptic meningitis, pseudomeningocele, and CSF leakage requiring reoperation. These complications may be related to the material used as a dural graft or perhaps the use of dural sealant [25].

Defects in Dura Following Surgeries in the Cerebellopontine Angle

These surgeries are commonly associated with inability to securely approximate the edges of dura. A patch can be used to achieve closure but, the location, usual small size, and shape of gaps in dura make the suturing of a patch awkward. An onlay graft in this location can be displaced by outflow of CSF unless it is snugly supported by a rigid material such as bone or artificial material. A tissue sealant is beneficial in sealing the site. There is an elevated risk of CSF leak if intracranial pressure is elevated, regardless of technique and materials used for closure. Small gaps in dural closure of about 1 mm or less can be covered with Gelfoam® or a small onlay graft of posterior cervical fascia and will almost always heal unless there is elevated CSF pressure.

Closure of dura in operations for Chiari I or II deformities should be planned to include expansion of the dural envelope with a fusiform patch.

Surgery of Spinal Dura Mater

Plastic neurosurgical concerns

- Protection of spinal cord and nerves during spinal durotomy
- Prevent desiccation

- Secure closure of durotomy
- Minimize risk of postoperative CSF leak

Exposing Spinal Dura

The exposure of normal spinal dura requires the removal of overlying bone and the pushing aside or removal of epidural adipose tissue. Tiny arterioles and veins in the epidural space, mingled with adipose tissue, present little difficulties and can be easily cauterized. An attempt should be made to preserve as much of the epidural fat as possible.

Spinal Durotomy

The spinal cord is attached laterally to dura by the dentate ligaments and surrounded by CSF but not in contact with dura. However, in many pathologic settings the dura may be in contact with or adherent to spinal cord. Preoperative neuroimaging, particularly MRI, can provide useful information on this relationship. Intraoperative gentle digital palpation of exposed dura, when possible, or with a surgical instrument can usually reliably detect the fluctuance of a CSF-filled space between dura and spinal cord.

Spinal dura, unlike cranial dura, has a dominant longitudinal directional orientation of fibroblasts. Also, unlike cranial dura, the spinal dura is in under constant longitudinal tension which accommodates movement of the spine without kinking of the thecal sac. Almost all surgical incisions made in the dorsal or dorsal-lateral dura should be made in the longitudinal direction; however, other incisions may be necessary to provide the necessary exposure of pathology. Unless the surgical target involves dura or the sleeve of the nerve root, it is usually best to make a longitudinal midline or para-midline incision and retract the dura laterally as necessary for exposure.

The initial incision in dura is made with a #11 blade and is then extended. After the initial full-thickness penetration of spinal dura, the durotomy can be safely extended by stretching the dura longitudinally and tearing it using two instruments, for example nerve hooks. This technique consistently extends the opening in a straight longitudinal direction with little or no bleeding. Also, the durotomy can be with opened with microscissors or with a knife, usually a #11 blade held in firm contact with a Penfield dissector tucked beneath the dura by slowly advancing the pair. If dura is gently incised, the arachnoid often remains intact. Spinal durotomies must have their edges retracted and this is accomplished with sutures placed along the edges of dura.

Closing Spinal Dura

Longitudinal incisions in normal dura are relatively easy to repair because of the spontaneous near-exact alignment and approximation of edges after retraction sutures are removed. Unlike cranial dura, the electrocoagulation of spinal dura tends to undergo less contraction, particularly in the longitudinal direction. Transverse or oblique incisions of 30° or more can be quite difficult to repair because of retraction that occurs in the longitudinal direction and because these sutures placed in the dura tend to tear through the edges when pulled tightly, probably because of the structure of spinal dura. Even though no dura was resected, this often results in a gap that requires a patch.

The author recommends use of 4–0 absorbable sutures, for example Vicryl®, because this material will disappear within a few weeks and will not be a haven for bacterial residence; however, many neurosurgeons prefer 4–0 silk or nylon. Opinions vary regarding whether a continuous technique or a locking technique should be used [12]. The author prefers the continuous non-locking technique because it is minimally easier and faster to execute and results in slightly less implanted foreign material. Smaller suture, for example 5–0 Vicryl®, should be used in neonates and small infants.

A round non-cutting needle should always be used for closing spinal dura. Cutting or spatula tipped needles commonly produce a cut in the dura that tears when tension is applied. Non-cutting round needles function best but opinions vary. Large needles are cumbersome when penetrating dura and should be avoided.

Surgery for Specific Spinal Dural Abnormalities

Spinal Dural Defects

Defects of any size in spinal dura will result in leakage of CSF into the epidural space and often beyond. In settings in which spinal cord is in continuous contact with a durotomy site, the spinal cord can herniate through the opening if not securely repaired. A strong attempt should be made to achieve a secure closure of all openings in spinal dura. There are settings, however, when this cannot be safely accomplished, for example the ventral defect in dura after surgery for diastematomyelia.

Small areas of missing spinal dura, such as accidently made by a Kerrison rongeur, can often be managed by suturing the opposing edges together with 5–0 Prolene®. But in the axilla of a nerve root sheath, this may be technically impossible. A small piece of muscle or fascia can be placed across the defect and covered with tissue sealant. Postoperatively the patient's trunk should be kept horizontal for 2–3 days to allow healing to begin.

Large areas of missing spinal dura must be patched. Occasionally fascia can be used for patching, but surgeons more often use a synthetic material or xenograft. For durotomies in the mid-thoracis region and lower, the patient's trunk should be kept horizontal for 3–5 days after surgery, because an upright position greatly increases the intrathecal pressure; however, the intrathecal pressure is decreased by upward tilt of head and trunk (Trendelenburg position).

Persistent Leak of CSF Following Lumbar Puncture

Persistent CSF leakage following lumbar puncture causes abnormally low intracranial pressure and can cause positional headache. The leak can usually be sealed by injection of homologous blood into the epidural space at the site of leakage, commonly known as a *blood patch*. This is most often done by an anesthesiologist. Rarely surgical exposure is required with placement of a stitch across the hole in dura, but intraoperative identification of the site can be problematic. Post-lumbar puncture headache can be a debilitating complication that may persist for years unless successfully treated [26].

Iatrogenic Spinal Dural Disruption

Iatrogenic disruption of spinal dura can occur during laminectomy for any indication but occurs most commonly during decompression of the lumbar thecal sac or exposing a spinal nerve. The injury can be anywhere on the dorsal or dorsolateral surface of the dura and the disruption may be either a linear tear or a small avulsion. This often occurs in the dura of the axilla of a spinal nerve as a Kerrison rongeur is used to remove bone. If the defect is recognized immediately and the precise site identified, it can usually be repaired with a 5–0 suture, followed by an application of fibrin glue. Larger tears in dura must be repaired with 4–0 suture. The author prefers the use of Vicryl® but nylon is commonly used.

The dura of the axilla of a nerve root can be violated with a rongeur during removal of bone over a nerve root during surgery for herniated intervertebral disk.

Chiari Malformations

Dural incisions for Chiari decompression are usually Y-shaped, with the vertical component in the high cervical midline; however, if there are only a few mm of tonsillar herniation, incision in cervical dura may not be needed. The durotomy in the posterior fossa is V-shaped or U-shaped, with each arm being 3–4 cm in length. When cervical exposure is needed, as is usually the case in Chiari decompressions, the incision should be made in the midline near the lowest extent of tonsillar herniation, but not necessarily to the tip of the herniation. There is rarely a problem with opening the cervical dura but sometimes the tonsils or PICA can be adherent, and this must be anticipated to avoid their injury. Most adhesions to dura are easily disrupted.

Vigorous venous bleeding may be encountered from a circular sinus and from dura which often has very prominent veins just above the foramen magnum. Opening dura and securing hemostasis across the cervico-medullary junction and for several mm above can be slow and time-consuming, particularly in newborns and infants and most problematic in patients with myelodysplasia of any age. Awareness of the risk of significant venous bleeding at this site and preparation for its management is extremely important. There is also risk of injury to a posterior inferior cerebellar artery (PICA), whose precise location and possible adherence to dura can be difficult to identify during durotomy, especially in patients with Chiari deformities in whom the tonsillar loop of the PICA may be displaced down to C3 or C4 and rarely even to C5. The management of herniated tonsils is not within the scope of this text. Expansion duraplasty across the cervico-medullary junction with an elliptical or diamond shaped patch is almost always required. The author strongly prefers to use cervical fascia, but some pediatric neurosurgeons prefer synthetic materials. (Patching dural defects is addressed in *Surgery on dura*.) [24] Tissues harvested for patching, for example cervical fascia, pericranium, galea, fascia lata, should be kept continuously moist. Often there is a smoother side of the graft, and it should be selected for the inner surface. Three or four temporary sutures can roughly stretch and align the patch over the defect. The patch should be sutured snugly to surrounding intact dura. Homografts, particularly cervical fascia is soft, pliable, and easy to manage. Patches at the cranio-vertebral junction, for Chiari decompressions, should remain baggy.

Most neurosurgeons use non-absorbable suture material, usually 4–0 Nurolon®, silk or sometimes Prolene® for closing dura; however, this author prefers absorbable 4–0 Vicryl® for all dural closures. The rational for absorbable sutures is a dislike of material that can harbor bacteria. Secure healing will occur long before the absorbable sutures are absorbed.

Lipomyelomeningocele, Myelomeningocele, Split Cord Syndrome (Diastematomyelia)

The unique surgical management of dura in each of these disorders is discussed in chapter on *Special Plastic Neurosurgical Disorders of Children*.

Arteriovenous Malformation of Spinal Dura

Some arteriovenous malformations that involve spinal dura may be dealt with by a combination of electrocoagulation and resection of the involved area of dura. Unless the defect is quite small, it will be necessary to repair the defect with a patch. (Details regarding management of arteriovenous malformations of dura will not be addressed.)

If the dural defect, perhaps tiny, can be visualized under magnification, it can usually be managed with one or two 5–0 Prolene® sutures. Care must be taken to not snag an underlying nerve or ganglion. Larger openings and those whose exact site cannot be identified can be addressed with a partially sutured onlay graft followed with 3–5 days of postoperatively remaining supine.

Most surgeons require the patient to remain horizontal position for 2–4 days after unintended surgical violation of spinal dura. Lumbar CSF drainage may be used to keep the intrathecal pressure quite low for several days.

Surgery of Dura for Intrathecal Approaches

Tumor

The most common tumor of spinal dura in adults is meningioma and it occurs most often in females. The surgery requires resection of dura with tumor and, when possible, a few mm of dura beyond the tumor's edge. It is usually possible to resect the tumor but sometimes unsafe or technically impossible to resect the desired amount of tumor and dura, particularly if involving the anterior or anterolateral thecal sac. Post-resection dural defects require a patch. The detailed management, including resection of tumors of spinal dura, is not within the scope of this text.

Transection of Filum Terminale

The management of skin bone and dura will be addressed with less attention to the filum terminale. The goal of surgery is to untether the spinal cord by transecting the filum terminale. Preferably but not necessarily at site of identified adipose tissue. Most surgeons chose to remove a section of the filum for histologic confirmation of transection of filum.

Positioning

Almost all patients are infants. Patients are positioned in the prone position on laterally placed, longitudinally oriented, soft rolls in a manner that prevents or greatly reduces pressure on the abdomen. This is done to reduce venous pressure in the surgical site.

Skin Incision

A midline incision of approximately 2.5 cm length and centered at the superior margin of a spinous process is made through full-thickness skin.

Fascia

A mildly curved (concave medial) incision of approximately 2.5 cm length is made in fascia approximately one to 1.5 from midline on the side chosen by the surgeon.

Muscle

Paraspinous muscles are separated from two spinous processes and scraped aside to expose most of two hemilaminae and the intralaminar space.

Bone

The lower half of the more cranial hemivertebra and upper half of the more caudal hemilamina are removed with a small Kerrison rongeur, being careful to not disrupt either entire hemilamina. The spinous processes and interspinous ligament remain intact. Some surgeons chose to do a complete laminectomy with removal of one spinous process, but this author considers this unnecessarily destructive of normal anatomy.

Dura

A straight longitudinal durotomy of approximately 10–15 mm length is made in the mid-portion of the unilaterally exposed dura and dural edges are retracted with sutures.

Filum Terminale

Filum is identified and transfixed with a suture. The filum is the coagulated with low power electrocautery and microneedle. It is then cut with microscissors or microneedle cautery. Consistent with the scope of this text, further details on identification and management of the filum terminale will not be addressed in detail. Gentle traction is applied to the filum using the suture, and the filum is coagulated at a site approximately 7–10 mm caudal to the first transection and transected. The free piece of filum is removed for histologic examination.

Closure

Newborn and infant dura is repaired with 5–0 running absorbable suture. A thin strip of thin Gelfoam® is laid over the durotomy, and available epidural fat is pulled over the Gelfoam®. Fascia is repaired with 3–0 Vicryl®, dermis with 4–0 Vicryl®, and skin edges aligned with 4–0 subcuticular Nylon. Patients older than 12 months should have fascia repaired with 3–0 sutures.

Transection of Distal Thecal Sac [27]

Rarely correction severe kyphotic deformity requires transection and removal of the lumbodorsal thecal sac to make room for intraspinal bone grafts and fusion by an orthopedic surgeon. This is also necessary in extremely rare hemicorporectomy in adults. The former indication is almost exclusively in children with myelodysplasia who have no neurologic function below an identified level. The transection is relatively simple and straightforward, after the sac is exposed along multiple levels. The greatest concern is postoperative leakage of CSF through the dural closure. The intuitive technique is simple ligation followed by transection and removal of the distal thecal sac and its contents. This technique may be satisfactory, but it occasionally is followed by death within a few hours from an unexpected cause. Many patients with myelodysplasia have hydrocephalus and syringomyelia, and the syrinx may be functioning as a conduit—i.e., shunt—for diversion of CSF from ventricles to spinal thecal sac. Therefore, if a patient has either a nonfunctioning implanted shunt, or no implanted shunt, there may be no clinical manifestations. However, ligation of the lumbar thecal sac acutely obstructs the only path for egress of CSF. Also, if the ligature on the sac slips or becomes slightly loose, CSF will leak past the ligature, and this will require reoperation to seal the leak.

There is a technique that greatly reduces the risk of these complications. The exposed thecal sac is circumferentially cut, and the nonfunctional spinal cord is transected approximately one to 1.5 cm cephalad. The two sides of dura are sutured together with 3–0 Nurolon® or silk suture, then the blunt sac is folded upward and oversewn with running 3–0 silk or Nurolon®.

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Part II

Opening and Closing Neurosurgical Doors

Frontal, Frontotemporal, and Related Approaches

11

A. Samy Youssef and Ken Rose Winston

Supraorbital Approach (Eyebrow Approach) [1–4]

Plastic neurosurgical concerns

- Protect cornea.
- Cosmetic incision.
- Minimize damage to hair follicles of eyebrow.
- Protect orbicularis oculi muscle.
- Protect supraorbital nerve.
- Plan shape and size of craniotomy.
- Execution of craniotomy.
- Durotomy.
- Repair dura (restore dural envelope).
- Replace and secure bone flap.
- Camouflage burr hole (if present).
- Cosmetic repair of scalp.

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Positioning and Immobilization.

The trunk is in the supine position, with 15°–20° of reverse Trendelenburg to reduce intracranial venous pressure. The head is positioned in mild extension and rotated 15°–30°, depending on location of intracranial target, to the contralateral side and immobilized with a Mayfield head-holder. A corneal protector or temporary tarsorrhaphy provides protection of the cornea during preparation of skin and during surgery. Under no circumstance should the eyebrow be shaved.

Scalp

The details of the skin incision are important for this approach [5]. An eyelid incision may be the most cosmetically acceptable as it lies in a skin crease; this is usually performed by a oculoplastic surgeon. Incision in the forehead may be made either a few mm above the eyebrow (supraciliary) or within the eyebrow, but the former is more popular among neurosurgeons. Incision within the eyebrow should be placed just below its upper margin, follow the curvature of the eyebrow, and be beveled to minimize destruction of hair follicles [6]. It is important for each incision to not injure the orbicularis oculi muscle.

Electrocautery should not be used in making an incision within the eyebrow or coagulating along the raw edges of this incision, which would destroy hair follicles and produce a cosmetically undesirable strip of alopecia alongside the healed scar. The incision needs to be 3–4 cm in length, slightly curved to follow an RST (*r*elaxed *s*kin *t*ension) line and extend approximately 1 cm beyond the lateral end of the eyebrow and *not* extend medially beyond the supraorbital notch/foramen because of high risk of injury to the supraorbital nerve. Scalp is dissected superiorly for 1.5–2 cm over frontalis muscle 1.5–2 cm.

Muscle

The frontalis muscle is cut transversely above the orbicularis oculi muscle. Cutting laterally beyond the temporal line risks injury to the frontalis nerve. Approximately 12 mm of additional lateral exposure is obtained by separating the temporalis fascia and muscle from bone with a periosteal elevator. The upper edge of *orbicularis oculi muscle* is subperiosteally dissected downward by a few mm. Injury to this muscle must be minimized during incision, dissection, and coagulation of bleeding sites.

Pericranium

A curved incision is made in pericranium approximately 1.5 cm above the supraorbital rim. The integrity of periosteum should be preserved as best as possible because of its value during repair.

Bone

An oval burr hole of sufficient size to accommodate the footplate of a craniotome is placed far laterally just above the fronto-zygomatic suture and usually beneath the edge of the temporalis muscle and fascia. A craniotomy of approximately 1.5–2 cm height and 2.5 cm width is made with a craniotome and small-diameter bit. A small burr is used to remove the inner table of bone along the lower edge of the cranial opening, to make the plane of the cranial edge flush with the floor of the frontal fossa.

If the frontal sinus extends laterally beyond the supraorbital notch, an eyebrow approach will usually require entering the frontal sinus. Most neurosurgeons consider this to be a contraindication to the eyebrow approach; however, elective entry into the sinus can be managed with relatively low risk of complication. (See discussion in **Surgery of Cranial bone**.)

Supraorbital roof craniotomy through a similar incision has been described by Jho [7].

Dura

A C-shaped durotomy is made and the edges of dura are retracted with sutures.

Reconstruction and Repair

Dura is repaired in the standard manner, preferably using running 4–0 Vicryl® suture, and the durotomy is covered with a strip of thin Gelfoam®. The bone flap is secured with thin titanium plates. Some surgeons place a titanium burr hole cover over the hole underlying the site where the temporalis fascia and muscle have been pushed aside. Bone dust should be pressed into the kerf. The pericranium should be spread across the craniotomy site with an attempt to cover the circumferential kerf. The edges of orbicularis oculi muscle are *smoothed* into its approximately normal position. A small passive wick drain placed in the far lateral extent of the incision will minimize periorbital edema. After repair of the dermis with absorbable 3–0 sutures, the edges of skin must be accurately approximated with running 5–0 or 6–0 Vicryl® or with subcuticular Vicryl®. Antibiotic dressing is applied and, if a drain has been inserted, a flat bandage is required. Intravenous antibiotics are administered for 24 h after surgery. The drain is removed after approximately 12–24 h.

Unilateral Frontal Approach

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Protect nerve to frontalis muscle.
- Protect superficial temporal artery.

- Minimize injury to temporalis muscle.
- Plan shape and size of craniotomy.
- Execution of craniotomy.
- Surgical entry into frontal sinus.
- Durotomy.
- Repair of dura (restore dural envelope).
- Replace and secure bone flap.
- Camouflage burr hole at keyhole site.
- Restoration of temporalis muscle and fascia.
- Cosmetic repair of scalp.

Positioning and Immobilization

The trunk is placed in the supine position with 15°–20° of reverse Trendelenburg, to lower the venous pressure in the head and neck and reduce venous bleeding during surgery. The head is positioned with slight extension, rotated 15°–45° to the contralateral side, depending on the location of the intracranial target.

Non-rigid immobilization of the head is commonly satisfactory for surgeries in which a microscope will not be required. The head may be non-rigidly immobilized either on a horseshoe or a donut-type headrest with a firm pillow or sandbag on each side of the head. A well-padded horseshoe headrest usually provides sufficient immobilization and support of the head for adults and children. Regardless, the head may be mildly unstable and tend to roll to one side, particularly in infants, requiring the surgeon to reposition the head. Non-rigid immobilization is necessary for infants and young children in whom immobilization with pins is thought to be unsafe or impossible.

Patients with limited cervical mobility and those with significant thoracic kyphosis require one or more firm pillows beneath the neck and upper chest. The cervical spine of infants with prominent occipital bossing or macrocephaly requires one or more pillows beneath the neck and chest to prevent excessive cervical flexion when in the supine position on a table.

Rigid immobilization is necessary for surgical procedures in which a microscope will be used for most open resections of tumor via frontal approaches. This is achieved with 3-pin fixation, usually with the two paired pins on the ipsilateral parieto-occipital area and the single pin in a contralateral frontal location. If repositioning, for example rotation, is required during surgery, the rigid fixation is inconvenient. Repositioning requires that a non-scrubbed assistant loosen the locking screws beneath the sterile drapes while the surgeon holds and repositions the head, and the screws are re-tightened.

Scalp

Question mark (eroteme) incisions accommodate frontal craniotomies of variable sizes and shapes. The incision begins at the hairline of the forehead, either on the ipsilateral or contralateral side of midline (not in midline), curves posteriorly, and extends down to a point 1 cm above the insertion of the pinna, then anteriorly around the insertion of the pinna and down through non-hair-bearing scalp posterior to the sideburn toward the root of the zygomatic arch.

The popular bilateral pretrichial incision closely follows the hairline of the forehead and then curves posteriorly and then downward, similar to that described above but less far posteriorly. A pretrichial incision is undesirable in children and young men, because of future regression of the hairline. The resulting scar at the hairline can be undesirable in all adults; however, this is not commonly appreciated by neurosurgeons. An incision that lies approximately 1 cm posteriorly *within* hair-bearing scalp is usually cosmetically satisfactory.

Protect nerve to frontalis muscle (see **Surgery of Scalp and Face**).
Protect superficial temporal artery for possible future use (see **Surgery of Scalp and Face**).

A unilateral frontal approach via U-shaped incision with one or both arms coursing downward on the forehead was commonly used in the early years of neurological surgery. This incision produces a cosmetically unacceptable scar and has been abandoned.

Periosteum

The periosteum overlying the area of planned craniotomy should be cut and reflected as a separate layer. There is no sufficient rational for intentionally destroying periosteum over the frontal convexity.

Temporalis Muscle

Depending on the required exposure, it is often necessary to dissect a few cm of the upper anterior attachment of the temporalis fascia and muscle from frontal bone.

Bone

The shape and size of the bone flap are determined by the location and size of the surgical target and by surgeon's preference and marked with ink. When exposure is required along the falx, medial side of the frontal lobe, or medial floor of the frontal fossa, the craniotomy must extend to within 1 cm of ipsilateral midline or approximately 1.5 cm across midline. Making a paramedian osteotomy that is near or overlying, the superior sagittal sinus can usually be safely executed but has a small risk of injuring the sinus. If far medial exposure is not required, the medial side of the craniotomy can be positioned more laterally.

This cranial opening most commonly has straight parasagittal and supraorbital osteotomies and a curved posterior osteotomy completing the triangle. An oval burr hole of sufficient size to accommodate the footplate of a craniotome is placed somewhere behind the location of the hairline and either approximately 1 cm to the ipsilateral side of midline or 1.5 cm to the contralateral side. Many neurosurgeons place a burr hole on each side of the superior sagittal sinus and remove the intervening strip of bone with a Kerrison rongeur or craniotome. A decision must be made whether the supraorbital osteotomy will skirt above the frontal sinus. If the frontal sinus lies within the path required for intracranial exposure, the surgeon must cranialize the frontal sinus. An osteotomy which violates the frontal sinus can often be managed without cranialization but is controversial. (See description in *Surgery on scalp and face*.) A craniotome is used to make osteotomies along the marked lines. The supraorbital osteotomy commonly encounters a midline keel of bone which can be disrupted with a small osteotome, *not* a craniotome. The bone flap is then easily removed unless dura is densely adherent.

Dura

Durotomies for frontal approaches can be of various shapes, but a transverse durotomy is commonly satisfactory. The durotomy should not be aligned with the edge of the craniotomy because of difficulty in closure and the risk of dehiscence and postoperative leakage of CSF.

Reconstruction

Dura is repaired in the standard manner, preferably using 4–0 Vicryl® suture and the durotomy line is covered with a narrow strip of thin Gelfoam®. The bone flap is replaced and secured with thin titanium plates. The burr hole near the site where the temporalis fascia and muscle have been pushed aside or reflected, must be well camouflaged with a burr hold cover or swarf. The pericranium should be spread over the craniotomy site with an attempt to cover the kerfs. After repair of the dermis with absorbable 3–0 sutures, the edges of the scalp are approximated with running Vicryl Rapide®; however, some surgeons prefer non-absorbable sutures or staples. Antibiotic dressing is applied and a bandage, although commonly applied, is rarely necessary. Opinions on the use of a subdural drain vary. The author routinely inserts a suction-type (Jackson–Pratt) subgaleal drain to reduce the accumulation of serum and blood. This should be removed after 24 h. Intravenous antibiotics are administered for 24 h after surgery.

Bilateral Frontal Approach

The bilateral frontal approach is not commonly used today except for resection of giant bifrontal meningiomas, large intracranial sinunasal malignancy and head trauma. Bilateral frontal decompression is significantly different in its details and is described in **Convexity Approaches to Cranial Vault**.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Protect nerve to frontalis muscles.
- Protect superficial temporal arteries.
- Minimize injury to temporalis muscle.
- Plan shape and size of craniotomy.
- Execution of craniotomy.
- Management of frontal sinus.
- Durotomy.
- Repair of dura (restore dural envelope).
- Replace and secure bone flap.
- Camouflage burr holes at the keyhole sites.
- Restore temporalis muscle and fascia.
- Cosmetic repair of scalp.

Positioning and Immobilization

The trunk is placed in the supine position, with 15°–20° of reverse Trendelenburg to lower the venous pressure in the head and neck and reduce venous bleeding during surgery. The head is positioned in neutral midline position with slight neck extension.

Pin-fixation is necessary for surgeries in which the microscope will be used. A well-padded horseshoe type headrest provides satisfactory immobilization of the head for removal of hematomas or repair of depressed fractures.

Scalp

A coronal incision is required, and the most favorable cosmetic result is achieved by a zigzag incision. A straight coronal (bucket handle) incision tends to result in a cosmetically undesirable scar in hair-bearing scalp. The ends of the coronal incision should course in non-hair-bearing skin just inside of the tragi and down to the zygomatic arches or slightly above. The bifrontal scalp flap is reflected forward and over the face as areolar tissue is split in the subgaleal space.

Protect nerve to frontalis muscle (see *Surgery of scalp and face*).
Protect superficial temporal artery (see *Surgery of scalp and face*).

Periosteum

Periosteum may be reflected with the scalp or as a separate layer; however, the author prefers the former. There is no satisfactory rational for destroying the periosteum. A vascularized split pericranial flap can be dissected for later reconstruction of cranialized frontal sinuses and/or anterior skull base.

Lateral frontal exposure is needed temporalis fascia and the superior anterior portion of temporalis fascia and muscles may be separated from bone for 2–4 cm with a periosteal elevator. The keyholes for the bifrontal craniotomy are subsequently placed at the exposed Dandy keyhole site.

Bone

A bifrontal cranial flap is outlined with ink. A burr hole is positioned approximately 1.5 cm from midline and behind the known location of the hairline. Many surgeons place a second burr hole on the side opposite side of the first burr hole, and some surgeons place several burr holes around the proposed craniotomy. The burr hole near the superior sagittal sinus should be behind the known position of the hairline and usually anterior to the coronal sutures. Many neurosurgeons are more comfortable with placing a second burr hole on the opposite side of the superior sagittal sinus and removing the bone across the sinus with a Kerrison rongeur; however, there is a relatively safe technique for extending the cranial osteotomy over the superior sagittal sinus with a craniotome.

The posterior extent of the craniotomy can be anywhere anterior to the coronal sutures. The supraorbital osteotomy should cross the supraorbital region approximately 2 cm above the supraorbital rim. The desired cranial opening is marked with ink and an osteotomy is made along the inked line. If very low exposure is desired, it will often be necessary for the transverse osteotomy to cross the frontal sinuses. The surgeon must decide whether to cranialize the frontal sinuses or preserve them. For elective surgeries that are not done for decompression, preservation of the frontal sinuses should be considered.

A sagittal keel of bone that prevents the craniotome from crossing the supraorbital midline is often present and persistence in trying cut across the midline can result in laceration of the dura and venous sinus. This keel can be safely disrupted with a small osteotome without penetration of dura or, if small, by fracturing it as the bone flap is pried outward.

Dura

Durotomies can be made in any of many patterns and lengths, but the transverse incision *should not* align to the transverse edge of the frontal osteotomy. Care must be taken to avoid disruption of bridging veins entering the superior sagittal sinus.

Transfrontal durotomy (possibly including falx)—A broad durotomy that crosses the midline and hence the superior sagittal sinus and falx may be required for resection of some large subfrontal tumors and for cranial decompression. Although the superior sagittal sinus can *usually* be transected anywhere in its anterior third without causing venous infarction, cerebral venous hypertension can occur in the form of bifrontal edema or infarctions.

The surgeon may choose to cut the falx after ligation and division of the anterior superior sagittal sinus just above the crista galli, to allow elevation of both frontal lobes of the brain and thereby improve access to a surgical target. This action is less difficult than often perceived by the inexperienced or timid surgeon. Two sutures of 2–0 Vicryl® or silk are separately passed around the lowest extent of the exposed superior sagittal sinus, via a needle through the falx, and tied tightly. If the two ligatures are separated by approximately 5 mm, the sinus and falx can be cut with Metzenbaum scissors. If venous bleeding occurs from the inner edge of the falx, it is likely from a small inferior sagittal sinus and can be controlled with electrocoagulation.

Reconstruction

Durotomies are repaired in the standard manner, preferably using 4–0 Vicryl® and simple running technique, and covered with narrow thin strips of Gelfoam®. The bone flap is replaced and secured with thin titanium plates. The temporalis muscle on each side must be restored. The pericranium should be spread over the craniotomy site with an attempt to cover the kerfs. After repair of the dermis with absorbable 3–0 or 2–0 sutures, the edges of scalp are approximated with running Vicryl Rapide®; however, some surgeons prefer to use non-absorbable sutures or staples. Antibiotic dressing is applied and a bandage, although commonly applied, is not necessary.

Transfrontal Subcranial Approach

The transfrontal subcranial approach provides access along the orbital and spheno-ethmoidal planes, into the nasal, paranasal, frontoethmoidal, sphenoidal spaces, and along the clival plane. It is rarely if ever used in sub-teenage children [8]. Neurosurgeons use this approach for resection of meningiomas that have infiltrated through the dura and bone of the floor of the frontal fossa and for sinonasal malignant tumors that have invaded upward through bone and dura into the frontal fossa. This approach can also be used for lesions of the base of skull, including upper clivus, and for managing frontobasal fractures. When compared to the various transfacial approaches, the transfrontal subcranial approach requires no facial incisions, minimal retraction of the frontal lobes, and is associated with reduced complications, shorter time in intensive care, and better cosmetic outcome [8, 9]. However, the expanded endoscopic endonasal approaches have replaced the transfacial approaches to a great extent. The transfrontal subcranial approach can be combined with the endoscopic endonasal approaches for craniofacial resection of extensive sinonasal tumors.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Protection of nerve to frontalis muscle.

- Protect superficial temporalis artery.
- Protect supraorbital nerve.
- Plan shape and size of craniotomy.
- Execution of craniotomy.
- Management of frontal sinus.
- Osteotomies for removal of supraorbital rims.
- Durotomy.
- Reflection of pericranial flap.
- Repair of bony floor of frontal fossa.
- Repair of dura.
- Replacement and alignment of supraorbital rims.
- Medial and lateral canthopexies.
- Replace and secure bone flap.
- Restoration of temporalis muscles and fascia (if disrupted).
- Cosmetic repair of skin.

Positioning and Immobilization

The trunk is placed in the supine position with reverse Trendelenburg of 15°–20° to lower the venous pressure in the head and face and thereby reduce venous bleeding during surgery. The neck is extended approximately 30°. Rigid immobilization of the head with Mayfield head-holder is essential.

Eyes

Bilateral temporary tarsorrhaphy or corneal protectors are necessary.

Scalp and Pericranium

A sinusoidal or zigzag coronal incision provides the needed cranial exposure. The incision must extend approximately 5 mm below the zygomatic arch on each side and perhaps lower in adults with thick scalps. A vascularized pericranial flap is harvested by sharply splitting the loose areolar layer using a #10-blade. The bifrontal scalp flap with pericranium is reflected forward and over the face. The supraorbital nerves must be freed from their supraorbital notches or foramina and protected. Subperiosteal dissection is continued across the supraorbital rims and then laterally and downward toward or across the frontozygomatic sutures. Medial subperiosteal dissection must extend across the frontonasal sutures and downward to expose the full length of the nasal bones. A blunt nerve hook is useful in freeing soft tissue around the tips of the nasal bones.

Bone (Craniotomy)

A bifrontal cranial flap is outlined with ink. Its straight transverse lower edge should be marked approximately 1.5–2 cm above the lower edge of the supraorbital rims, regardless of the location or size of the frontal sinuses and should extend approximately two to 2.5 cm lateral to each supraorbital notch. The curved upper border of this bifrontal bone flap is marked about 1 cm behind the known location of the hairline.

If the surgeon has concern regarding precise repositioning of the bone flap at time of reconstruction, a dog-bone or square titanium plate can be placed across the marked supraorbital line about 2 cm to each side of midline, and each is tightly secured with four screws. Three of the screws of each plate are then removed, leaving each plate loosely attached to the planned frontal bone flap with a single screw. This will facilitate precise realignment at time of construction. The authors believe this subroutine is usually unnecessary for satisfactory cosmetic results but not all surgeons agree.

A burr hole is made adjacent to the superior sagittal sinus at the upper edge of the marked bone flap. Surgeons who are uncomfortable with cutting across the midline with a craniotome commonly make a second burr hole on the contralateral side of the sinus. A craniotome is used to make osteotomies along the marked lines, often passing through both walls of the frontal sinuses. A small osteotome may be required to complete the transverse supraorbital osteotomy across posterior walls of the sinuses and to disrupt a midline supraorbital keel of bone. The bifrontal bone flap is removed, usually without difficulty.

Orbital Dissection (Superior and Lateral)

The periorbitum is dissected from both orbital roofs and laterally and down by a few mm below the frontozygomatic sutures. The separation of periorbitum must extend down the medial wall of the orbits beyond the level of the frontonasal sutures. These dissections will include bilateral disconnection of both medial and lateral canthal tendons. Attempt should be made to identify these tendons before disruption and tag each with a suture to assist their identification at time of repair. If periorbitum is disrupted, it should be repaired immediately with 4–0 chromic sutures.

Bone (Additional Osteotomies)

1. While protecting the dura and the periorbitum with flat brain retractors, an oscillating saw is used to cut vertically across each supraorbital rim 10–15 mm lateral to each supraorbital notch but should end a few mm short of the lateral extent of the frontal craniotomy. This bony offset on each side is beneficial in aligning and securing the bone flap during restoration.

2. An osteotome or oscillating saw is used to cut across each floor of the frontal fossa (roof of the orbit) and down the medial wall of each orbit, passing behind the lacrimal crest and continuing down to the nasal aperture.
3. An osteotome of approximately 1 cm width is positioned in the anterior floor of the frontal fossa, just anterior to crista galli, and driven through the floor of the frontal fossa to sever the septum, as determined by tactile input.

Using one hand to grasp each supraorbital rim, the supraorbital rims are rotated forward to identify any remaining bony attachments, and, if present, these are disrupted with an osteotome. The supraorbital rims and nasal bones can then be removed as a single bony fragment. In many patients who undergo this approach, much of the medial floor of the frontal fossa and ethmoid sinuses has been destroyed by invading tumor.

Transfrontal subcranial approaches for lesions in the skull base that do not have subfrontal dural involvement, for example lesions in the clivus, can sometimes be accomplished with preservation of the frontal sinus [10]. This should be considered in patients with small frontal sinuses, such as those present in teenagers and some adults. A wider transbasal exposure with *en bloc* osteotomy of the orbital roofs and frontal sinus has been described [11].

Dura

The dura is separated from the floor of the frontal fossa, to which there is usually no significant attachment except in the midline and over the crista galli. The crista galli can be cleared of dural attachments to its midpoint with freer and Penfield elevators.

Often tumor has invaded through dura, and if so, it will be firmly attached to dura across the floor of the frontal fossa, making bilateral transverse durotomy necessary. Transection of the falx is often necessary to allow satisfactory exposure of the lesion. Details on the resection of tumor, including the neoplastic involvement of dura and brain, will not be addressed.

Approaches to far posterior lesions of the base of the skull do not require a frontal durotomy.

Reconstruction

The anatomical restoration after this surgical approach is complex and requires attention to details. A reliable barrier must be established between the cranial cavity and both the nasal cavity and air sinuses.

A large flap of vascularized pericranium is dissected from the bifrontal scalp flap, if not already reflected as a separate flap, folded epidurally across the bony defect, and tucked snugly. It is usually not possible to secure its edges with sutures and in such case, tissue glue can be used instead of sutures. Some surgeons prefer to use a flap composed of pericranium and galea for this part of the repair. Split calvarial bone graft can be used to reconstruct a large bony defect. The graft is harvested from the undersurface of the free bifrontal bone flap using an oscillating saw and modified as necessary to allow it to be wedged into place on top of the pericranial flap, thereby re-establishing a solid floor across the frontal fossa. This bone graft must fit snugly and not be left mobile. If postoperative radiotherapy is anticipated, a vascularized pericranial graft is preferred due to the risk of necrosis of the bone graft.

A free piece of pericranium or Suturable DuraGen® is tucked into the subdural space across the defect in dura and sutured in place as best possible; however, it is rarely if ever possible to place sutures along the posterior edge of the dural defect. The transfrontal durotomy is repaired with absorbable suture, such as 4–0 Vicryl®.

The frontal sinuses must be cranialized (see *Cranialization of frontal sinuses* in **Surgery of Cranial Bone**) in patients in whom this surgical approach is used for tumors which have invaded the frontal and ethmoid sinuses. Often the frontal sinus may be preserved in patients with tiny frontal sinuses and those having no tumor invasion. The supraorbital rim with frontal bandeau is seated in its normal position and secured laterally to the intact cranium using thin titanium plates. The frontal bone flap is returned to its normal position and secured with thin plates. If alignment plates were placed before the transverse supraorbital osteotomy was made, these plates are used to ensure accurate alignment. Although this technique prevents tight bone-to-bone abutment, it ensures the persistence of a transfrontal kerf, which increases the chance for survival of the vascular supply to the pericranial flap.

Medial Canthopexy (Latin: Corner of Eye + Greek: Fix in Place)

The medial canthal tendon (medial palpebral ligament) has three components. Their function is maintenance of the medial upper and lower eyelids and to facilitate drainage of the lacrimal sac. Medial canthopexy (fixation of the medial canthus) is *very important*. Failure to do this well will result in telecanthus, which is a significant cosmetic concern.

Identification of untagged tendon—This is done by grasping tissue in the approximate correct location (trial and error) and applying traction while observing the media canthus. Discrete medial displacement of the canthus indicates that the tendon has been grasped.

Reattaching tendon to medial wall of orbit—A 2–0 nylon suture is passed through the tendon, and traction on the suture, while observing the medial canthus, can confirm correct placement of the suture in the tendon. Some surgeons prefer to use a #30 wire suture instead of nylon suture, believing this allows better control while tying the suture. Absorbable sutures should never be used.

In most craniofacial surgeries, the medial canthal tendon on the contralateral side has also been disrupted. The suture is then passed through the medial orbital wall at the posterior superior portion of the lacrimal groove and then through the contralateral wall into the contralateral orbit. There is a tendency for a less experienced surgeon to attach the tendon too far anteriorly. The passage through bone can often be done in young children with a needle, but a small trephine will be necessary in older patients. The suture is passed through the contralateral tendon and then either tied or, more often, passed back through the nasal bones to the first side for tying. Excessive tightness can fracture the contralateral wall medially. This allows the surgeon to apply approximately equal tension to each tendon and to adjust the desired intercanthal distance. If latter revision is required, this should be done by a plastic surgeon.

If the tendon on the second side is intact, the suture can be tied across a small fragment of bone on the contralateral side or to an ipsilateral screw inserted for this purpose. Attention must be given to hiding the knot and bone fragment or screw, preferably by pressing it tightly against the side of the nasal bone. If the transnasal wire or suture is pulled excessively tight, the thin contralateral orbital wall can be fractured medially.

Lateral Canthopexy [12, 13]

A disconnected lateral canthal tendon should always be reconstructed. The major difficulty in reattaching the lateral canthal tendon is its identification.

Identification of untagged lateral canthal tendon—This is done by grasping tissue with toothed forceps in the approximate correct location of the tendon (trial and error) and applying traction while observing the lateral canthus. Lateral displacement of the canthus indicates that the tendon has been grasped.

Reattaching tendon to lateral wall of the orbit—A 3–0 nylon suture is passed through the tendon and traction is applied while observing the lateral canthus to confirm placement of the suture in the tendon. This suture is then attached to pericranium, if present, or through a small drill hole in the lateral rim of the orbit. Ideally, the attachment should be approximately 2 mm inside the orbit with slight overcorrection to allow for postoperative relaxation. Malposition results in dystopia with downward and rounded slanting of the palpebral suture. If there is a need to correct a downward slope of the palpebral fissure, this can be accomplished by attaching the tendon more superiorly. If latter revision is required, this should be done by a plastic surgeon.

Restoration

The scalp is repaired with a galeal layer of absorbable 3–0 sutures and the edges of scalp approximated with 4–0 Vicryl Rapide® sutures; however, some surgeons prefer to use nylon sutures or staples. A Jackson–Pratt type subgaleal drain is commonly placed beneath the scalp but may prove to be useless because of suction of air. If so, it should be removed immediately to prevent ongoing contamination of the surgical wound. The wound is covered with Bacitracin ointment as dressing, and a bandage is not required. Intravenous antibiotics are administered for 24 h after surgery. The drain should be removed after 24 h. These surgeries are classified as *clean contaminated* because of the intraoperative communication with the nasal pharynx.

Caveat

Nasal suction or introduction of a nasogastric tube is dangerous because of the risk of penetrating the floor of the frontal fossa and puncturing brain parenchyma. If a gastric tube is required, the oral route is preferred; however, if the nasal route is chosen, its insertion should be done by the anesthesiologist before the patient leaves the surgical suite. Under no circumstance, should a nasogastric tube be re-introduced after surgery by a nurse or physician who is not familiar with the anatomy and associated risk of penetrating brain.

Frontotemporal Approaches

Anterolateral surgical approaches designated as frontotemporal, pterional, fronto-zygomatic, orbitozygomatic, and their variations require similar positioning, cranial immobilization, scalp incision, attention to hemostasis, and wound closure. Terminology for these technically related surgical approaches can be confusing because of shared components, yet each is different and is used to approach different surgical targets. A pterional approach is centered about the pterion and may have a cranial opening of any size; however, if its maximum diameter is approximately 20 mm or less, it is commonly designated as a keyhole, pterional, or micro-pterional approach. All of these cranial openings require a Dandy and/or McCarty burr hole.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Protect nerve to frontalis muscle.
- Protect superficial temporal artery.
- Minimize injury to temporalis muscle.
- Plan shape and size of craniotomy.
- Protect supraorbital nerve.
- Damage to temporalis muscle.
- Management of frontal sinus.
- Execution of craniotomy.
- Management of middle meningeal artery.
- Durotomy.
- Repair of dura (restore dural envelope).
- Replace and secure bone flap.
- Restoration of temporalis muscle and fascia.
- Cosmetic repair of scalp.

Positioning and Immobilization

The trunk is positioned in the supine position, with 15°–20° of reverse Trendelenburg and a pillow beneath the knees. The head is rigidly immobilized with a Mayfield 3-pin head-holding devise with approximately 20°–30° of cervical rotation.

Non-rigid immobilization is used for infants, young children, and some surgeries for trauma in adults in which a microscope and navigation will not be used. Immobilization can be accomplished with a horseshoe headrest or with sandbags and pillows on a flat table. The chief problem with non-rigid fixation is the tendency for the head to roll or shift from the initial position.

Scalp

The preferred incision in scalp begins behind the hairline of the ipsilateral forehead at approximately the mid-pupillary line, passes posteriorly for approximately 4 cm, and then arcs downward to the hairline above the insertion of the pinna. It then arcs acutely anteriorly around to the front of the pinna and straight down immediately anterior to the tragus through non-hair-bearing scalp toward the root of the zygomatic arch [14, 15]. At 5 mm above the zygomatic arch, the incision should deviate anteriorly at a 30° angle to minimize risk of injury to the superficial temporal artery. However, if the zygoma is to be cut, the skin incision should extend straight across the bone and for 5–10 mm below. The preauricular portion of the incision should never be made within the sideburn.

The most popular incision in use for frontotemporal approaches follows a pretrichial course across the forehead before arcing posteriorly, as described above. A pretrichial incision is not recommended in children and young men, because of concern for future regression of the hairline, making the scar more obvious in later years.

The frontotemporal scalp flap, including pericranium, is reflected to expose the lateral forehead and most of the temporalis muscle down to the zygomatic arch. The frontal branch of the nerve to frontalis muscle and the superficial temporal artery are vulnerable and must be protected. Pitanguy's line, which begins 0.5 cm below the tragus and extends 1.5 cm above the lateral end of the homolateral eyebrow, can be helpful in identifying the course of the nerve to frontalis muscle.

Temporalis Muscle [16, 17]

Undesirable cosmetic and functional outcomes may follow incision and disconnection of the origin of temporalis muscle from bone. These complications can be severe but are usually avoidable. Survival and function of the muscle require not only the protection of the muscle mass, but preservation of its innervation and vascular supply [16]. Blood supply to the medial side of the muscle is from the deep temporal arteries and to the lateral side from the middle temporal artery, which is a branch of the superficial temporal artery [16].

Disconnection along superior and inferior temporal lines—Separation of fascia and muscle from bone is most commonly accomplished by making an incision with scalpel approximately 10–12 mm below the superior temporal line. This will leave a myofascial cuff which will greatly assist closure. Less damage to muscle will occur if the separation is complete, leaving no cuff, but closure will require drilling holes in bone.

Myotomy Along Fibers of Muscular Fan

A full-thickness vertical myotomy that starts at the posterior extent of the zygomatic arch and courses obliquely upward, in a line parallel to the muscle fibers, to the posterior end of the first incision—i.e., usually the inferior temporal line. This incision can cause some denervation [18]. All incisions through muscle should be made with a scalpel, not cautery, to minimize damage to muscle. Transverse incision across the temporalis muscle a few cm below its insertion makes closure easier but should be avoided because the entire muscle above the incision will atrophy as a consequence of its denervation and devascularization, and some of the muscle below the transverse myotomy will also atrophy from its being structurally damaged.

Dissection of Muscle from Bone

Separation of muscle from underlying bone is relatively easily accomplished with a periosteal elevator or Penfield No. 1 dissector. This is usually done by dissection from the upper edge of muscle down toward the zygoma, but retrograde dissection of the temporalis muscle is reported to cause less damage to the muscle and therefore less postoperative atrophy [19]. Separation of muscle from bone with electrocautery produces significant injury because of damage to the medial arterial supply and also nerves on the medial surface of the muscle.

If muscle is to be separated from the lateral orbital rim, this can be done with electrocautery and a microneedle. The lowest power setting which efficiently accomplishes the task should be used. High power settings with a flat cautery tip allow more rapid dissection with almost no bleeding but causes unnecessary and unacceptable damage to muscle.

Retraction

Lengthy periods of tight compression or retraction tightly over the zygoma during surgery will damage the muscle and cause postoperative atrophy. The retracted muscle must be kept moist throughout the time of retraction and this is best done by keeping the muscle covered by wet Telfa™ or Bicol® covered with Cottonoids® or gauze sponges. These must be frequently irrigated with saline.

Periosteum

At the start of reflection of the scalp, a decision must be made regarding the periosteum. If the cranial opening will involve only the lower forehead, the periosteum above the upper frontal osteotomy should remain intact. For large frontal craniotomies, all exposed periosteum should be reflected, with the scalp and preserved. Some surgical procedures require a dural patch and periosteum is an excellent material for this. There is no satisfactory rational for intentionally destroying the periosteum.

Osteotomies for Frontotemporal (Pterional) and Related Approaches [20–23]

A frontotemporal approach requires a large pterional craniotomy that includes, as the name implies, portions of frontal and temporal bones. The proposed cranial opening should be marked with ink, with its size and shape are determined by the surgical target and surgeon's preference. A burr hole near pterion is made with a five or seven craniotome bit. Starting at the keyhole, an osteotomy is made along the marked outline of the craniotomy until the footplate of the craniotome encounters the sphenoid wing. If the bone flap remains attached at the sphenoid wing, attempt not be made to disrupt this connection with the craniotome because of the risk of violating dura. If the lesser wing of the residual sphenoid wing is small, it can often be cracked by prying the opposite side of the bone flap with a periosteal elevator or other instrument into the kerf. If the sphenoid wing cannot be easily cracked, a small burr should be used to make a groove across the bone to facilitate its being cracked by prying; however, it may be necessary to further weaken or disrupt the sphenoid wing with a narrow osteotome.

The cranial opening can be enlarged, or its edges modified with a burr and rongeurs along the floors of the frontal and middle fossae. Some exposures, for example aneurysmal surgery, often require the removal of much of the lesser wing of the sphenoid bone. This is accomplished under magnification with a diamond burr, but the details are beyond the scope of this book [24].

Hemostasis

The anterior branch of the middle meningeal artery, whether partially or totally surrounded by bone, may be disrupted while drilling the burr hole or making an osteotomy near the sphenoid wing. The middle meningeal artery is often surrounded, partially or totally, by bone along the greater wing of the sphenoid bone, and it may be torn or transected by the burr or osteotome, occasionally with laceration of the dura. Control of bleeding from the middle meningeal artery can be tedious and frustrating. Bleeding can usually be halted or greatly reduced by the application of bone wax. If the arterial bleeding from the burr hole or kerf is vigorous and cannot be halted or greatly reduced with bone wax and cotton patties without unacceptable loss of blood, it will be necessary to quickly complete the circumferential osteotomy while an assistant sequentially presses bone wax into the kerf as the craniotome is advanced along the marked line. After the bone flap is removed, the site of bleeding can be visualized and managed by a combination of tamponade, electrocoagulation, or a ligature. In some cases, additional bone must be removed with a rongeur to expose the source of bleeding. It may be necessary to temporarily pack the hole with wax and/or cotton patty and then make a new burr hole slightly inferior and posterior to the original burr hole.

Osteotomies for Orbitozygomatic Approaches [25]

An orbitozygomatic craniotomy is a frontotemporal craniotomy plus orbital and zygomatic osteotomies.

Scalp Incision [14, 15, 26]

The incision in scalp begins near the hairline of the contralateral forehead at approximately the mid-pupillary line, curves posteriorly across midline and then downward to a point above the insertion of the pinna. It then arcs anteriorly around the pinna and down approximately 5 mm anterior to the tragus through non-hair-bearing scalp toward the posterior extent of the zygomatic arch.

At a point 5 mm above the zygomatic arch, the lowest extent of the incision should deviate anteriorly at a 30° angle to minimize risk of injury to the superficial temporal artery. However, if the zygoma will be cut, the skin incision should extend approximately 5–8 mm below the zygomatic arch. The preauricular portion of the incision should never be made within the sideburn. A pretrichial incision across the forehead is not recommended particularly in children and young men, because of concern for future regression of the hairline.

A frontotemporal flap, including pericranium, is reflected anteriorly and over the lateral orbit and temporal fascia via subgaleal dissection with an index finger or periosteal elevator, but it is often necessary to assist the dissection by cutting some of the areolar tissue. This will expose a large portion of the temporalis muscle [26]. The frontalis branch of the temporal division of the facial nerve and the superficial temporal artery are vulnerable and must be protected. Pitanguy's line, which begins 0.5 cm below the tragus and extends 1.5 cm above the lateral end of the ipsilateral eyebrow, can be helpful in identifying the course of the nerve to frontalis muscle. Some surgeons make a transverse incision across the upper extent of the temporalis fascia and reflect this fascia and its underlying nerve to frontalis muscle with the scalp—i.e., subfascial dissection. Interfascial dissection should be performed in order to expose the zygoma and perform zygomatic osteotomies.

One-Piece Orbitopterional Craniotomy [27–29]

A MacCarty burr hole is placed at the frontosphenoid suture, to expose the periorbitum and dura of the anterior fossa and enlarged with Kerrison rongeurs to approximately 20 mm diameter. A second burr hole is placed in the temporal squamous bone just above the zygomatic process of the temporal bone. Osteotomies are performed as follows:

Osteotomy #1 begins at the temporal keyhole and arcs upward and toward the supraorbital notch until the orbital roof is encountered. If far medial exposure is required, the supraorbital nerve must be freed from the supraorbital notch or from its foramen with a small osteotome. An osteotomy lateral to the notch is less likely to enter the frontal sinus but will limit medial exposure. A craniotome produces an unnecessarily wide kerf which will affect cosmetic closure.

Osteotomy #2 begins at the *temporal keyhole* and extends anteriorly across the temporal bone across the sphenoid ridge to the frontal portion of the MacCarty bur hole. Bleeding from the middle meningeal artery can be temporarily controlled with bone wax.

Osteotomy #3 begins at the orbital MacCarty keyhole and extends anteriorly across the zygomatic process of the frontal bone just proximal to the frontozygomatic suture.

Osteotomy #4 extends from osteotomy #1 into the orbital cavity and usually lateral to the supraorbital notch. If a need for more medial exposure is anticipated, the supraorbital nerve must be freed from the supraorbital notch or foramen with a small osteotome. An osteotomy lateral to the notch is less likely to enter the frontal sinus but will limit medial frontal exposure. A craniotome produces an unnecessarily wide kerf which will affect cosmetic closure.

Osteotomy # 5 extends, using a narrow osteotome, along the orbital roof about 2 cm behind the orbital rim, from the intraorbital part of osteotomy #4 to the MacCarty keyhole.

The final drilling is made over the line of the second cut with the B1 or B5 drill bit over the sphenoid ridge, which is thinned to elevate the bone flap. This cut should continue the projected line between both keyholes.

The free bone flap can then be removed; however, this may require disruption with an osteotome of a few remaining bony connections. The sphenoid wing is drilled away until the superior orbital fissure osteotomy is reached.

One-Piece Orbitozygomatic Craniotomy [28]

Interfascial dissection of the temporalis muscle fascia is performed in order to fully expose the zygoma down to the body and arch. A MacCarty burr hole is placed at the on suture, to expose the periorbitum and dura of the anterior fossa and enlarged with Kerrison rongeurs to approximately 20 mm diameter. A second burr hole is placed in the temporal squamous bone just above the zygomatic process of the temporal bone. For a full variant, osteotomies are performed as follows:

Osteotomy #1 begins at the temporal keyhole and arcs upward and toward the supraorbital notch until the orbital roof is encountered. If far medial exposure is required, the supraorbital nerve must be freed from the supraorbital notch or from its foramen with a small osteotome. An osteotomy lateral to the notch is less likely to enter the frontal sinus but will limit medial exposure. The second part begins at the *temporal keyhole* and extends anteriorly across the temporal bone across the sphenoid ridge to the frontal portion of the MacCarty bur hole. Bleeding from the middle meningeal artery can be temporarily controlled with bone wax.

Osteotomy #2 using the foot plate attachment to the craniotome, it begins at the orbital MacCarty keyhole and extends down to the inferior orbital fissure.

Osteotomy #3 the masseter muscle is detached from the zygomatic arch to be reattached at the end. Using the foot plate attachment to the craniotome, a tangential zygomatic osteotomy is performed at the root just in front of the temporomandibular joint. The tangential osteotomy allows the arch to sit back on a larger fusing surface.

Osteotomy #4 the myocutaneous flap is retracted antero-inferiorly to expose the body of the zygoma down to the zygomatico-facial foramen. Using the pediatric router craniotome, a V-shaped osteotomy is made across the body of zygoma.

Osteotomy #5 extends from osteotomy #1 into the orbital cavity and usually lateral to the supraorbital notch. If a need for more medial exposure is anticipated, the supraorbital nerve must be freed from the supraorbital notch or foramen with a small osteotome. An osteotomy lateral to the notch is less likely to enter the frontal sinus but will limit medial frontal exposure. A craniotome produces an unnecessarily wide kerf which will affect cosmetic closure.

Osteotomy #6 extends, using a narrow osteotome, along the orbital roof about 2 cm behind the orbital rim, from the intraorbital part of osteotomy # 5 to the MacCarty keyhole.

The free bone flap can then be removed; however, this may require disruption with an osteotome of a few remaining bony connections. The sphenoid wing is drilled away until the superior orbital fissure osteotomy is reached.

The single-piece bone flap can then be removed; however, this may require the use of an osteotome to disrupt a few remaining bony connections. The removal of orbital roof can be initiated by using a narrow osteotome to cut through the thick lateral sphenoid bone, allowing the thin roof to be removed with osteotomes and rongeurs.

Zabramski et al. described a technique for using a reciprocating saw to free an orbitozygomatic bone flap in one piece [29].

Durotomies for Frontotemporal and Related Approaches

Each durotomy must be tailored to the surgical. Size and contour of the dural flap are dictated by the surgical target and surgeon's preference. A U-shaped durotomy is most commonly use.

Restoration for Frontotemporal and Related Approaches

Dura

Dura is repaired in the standard manner with running 4–0 sutures. The author prefers absorbable suture, for example Vicryl®, but silk or Nurolon is commonly used. It is always preferable in older children and adults (*essential* in infants and young children) to achieve the approximation of dural edges along the full length of the durotomy, but this is not always possible. Gaps up to a cm in width in older teens and adults can be managed with an onlay graft of pericranium but larger defects require a patch. Tiny gaps of no more than 1–2 mm can be covered with a thin strip of Gelfoam®, with expectation for continuous dural healing. Small durotomies, such as those that accompany keyhole surgeries, require dural approximation followed by coverage with Gelfoam®, with expectation for continuous dural healing.

Bone

The bone flap is returned to its home position and secured in a manner that reestablishes normal surface contour. Most surgeons choose to use thin titanium plates, but the suture and shim technique is equally satisfactory. Careful bone-to-bone abutment along the supraorbital osteotomy minimizes deformity. Plates are avoided around the orbit. Although this doubles the width of the kerf along the lower end of the flap, this will not be a cosmetic problem, because it will lie beneath temporalis muscle.

A small and seemingly insignificant residual cranial defect in the keyhole area, which will underlie the site of thin temporalis fascia, can be a site of significant cosmetic problem. Whether the site of a burr hole or a defect resulting from a small craniectomy, it can cause a severe postoperative cosmetic concern. The bony defect in this location can be managed with autologous bone harvested from the inner table of the free bone flap, by titanium mesh or with other synthetic material such as hydroxyapatite bone cement [30, 31]. Burrs in any other locations should be filled with bone chips, a titanium burr hole cover, or bone cement.

The lower part of a frontotemporal bone flap will be immobilized when the portion of the bone flap above the superior temporal line is secured. There is little value in securing the lower end of a frontoparietal flap which will lie beneath temporalis muscle and therefore isolated from atmospheric pressure. The zygomatic arch is reattached with low profile titanium plates.

Muscle

The closure of temporalis muscle, particularly near the keyhole, has cosmetic importance. For details in restoring the temporalis muscle see, see *Restoration of temporalis muscle* in muscle, fascia, and mucosa.

The myofascial flap is returned to its normal position and sutured to the cuff of fascia remaining across both intact cranium and repositioned bone flap. It is important that the upper edge of the temporalis muscle be included in these sutures to prevent separation during healing. Direct attachment of muscle to bone is required if the fascial cuff across the frontotemporal bone is not present or insufficient to hold sutures [16]. This requires that four or five pairs of holes be obliquely drilled along the superior temporal line and used to secure the temporalis fascia and muscle with interrupted 2–0 absorbable sutures [32]. If the patient will soon receive chemotherapy or radiation, non-absorbable sutures should be used.

If there is insufficient muscle and fascia to cover the bone and burr hole anteriorly, the upper end of the reflected section of temporalis muscle should be shifted anteriorly and secured to frontal bone and orbital rim as described above with absorbable sutures. The resulting gap in temporalis muscle does not result in a significant cosmetic or functional defect. Attempt to pull muscle fibers together will cause unnecessary damage.

Failure to pull the muscle anteriorly and superiorly over the keyhole area consistently results in a significant cosmetic defect. It is often necessary to pull muscle and fascia anteriorly to the rim of the orbit with one or more sutures over the burr hole which is filled with bone chips.

If the temporalis muscle has insufficient bulk to provide sound coverage of the keyhole area, whether resulting from acute surgical damage, prior surgery, radiation, cachexia, or advanced age, it will be necessary to shift the fan of temporalis muscle forward by 1 cm or more. This can be accomplished by making an incision in the temporalis muscle in a line parallel to the fibers of the muscle, beginning about four or more cm from its anterior edge and extending down to the zygomatic arch. When this flap of muscle is shifted anteriorly and snugly secured with sutures, there will be a gap in the temporalis muscle at the site of myotomy, but no attempt should be made to pull these edges of muscle together. Leaving this gap in temporalis muscle does not cause a functional or significant cosmetic defect [32]. If the anteriorly shifted muscle is poorly attached and separates, it will contract downward into a ball-like configuration, resulting in impaired function and significant cosmetic defect.

Scalp

A subgaleal drain should be used to prevent the postoperative collection of fluid beneath the scalp and to minimize periorbital swelling. Galea is repaired with 3–0 or 2–0 absorbable suture and the dermis in the preauricular region is also closed with absorbable interrupted sutures. The edges of scalp are approximated with 4–0 Vicryl Rapide® sutures, using a running, non-locking technique or with staples. Antibiotic dressing is applied, but a turban bandage, although traditional, is optional [33].

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Convexity Approaches to the Cranial Vault

12

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Surgical approaches across the cranial convexity have significant similarities and will be described together. Frontal approaches surgeries for decompression are described elsewhere.

Lateral Cranial Convexity Approach

Positioning and Immobilization

The trunk must be rotated 60–90°, depending on location of surgical target and surgeon's preference, with approximately 10–15° of reverse Trendelenburg. The head is positioned in a full lateral, or near-lateral position, depending upon the surgical goal and the surgeon's desired angle of view. It is important that the neck not be rotated more than 45° in order to avoid contralateral internal jugular vein compression with negative impact on intracranial pressure. In addition, some patients, particularly the elderly, cannot safely tolerate significant neck rotation.

Rigid immobilization of the head with a Mayfield head holder is required for many convexity approaches; however, approaches to evacuate hematomas, repair fractures, or implant recording grids can be safely accomplished with the head immobilized by pillows and sandbags.

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Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Plan exact location, shape, and size of craniotomy
- Execution of craniotomy
- Durotomy
- Repair of dura (restoration of dural envelope)
- Replace and secure bone flap
- Camouflage burr holes
- Restoration of temporalis muscle (if disrupted)
- Cosmetic repair of scalp

Scalp

A *flat-top horseshoe incision* of 6 cm or greater in width has been used for most neurosurgical approaches over the cranial convexity. The vertical arms of the horseshoe incision should be tilted 15–20° from the fall line of hair. This will result in a scar that is less noticeable, particularly if hair is short or very thin.

A *sigmoid incision* often provides satisfactory exposure for craniotomies of approximately 5 cm diameter or less, and the resulting scar tends to be less noticeable than U-shaped scars, as only small sections of these continuously curved incisions will lie in the fall line of hair-bearing scalps.

A *Linear incision* has become more popular after neuronavigation was introduced to cranial procedures. The incision is placed over the epicenter of the lesion with great precision. Linear or curvilinear incisions have shown superior healing and cosmetic outcomes.

All surgical scars resulting from convexity approaches will be visible in bald scalps and in patients with very thin or closely cut hair.

Bone

Most craniotomies on the cranial convexity require a single burr hole; however, many surgeons are more comfortable with multiple burr holes. The outline of the proposed osteotomy, most commonly quadrilateral in shape with tightly rounded corners, should be marked with ink. Circular and oval craniotomies should not be used, because much of the exposed dura cannot be used unless the dura is to be opened with a circular incision or radial incisions. The osteotomy is made along the marked line with a craniotome.

Dura

The most efficient use of a rectangular exposure of dura is a flat-top U-shaped or X-shaped durotomy. Most surgeons choose to hinge a U-shaped dural flaps in the direction of the base of the skull, but this is not essential. Dural flaps near the superior sagittal sinus should be hinged approximately 1 cm from the sinus. There is significant risk of disrupting bridging veins and veins within the parasagittal dura, if a durotomy is made parallel to and near superior sagittal sinus.

Restoration

The restoration of most surgeries on the cranial convexity is straightforward. Dura is repaired with running 4-0 absorbable suture. Dural tenting sutures are occasionally needed to achieve hemostasis but, contrary to traditional practice, tenting sutures are not necessary for prophylaxis. Bone flaps can be secured in place either with titanium plates or with sutures and shims of bone.

A vacuum drain, usually Jackson-Pratt, in the subgaleal space will prevent the accumulation of blood or serum; however, many surgeons are averse to using a subgaleal drain because of concern for infection. Scalp is repaired in two layers with galea being closed with 2-0 or 3-0 absorbable sutures and skin edges approximated with 4-0 Vicryl Rapide® or staples.

Temporal Approach (Middle Cranial Fossa Approach) [1–3]

The middle fossa approach can provide exposure of the petrous apex, upper clivus and for management of small acoustic tumors, and some aneurysms. Surgical targets far anteriorly in the middle fossa and along the sphenoid wing are better exposed by a frontotemporal approach.

Positioning and Immobilization

The trunk is rotated 45–90° from supine with approximately 10–15° of reverse Trendelenburg. The head is placed to a full lateral position with the neck extended approximately 30°. Rotation of the neck must not be more than 45, and some elderly patients cannot safely tolerate 30° of rotation.

Rigid immobilization of the head is required for many but not all surgeries in which the middle fossa approach is used. The double-pin arm of the Mayfield clamp is placed over the contralateral far posterior occipital region and the single pin on the ipsilateral forehead. This ipsilateral pin can produce a significant scar in the forehead and therefore an attempt should be made to place it either in the exact midline of the forehead or extremely near the hairline.

If not rigidly immobilized, the heads of infants, children, and some adult, regardless of rotation, end to roll to one side. A small firm pillow or sandbag on each side of the head will minimize instability and allow the surgeon to easily reposition the head.

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Protect nerve to frontalis muscle
- Protect superficial temporal artery
- Avoid violation of skin of external auditory canal
- Minimize injury to temporalis muscle
- Plan exact location, shape, and size of craniotomy
- Management of middle meningeal artery
- Execution of craniotomy
- Durotomy
- Repair of dura (restoration of dural envelope)
- Replace and secure bone flap
- Camouflage burr holes
- Restoration of temporalis muscle and fascia
- Cosmetic repair of scalp

Scalp Incision

Significantly different incisions may be chosen for approaches to the middle cranial fossa, and each provides a somewhat different exposure via a different myotomy. Care must be taken to protect the nerve to frontalis muscle and the superficial temporal artery. (See description in *Surgery of scalp and face*.) Each incision includes a vertical arm passing upward from the posterior zygomatic arch or a few mm below to approximately 1 cm above the insertion of the pinna. This arm of the resulting scar can be nearly invisible if the mid-portion of this incision is made along the posterior edge of the tragus.

Eroteme (question mark) incision—This is the most commonly used incision for middle fossa approaches. The incision extends upward from the posterior zygomatic arch for approximately 6 cm, arcs quickly posteriorly over the pinna, and then curves upward and anteriorly, exposing the origin of the anterior half of the temporalis muscle along the inferior temporal line. Although this scalp incision extends more superiorly than necessary for most middle fossa approaches, it allows exposure with minimal damage to the muscle and thus a better cosmetic result.

High horseshoe incision—This incision extends straight upward from the posterior zygomatic arch, as described above, for approximately 6 cm, then curves posteriorly and downward behind the pinna to the level of the transverse sinus or even down over the mastoid. It is important to protect the superficial temporal artery which, with posterior auricular artery, supplies the scalp flap.

Low flat-top horseshoe incision—This incision extends straight upward from the posterior zygomatic arch for approximately 4 cm, then passes posteriorly at approximately 1 cm above the pinna, and downward behind the pinna. A significant disadvantage of this incision is the usual requirement that the temporalis muscle be transected in its mid-portion or lower, thereby ensuring atrophy of muscle with impaired cosmesis.

Straight vertical incision—This incision extends straight upward from the posterior zygomatic arch for approximately 5–6 cm. It may be adequate for small craniotomies over the low lateral cranial convexity.

Temporalis Muscle

A radial incision is made through temporalis fascia and muscle in a direction corresponding to the radially oriented muscle fibers. This should be done with a scalpel, in a plane corresponding to underlying muscle fibers. Next the temporalis fascia and muscle can be mobilized along their upper border, either by disrupting the connection with a periosteal elevator or incising with a scalpel in a line approximately 1 cm below the inferior temporal line. Some surgeons prefer to incise with the electrocautery because this can be quickly accomplished while simultaneously achieving hemostasis; however, the cautery causes unnecessary damage and shrinkage of temporalis muscle and fascia. A transverse myotomy across the belly of the temporalis muscle results in atrophy of muscle above the myotomy, which will be cosmetically apparent when edema resides. The incised muscle is dissected free from bone with a periosteal elevator. Hemostasis is obtained with bipolar cautery.

There are many techniques for retracting temporalis muscle, using various self-retaining retractors, Alice clamps, fishhooks, and sutures. Sustained periods of tight retraction or compression of muscle can cause ischemia or infarction with the consequence being postoperative atrophy. The retracted muscle must be kept moist throughout the period of retraction and exposure to air. This is best done by keeping the muscle covered with Bicol® sponge, Telfa® or gauze sponges kept moist by frequent irrigation with saline.

Bone

The outline of the proposed osteotomy, most commonly quadrilateral in shape with tightly rounded corners, should be marked with ink. Circular and oval craniotomies should not be used because much of the exposure will not be used unless dura is to be opened with a circular incision or radial incisions. Most craniotomies on the cranial convexity require only a single burr hole; however, many surgeons are more comfortable with multiple burr holes.

Craniotomy for *low exposure into the middle fossa* can be appropriate for evacuation of some hematomas and elevation of low depressed temporal fractures. One burr hole is placed anteriorly in the exposed bone and approximately 3 cm above the zygomatic arch, which will be below the squamosal suture. The desired craniotomy or craniectomy, usually approximately three by 4 cm in maximum diameter, is marked with ink and the osteotomy is made with a craniotome. It is usually necessary to remove additional bone with a Leksell rongeur or burr across the inferior edge of the cranial opening.

C*raniotomy for large exposure into the middle fossa*, for example, for temporal lobectomy or resection of intracerebral tumor, requires an eroteme craniotomy, which begins with a burr hole placed in the position commonly referred to as the *keyhole*. This site is far anterior-superior and below the attachment site of temporalis fascia and muscle to frontal bone. Preferably the burr hole enters the middle fossa just below the lesser wing of the sphenoid bone, but it may straddle the wing. The proposed cranial opening should be marked with ink. The upward extent and size of the craniotomy are determined by the surgical target and surgeon's preference. Surgery for temporal lobectomy requires a cranial opening that extends above the Sylvian fissure and to the anterior extent of the middle fossa.

An osteotomy is made along the inked line in the direction of the sphenoid wing, which is usually only a few mm from the burr hole and then courses in the reverse direction along the inked line. Often the bone flap remains attached by a portion of the sphenoid wing, and an attempt to disrupt this connection with the craniotome risks disrupting dura. This bony connection can usually be cracked by prying the bone flap with a periosteal elevator or other instrument inserted into the kerf. If this is unsuccessful, the sphenoid wing can be further weakened or disrupted with a narrow straight osteotome.

If more exposure is needed in the middle fossa, Leksell and Kerrison rongeurs can be used to enlarge the cranial opening anteriorly or inferiorly. It is often necessary to remove the lower edge of the cranial opening and make it flush with the floor of the middle fossa. This can be done with a Leksell rongeur and a burr. Approaches for aneurysmal surgery often require removal of much of the sphenoid wing, which can be accomplished with a diamond burr.

Dura

Extradural approach—The dura is elevated from the floor of the middle fossa, usually with little difficulty. This should be done with caution to prevent injury of the *greater superficial petrosal* and *lesser petrosal* nerves which lie immediately beneath the dura. The middle meningeal artery will be encountered as dura is retracted and must be thoroughly cauterization and transect with microscissors. Accidental disruption of this artery by traction on dura results in bleeding from the foramen spinosum, and its control is best accomplished with a peg pushed firmly into the foramen [4].

Transdural approach—The shape and size of durotomy are dictated by the surgical target and surgeon's preference. A superiorly based U-shaped durotomy serves the needs for most surgeries but some surgeons prefer to base the dural flap inferiorly.

Restoration

Dura is repaired in the standard manner with running 4-0 sutures. The author prefers absorbable suture but silk or Nurolon®is satisfactory. Most surgeons secure the bone flap beneath temporalis muscle with titanium plates; however, small bone flaps which will lie beneath normal-thickness temporalis muscle do not require rigid fixation, because the muscle isolates the free bone flap from the effects of atmospheric pressure, and bone-to-bone healing commonly occurs with good alignment. Swarf (bone dust and chips) or a titanium hole cover should be placed in the burr hole at the keyhole location, which can usually be poorly covered by thin temporalis muscle.

The temporalis muscle and fascia are returned to their normal positions. If a sturdy cuff of fascia remains along the intact frontal bone or on the upper edge of the reattached bone flap, the edge of the musculofascial flap is sutured to the cuff. It is important to include a few mm of the upper edge of temporalis muscle in these sutures to minimize its retraction during healing. If there is insufficient fascial cuff for musculofascial attachment, three to five pairs of obliquely drilled pairs of holes can be easily placed along the inferior temporal line and used for securing the temporalis muscle and fascia [5]. The vertical fasciotomy overlying the vertical myotomy should be approximated with 3-0 absorbable sutures. The sites of the radial myotomies usually coapt as fascia is repaired, but if not, the two sides of muscle can be approximated with a few 3-0 absorbable sutures.

Galea and the fibro-adipose tissue in the 2–3 cm above the zygomatic arch are repaired with 3-0 (4-0 in infants) absorbable sutures. Edges of skin are aligned and secured with 4-0 Vicryl Rapide® suture or staples.

Occipital Approach

Targets located on or within the occipital convexity, posterior falx, and upper surface of the tentorium can be approached via a horseshoe incision which does not cross the midline. Approach to the posterior fossa via an occipital route is addressed in *Approaches to the posterior cranial fossa*.

Positioning and Immobilization

There are four positions used for occipital approaches. The prone and three-quarter prone positions are most commonly used.

Prone position—The trunk is prone with 10–15° of reverse Trendelenburg and the chest on two longitudinal rolls. The neck is rotated approximately 30° and flexed 15–30°, depending on the location of the surgical target. The head is supported with a padded horseshoe head rest or by rigid immobilization. The prone position is used most often for infants and small children but occasionally for teenagers and adults.

Three-quarter prone (park bench) Position—The trunk is rotated 30–45° beyond full lateral and then moved sufficiently cephalad on the surgical table to allow the dependent upper extremity to hang from the table. A padded roll (axillary roll) is placed beneath the upper lateral chest. The dependent extremity must be supported on an arm rest or sling. The superior upper extremity usually requires support on a fixed elevated arm rest. The upper shoulder often requires caudal retraction with adhesive tape. The neck is extended approximately 20° and rotated approximately 45° toward the floor. Rigid immobilization is required.

Supine position—The trunk is rotated 30–45° and neck is rotated another 30–45°. It is important to avoid farther rotation of the neck.

Lateral position—The lateral position is not commonly used for surgeries in the occipital region because of its awkwardness. Lesions on the occipital convexity may be approached with the trunk in the lateral position and in 20–30° of reverse Trendelenburg. The head may be tilted laterally (i.e., upward), depending on location of target and surgeon's preference. Rigid immobilization is usually necessary to maintain stability.

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Plan exact location, shape, and size of craniotomy
- Execution of craniotomy
- Durotomy
- Protection of venous sinuses
- Repair of dura (restoration of dural envelope)
- Replace and secure bone flap
- Camouflage burr holes
- Cosmetic repair of scalp

Scalp

An inverted U-shaped flap, with its base approximately 1 cm below the position of the transverse sinus, is marked with ink. Incision begins laterally just below the transverse sinus, near the postauricular hairline, passes vertically upward for approximately 5 cm, and then arcs medially to cross the midline by approximately 1 cm. From that location, the medial arm of the U-shaped incision has a straight downward parasagittal course and a few mm across the location of the contralateral transverse sinus.

Bone

An occipital craniotomy of spherical triangular shape provides exposure of the convexity of the occipital lobe and can provide parasagittal exposure down to the tentorium. If deep medial exposure along the falx is required, the craniotomy must extend either to the edge of the superior sagittal sinus or approximately 1.5 cm across the midline.

Durotomy

An inverted U-shaped durotomy is satisfactory for approaching most targets on the occipital convexity surface. Targets near the falx-tentorial junction are best approached via a curved durotomy arcing from the high parasagittal exposed dura and extending toward transverse sinus, followed by a straight oblique durotomy extending from mid-portion of the first durotomy and directed toward the torcular Herophili. There tends to be few if any bridging veins along the lower section of the sagittal sinus and medial portion of the transverse sinus.

Restoration

The repair of surgeries for occipital surgical approaches is relatively simple. Dura is repaired with running 4-0 absorbable sutures. Dural tenting sutures are sometimes needed to achieve epidural hemostasis but are not necessary for prophylaxis. Bone flaps are secured in place with either titanium plates or with sutures and shims of bone. Scalp is repaired in two layers with galea being closed with 2-0 or 3-0 absorbable sutures and skin edges approximated with 4-0 Vicryl Rapide® or staples.

Occipital Transtentorial Approach (Occipito-Cerebellar Approach) [6]

This approach provides exposure over one leaf of the tentorium and obliquely downward into the anterior upper region of the posterior fossa and the pineal region. It differs from the *Suboccipital transtentorial approach*, which provides upward visualization through the tentorium.

Positioning and Immobilization

The patient is placed in the prone position with approximately 20° of reverse Trendelenburg and the neck flexed 10–30°. The head is rotated approximately 20° to position the ipsilateral side uppermost and then rigidly immobilized.

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Plan exact location, shape, and size of craniotomy
- Execution of craniotomy
- Durotomy
- Repair of dura (restoration dural envelope)
- Replace and secure bone flap
- Camouflage burr holes
- Cosmetic repair of scalp

Scalp

An asymmetric U-shaped flap with its base approximately 1.5 cm below the transverse sinus is marked with ink. The medial arm of the incision is parasagittal and, depending on surgeon's preference, on either the ipsilateral or contralateral side of midline. The lateral arm of the incision arcs laterally and downward for approximately 7 cm from the upper end of the parasagittal incision, depending on required exposure. Both vertical arms of the flap cross the bone overlying the transverse sinus. The vertical height of the flap is approximately 5 cm. In adults with very thick occipital scalps, the scalp flap must extend lower to allow reflection without kinking of the scalp.

Bone

The locations of the superior sagittal sinus, torcula, and transverse sinus should be located with a neuro-guidance system and marked with ink. A decision must be made regarding whether the craniotomy will extend across the superior sagittal sinus and whether it will cross the transverse sinus. A rectangular or trapezoidal craniotomy is marked with ink. The inferior side of the craniotomy lies approximately 1 cm above the transverse sinus. Some surgeons make the transverse osteotomy below the transverse sinus; however, this requires separating suboccipital muscle from bone and making one or more additional burr holes to assist in protecting the transverse sinus. The medial side of the craniotomy is marked either as an ipsilateral or contralateral parasagittal osteotomy, depending on required exposure. It is important that no osteotomy pass directly along the path of a venous sinus or over the torcula.

A burr hole is made adjacent to the superior sagittal sinus at the upper medial corner of the planned craniotomy. Osteotomy for the marked craniotomy is then made with a craniotome and the bone flap removed, with attention to protection of the venous sinuses. A small emissary vein over or near the torcular Herophili is often present and requires control by tamponade with Gelfoam® and a small cottonoid, until the bone flap is removed. It can then be visualized and coagulated [6].

Dura

A U-shaped durotomy with its base a few mm above the transverse sinus is most commonly used. There are usually no bridging veins along the lower three to 5 cm of the superior sagittal sinus, the torcular Herophili, or medial few cm of the transverse sinus. The edges of the dural flap and the surrounding edges of dura must be retracted to provide the needed exposure and covered w Bicol® or Telfa® to prevent their contraction from desiccation.

Tentorium

The upper surface of the tentorium comes into view when the occipital lobe is retracted. (Retraction of brain is not within the scope of this text.) The exposed leaf of tentorium should be inspected under magnification for presence and location of veins. An avascular appearing strip extending from approximately 1 cm anterior to the transverse sinus toward the free edge of the tentorium is cauterized. An incision is with a #11 blade and extended with microscissors toward the middle of the free edge of the tentorium. This edge of the tentorium contains the medial tentorial artery which arises from the meningohypophyseal trunk. The free edge of the tentorium must therefore be coagulated before it is cut. It should not be cauterized far laterally because of risk to cranial nerves which can receive arterial supply from tiny branches of medial tentorial artery. Cauterization of the edges of the tentorial incision can secure hemostasis and expand the exposure by desiccation. The medial tentorial artery, when enlarged and supplying tumor or vascular malformation, has the name *artery of Bernasconi-Cassinari* [7].

Restoration

The incision in the tentorium is not repaired. Dura of the convexity is repaired in the standard manner with 4-0 Vicryl®. The bone flap is returned to its normal position and secured in place with titanium plates. Repair of the scalp is done in two layers in the standard manner.

Vertex and Parafalcine Approaches

Vertex approaches are used to expose epidural hematomas, falcine and parafalcine lesions, the corpus callosum, lesions within the lateral and third ventricles, and for placement of interhemispheric recording electrodes [8].

Positioning and Immobilization

Supine position—The most common position for vertex approaches is supine with approximately 20° of reverse Trendelenburg and cervical flexion of 20–45°, depending on the surgical target and mobility of neck. The head usually rigidly immobilized with a Mayfield 3-pin holder for deep parafalcine approaches but not for evacuation of hematomas, repair of fractures, or placement of recording grids.

Lateral position—Some surgeons prefer, when approaching lesions in the third ventricle, that the patient be in the lateral position, with the trunk in approximately 20° of reverse Trendelenburg and the lesion-side downward to allow gravity to assist retraction while the falx prevents sagging of the contralateral hemisphere. The lateral position requires that the head be rigidly immobilized and tilted laterally (upward) approximately 30° which, with tilt of trunk, positions the sagittal plane of the head at approximately 45–50° from horizontal [9].

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Plan exact location, shape, and size of craniotomy, including possible extension across midline

- Execution of craniotomy
- Durotomy
- Protection of superior sagittal sinus and bridging veins
- Repair of dura (restoration dural envelope)
- Replace and secure bone flap
- Camouflage burr holes
- Cosmetic repair of scalp

Scalp

The surgeon may choose, based on the nature and location of the surgical target, to choose either a unilateral or bilateral approach. This influences the choice of scalp incision; however, a planned unilateral approach may, during surgery, be expanded to a bilateral approach.

Both unilateral and bilateral vertex approaches can be accomplished via either a coronal incision or a laterally based flap with right-angle corners. The top of a laterally based flap is located approximately 1.5 cm to the contralateral side of midline, with its two arms crossing the midline and extending coronally for approximately 4 cm on the ipsilateral side. Retraction of very thick scalp may necessitate extension of the arms to facilitate reflection. It is occasionally recognized during surgery through a unilateral flap incision that bilateral exposure is necessary. The incision can be easily converted to a bilateral approach by extending the vertical arms onto the contralateral side, thereby producing an H-shaped incision. The right-angled corners make this extension of scalp incisions safer than would be possible with curved corners.

A coronal incision can be centered across the surgical target and have length of 10–15 cm or more, depending on required cranial exposure. Some surgeons choose a broad anteriorly arcing coronal incision to prevent having a surgical incision passing across the craniotomy site.

Pericranium

Pericranium should be preserved to the extent possible by being cut along three sides of the proposed craniotomy and pushed aside with a periosteal elevator. This is particularly important in infants and children, whose pericranium contains many osteoblasts that assist in osseous healing.

Bone

The location of the superior sagittal sinus and outline of the proposed bone flap should be marked with ink. The sagittal suture is a reliable indicator of the location of the superior sagittal sinus, but the sinus is often not precisely centered beneath the suture. The coronal suture can be identified after scalp has been reflected, but its location with respect to cerebral sulci is not reliable; however, when seen on neuroimaging, the coronal suture in a specific patient can be an especially useful surgical landmark.

Sagittal MR images are quite useful in planning the angle of approach and hence the best position for craniotomy. The location of bridging veins apparent on MRI can influence the planned approach. For surgical targets that lie between the convexity surface of the brain and the corpus callosum, the bone flap should be centered, directly over the target. For targets in the posterior third ventricle, the craniotomy should be positioned one to 1.5 cm more anteriorly to facilitate exposure through the foramen of Monro.

Unilateral vertex craniotomy is accomplished via rectangular cranial opening whose medial edge lies approximately 1.5 cm ipsilateral to the midline. Placement of the edge of the craniotomy over the superior sagittal sinus may allow better unilateral exposure along the fall, but this increases the risk of injury to the sinus. The lateral edge of the craniotomy is placed three to 4 cm from midline, depending on needed exposure. The anterior-posterior dimension of the cranial opening is determined by the size and position of the surgical target, location of bridging veins, and surgeon's preference, but is usually approximately 6 cm. Outline of the proposed craniotomy should always be marked with ink.

An oval burr hole of sufficient size to accommodate the footplate of a craniotome is made at the posterior medial corner of the planned craniotomy approximately 12–15 mm from midline. Some surgeons make a much larger burr hole (18 mm diameter) centered over the superior sagitta sinus at the anterior and posterior extents of the planned craniotomy [10]. Also, some surgeons choose to make more burr holes before making osteotomies. A craniotome is used to cut bone along the marked line. and the bone flap is usually easily removed. The osteotomy nearest the midline is made last because it has the greatest risk of encountering venous bleeding and thereby requiring quick removal of the flap.

Bilateral vertex craniotomy symmetrically straddles the midline, extends on each side for 3–3.5 cm, and can be accomplished in one or two bone fragments. A single-flap bilateral vertex craniotomy requires two osteotomies across the sinus. The traditional technique for craniotomy across the superior sagittal sinus required one burr hole on each side of the superior sagittal sinus at both the anterior and posterior ends of the planned craniotomy plus a burr hole in each lateral corner of the craniotomy, for a total of eight burr holes.

The author prefers to use only one oval burr hole, having sufficient size to accommodate the footplate of a craniotome, positioned approximately 1 cm lateral to the superior sagittal suture at the posterior end of the planned cranial opening. An osteotomy is then made around the marked bone flap, including twice crossing the superior sagittal sinus. This technique requires less time and minimizes the residual bony defect. However, the single burr hole technique *should not be used* in patients with prior craniotomy in the same site or for cases that have neoplastic invasion of dura over the superior sagittal sinus because of risk of injury to the sinus.

Many surgeons are uncomfortable with the single burr hole technique and either cut across the midline with a Kerrison rongeur or first cut a partial-thickness slot across the sinus with a drill, thereby allowing the osteotomies across the sinus to be made with a Kerrison rongeur in a manner perceived to be more safe [11–13].

The *two-piece technique* for bilateral vertex craniotomy begins with a unilateral craniotomy, as described above. All attachments of dura to bone across the superior sagittal sinus are then disrupted with Penfield dissectors [14]. A craniotome is then used to cut the cranial bone across the midline and around the marked flap on the second side [15]. The two osteotomies crossing the superior sagittal sinus are made while a flat or Penfield retractor gently protects the sinus.

Dura

Durotomies for vertex approaches usually have a shallow flat-toped U-shape with its base near the lateral extent of exposed dura. The flap is approximately 5–7 cm in anterior-posterior dimension, and the two legs are approximately 2.5 cm length. This allows the flap to be folded and retracted gently over the superior sagittal sinus. A straight parasagittal durotomy about 1 cm lateral to the superior sagittal sinus and having slightly curved ends is satisfactory for narrow exposures, as required for insertion of recording grids. Occasionally a planned unilateral parafalcine approach proves to be problematic because of close spacing of bridging veins or simply inadequate for tumor resection. Bridging veins entering the sinus do not commonly have right-left symmetry. In such circumstances, the surgeon may choose to make a similar durotomy on the opposite side (requires extension of craniotomy). Bilateral parafalcine approaches, as required for most tumors involving the falx, require a dural flap on each side of the sinus with alternating retraction across each flap as needed.

It is important when making parafalcine durotomies to protect bridging veins, which can be disrupted during dural incision or by traction. Tiny bridging veins can be coagulated and cut but, as the dura is being retracted, it can be difficult to assess the size of veins that are collapsed. It is best to not disrupt bridging veins; however, the sacrifice of a few bridging veins, particularly if small, is usually tolerated without adverse consequence.

Strong retraction of the dual flap across the superior sagittal sinus can compress the sinus, compromise flow, and elevate venous pressure within the cerebral veins receiving blood from that section of the sinus that is anterior to the compression. This may be manifested by increased bleeding from veins on or within brain which has elevated venous pressure.

Restoration

Dura is repaired with running 4-0 absorbable sutures. Dural tenting sutures may be needed to achieve hemostasis but are not necessary for prophylaxis. Bone flaps are secured in place with titanium plates. Scalp is repaired in two layers—galea with absorbable sutures and skin edges with 4-0 Vicryl Rapide® or staples. The repair of scalp following vertex craniotomy is relatively simple; however, repair of a coronal incision is easier and requires less time because of the absence of corners.

Hemicranial Decompression

Hemicranial decompression is done to relieve structural constraints to predominantly unilateral, edematous cerebral expansion resulting from cerebral infarction, trauma, or other causes, and which is predominantly unilateral [16].

Positioning and Immobilization

The torso must be in a lateral to three-quarter lateral position with approximately 20° of reverse Trendelenburg. The head must be in a full lateral position, usually supported on a horseshoe headrest. Rigid immobilization is not necessary.

Plastic Neurosurgical Concerns

First Surgery: Decompression

- Incision of scalp
- Protect superficial temporalis artery
- Minimize injury to temporalis muscle
- Plan size and boundaries of craniectomy
- Execution of craniectomy
- Cryopreservation of bone flap and fragments
- Durotomy
- Protection of superior sagittal sinus and bridging veins
- Hemostasis; possible need for packing (uncommon)
- Provide a barrier between brain and galea to prevent adhesion
- Secure two-layer repair of scalp

Second Surgery: Restoration

- Safe reflection of scalp
- Reestablish dural envelope
- Cranioplasty
- Restoration of temporalis muscle
- Cosmetic repair of scalp

Scalp Incision (Three Options)

Large eroteme (question mark) incision—This is the most common incision used for unilateral cranial decompressions. The incision begins at the hairline of the forehead or a cm anterior to the hairline and approximately 1 cm ipsilateral to the midline. The full-thickness incision extends straight posteriorly for approximately 15–20 cm, then arcs downward behind the lambdoid suture, anteriorly to a point about 1 cm above the insertion of the pinna, and then straight down in front of the tragus to the zygoma. There is a small risk of infarction of the posterior-inferior portion of the scalp flap, if the incision loops downward behind the pinna and particularly if the superficial temporal artery has been disrupted.

Modified eroteme (question mark) incision—This incision provides more posterior parietal exposure than the standard eroteme incision. It begins as described above for the eroteme incision but has two differences: (1) the incision arcs down a few cm anterior to the lambdoid suture and (2) a radial extension begins in the mid-parietal portion of the curved incision and passes a variable distance toward lambda. The two resulting scalp flaps can be easily reflected.

T-incision—This incision provides high posterior parietal exposure but less exposure in the occipital-temporal region. The incision begins at the hairline of the forehead or a cm onto the forehead and approximately 1 cm ipsilateral to the midline. A full-thickness incision extends straight posteriorly to within a few cm of the lambdoid suture and then curves downward for a variable distance. A second incision, perpendicular to the first, is made from the middle of the first incision straight down to the zygoma, passing just anterior to the tragus. The resulting two scalp flaps are easily reflected.

Muscle

The temporalis muscle and fascia are reflected with scalp, using a periosteal elevator. Some surgeons separate and reflect muscle and fascia as a separate flap. This may limit the decompression over the anterior middle fossa. Some surgeons dissect and reflect the muscle as a separate flap. The temporalis fascia and muscle are reflected downward over the zygoma.

Bone

A large circumferential osteotomy is marked with ink. The parasagittal line should be approximately 1.5 cm from midline and extend from approximately 3 cm above the supraorbital rim, depending on exposure, to the lambdoid suture or beyond. Only one burr hole is required for most large cranial decompressions, but some surgeons are more comfortable with several. The location of the initial burr hole can be anywhere along the marked line, but it is the author's preference to place the initial burr hole in the anatomical keyhole location or slightly above the sphenoid wing and advance the craniotome initially upward from the burr hole and then circumscribe the entire marked bone flap. It is important to avoid lacerating the dura, particularly along the parasagittal region because of risk of disrupting large dural veins, bridging veins, or the superior sagittal sinus. The flap of bone can be adherent to bone along the cranial sutures, in many elderly patients, and those who have undergone prior surgery in the area. It is occasionally necessary to disrupt the sphenoid wing with a narrow osteotome to free the bone flap. It may be necessary to make a coronal osteotomy through the large bone flap to facilitate its separation from dura and to allow removal of the bone in two fragments. The cranial opening can be easily expanded along the floor of the middle fossa and across the sphenoid wing with a Leksell rongeur. The bone flap and other fragments of bone should always be preserved, regardless of extent of contamination which may have occurred from severe cranial trauma.

Patients ill enough to require cranial decompression always require a large craniectomy. There is a tendency to make too small a craniotomy.

Dura [17]

Dura should be opened with multiple radial incisions, preferably not meeting at a single point. No attempt should be made to open dura in a large single flap. Care must be exercised to avoid injuring the superior sagittal sinus or large veins within the dura as durotomies are extended toward the sinus.

Hemostasis

Bleeding from vessels in dura is controlled by bipolar coagulation or brief clamping with a hemostat or needle holder. However, venous hemorrhage can become severe (sometimes life-threatening), as the dura is being opened and reflected. The source of massive subarachnoid hemorrhage is almost always from bridging veins that were disrupted preoperatively by depressed fragments of bone or, in infants, from multiple bridging veins disrupted by acceleration-deceleration of the head. If the source cannot be quickly identified and directly controlled, packing can often be a life-saving maneuver [18, 19]. It is usually possible to determine the general location and probable source of bleeding, for example, multiple disrupted bridging veins somewhere along the cerebral convexity. The site of hemorrhage should be quickly packed with strips of Gelfoam® held firmly in place with a sucker over multiple wet cottonoids. It is often necessary to place wet RAY-TEC sponges over the cottonoids and apply suction to them to achieve cessation of hemorrhage.

Slow removal of cottonoids® with electrocoagulation of identifiable bleeding vessels should be tried. After two or three failures to achieve hemostasis, the packing should be left in place. Dura is left open, bone cryopreserved, and scalp is closed in two layers.

Closure Immediately after Decompression

The multiple triangular flaps of dura are stretched loosely over the exposed bulging brain and all exposed brain is covered but not sutured with an onlay barrier (e.g., Duragen®) to prevent adhesion of galea to brain [20, 21]. This unattached barrier will allow further expansion of brain without becoming constrictive. Some surgeons place very loose sutures between the tips of the dural triangles to minimize their contraction over time and to assist in their identification at the time of reconstruction; however, these initially loose connecting sutures can become tight and deeply indent brain as the brain continues to expand.

Some surgeons suture the upper edges of temporalis muscle and fascia to the galea on the undersurface of the scalp flap in attempt to limit contraction of temporalis muscle in the weeks following decompression. The benefit of this maneuver is unclear, but it may prevent extreme contraction. Scalp is closed in two layers, using 2-0 (3-0 in infants and young children) absorbable suture for galea and staples for skin. Snug repair is important to prevent leakage of CSF and minimize risk of infection.

Restoration (After Resolution of Cerebral Edema)

S*calp incision and reflection*—If the scar has an acceptable narrow appearance, incision should be made along the middle of the scar. The scalp flap can be difficult to reflect as a result of fibrosis within the flap. Therefore, in order to expose the entire cranial defect, it may be necessary to extend the ends of the incision, but not below the zygoma.

Repair of dura—The dural envelope should be reestablished. All edges of dura must be identified and cleared of attachments, while protecting brain. Surviving Duragen® or other artificial material should be removed to the extent compatible with protection of cerebral cortex, but areas significantly adherent to brain should not be pursued. The dura will have contracted, and no attempt should be made to reapproximate all of the edges, but it may be possible to loosely approximate a few of the edges. A patch with biologic or synthetic materials is probably always required [22]. Sufficient pericranium for patching is rarely available, but fascia lata, xenograft, or a synthetic material such as Suturable Duragen® may be used. The patch should be sutured in a manner that reestablishes a snug dural envelope in children and teenagers; however, snugness of the envelope is less important in adults.

Cranioplasty—The full-thickness edges of intact cranial bone should be cleared of soft tissue, during which more bleeding often occurs from the epidural space than expected. A few dural tenting sutures may be required for hemostasis. Clean exposure across the inferior and anterior edges of the middle fossa are not essential. Cranioplasty can be accomplished with cryopreserved autologous bone, other autologous bone, allograft, or synthetic material [23].

When repair is being done with cryopreserved autologous bone, it is this author's practice to use a craniotome to "roughen" the edges of surrounding intact cranial bone and make multiple radial osteotomies of 8–10 mm length into the living bone, preferably entering cancellous bone that bleeds. This may enhance the healing of bone-to-autologous bone but is not proven. Little or no bone wax is used for hemostasis because it impairs healing, but Avitene™ can be used. After the cryopreserved bone flap is thawed, in mildly warm but *never hot saline*, it is returned to its normal cranial position and secured with titanium plates. Usually, four or five plates are sufficient, but there is a tendency to use more plates than necessary. In a review by van der Vijfeiken et al. of 10,346 cranioplasties, bone resorption occurred in 1% of autologous grafts and infection in 5.6% [24].

In infants and young children in whom many weeks have elapsed since decompression, the size of the cranial defect may have become smaller and the contour of the intact cranium may have changed, thus necessitating modification in a cryopreserved bone flap.

Restoration of temporalis muscle—There is no reliably satisfactory technique for restoring temporalis muscle after being disconnected for several weeks or months. As cerebral edema resolves, the disconnected temporalis muscle, and its fascia contract into a globular configuration with intramuscular fibrosis, thereby greatly impeding functional and cosmetic reconstruction.

The temporalis muscle must be mobilized down to the zygoma, stretched, to the extent thought safely possible, and securely reattached to bone. Temporalis fascia over the temporalis muscle and any associated fibrous tissue on the muscle often require several transverse incisions to facilitate its expansion; however, this does cause some damage and possible denervation. Little or no useful fascial cuff will likely be present on the re-implanted bone flap, to which muscle can be sutured. Five to six pairs of holes can be drilled shortly below the superior temporal line and used to tightly secure the outstretched temporal muscle [5]. It will not be possible to expand this muscle to its original full length without severely damaging it, but stretching it to the extent thought safely possible and securing it to bone will facilitate the return of useful function and will minimize cosmetic deformity. Attempt to stretch the muscle to its presurgical length will fail and cause considerable damage to muscle fibers, its vascular supply and innervation. If left unattached, the temporalis muscle will remain as a globular mass with little useful function and persistent cosmetic deformity.

Repair of scalp after reconstruction—During the healing process, one or both edges of the scalp wound may have become everted or the scar may be wide or quite thin, thereby impairing healing and elevating the risk of dehiscence and infection. Therefore, all edges of scalp that are very thin, very thick, or have a "rolled in" appearance must undergo full-thickness resection to allow a reliable two-layer repair with everted edge abutment. Conservative piecemeal resections of epidermis with some dermis are very unlikely to lead to satisfactory healing. If resection of more than a few mm in width is required, the flap may necessitate expansion by crosshatching of the galea in order to achieve satisfactory approximation. Secure snug approximation of the galea is important and should be done with absorbable 2-0 (3-0 in infants and young children) sutures. Edges of the scalp are approximated with Vicryl Rapide® or, if taut, with staples.

Bilateral Frontal Decompression

Bilateral frontal decompression is done to relieve bony constraints to predominantly bifrontal edematous cerebral expansion resulting from cerebral infarction, trauma, or other causes [16].

Positioning and Immobilization

The head and trunk are placed in the supine position with approximately 20° of reverse Trendelenburg, and the neck is extended by 20–30°, preferably on a horseshoe headrest but a donut type pillow is acceptable. Rigid immobilization is not necessary, and the Mayfield device can impede the surgery.

Plastic Neurosurgical Concerns

First Surgery: Decompression

- Scalp incision
- Protect superficial temporalis arteries
- Minimize injury to temporalis muscles
- Plan size and boundaries of craniectomy
- Execution of craniectomy
- Cryopreservation of bone flap and fragments
- Pattern of durotomies for decompression
- Possible transection of falx
- Protection of superior sagittal sinus and bridging veins
- Provide a barrier between brain and galea to prevent adhesion
- Secure two-layer repair of scalp

Second Surgery: Restoration

- Safe reflection of scalp flap
- Reestablish dural envelope
- Cranioplasty
- Restoration of temporalis muscles (if disrupted)
- Cosmetic closure of scalp

Scalp

A coronal scalp incision is required and should cross the midline approximately 3 cm posterior to the coronal suture. The incision should course just anterior to the tragi and down to within a few mm above the zygomatic arches. Because of the emergent nature of these surgeries, a straight coronal incision is acceptable; however, a wavy incision requires little longer. The frontal scalp flap with pericranium is reflected anteriorly over the supraorbital rims.

Muscle

A full-thickness incision is made in each temporalis muscle beginning near the coronal suture and extending down in a line parallel to muscle fibers for 2–3 cm. The anterior portion of the temporal fasciae and muscles are separated from their bony attachments, using a periosteal elevator, and then reflected downward. Some surgeons do not incise and reflect the temporalis muscles.

Bone

A broad bifrontal bone flap is marked with ink. Its posterior border usually lies just anterior to the coronal sutures. The lower border should be marked straight across the frontal bone approximately 1.5 cm above the supraorbital rims, ignoring the presence of frontal sinuses. The supraorbital osteotomy must not skirt above large frontal sinuses because the progressively expanding frontal lobes can be significantly damaged if stretched over a ledge of frontal bone.

If a larger decompression is desired, the bicoronal osteotomy can be marked a few cm behind the coronal sutures and down across the anterior part of one or both middle fossae. Extremely large bifrontal decompressions have the disadvantage of allowing brain to sag over the edges of the parieto-temporal bones and be further injured before the resolution of cerebral is sufficient to allow reconstruction.

Only one or two burr holes are necessary for most bifrontal decompressions, but many surgeons are more comfortable with more burr holes. Regardless, one burr hole should be adjacent to the superior sagittal sinus at the posterior edge of the planned cranial opening. Osteotomy passing across both walls of the frontal sinus is described in chapter on *Surgery of Cranial Bone*.

The frontal flap can usually be easily separated from dura and removed in a single fragment without difficulty. If dural adhesions to bone make separation difficult, the large bifrontal flap can be divided by a parasagittal osteotomy and removed in two fragments. If the frontal sinuses are entered, as is usually the case in older teens and adults, the sinus mucosa must be removed from the free bone flap and the exposed portions of the sinuses covered with absorbable Duragen® or other material to form a separation between frontal sinus and intracranial spaces.

The bone flap and other fragments of bone should always be cryopreserved, regardless of extent of contamination, which may be present in patients with severe cranial trauma. If the supraorbital osteotomy crossed the frontal sinuses, the sinuses are usually cranialized.

Dura

A durotomy is made transversely approximately 1.5 cm above each supraorbital rim and extended as far laterally around each side as permitted by the cranial opening.

This is followed by several radial durotomies, with care exercised to avoid injuring the superior sagittal sinus or any large veins within the dura.

Transection of falx—If brain immediately bulges through the dural opening or if this is anticipated to occur postoperatively, the surgeon may choose to cut the falx to accommodate farther anterior expansion of edematous brain and minimize risk of disrupting bridging veins. This action is less difficult and less risky than often perceived by the inexperienced. Two ligatures of 2–0 Vicryl or silk are separately passed around the lowest extent of the exposed superior sagittal sinus, via a needle through the falx, and tied tightly. If the two sutures are separated by approximately 5 mm, the sinus and falx can be cut with Metzenbaum scissors. If venous bleeding occurs from the inner edge of the falx, it is likely from a small inferior sagittal sinus and can be controlled with electrocoagulation.

Closure after Decompression

The irregularly shaped flaps of dura are laid loosely across the swollen brain, and the exposed brain is generously covered with Duragen® to prevent fibrotic adhesion between brain and galea. Scalp is returned to its normal position. This unattached barrier will allow further expansion of brain without becoming constrictive. Some surgeons place loose sutures between the tips of the dural triangles to minimize their contraction over time and to assist in their identification at the time of reconstruction; however, these initially loose connecting sutures can become tight and indent brain as the brain continues to expand. The galea is closed with 2-0 (3-0 in infants and young children) absorbable sutures, and scalp edges are approximated with staples. Snug repair is important to prevent leakage of CSF and minimize risk of infection. Scalp is closed in two layers, using 2-0 (3-0 in infants and young children), absorbable suture for galea, and staples for skin. Snug repair of scalp is important to prevent leakage of CSF and minimize risk of infection.

Restoration (After Resolution of Cerebral Edema)

Opening and reflection of scalp—Incision should be made along the middle of the coronal scar if the scar has an acceptable appearance. Often the scar becomes everted during the healing of scalp or is unacceptably wide and thin, in which cases healing will be impaired with possible dehiscence, and therefore revision is required. Revision of the scar requires full-thickness excision of the abnormal scar. Piecemeal resections of epidermis with some dermis are highly likely to produce an unsatisfactory result.

The scalp flap may be difficult to reflect as a result of fibrosis within the flap, and therefore in order to expose the entire cranial defect it may be necessary to extend the ends of the coronal incision.

Repair of dura—The dural envelope must be reestablished. It is important to identify and clear the edges of the flaps of dura from attached fibrous tissue while protecting brain. The surviving Duragen® should be removed to the extent safely possible but areas adhered to brain should not pursued. The dura will have contracted greatly. No attempt should be made to achieve primary repair; however, it may be possible to loosely approximate a few of the retracted triangular dural flaps. A patch will be required to close the residual defect in the dural envelope. It is sometimes possible to harvest pericranium from the reflected scalp flap, but sufficient pericranium is rarely available, in which case fascia lata, xenograft, or a synthetic material such (e.g., Suturable Duragen®) may be used. The patch should be sutured snugly in place to reestablish a dural envelope in children and young teenagers, and this is preferable in adults; however, snug reestablishment of the envelope in adults is less important.

Cranioplasty—The full-thickness edges of intact cranial bone should be cleared of all soft tissue during which more bleeding often occurs from the epidural space than expected, and a few dural tenting sutures may be required for hemostasis. Cranioplasty can be accomplished with cryopreserved autologous bone, allograft, or synthetic material [23]. When repair is being done with cryopreserved autologous bone, it is this author's practice to use a craniotome to "roughen" the edges of the intact cranial bone and, make multiple radial osteotomies of 8–10 mm length into the bone, preferably entering cancellous bone that bleeds. No bone wax is used for hemostasis because it impairs healing, but Avitene® can be used. After the cryopreserved bone flap is thawed in mildly warm, never hot, saline, it is returned to its normal cranial position and secured with titanium plates and screws. Usually, four or five plates are sufficient.

Restoration of temporalis muscles—The temporalis muscles, if partially detached to assist with craniectomy, should be mobilized, stretched, to the extent thought safely possible, and securely reattached to bone. The free upper anterior edges of the temporalis fasciae and temporalis muscles must be reattached to bone, using either surviving fascial cuffs or holes drilled in bone along the superior temporal line [5]. It may not be possible to expand these muscles to their presurgical full length, but stretching them to the extent possible and securing them to cranial bone will minimize cosmetic deformity.

Closure of scalp—During the healing process, one or both edges of the scalp may have become everted or the scar may have become wide and thin. If closed without revision, these edges will heal slowly and there is elevated risk of dehiscence and infection (with or without dehiscence). Therefore, all edges of scalp that are very thin, unusually thick, or have a "rolled in" appearance must undergo full-thickness resection to allow two-layer repair with everted edge abutment. Therefore, the edges of scalp that have a "rolled in" appearance and sections of very thin broad scar must be excised to allow two-layer repair with accurate edge abutment. If resection of more than a few mm in width occurs during edge revision, the flap may require expansion by crosshatching of the galea to achieve satisfactory approximation.

Secure snug approximation of the galea is important and should be done with absorbable 2–0 sutures. Edges of the scalp are approximated with Vicryl Rapide® or, if taut, with staples.

Presigmoid Approaches (Transpetrosal Approach) [25–29]

A. Samy Youssef and Ken Rose Winston

The presigmoid and transpetrosal approaches, commonly considered as petrosectomies, include retrolabyrinthine [30, 31], translabyrinthine [32, 33], transcochlear [34], and anterior transpetrosal [35, 36] approaches. The details of each will not be described.

Positioning and Immobilization

The patient is placed in the supine position or modified park bench position with the head immobilized by a Mayfield three-point fixation device with the sagittal suture parallel and the vertex angled toward the floor to position the mastoid process uppermost. Head rotation may be limited by neck compression or an elevated ipsilateral shoulder. The upper shoulder must be retracted caudally with adhesive tape. Some surgeons prefer the supine position, in which the ipsilateral shoulder is elevated on a pad and the head is rotated to the contralateral side. A system for stereotactic guidance is commonly used as are monitoring of the cranial nerves V-XI, and auditory brain stem evoked response (ABR) .

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Protection of nerve to frontalis muscle
- Protect superficial temporalis artery
- Avoid violation of skin of external auditory canal
- Minimize injury to temporalis muscle
- Management of middle meningeal artery
- Execution of craniotomy
- Durotomy
- Repair of dura (restoration dural envelope)
- Replace and secure bone flap
- Restoration of temporalis muscle and fascia
- Cosmetic repair of scalp
- Optimum exposure
- Injury of superficial temporal artery
- Replace and secure bone flap
- Restoration of temporalis muscle
- Cosmetic closure of scalp

Scalp

A horseshoe-shaped incision begins just above the zygoma in non-hair-bearing scalp, extends up and posteriorly passing approximately 3.5 cm above the pinna and then downward in the suboccipital scalp three finger width behind the ear and down to the bottom of the ear level. The scalp flap is reflected downward and anteriorly to the level of the bony external auditory canal, while carefully avoiding penetration of the integument of the canal. Retraction with spring-hook retractors will expose the temporal and occipital-retrosigmoid area, including the upper mastoid process of the temporal bone and the upper extent of the sternocleidomastoid muscle.

Muscle

After the scalp is reflected, the temporalis fascia and muscle are incised vertically above the zygoma in a line parallel to muscle fibers, from the zygoma to the approximately 1.5 cm below the facial insertion of the muscle to bone and then in a posterior arc corresponding roughly to the edge of the scalp incision. The higher the arc of the incision, the less muscle will be destroyed. Muscle is then reflected downward with a periosteal elevator to mobilize the myoperiosteal flap. Some surgeons choose to incise temporalis muscle as scalp is being cut, resulting in a myocutaneous flap; however, this incision will transect or denervate more muscle than separately reflecting the muscle. However, this myocutaneous incision usually does not produce significant adverse consequences.

Bone

The presigmoid approaches typically include a temporal-occipital execution of craniotomy and mastoidectomy, to expose dura of the middle fossa and lateral suboccipital area and allow identification of the locations of the superior petrosal, sigmoid and transverse sinuses [37]. Removal of the squamous part of the temporal bone provides a visual path over the tentorium which will minimize the required retraction of the temporal lobe. For a description of safe placement of burr holes for the retrosigmoid approach, see Lang and Samii and also Raza and Quinones-Hinojosa [38, 39]. The drilling of the temporal bone, which is commonly done under high magnification by an otologist, is not within the scope of this text. The required extent of removal of bone is determined by the exposure needed to achieve the surgical goal. Exposed air cells of the mastoid bone must be sealed with bone wax as they are encountered.

Dura

Dura must be gently and carefully separated from the petrous portion of the temporal bone as the sinodural angle is expanded and the presigmoid dura exposed. The durotomy is dependent on the surgical target and surgeon preference. An approach which includes dividing the superior petrosal sinus will be described. A horizontal incision is made in the temporal dura mater above and parallel to the superior petrosal sinus (SPS) and extended posteriorly toward the sinodural angle. A vertical incision is made in the presigmoid dura and below the SPS. The SPS is ligated and severed between hemoclips. The dural incisions are then connected, and the cut is extended medially to divided the tentorium all the way to the incisura. The tentorial flap can then be retracted with sutures. (See detailed description of the petrosal venous complex by Tanriover et al.) [37].

Restoration

The temporal dura mater is repaired primarily with sutures. The posterior fossa dura cannot be primarily repaired; instead, reconstruction is done in layers. If the mastoid antrum was opened during a translabyrinthine approach, it should be obliterated with myoperiosteal tissue then a temporalis fascia graft is laid over. The open mastoid air cells must be inspected and sealed with bone wax. The mastoid recesses are packed with fat graft harvested from the abdominal subcutaneous fat. The mastoid cortex is restored with hydroxyapatite bone cement. The bone flap is secured with titanium plates and any bone chips that are available are placed in the defect in mastoid bone and covered with Surgicel® to prevent its immediate displacement during irrigation. Soft tissue near the lower end of the incision is approximated with 2-0 or 3-0 absorbable sutures. The myoperiosteal layer is tightly closed with 2-0 Vicryl sutures.

Skin is repaired in two layers in the usual manner. The edges of skin are aligned and repaired with running non-absorbable 3-0 sutures. If there will be ventricular drainage of CSF for a few days, the skin edges can be repaired with running 4-0 Vicryl Rapide® sutures.

Retrosigmoid Approach [40]

This is an approach to the cerebellopontine angle immediately posterior to the sigmoid sinus and is often described as a keyhole approach, because of its usual small size; however, it can be quite large. There are several variations, and the details of teach will not be described [41–44]. Common uses include resection of tumors in the cerebellopontine angle, for example, meningiomas and acoustic neuromas. The term “retrosigmoid approach” is occasionally applied to a much larger cranial opening.

Positioning and Immobilization

The supine position is commonly used for retrosigmoid approach. The patient is in the supine position with trunk in approximately 15° of reverse Trendelenburg and rotated 45–60° in the contralateral direction. The head is immobilized in a Mayfield three-point fixation device and depending on body habitus and flexibility of the cervical spine, rotated 45–60°, and slightly extended.

The full lateral position is also commonly used. The trunk is placed in approximately 20° of reverse Trendelenburg and a 3-point Mayfield clamp used to immobilize the head in the lateral position.

Plastic Neurosurgical Concerns

- Cosmetic incision of scalp
- Avoid violation of skin of external auditory canal
- Minimize injury to sternocleidomastoid muscle
- Plan exact location, size, and shape of craniectomy
- Execution of craniotomy
- Durotomy
- Protect sigmoid sinus
- Repair of dura (reestablish dural envelope)
- Replace and secure bone flap
- Restoration of muscle
- Cosmetic repair of scalp

Scalp

Several incisions have been described for retrosigmoid approaches, each with variations. A common incision is a curved incision beginning approximately 2.5 cm above and behind the pinna and arcing down and anteriorly to a point near the tip of the mastoid process of the temporal bone; however, a less curved incision is sometimes used.

Muscles

The suboccipital muscles are incised in a C-shaped fashion to create a flap away from the line of skin incision which facilitates repair and minimize the incidence of CSF fistula. The myoperiosteal layer is stripped off occipital and mastoid bones to expose the asterion which roughly corresponds to the transverse sigmoid sinuses junction.

Bone

A neuronavigation system is extremely helpful in identifying and marking the locations of transverse and sigmoid sinuses. A burr hole is placed just below the transverse sinus and behind the sigmoid sinus, at the asterion. A roughly circular craniotomy is marked with ink posteriorly and inferiorly from the burr hole [45]. The size of the craniotomy is determined by the size and location of the surgical target and by surgeon preference. An osteotomy is made along the inked line and the free bone flap removed. It is often necessary to enlarge the cranial opening, particularly anteriorly, with a Kerrison rongeur flush with the edge of the sigmoid sinus. All open-air cells of the mastoid bone must be sealed with bone wax. This cranial opening exposes the junction of the transverse and sigmoid sinuses.

Durotomy

The dura that is adherent to bone near the sigmoid sinus must be gently and carefully separated from the petrous portion of the temporal bone as far down as the jugular bulb. An anteriorly based C-shaped durotomy produces a flap that can be reflected forward over the sigmoid sinus. The upper anterior end of the durotomy should be near the junction of sigmoid and transverse sinuses. It is important to leave a cuff of dura below the transverse sinus of sufficient size to allow safe placement of sutures during repair of the durotomy. A moist strip of Duragen is kept on the dural flaps that are reflected toward the transverse and sigmoid sinuses with sutures. These will keep the dura from drying up and shrinking under the microscope light heat during the procedure. The Duragen needs to be intermittently irrigated and kept moist.

Restoration [46]

Closure should be performed in 5 layers as follows: dura, bone, muscle, subcutaneous tissue, and skin. This multilayer closure prevents CSF leak and ensures optimum restoration.

Dura is repaired with running 4-0 non-absorbable or absorbable suture. Often the edges of dura cannot be coapted perfectly, in such case a dural graft using autogenous muscle or fascia can be used to achieve watertight closure. Regardless, it is best to place a strip of Gelfoam® or absorbable Duragen® over the durotomy and apply a tissue adhesive to assist in sealing the durotomy. A search should be for air cells of the mastoid bone, and bone wax should be packed into all identifiable or suspicious openings. The cranial defect should be repaired in a manner that reestablishes the bony contour and prevents contact with, and therefore healing of, muscle to dura. There are multiple techniques for doing this, each with claims of success. The bone flap can be secured with titanium plates and swarf loosely packed into the cranial defect and covered with sealant; however, some surgeons do not secure the flap in place. A synthetic material, for example, hydroxyapatite bone cement HydroSet (Stryker) is used to replace the bone flap and conform to the bony convexity.

Muscles and fascia should be sutured to their counterparts. The upper edge of the freed muscles and fascia should be firmly sutured to either a surviving cuff of fascia on the occipital bone [5].

Subcutaneous closure is performed in a tight fashion using 3-0 Vicryl sutures. Tight closure will prevent percutaneous CSF leak and if a fistula develops, it will lead to pseudomeningocele instead. This will minimize the risk of meningitis.

Skin edges can be repaired with running 4-0 Vicryl Rapide® sutures.

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13 Approaches to the Posterior Cranial Fossa

Ken Rose Winston

Midline Approach

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Minimize injury to suboccipital muscles.
- Execution of craniotomy.
- Durotomy.
- Repair dura (restore the dural envelope).
- Replace and secure bone flap.
- Restore occipital muscles and fascia.
- Cosmetic repair of scalp.

Positioning and Immobilization

The patient is placed in the prone position with the trunk in 15°–20° of reverse Trendelenburg. The semisitting position provides excellent exposure for surgery in the posterior fossa. It provides a low intracranial venous pressure and gravity assisted drainage of blood and CSF, and risks of air embolism and systemic hypotension are relatively low. The semisitting position is avoided by surgeons unfamiliar with its use because of concern for the risks associated with the sitting position [1]. The true sitting position has high risks of serious complications and should not be used.

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Both of these positions require rigid cranial fixation with (Mayfield head holder) immobilization of the head in the *position of military attention*. The upper cervical spine is flexed with straightening and extension of the mid and lower cervical spine. The chin must be separated from the manubrium by approximately two finger breadths (determined by palpation) to prevent cervical venous compression which will raise the intracranial venous pressure, elevate the intracranial pressure, and increase intraoperative venous bleeding.

Scalp

A midline incision is marked with ink from approximately 1 cm below the occipital protuberance down to approximately the fourth spinous process. Most surgeons choose to make a straight midline incision. A sigmoid curve through the hair-bearing portion of occipital scalp results in a less noticeable scar but does require undermining along the convex areas on each side of the incision.

Muscle

A midline incision is made with a scalpel, beginning at the external occipital protuberance, within or along the ligamentum nuchae through fascia and down to the squamous part of the occipital bone and over the spinous processes of C1, C2, and C3. Muscles are retracted aside with self-containing retractors. Separation and tight lateral retraction of the muscles can avulse the musculofascial attachment of the posterior cervical muscles along the superior nuchal line. This will make their anatomical reattachment difficult, but if it occurs, it can be easily managed. It is best to transversely cut the fascia and muscle approximately 1–1.5 cm below the superior nuchal line, thereby leaving a cuff of fascia to be used for reattachment.

The fascia on each side of the C2 and C3 spinous processes is cut and the muscles attached to these processes are cut. In young children, it is often not necessary to expose the C3 process.

A curette is used to clear soft tissue attachments from each hemilamina of the C1 arch and the inferior edge of the undersurface of the foramen magnum. Self-retaining retractors are used to hold muscles aside as they are separated from the occipital squama and cervical arches. Firm retraction of muscles to the depths of the incision assists greatly with hemostasis. It is important to expose a wide portion of the occipital bone. Straight and angled curettes are used to clear soft tissue attachments from the inferior edge of the foramen magnum. Neither knife nor electrocautery should be used far laterally on the C1 laminae because of the risk of injuring a vertebral artery, which can result in infarction of the brainstem and death.

Bone

Some surgeons, as a matter of perceived necessity, routinely remove the posterior arch of C1 with a Kerrison rongeur before making the craniotomy. This author removes the C1 arch *only when recognized as necessary* for adequate exposure. Using curettes, the arch must first be cleared of soft tissue attachments. A microneedle cautery can be quite helpful in clearing the medial halves of the arch but should not be used laterally because of risk of injuring a vertebral artery. A midline defect in the posterior arch of C-1 may be present in infants and occasionally in older patients. Failure to recognize this can lead to accidental violation of the spinal dura.

The cranial opening is usually made with right-left symmetry but can be intentionally made asymmetric to address an off-center lesion. A straight transverse osteotomy is marked with ink below the transverse sinuses and, in teenagers and adults, extending for 3.5–4.5 cm to each side of the midline. It then arcs acutely downward on each side toward the lateral part of the exposed edge of the foramen magnum. Two burr holes are required, each being just below the transverse sinus and having their medial edges approximately 8 mm from the midline. It cannot be safely assumed that the bone on the two sides is of equal thickness. A craniotome is used to make two osteotomies, each beginning at a burr hole and extending laterally along the inked line and down to within a few mm above the foramen magnum. After carefully separating the underlying dura between the two burr holes with a nerve hook, the remaining midline bone at the top of the developing bone flap is removed with a narrow Kerrison rongeur. If there is a significant bony keel, it can be disrupted with a narrow osteotome.

Depending on the size of the two remaining bridges of bone at the lip of the foramen magnum, they can usually be fractured by prying outward on the upper edge of the otherwise free bone flap, but these sites may require disruption with an osteotome or Kerrison rongeur. The craniotome cannot smoothly and safely be used to cut across the rim of the foramen magnum. The free bone flap must be removed slowly because it often includes a curved spike of bone wrapping laterally on one or both sides. Quick removal can dangerously indent and scrape against the dura at the foramen magnum. These bony spikes may require removal with a narrow rongeur to allow safe removal of the free bone flap. The dura is always densely adherent along the inner edge of the foramen magnum and its separation must be completed with curettes.

Off-Midline Posterior Fossa Craniotomy Through Midline Scalp Incision

The technique is the same as described above but, depending on the surgical target, may not require extension to the foramen magnum. This exposure is most appropriate for managing unilateral epidural hematomas and small lesions within one cerebellar hemisphere.

Dura

A U-shaped durotomy with its base at the top of the cranial opening is most commonly used for surgeries into the posterior cranial fossa [2]. The durotomy is begun with a vertical incision with a #11 blade, approximately 8 mm from the mid-lateral extent (either side) of the exposed dura and extended upward with microscissors to approximately 4 mm below the transverse sinus. The durotomy is then extended downward in an arc toward, but not across, the midline and just above the location of the foramen magnum. An identical durotomy is made on the opposite side, meeting the first incision near the midline. This produces a dural flap that can be retracted upward with sutures. The retraction sutures should be inserted near the edges of the flap to maintain constant tension until the time of repair, thereby limiting contraction. The lateral edges of the intact dura are also retracted with sutures. If the dura remains slack or has only minimal tension, it will contract during surgery, making the approximation of the edges quite difficult or impossible. Beginning just above the location of the foramen magnum, a vertical midline durotomy extends across the craniocervical junction toward the C1 vertebral arch. If more cervical exposure is necessary, as is often true, one or more of the cervical arches must be removed. Cervical extension should be done on an as-needed basis and not as a matter of routine. The vertical incision in the cervical dura can be extended as far as needed and its edges retracted with sutures.

Some surgeons prefer a Y-shaped incision instead of the U-shaped incision, but this provides a little less-wide exposure. Transverse incisions in the dura may be used to approach small lesions near the posterior surface of the cerebellum, but snug dural repair can be difficult.

Hemostasis—Small bleeding sites along the lateral portions of the durotomy are typically easy to control by brief compression with a hemostat or needle holder. Electrocautery should be used minimally but preferably avoided. However, the dura near the foramen magnum contains many veins and hemostasis can be frustratingly difficult to attain. For this reason, the dura should be cut approximately 2–3 mm at a time, followed with hemostasis by the compression technique or with sutures. Hemostasis by cauterization can be useful for small bleeding sites but is not effective for large venous sites, and prolonged failed attempts desiccate the dura and causes shrinkage, which will make repair difficult. Infants and newborns typically have prominent veins, for example occipital and circular sinus, that can pose difficulty for hemostasis, particularly in patients with Chiari II malformations.

Restoration

Dura

Repair of the dura of the posterior fossa can be difficult, particularly for the inexperienced. It is usually possible to achieve a complete primary repair (direct apposition) if minimal shrinkage has occurred from cauterization and if suturing is done correctly. Using a running “cheating” technique with absorbable 4–0 suture, repair should begin at one end of the durotomy, not near the middle. Some surgeons use the interrupted technique with non-absorbable sutures. A thin strip of Gelfoam® is placed along the durotomy, not over the entire exposed dura.

Bone

The bone flap is returned to its normal position and secured at two sites along its top, using two absorbable 2–0 sutures, each positioned approximately 1.5 cm from the midline. This requires holes to be drilled near the upper edge of the bone flap and matching holes drilled through the intact occipital bone. Some surgeons prefer to secure the bone flap with multiple plates; however, plates are not required unless the craniotomy extends above the transverse sinus. Lateral fixation is not necessary unless the cervical musculature is severely deficient, as may occur following multiple surgeries or prior irradiation.

Muscle

If the upper end of the muscle mass has been surgically separated from the occipital bone, or avulsed during retraction of muscles, it is important that the muscle be reattached either to a fascial cuff or directly to the bone via holes drilled in the bone for this purpose. The reattachment of the muscle can be difficult or impossible without reducing the extension of the neck, which requires that the rigid cervical flexion be reduced. The surgeon must hold the head while a non-sterile person loosens the arms of the Mayfield head-holder. The neck is extended by a few degrees and the head-holder is then re-tightened. The anesthesiologist must always participate in advance of this repositioning. A 2–0 suture is used to pull the upper medial corner of each paraspinous muscle and fascia snugly upward and sutured to the medial edge of the fibromuscular cuff on the contralateral side or secured directly to bone.

The abutting sides of the occipital and paraspinous muscles are sutured together, in a minimum of three layers, starting in the deepest portion of the surgical site. The fascial layer requires many sutures of snugly tied 2–0 Vicryl® (3–0 in infants and young children) placed approximately 6 mm apart. There is a tendency to inadequately approximate the deepest layer of muscles and the muscles overlying the upper portion of the occipital bone flap. It is important to avoid encircling large amounts of muscle with each interrupted suture as this causes necrosis of muscle and does not improve the security of repair or better reduce the risk of accumulation of CSF.

Scalp

The scalp is repaired in two layers in the usual manner. If the patient will have postoperative ventricular drainage and *not be receiving steroids*, the edges of the scalp can be approximated with absorbable suture such as Vicryl Rapid®. If there will *not* be postoperative ventricular drainage of CSF or if steroids will be administered, the edges of scalp should be closed snugly with *non-absorbable* sutures in a running technique or with staples.

Off-Midline Approach (Paramedian Suboccipital Approach) [3]

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Plan shape and size of craniotomy.
- Minimize injury to occipital muscles.
- Execution of craniotomy.
- Durotomy.
- Repair dura (restore dural envelope).
- Replace and secure bone flap.
- Restore occipital muscles and fascia.
- Prevent postoperative CSF leak.
- Cosmetic repair of scalp.

Positioning and Immobilization

The required position and immobilization are almost identical to those required for the *midline posterior fossa approach* as described above), however, the head is rotated approximately 20° to position the planned site of surgery uppermost.

Scalp

Option 1

A wavy vertical incision is made approximately 4 cm lateral to the midline and extending from about 1 cm above the transverse sinus, as identified on neuroimages, to approximately 3 cm below the occipital bone as identified by palpation. The planned incision should be marked with ink.

Option 2

A hockey stick-shaped incision begins as described above for the *Midline Posterior Fossa Approach*, but the upper end the incision is extended laterally and courses above the transverse sinus, as identified on neuroimages, for approximately 3–5 cm. Most surgeons choose to make a straight vertical incision but a sigmoid curve through the hair-bearing scalp results in a scar that is less noticeable.

Muscle and Other Soft Tissues

In association with the option 1 scalp incision, a vertical full-thickness incision is made with a scalpel through fascia and muscle, approximately 4 cm from the midline in a plane, parallel to the fibers of the exposed muscle, beginning at the musculofascial attachment on the occipital bone and extending downward over the occipital bone. Cutting with electrocautery causes excessive damage to the muscle. The occipital muscles are separated from the occipital bone with a periosteal elevator. Self-retaining Weitlaner retractors (upper one angled and lower one straight) are used to hold the muscle fibers aside and assist in hemostasis as the muscle is separated from the bone. Occasionally the retraction will separate a few cm of the fascial attachment of muscle from bone.

In association with option 2 scalp incision, a vertical midline full-thickness incision is made with a scalpel in the cervical midline along the ligamentum nucha and down to the spinous process of C1. The fascia is cut on each side of the C2 and C3 spinous processes and the cervical muscles attached to these processes are cut. A transverse incision in made through fascia and upper edge of the muscle starting at the upper end of the midline incision and extending laterally for approximately 5 cm, leaving a musculofascial cuff on the occipital bone. The occipital muscles are separated from the occipital bone with a periosteal elevator and the myocutaneous flap is reflected with Weitlaner retractors.

Bone

The planned craniotomy is marked with ink. Only one burr hole is required, and it is usually placed below the transverse sinus but can be placed above the sinus to facilitate higher exposure. The upper side of the craniotomy is straight transverse, and the sides are curved. The cranial opening can extend down across the edge of the foramen magnum, but this is not always necessary. An osteotomy along the marked line is made with a craniotome and the bone flap is removed. If the rim of the foramen is to be removed, this is best accomplished with rongeurs instead of craniotome. The dura is always densely adherent to the bone at the foramen magnum and separation should be done with curettes. The vertebral artery lies nearby and must be anticipated and avoided.

Dura

A vertical or hockey stick incision is commonly chosen but occasionally a U-shaped durotomy may be chosen. Retraction sutures should be inserted near the edges of the flap and around the intact free edges of the dura to maintain the dura under tension throughout the surgery and minimize desiccation and retraction. Small bleeding sites along the dural edges are typically easy to control by brief compression with a hemostat or needle holder. Use of cautery desiccates the dura, causes shrinkage, can increase the difficulty of repair, and should be used sparingly.

Restoration

Dura

Primary repair of the dura can be difficult or impossible if significant desiccation has occurred from cauterization or exposure to air, and, very importantly, if suturing is not done correctly. The "cheating" technique should always be used. Each needle puncture should be made no more than 2.5 mm from the edge of the dura and the dural edges pulled snugly together. The dural flap can often be stretched a few mm with a needle holder or hemostat. If the dural edges cannot be approximated, a patch will be required. An excellent and convenient material for patching is fascia harvested from the surface of the cervical musculature. However, if this is not available, a synthetic material such as Suturable Duragen® can be used [4]. The dural approximation should bring the edges snugly together, but a long-lasting *water-tight repair*, although commonly claimed, is not often achieved. A narrow strip of thin Gelfoam® is placed over the suture line but not over the entire exposed dura.

Bone

The bone flap is returned to its normal position and secured along its top with two absorbable 2-0 sutures. This requires the matching holes to be drilled in both the bone flap and in the intact cranial bone. If the craniotomy extends above the site of the expected reattachment of the muscle to the bone, plates are required to secure the bone flap along its top side. Some surgeons prefer to use titanium plates across the top, but this is rarely if ever necessary in the author's opinion, to secure the sides of the bone flap.

Muscle

Muscle which has been separated from its insertion to bone, either by surgical incision or by traction, must be reattached. If a secure musculofascial cuff remains on the intact bone, this should be used for the reattachment of the muscle and fascia. If not, approximately three oblique holes can be drilled in the bone along the superior nuchal line and used for attaching the muscle to the bone with 2–0 absorbable sutures. If the muscles cannot be stretched sufficiently to achieve reattachment at their original sites, it will be necessary to have a non-scrubbed person loosen the tightening screws of the Mayfield head holder while the surgeon holds the head and extends the neck by a few degrees before the screws are retightened. The midline muscle-to-muscle approximation should be done in at least three layers, starting in the deepest portion of the surgical site, and grasping small bites of the muscle. Grasping large bites causes infarction.

Scalp

The scalp is closed in two layers in the usual manner. If there will be no ventricular drainage or if steroids will be administered postoperatively, the edges of the scalp should be closed snugly with non-absorbable sutures, in a running technique or with staples. Otherwise, scalp edges can be approximated with an absorbable suture such as Vicryl Rapide®.

Far Lateral Suboccipital Approach (Broad Unilateral Approach) [5–9]

The far lateral suboccipital approach provides a broad unilateral exposure into the posterior cranial fossa and may be thought of as a large retrosigmoid approach.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Execution of craniotomy.
- Durotomy.
- Repair dura (restore dural envelope).
- Replace and secure bone flap.
- Restore occipital muscle and fascia.
- Prevent postoperative CSF leak.
- Cosmetic repair of scalp.

Positioning and Immobilization

The patient is placed in a three-quarter prone position with the trunk in approximately 20° of reverse Trendelenburg. The head is rigidly immobilized in a Mayfield head holder with approximately 30° of upper cervical flexion, head tilt of approximately 20° to the contralateral side, and cervical rotation of about 30°, in order to place the site of surgical interest uppermost.

Scalp

A flat-topped U-shaped incision is made with its top about 1.5 cm above the transverse sinus. The arm of the U-shaped incision includes a straight or wavy vertical incision approximately 2 cm ipsilateral to the midline in the hair-bearing scalp and a downward directed retrosigmoid incision across to the midportion of the mastoid process. Most surgeons choose to make straight incisions for the vertical limbs which lie in the hair-bearing scalp, but a gentle sigmoid curve results in a scar that is less noticeable.

Muscle

The muscle is dissected from attachment to the occipital bone and upper portion of the mastoid process and reflected downward. Soft tissue can then be separated from the bone across the occipital squama and, depending on exposure required, down across the foramen magnum and the hemilamina of C1–2. Care must be taken to avoid injury of the vertebral artery. The myocutaneous flap is reflected down and retracted laterally with Weitlaner retractors.

Bone

The planned osteotomy is outlined with ink. The size of the required craniotomy varies greatly and must be tailored to the size and location of the surgical target and surgical goals. A large cranial exposure will be described but not all far lateral approaches require craniotomy of this size.

One burr hole is placed just below the transverse sinus and approximately 1.5–2.5 cm from the midline and a second burr hole is placed just below and behind the asterion. An osteotomy is made from the first burr hole down to near the foramen magnum and a second osteotomy connects the two burr holes. A third osteotomy arcs downward from the second burr hole to near the foramen magnum. The bone at the edge of the foramen magnum can be disrupted with a rongeur or, if small, by prying the bone flap outward to fracture these connections. Persistent soft tissue attachment at the inner edge of the foramen magnum can be disrupted with an angled curette. If exposure of the vertebral artery is desired (not common), additional occipital bone can be removed laterally with rongeurs. The dura is often adherent to the bone laterally. If exposure in that area is necessary, this dura can be dissected free as far as the jugular bulb. As much of the mastoid process as necessary may be removed with a burr and Kerrison rongeurs. The posterior third to half of the occipital condyle may also be removed with a burr without compromising stability. If lower cervical exposure is needed, hemilaminectomy of C1 and possibly lower vertebrae will provide this.

Dura

Entry is made in the lateral midportion of the dura and extended with scissors in an arc toward the junction of the sigmoid and transverse sinuses and is then extended downward and posterior-laterally toward the foramen magnum and, if needed, into the cervical dura. It is important to leave sufficient dura behind the vertebral artery to accept sutures during repair. Significant venous bleeding can be encountered as the durotomy crosses the dura at the foramen magnum and the surgeon must be prepared to deal with this.

Reconstruction

Dura

Dura is closed with running 4–0 absorbable suture, and usually no serious difficulties are encountered. A patch is sometimes required. A narrow strip of Gelfoam® is placed along the sutured durotomy but not over the entire exposed dura.

Bone

The mastoid bone should be carefully inspected for exposed air cells, and all of these, including suspicious sites, should be sealed with bone wax. The bone flap is replaced and secured with two plates at the upper edge of the flap and perhaps one across the paramedian osteotomy. Bone swarf can be loosely packed into the lateral kerf and over the site of mastoidectomy.

Muscle

Muscles should be sutured to their posterior counterparts in two or three layers. The upper edge of the freed muscles and fascia should be firmly sewn either to a surviving cuff of fascia on the occipital bone or directly to the bone, using holes drilled for this purpose.

Scalp

The scalp is closed in two layers in the usual manner. The edges of the scalp are aligned and closed with running non-absorbable 3–0 or 4–0 sutures.

Supracerebellar Approach [3, 10]

This approach provides exposure across the upper surface of the cerebellum, beyond the tentorial hiatus, and into the lower portion of the pineal region. The tentorium remains *intact*.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Execution of craniotomy.
- Durotomy.
- Replace and secure bone flap.
- Restore occipital muscles and fascia.
- Prevent CSF leak.
- Cosmetic repair of scalp.

Positioning and Immobilization

The most commonly used position for this approach is the same as that described for the *midline cerebellar approach* but with slightly more cervical flexion.

Scalp and Muscle

A midline incision is marked with ink from approximately 1 cm below the occipital protuberance down to the fourth or fifth cervical spinous process. Most surgeons choose to make a straight incision, but a sigmoid curve through the hair-bearing scalp results in a scar that is less noticeable.

Bone

A moderately large cranial opening is necessary to safely accommodate the mild outward displacement of cerebellum that occurs as it is *gently* retracted downward. (A small craniotomy will require the surgeon to apply more downward force on the cerebellum to achieve adequate exposure, and this increases the risk of injury to the brainstem. A broad craniotomy which extends up to the inferior edge of the transverse sinuses usually provides adequate exposure, but some surgeons extend the craniotomy upward across the transverse sinuses and torcula. The craniotomy only needs to extend inferiorly to approximately 1 cm above the foramen magnum. Extension across the foramen magnum contributes little if any additional benefit to supracerebellar exposure.

A straight transverse osteotomy is marked with ink immediately below the transverse sinuses and, in teenagers and adults, extending for 3.5–4.5 cm to each side of the midline. It then arcs acutely downward on each side to meet at the midline approximately 1 cm above the foramen magnum.

Two burr holes are required, each being just below the transverse sinus and having their medial edges approximately 8 mm from midline. It cannot be safely assumed that the bone on the two sides is of equal thickness. A craniotome is used to make two osteotomies, each beginning at a burr hole and extending laterally and then downward along the inked lines to meet near the midline. After carefully separating the underlying dura between the two burr holes with a nerve hook, the remaining midline bone at the top of the bone flap is removed with a narrow Kerrison rongeur. Often there is a significant bony keel, which can be easily disrupted with a narrow osteotome. It is critically important to protect the transverse sinuses and torcula. Occasionally there are one or two small emissary veins over the torcula that require immediate coagulation and their presence should be anticipated.

Dura

A U-shaped durotomy is made with its base immediately below the transverse sinuses and torcula in the manner described above for the *midline posterior fossa approach*; however, the durotomy does not extend down to the foramen magnum. The flap of the dura is retracted upward with sutures. Any veins between the dura and upper region of the exposed cerebellum must be identified, cauterized, and cut, lest they be torn as the dura is retracted. If bone has been removed over the transverse sinuses, care must be taken when retracting the dural flap not to compromise the flow in the transverse sinus. The flap of the dura and the edges of the dura around the exposure should be snugly retracted and covered with wet cottonoids to minimize contraction which can greatly hamper its later repair.

Reconstruction

Repair of the dura, bone, muscle, and scalp is the same as described above for repair following the *midline posterior fossa approach*. If the craniotomy extended above the transverse sinuses, the upper edge of the bone flap should be secured with plates.

Supracerebellar-Transtentorial Approach

This approach provides exposure over the upper surface of the cerebellum and *upward* visualization through one leaf of the tentorium into the pineal region. It differs from the *suboccipital transtentorial approach* (described in **Convexity approaches to the cranial vault**), which provides exposure over one leaf of the tentorium and oblique d*ownward* exposure through one leaf of the tentorium into the anterior upper region of the posterior fossa and the pineal region.

Plastic neurosurgical concerns

- Cosmetic incision of scalp.
- Execution of craniotomy.
- Durotomy.
- Repair dura (restore dural envelope).
- Replace and secure bone flap.
- Restore occipital muscles and fascia.
- Prevent CSF leak.
- Cosmetic repair of scalp.

Positioning and Immobilization

The most commonly used position for this approach is the same as that described for the *midline cerebellar approach* (see above description) with slightly more cervical flexion and less reverse Trendelenburg.

Scalp

The surgery of the scalp and muscles required for this approach is identical to that of the *supracerebellar approach* described above.

Muscle

A midline incision is made with a scalpel through fascia and down to the squamous part of the occipital bone, then over the spinous process of C1, C2 and C3. The fascia on each side of these spinous processes is cut, and the muscles attached to these processes are separated from the bone. In young children, it is often not necessary to expose the C3 spinous process. Muscles are dissected aside with a periosteal elevator to expose the laminae of C1 and C2. Self-retaining retractors are used to hold the muscles aside as they are separated from the occipital squama and cervical arches. Firm retraction of the muscles to the depths of the incision assists hemostasis. It is important to expose a wide portion of the occipital bone. Neither knife nor electrocautery should be used laterally on the C1 arch because of the risk of injuring a vertebral artery, which can be fatal.

Bone

The cranial opening for this approach is the same as that for the *supracerebellar approach in* ***Convexity approaches to the cranial vault***.

Dura

The durotomy required for this approach is identical to that described above for the *supracerebellar approach.*

Tentorium

The tentorium can be easily viewed when the cerebellum is gently retracted downward. (Details on the retraction of the cerebellum are not within the scope of this text.) The exposed leaf of the tentorium to be incised should be closely inspected *under magnification* for the location of tentorial veins [11]. A minimally vascular appearing area of tentorium extending from approximately 1 cm anterior to the transverse sinus to the free edge of the tentorium is cauterized. A short incision is made with a #11 blade and extended with microscissors toward the middle of the free edge of the tentorium. The free edge of the tentorium must be coagulated before it is cut because it contains the medial tentorial artery, which arises from the meningohypophyseal trunk. The medial tentorial artery, when enlarged and supplying a tumor or vascular malformation of the tentorium, has the designation *artery of Bernasconi and Cassinari* [12]. Cauterization of the cut edges of the tentorial incision can safely shrink the tentorium, secure hemostasis, and improve exposure; however, the tentorium should *not* be cauterized far laterally because of the risk to cranial nerves which can receive tiny branches from this artery.

Reconstruction

The incision in the tentorium is not repaired. Repair of dura, bone, muscle, and scalp is the same as described above for repair following the midline posterior fossa approach. If the craniotomy extended across the transverse sinuses, the upper edge of the bone flap should be secured with plates.

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Plastic Neurosurgical Approaches for Spinal Surgery

14

Jens-Peter Witt

Posterior Approaches to the Spine

Plastic neurosurgical concerns

- Optimal exposure.
- Minimize injury to the paraspinous muscles.
- Minimize blood loss at the time of exposure.
- Secure hemostasis.
- Cosmetic restoration.

Positioning and Immobilization

Posterior access to the spine requires the patient to be in a prone position. The available spinal surgery tables (e.g., Mizuho OSI, ProAxis® and Berchtold) allow minimizing the intraabdominal pressure and secure fixation of the patient's head and neck. For all posterior spinal approaches, the pelvis should be softly resting on the *A*nterior *S*uperior *I*liac *S*pine (ASIS). The hips and knees should be slightly flexed to minimize traction on the nerves and muscle in the lower extremities. Specific attention should be given to chest padding to avoid pressure sores on the mammillae.

Posterior Cervical Spine

The patient's head is securely placed in a Mayfield-type head holder with a pressure of approximately 60 lbs./sq. inch. The placement of the pins is biased slightly anterior to avoid slippage and injuries to the bridge of the nose. The alignment of the neck should be neutral to avoid extensive flexion leading to upper respiratory tract

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swelling and compromise of the airway. A distance of two finger widths between the chin and chest or lower mandible should be maintained. Exceptions may be necessary in patients with severe congenital deformity or extreme obesity. In some cases, at the craniocervical junction, increased head flexion is necessary to gain access to the spinal canal. When planning for instrumentation of the posterior cervical spine, the alignment of the head and neck is a primary consideration. The safe final position should be verified and confirmed with intraoperative lateral X-ray before an incision is made. The placement of a reference frame on one of the lower cervical spinous processes must be considered, when using stereotactic navigation and planning the length of the cervical incision. The author prefers to not tape or pull the shoulders down to the end of the table because undue tension on arthritic shoulder joints, rotator cuffs, and brachial plexus can lead to significant complications.

Posterior Thoracolumbar and Sacral Spine

When planning for surgeries in the high upper posterior thoracic spine, the arms should be positioned by the side of the body, padded well, and loosely hanging in a sling that crosses the lumbar spine. If a T3 to ilium-type spinal reconstruction is planned, the arms are secured on the side of the body by tucking overlong sheets around the well-padded arms under the patient's body.

The lower thoracic and lumbosacral approaches require a forward flexed position of both arms ('superman position'). The author prefers increased lordosis for lumbar stenosis surgeries to invoke the "worst-case-scenario" for the lumbar spine. In contrast to that, a kyphotic lumbar spine position (Wilson frame, large gel rolls, with ProAxis® table flexion to 35°) is chosen to increase the interlaminar space in young patients with disc herniations.

Skin

Although scars resulting from posterior spinal surgery cannot be seen by patients without a mirror or camera and, with the exception of anterior cervical scars, most are camouflaged by clothing. Those who do see their scars may opine on the surgeon's expertise on the basis of the appearance of scars. The appearance of scars, regardless of location, is important to their owners [1]. Most incisions for spinal surgeries are straight and oriented vertically in the posterior midline, directly over spinous processes or a few cm lateral to the midline. Short incisions for placement of screws and other hardwares may be positioned a few cm lateral to the midline. The length of the incisions for spinal surgery has significantly decreased over the last few decades. This is partly due to the development of "minimally invasive spinal surgery", such as transtubular discectomy and endoscopic spinal surgery.

Closure

Subcutaneous tissue is approximated tightly with interrupted 2–0 or 3–0 absorbable sutures. If there is a significant amount of adipose tissue, this should be brought together in one or two additional layers with 2–0 absorbable sutures to minimize or eliminate the dead space. Care must be taken not to strangulate the less perfused adipose tissue and cause necrosis of fat. When approximating the deep subcutaneous layer, larger needles for increased tissue purchase are recommended to allow for a "just tight enough" closure that precludes compromise of blood supply. Sutures should be placed 1–3 cm apart in this sometimes-tenuous layer. The suture placement should be inverted when encountering the shallowest depth of the subcutaneous tissue or even dermis to avoid suture knots being expelled or leading to wound infection during the healing process. In case of a dural leak that is difficult to repair, watertight closure of the fascia and the skin is important. A locking running monofilament suture or a running vertical mattress suture (Donati) has shown the best maintained closure tightness [2].

Skin edges are approximated with staples or subcutaneous absorbable 4–0 monofilament sutures. The author prefers additional dermal glue in the area of increased need for cosmesis, e.g., anterior cervical, anterior, or lateral abdominal incisions, very soft skin, and first-time posterior spine incisions. Staples are preferred for redo posterior lumbar incisions with very tough skin. The same applies generally to posterior thoracic and cervical incisions due to their tendency for skin pressure and wound dehiscence. Poor skin repairs, for example overlapping edges, excessively tight sutures, and too few or too many sutures, significantly increase the risk of complications, such as poor healing, dehiscence, and infarction along wound edges.

Scar Revision

Incisions through scars often heal slowly, poorly, and become more cosmetically undesirable. If incision is required through a previously operated site, most scars should be excised, particularly wide, thin, and hypertrophic scars. (See *Revision of scar* in **Surgery of Skin**.) The skin on each side should be undermined to allow approximation of edges with minimal tension and subcutaneous layers brought together with USP 2–0 or 3–0 absorbable interrupted sutures that should be inverted because of the often-shallow depth of scar excision. The edges of the skin are approximated with a running USP 4–0 absorbable monofilamentous suture (e.g., Vicryl Rapide®) and/or glue (e.g., Dermabond®). In cases of hardening and unforgiving stiffness of the upper layers of the skin, skin staples and possibly vertical mattress sutures (2–0 Nylon) are needed. Wide Steristrips across the wound can minimize the tension during the early stages of healing. If broader soft tissue gaps must be closed, it is useful to employ Montgomery straps attached 5–10 cm along each side of the incision [3]. In these difficult situations, it should be considered to patiently place multiple approximating sutures starting at the midpoint of the incision and then to place subsequently more sutures with better purchase and improving closure. Orthopedic and plastic tendon repair techniques (e.g., triple pulley design) should be employed. Other strategies involve relaxing horizontal plane dissections in the scarred paraspinal musculature or in the rigid subcutaneous tissue, carefully avoiding devascularization of the skin. More recent development of reliable serrated suture materials (e.g., STRATAFIX™, V-loc™, Ethicon) has helped to reduce dehiscence in these difficult closures. If the fascia cannot be closed despite all intraoperative efforts, negative pressure wound therapy (NPWT), also called vacuum assisted closure (VAC) [4, 5] can be used. This technique is usually managed by a plastic surgeon. (See discussion in **Surgery of Skin**.)

Hemostasis of the Skin

Care must be taken to avoid heat damage to the most superficial layer of the skin. Hemostasis should be performed with irrigated bipolar forceps to deliver discriminating heat to specific small bleeding vessels. Monopolar electrocautery should be avoided in the upper most layer of the dermis. Most commonly sufficient hemostasis at the layer of the skin for spinal approaches can be achieved with tightly knotted inverted epidermal sutures.

Fascia

All posterior approaches to vertebrae require that fascia be incised longitudinally either in the midline or lateral to the spinous processes. For the unilateral lumbar and thoraco-lumbar approaches, most neurosurgeons incise the fascia in the midline. The incision of the spinal fascia should be planned with regards to the length and width of the needed exposure and to the availability and necessity. A slightly off midline, curved incision that is concave to the midline preserves the attachment of fascia to spinous processes and facilitates correct repositioning of paraspinous muscles. A curved fascial incision is as easy to make as a straight incision. If the removal of spinous processes and laminae is necessary, the midline fascial insertion to spinous processes should be painstakingly preserved on one or the other side. This is particularly important at the cervicothoracic junction where the functions of the trapezius and rhomboideus muscles rely heavily on solid midline insertions. Short transverse cuts in the caudal part of the lumbosacral fascia help to allow for more lateral exposure to the transverse processes without having to make the incision longer.

During closure, thin muscular tendon layers in the paraspinal musculature can be mistaken for the more robust fascial layer. Fascia tends to retract several centimeters beneath the subcutaneous layer, particularly in the cervical and cervicothoracic parts of the spine. Tight and solid closure of fascia is paramount to re-establishing the functionality of the underlying musculature, reduce postoperative pain, maintain spinal stability, build a barrier to CSF leakage, prevent wound dehiscence, and minimize dead space with its risk of fluid collection and hematoma. The author prefers to begin the closure of the fascial plane starting from the hard-to-access ends of the incision and continue toward the middle with tightly placed interrupted and absorbable USP 1–0 or 1 sutures, 0.5–1.0 cm apart. An overlapping pattern of figure-eight suture placements is preferred when dealing with CSF leaks that are difficult to repair. Fascial closure can be difficult over bulky spinal fixation hardware. Also, increased rigidity of tissue may have been caused by scarring after multiple surgeries or from prior wound infection.

Muscle

The paraspinous muscles have minimal and loose attachment to the dorsal fascia and strong discrete attachments to the vertebral laminae, transverse, articular and spinous processes but no attachment to the interspinous ligaments. Most often, the muscles are separated from their insertion on bone with electrocautery, a scalpel, or sharp periosteal elevator. The discrete attachments and insertion of the medial tract of the long and short muscles of the erector spinous muscle group can usually be identified by using a periosteal elevator to identify a plane along the interspinous ligaments and the lower part of the spinous processes. Each separate muscle bundle can be individually disconnected with the least amount of damage to the muscle bulk, using Mayo scissors, scalpel, or electrocautery. As the paraspinal musculature is very well perfused, great care must be taken to stay in the subperiosteal plane to prevent excessive blood loss and to minimize damage to the musculature. The vascular supply of the erector spinae muscles is segmental from the dorsal branch of the segmental vertebral artery. This artery passes just inferior to the transverse vertebral process and runs posteriorly beyond the inferior lateral border of the superior articular process and lateral to the pars interarticularis of the lamina to supply the medial and lateral paraspinal muscle groups with medial and lateral posterior arterial branches, respectively. The posterior branches of the segmental vertebral arteries build circumferential anastomoses around the facet joints, laminae, and spinous processes. During posterior exposure of the spine, significant blood loss can result from unknowingly injuring the dorsal segmental vertebral artery branches. Hemostasis can be challenging as these vessels tend to retract. The author advocates prospectively surveying and continuing to survey these vulnerable vascular sites. Paraspinous muscles must be retracted with self-retaining retractors and surgeons often have personal preferences regarding retractors. Retraction of paraspinous muscles serves two purposes: (1) provision of exposure and (2) assistance with hemostasis. The tightness of retraction and the size of the retractors play a major role in muscle damage and scarring. Muscle hypoperfusion and necrosis are related to retraction pressure and duration of retraction. Shorter skin incisions combined with smaller fascial openings and less muscle dissection can reduce visibility and necessitate increased demand on the retractor. This can lead to unnecessary retraction pressure and unplanned extension of the retraction time. Optimal access should never be compromised to achieve minimal invasion. It is optimal access, not minimal incision, which leads to safe and successful *minimal invasive spine surgery*.

Approximation of the paraspinal musculature after long posterior approaches along the entire length of the spine encounters several challenges (see Fig. 14.1) for layers requiring closure. The tightness of the sutures, which have considerable strength (1–0 and 1 USP), should be loose to moderately loose to prevent muscle necrosis and minimize pain. However, the bulk of the paraspinal muscle group should cover the exposed dura and vertebrae and return the muscle to its function as an erector and rotator of the spine. The approximation of the deepest musculature in the wound minimizes the deep dead space, which can become filled with

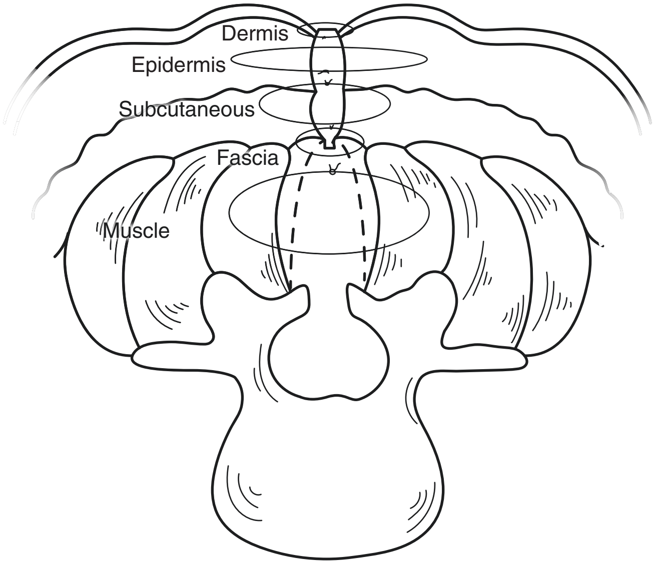

Fig. 14.1 Layers of closure for posterior spinal approaches

Table 14.1 Posterior spinal closures: description of suture intervals, size of suturing needle, tightness of knot, suture size appropriate for each tissue layer

Layer	Interval	Needle radius	Tightness (1–5)	Suture size USP
Dermis	5 mm	Small	2–3	4–0 or 3–0
Epidermis	5–8 mm	Small/medium	3–4	2–0 or 3–0
Subcutaneous	10–30 mm	Large	2–3	2–0, 1–0 or 1
Fascia	5–10 mm	Small/medium	5	1–0 or 1
Muscle	20–30 mm	Large	1–2	1–0 or 1

blood or CSF, harbor infection, delay healing, and cause pain. Some surgeons prefer to place no sutures in the musculature and rely solely on the fascial closure [6], and others place very shallow sutures to eliminate the dead space. The author prefers large radius needles with USP 1–0 absorbable sutures to achieve loose approximation of the muscle every 2–3 cm [(see Table 14.1) for details]. Attention should be paid to the reattachment of the musculature to the spinous processes. The author prefers a technique which guides the ipsilateral muscular suture loop anteriorly through the interspinous ligament between the two spinous processes to the contralateral side, curving through the paraspinal musculature then heading back between the spinous processes to the ipsilateral space and then tied with a loose to moderate strength. This technique allows for an anatomic anterior position of the paraspinal musculature and for a strong fascial closure to the posterior spinal ligament (Fig. 14.2).

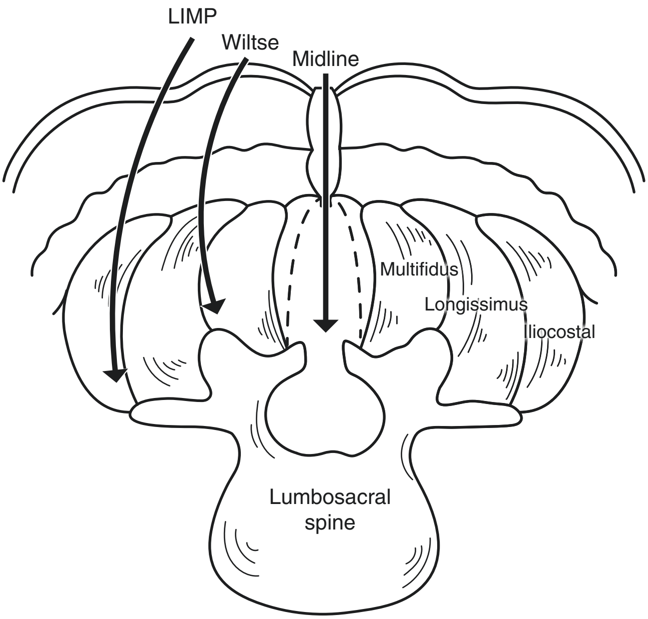

Fig. 14.2 Posterior approaches to the lumbar spine

Hemostasis of Muscle

The pre-incision injection of generous amounts of epinephrine into the paraspinous muscles is extremely beneficial in limiting blood loss and facilitating hemostasis from the arterioles. The prompt application of retraction against themuscles is also effective in establishing immediate hemostasis. Discrete sites of bleeding must be controlled by bipolar cauterization. The estimated blood loss varies greatly among different spinal procedures as shown in Table 14.2. These numbers are the author's approximations for preparing for spinal surgery. Longer surgeries and difficult hemostasis result in greater blood loss, and the rate of loss can vary widely. Meticulous hemostasis during the approach to the spine is important. In thoracolumbar surgeries that extend from T3 to the ilium, one might first consider making an incision from T2 to T11, performing the necessary hemostasis, decompression, instrumentation as planned, and partial closure of this incision. Then the lumbosacral part of the surgery is done. This approach can result in less early loss of blood from the very long incision before hemostasis is obtained and possible development of coagulation deficiencies. Uncontrolled bleeding and disseminated intravascular coagulation (DIC) have been reported. Two experienced spine surgeons or two teams operating simultaneously on surgeries with long exposures (e.g., scoliosis corrections) can reduce surgical times, blood loss, and complications [7]. In tumor surgery one might encounter such extended exposures with large resections.

Table 14.2 Length of procedure time and estimated blood loss volume for the representative spinal procedures

Procedure	Approximate length of surgery (h)	Estimated blood loss (mL)
Full-endoscopic lumbar discectomy	0.5	0–3
Cervical disc arthroplasty (cervical ADR)	0.5–1.5	5–20
Anterior cervical discectomy and fusion (ACDF)	0.5–1.5	10–25
Lumbar one-level microdiscectomy	0.5–1.5	
Lateral anterior-to-the-psoas lumbar interbody fusion (OLIF)	0.75–2	10–100
Lateral anterior transpsoas lumbar interbody fusion	0.75–2	20–150
Lumbar minimal invasive transforaminal interbody fusion (MIS-TLIF)	1–2	20–150
Lumbar three-level decompressive laminectomy	1.5–3	50–300
Thoracic three-level laminectomy and intradural tumor resection	3–5	50–500
Posterior two-level lumbar interbody fusion (PLIF)	3–5	100–800
Thoracolumbar 1-level anterior corpectomy, posterior 1-level decompressive laminectomy, repair of traumatic durotomy and posterior 4-level instrumentation and fusion for L1 burst fracture	4–6	400–1500
Thoracic 2-level transthoracic complete corpectomy with resection of 2-level posterior element and 5-level instrumentation and fusion, 2-level nerve ligation for metastatic tumor	6–8	500–2000
T3-ilium posterior revision surgery for previous hardware failure with 1-level pedicle subtraction osteotomy (PSO), 2-level Smith-Peterson osteotomy and 3-level transforaminal lumbar interbody fusion with repair of inadvertent CSF leak and use of vertebral body cement augmentation	7–10	1500–6000

Anterior Approaches to the Cervical Spine

Plastic neurosurgical concerns

- Optimal exposure.
- Minimize injury of the platysma muscle.
- Protection of the jugular vein, carotid artery, and trachea.
- Avoid injury of the thoracic duct.
- Avoid injury to the hypoglossal nerve (CN XII), superior pharyngeal nerve, and recurrent laryngeal nerve.
- Secure hemostasis.
- Cosmetic restoration.

Position and Immobilization

Anterior Cervical Spine

Placement of the head in a gel ring with slight extension of the neck and the body in 15°–20° of negative Trendelenburg to reduce venous bleeding. Some surgeons prefer careful shoulder traction with a long three-inch tape and/or neck traction with a chin strap or cranial tongs and a 5–15 lbs. weight. Special attention should be paid to positioning for repair of an odontoid fracture with odontoid screws and to positioning for transoral access to the craniocervical junction and axial cervical spine. Placement of an odontoid screw requires significant cervical spinal extension to allow for clearance of the trajectory over the patient's sternum and chest. The patient's head is taped to the posteriorly tilted head of the surgical bed with the placement of a soft but maximal dental block to allow for clear anterior–posterior odontoid X-rays [8]. Very wide opening of the mouth is required for transoral spine surgery, where specific intraoral retractor systems are required to optimize visualization of the posterior oropharynx [9].

Skin

For resections of one to four anterior cervical discs with fusion, anterior disc replacements, and two-level corpectomies, a skin incision is marked from the anterior midline laterally following a skin crease, skin fold or Langer lines for 5–7 cm (see Fig. 14.3). If a larger exposure is required to accommodate a skipped level or for more than a two-level corpectomy, the incision at its lower end is started in the midline and follows a skin crease laterally to the medial edge of the sternocleidomastoid muscle where the incision continues cranially. This skin incision allows for extended

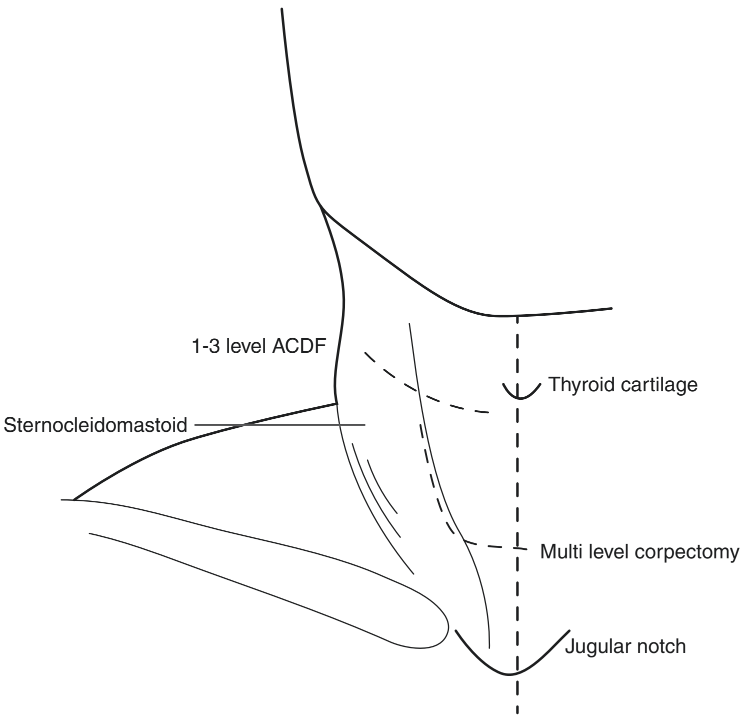

Fig. 14.3 Incisions in the skin for anterior approaches to the cervical spine

exposure but invariably leads to worse cosmetic results as Langer lines are being crossed [10].

Closure
The skin in the anterior neck is closed with USP 4–0 Monocryl resorbable suture in the subcuticular layer and with interrupted inverted USP 3–0 Vicryl as needed in the subcutaneous fat. Care must be taken not to excessively tighten these suture knots as this might lead to unwanted bulging skin folds.

Muscle and Other Soft Tissues

The platysma muscle is opened either by a careful split along the medial edge of the sternocleidomastoid muscle or with a cut through its fibers along the skin incision. The superficial and deep jugular veins can be ligated along its course on the medial edge of the SCM. The thin enveloping fascia along the medial edge of the sternocleidomastoid muscle is identified and followed medially with blunt and sharp dissection to the neurovascular sheath which contains the common carotid artery, internal jugular vein, and the vagus nerve. This bundle is carefully retracted laterally and the larynx–pharynx-complex with its lateral border comprised of sternothyroid, sternohyoid and thyrohyoid muscles is retracted contralaterally. At the C5–6 level, the omohyoid muscle commonly is seen to cross from medial cranially to lateral caudally. In some patients, this muscle must be transected to gain straight access to the anterior aspect of the cervical spine. The medial edges of the longus colli muscle are freed from their vertebral body insertion by about 5 mm on each side to allow for adequate exposure of the vertebral bodies and discs. Care must be taken to avoid injury of the more laterally positioned cervical sympathetic superior, middle and stellate ganglia on the longus colli muscle to avoid Horner syndrome [11]. Other important nervous structures to avoid are the recurrent laryngeal nerve, the superior pharyngeal and laryngeal nerves, and the inferior loop of the hypoglossal (CN XII) nerve. Direct low amperage nerve stimulation can be used to identify muscle innervation, for example the non-recurrent laryngeal nerve, which crosses the surgical approach in unexpected locations [12].

Closure
Anterior cervical incisions only require closure of the platysma muscle and the skin. Closure of the platysma muscle is strongly recommended because it contributes to the appearance and silhouette of the anterior neck. The author uses either interrupted and inverted or running USP 3–0 resorbable sutures for closure of this muscle.

Anterior Approaches to the Lumbar Spine

Plastic neurosurgical concerns

- Optimal exposure.
- Prevent postoperative anterior abdominal hernia formation.

- Protection of the intraperitoneal organs.
- Avoid injury during exposure to the psoas muscle, genitofemoral nerve, and gonadal vessels as well as presacral inferior hypogastric plexus.
- Avoid injury during retraction to the iliac vasculature.
- Secure hemostasis.
- Cosmetic restoration.

Position and Immobilization

Depending on the required access, the patient's arms are positioned straight out to the side and pillows are placed under the knees to decrease the abdominal wall tension and psoas stretch.

Skin

Depending on the level of lumbar spine surgery, either a paramedian or median vertical incision bypassing the umbilicus is chosen (see Fig. 14.4). In selected cases, for example approaching the L5–S1 disc space anteriorly, a low horizontal Pfannenstiel incision is made [13]. Under the dermis, the superficial fatty layer of subcutaneous tissue (Camper's fascia) is transected. A thin deep membranous layer of the subcutaneous tissue is encountered, and it closely follows the course of the main external muscle fascia (Scarpa's fascia). This layer is commonly closed together with the linea alba.

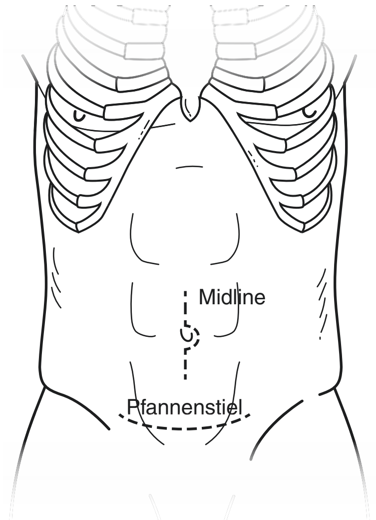

Fig. 14.4 Incisions in the skin for anterior approaches to the lumbar spine

Fascia

The fascia of the rectus abdominis muscle has a superficial and deep layer. However, the transection of this muscle and its fascial sheath is avoided by a vertical midline transection along the linea alba. The preperitoneal fat layer just off the midline can then be followed left laterally into the ever-widening retroperitoneal space. Previous abdominal incisions, trauma, and infections in the abdominal wall must be noted and carefully avoided. The fascia transversalis, which often can be identified just paramedian to the linea alba, inferior to the arcuate line as the lower part of the internal rectus abdominis muscle sheath covers the preperitoneal fat layer, can be mistaken for the peritoneum itself. In some cases, the mistake is only noticed when development of the false preperitoneal plain leads laterally into the thick aponeurosis of the quadratus lumborum muscle, making blunt and easy dissection to the psoas impossible. At this point, an opening of the fascia transversalis should be made in the anterior midline.

Retroperitoneum

The peritoneal sac with contents is carefully mobilized and retracted away from the inner abdominal wall. The left psoas muscle is identified and carefully followed to its medial edge.

The genitofemoral nerve, the ureter, and vascular structures, including the gonadal vessels and iliac artery and vein are oriented on the anterior surface of the long course of the psoas muscle and must be carefully preserved. Ligation of the iliolumbar, sacral, and ascending venous branches appears to ease the retraction of the iliac vessels specifically at the L4/5 level. Selective bipolar electrocautery should be used to prevent injury to the prevertebral autonomous genital innervation and retrograde ejaculation.

Retraction within the retroperitoneal space is used to prevent bowel injury and vascular injury, keeping in mind the particular needs to straight access with rongeurs, osteotomes and instrumentation to the lumbar spine.

Closure

The tight closure of the unifying fascial layer of the linea alba is important for the structural realignment of the abdominal wall. Strong resorbable interrupted USP 1–0 Vicryl sutures are being used or a running barbed or serrated suture (e.g., STRATAFIX USP 1 or 1–0). If possible, the underlying fascia transversalis is closed separately.

The subcutaneous and cutaneous layer is closed in a similar fashion to the posterior spine approaches.

Lateral Approach to the Lumbar Spine

Plastic neurosurgical concerns

- Optimal exposure.
- Avoid injury to innervation of the abdominal wall including T12, L1, L2 nerve roots, and iliohypogastric and ilioinguinal nerves.
- Secure closure of the fascial layers to avoid abdominal hernia.
- Cosmetic restoration.

Position and Immobilization

These approaches are defined by the lateral positioning of the patient [14]. More recently, lateral approaches to the lumbar spine have also been described with the patient in a prone position [15]. See above notes for *posterior spinal approaches*. (e.g., lateral ALIF, OLIF, etc.)

For lumbar spine access, the patient is commonly positioned on the right side. When operating with X-ray fluoroscopy to gain safe lateral access to the spine, it is paramount to establish an absolute lateral position of the C-arm gantry. This is being achieved by avoiding double lines of the posterior walls of the targeted vertebral bodies and confirming the lateral positioning by obtaining an anterior–posterior X-ray showing the spinous processes in the midline between the pedicles. In both views, the endplates outlining the disc space should be clearly visible. This can be challenging because coronal deformity may lead to a 45° rotation of the wedge that represents the targeted lumbar disc. Once this optimal lateral position of the patient in the C-arm X-ray beam has been established and secured, direct lateral retroperitoneal access to the disc space between L2 and L4 or even L5 is as safe and reproducible as possible. Any deviation of dissection away from a perfect vertical can be easily monitored and spatial orientation becomes less complicated. It must be mentioned that anatomic limitations to this approach might require adjustment and an advanced understanding and experience of this approach. Stereotactic navigation systems (e.g., Stealth, Brainlab, etc.) allow for some deviation from a precise lateral position, and surgeons have adopted up to 30° rotation of the patient for the oblique anterior-to-psoas approach and particularly for the lower lumbosacral spine L4–S1. A low-lying rip cage with steeply down-angling ribs and a high-riding iliac crest may require an angled approach with a cranial or caudal bias up to 15°. The patient is positioned on a large roll with approximately 1/3 of weight under the right hip crest and 2/3 just above the crest, thereby providing support of the right spinopelvic junction.

Alternatively, the table can be flexed 15° to allow for a straightening of the lumbar spine between the hip and chest. The lower extremities are brought up towards the chest, ideally with 90° flexion of the knees and hips. Two-inch-wide tape is used to secure the patient in a lateral position to the flat table. Pressure points under the right shoulder, axilla, hips, knees, and ankles are padded well. The arms are usually kept in a straight position forward from the body on height-adjusted armrests. Care must be taken to allow space for anterior–posterior X-ray imaging that is colinear to the targeted disc.

Skin

The incision in a direct lateral approach is centered over the projected disc space for a length of 4–8 cm along the Langer lines or parallel to the lowest rib (see Fig. 14.5). The subcutaneous fat can be of substantial thickness especially immediately close to the hip crest.

In a variant of the direct lateral approach, the oblique lateral approach targets the space anterior to the psoas and uses the anterior vertebral line as a radiographic landmark. Depending on the size of the patient, the skin incision is centered 5–8 cm anterior to the anterior vertebral line at a length of 2–3 inches along the Langer lines.

Muscle

The abdominal wall in its lateral aspect consists of three layers of musculature and an outer and inner strong fascial layer that flow towards anterior medially and form into the rectus abdominis muscle sheath. First, the external oblique muscle is encountered and split along its muscle fibers that run from posterior superior to anterior inferior. The second layer is the internal oblique muscle that courses from posterior inferior to anterior superior. Handheld retractors enable

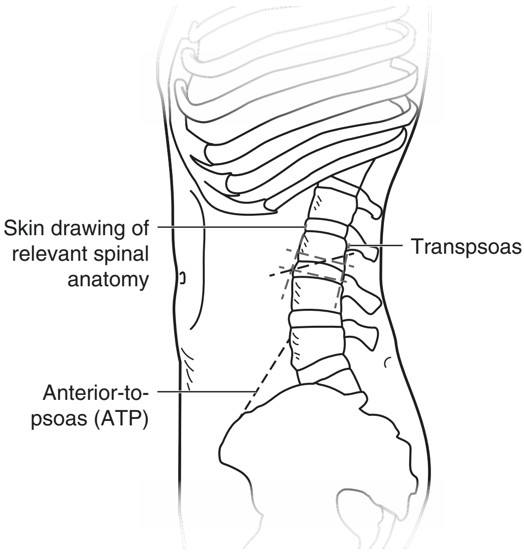

Fig. 14.5 Incisions in the skin for lateral approaches to the spine

visualization through these different muscle layers. Here we might identify the iliohypogastric nerve or the ilioinguinal nerve, originating mainly from L1 and supplying the abdominal wall with motor innervation. The course of these two nerves is highly variable as to a more superficial constraint course in the internal oblique muscle or a deep course just above the peritoneum in an unconstrained position [16]. Finally, the transversalis muscle with a horizontal fiber direction is being carefully split as well and the internal fascia comes into view. Together with Scarpa's fascia it covers the retroperitoneal space and should not be mistaken with the peritoneum itself. This fascial layer is carefully lifted and put under tension and a vertical incision is made allowing for digital palpation of the retroperitoneal fat space. This palpation reveals the transverse process and the string-like consistency of the lateral aspect of the psoas. If possible, the fibers of the psoas muscle should be identified with direct visualization. Failure to visualize the fibers might lead to inadvertent puncture of a peritoneal leave adhesion which might have adhesions to the anterior aspects of the psoas muscle due to inflammatory intraabdominal processes, e.g., IBS, Crohn's, diverticulitis, and others. Small and then sequentially enlarging dilators and retractor pedal are being inserted either directly through the psoas muscle fibers onto the center of the disc or under retraction of the anterior edge of the psoas onto the anterior part of the disc. Neuromonitoring with the tip of the dilators ensures that elements of the lumbosacral plexus are not being directly pinched but carefully translated and retracted posteriorly.

Closure

Skin closure is done in layers with interrupted 2–0 or 3–0 absorbable sutures. The skin edges are closed with a running 4–0 subcuticular monofilament suture, skin glue and a sterile dressing. A drain in the retroperitoneal space is rarely needed due to the small amount of bleeding. The musculature for the main part falls back into position as no muscle insertion needed to be removed, cut, or disconnected during the approach. If possible, the inner sheath of the abdominal fascia is closed with interrupted or a running 2–0 absorbable suture. The outer sheath of fascia covering the external oblique muscle closed in the same fashion.

Thoracic Approaches to the Spine

Plastic neurosurgical concerns

- Optimal exposure.
- Partial rib resection might lead to cosmetic complaints if the defect in the rib cage is substantial.
- Secure closure of the fascial layers to avoid abdominal hernia.
- Cosmetic restoration.

Position and Immobilization

For thoracic spinal access from T5 to T10, the patient is commonly placed on the left side to avoid the thoracic aorta. Vertebral bodies and disc spaces above T5 are difficult if not impossible to reach in a true orthogonal way for vertebral body replacements or decompressive discectomies [17]. The lower thoracic spine and thoracolumbar junction, which are often involved in traumatic injuries, can be accessed more readily with the patient lying on the right side. This allows improved access for diaphragmatic repair without the unmovable liver, making the retraction impossible.

Skin

Skin incisions follow the orientation of the ribs. As in the lateral lumbar spine access, the incisions should be projected truly lateral over the targeted spine pathology (see Fig. 14.6). High danger lies in the angulation of the approach angle in the lateral access to the spine in the lumbar region as well as in the thoracic spine: An incision that is made too inferior or superior to the targeted disc spaces and vertebral body will make efficient and safe discectomy and corpectomy impossible as one will not be able to directly visualize the entire disc space. The thoracoscopic assisted minimal invasive approach uses the angled optics to allow for visualization from multiple angles; however, the instrumentation (e.g., VBR insertion, screw, and plate fixation) again requires a strict orthogonal approach. An incision planned too

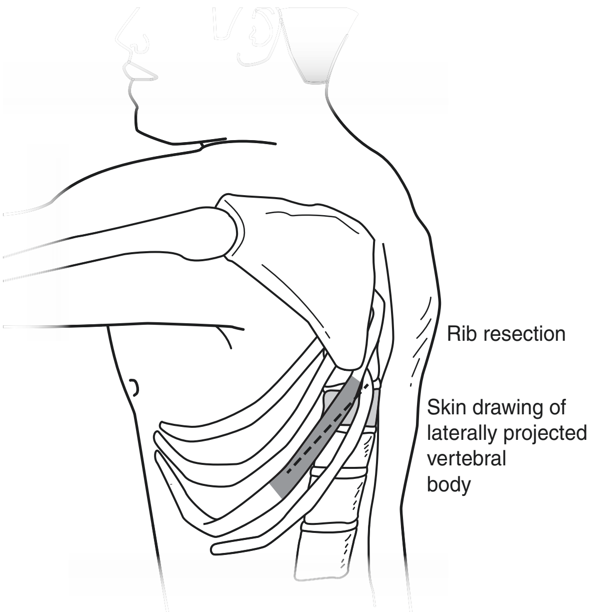

Fig. 14.6 Incision in the skin for transthoracic approaches to the spine

anteriorly may lead the corpectomy into the spinal canal and endanger the spinal cord. If the incision is planned too far posteriorly, the reach with rongeurs and curettes can threaten mediastinal organs and the thoracic vessels.

Muscle

The thoracic wall consists of rib cage and intercostal musculature. The external intercostal musculature displays a fiber direction from lateral superior to medial inferior. The internal intercostal musculature runs from lateral inferior to medial superior. The muscle layers are being separated from the rib insertion by following the fiber direction with a sharp periosteal elevator (Alexander type). In a cranial to caudal sequential arrangement, the intercostal vein, artery, and nerve course between the internal intercostal muscle fibers and a third muscle layer, the innermost intercostal muscles just on the underside of the corresponding rib. The first 6–8 cm lateral to the vertebral column, the intercostal neurovascular bundle, tends to be oriented more equally distant between the ribs. Resection of 5–10 cm of the rib is performed with the appropriate rib cutting tool. The endothoracic fascia is identified and incised in a line parallel to the ribs. The parietal pleura is now visible and with the help of thoracic surgery expertise can be opened for a true transthoracic approach or can be followed in the retropleural space laterally with careful sponge stick dissection towards the rib head insertion on the targeted vertebral body and disc space [18].

It may be necessary to split the diaphragmatic muscle for multilevel spine surgery that involves the thoracolumbar junction between T12 and L1. In these instances, the left crus of the diaphragmatic muscle insertion and the left medial and sometimes the lateral arcuate tendon insertion over the origin of the psoas insertion will be transected parallel to the anterior spinal line allowing for full access to the injured or affected vertebral level. Repair of this diaphragmatic split is recommended with 2–3 interrupted USP 2–0 absorbable sutures to avoid a left-sided transdiaphragmatic hernia.

Closure

The thin layer of endothoracic fascia should be closed, when possible, with a USP 3–0 running or interrupted absorbable sutures with medium tightness. In some patients, the intercostal musculature can be closed with the endothoracic fascia. Rib replacement and fixation may be attempted but can be problematic and disadvantageous when plate and screw fixation does not provide immediate stability as it can occur for the lowest floating ribs. A chest tube is routinely placed to continuous suction to allow for the drainage and seal of inadvertent lung tissue injuries and air leaks. The subcutaneous layer is closed with interrupted and inverted USP 2–0 absorbable sutures to achieve an airtight seal. The skin edges are approximated with USP 4–0 subcuticular running monofilament suture and STERISTRIPS or glue.

Other Approaches to the Spine

The transoral approach provides anterior exposure of the craniocervical junction, including the clivus and upper cervical spine. The details of this uncommonly required neurosurgical approach are described in excellent reviews. The soft tissue transection during this procedure involves the careful fenestration and flap dissection of the mucosa and thin muscular wall of the oropharynx over the anterior aspect of the C2 vertebral body. When possible, the placement of oral retractors, supine positioning, and closure should be performed with assistance of an otolaryngologist [19].

The presacral anterior approach to the lumbosacral junction is an approach that had been mostly developed around the implantation of one specific interbody fusion device (Axial IF, Trans1) for the L5–S1 or even more rarely L4–S1 interbody fusion [20]. The prone positioning requires hip and knee flexion. The 2 cm skin incision is made pericoccygeal with the help of guidance from ap and lateral X-ray imaging. Together with the coccygeal bone medially, the sacrotuberous and sacrospinous ligaments make up the coccygeal notch and guide the approach laterally and posteriorly. The pararectal fat space between the rectum and the sacrum is variable in thickness and adhesions and must be assessed before surgery carefully through medical history and MRI imaging of the sacrum or pelvis. The rectum in the sacral flexure is commonly not covered by the peritoneum. Closure is concerning skin closure only and can be problematic due to its vicinity to the anus. Minimal invasive posterior approaches to the spine might use a 2-inch and more off-midline skin incision to gain access to the lateral facet joints of the lumbar spine between the fascial enclosure of the multifidus and the longissimus musculature (Wiltse [21]) or the longissimus and the iliocostal muscle group (lateral intramuscular planar LIMP [6]) reducing intraoperative blood loss and the trauma of muscle dissection when compared to a midline approach. During closure, muscular sutures are not needed.

Problematic Surgical Wounds of the Spine

Draining wounds, infected wounds, and dehiscence are discussed in **Surgery of Skin.**

However, in cases of deep spinal infections, either as a complication of previous spinal surgery or as a primary infection site without prior surgery, the placement and removal of a hardware is dictated by the need for mechanical stabilization and decompression of the nerves and spinal cord. In the case of exposure of hardware and dura, primary closure of the wound is priority. The author, only in exceptional circumstances, will use a vacuum assisted closure device when skin and soft tissue closure is impossible due to mechanical restraints. As soft tissue scars harden and retract the exposed wound layers away from the midline of the original incision, care must be taken to reestablish anatomical perifascial layers with careful lateral dissection. Paraspinal multifidus and longissimus muscle bulk can be partially released laterally to allow for adequate hardware, dura, and bone coverage. The author prefers sharp mechanical debridement of soft tissue and bone with knife, curettes, and sharp Cobb dissectors accompanied by high pressure normal saline irrigation, 1.5% hydrogen peroxide solution and antibiotic powder placement (e.g., Vancomycin). Repeated incisions and debridement are scheduled until the obtained cultures become negative or the pathogen can be suppressed. Spinal hardware should be replaced only after cultures become negative. The management of these challenging wound situations is made with infectious disease specialists.

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15 Exposure of Peripheral Nerves

Kevin O. Lillehei

Plastic Neurosurgical Concerns in Exposure of Peripheral Nerves

- Place incisions in natural skin folds and creases when possible, e.g., Langer's lines.
- Attain adequate exposure.
- Cosmetic repair of skin.

Compromises often need to be made in order to adequately address the problem at hand. Peripheral nerves tend to run along the long axes of extremities and, most often, directly in opposition to Langer's lines. Surgery often requires exposure of segments of the nerve above and below an area of injury and therefore directly perpendicular to natural skin folds, resulting in inevitably undesirable scars. Following certain principles, however, this scarring can be minimized.

Anterior Supraclavicular Approaches

The anterior supraclavicular approach is a particularly useful approach for exposing the upper brachial plexus and lesions involving the C5, C6, C7 nerve roots, and the upper trunk of the brachial plexus. The most common indications for this approach include acute penetrating injuries, traumatic stretch injuries, and tumors of the brachial plexus. Occasionally, this exposure is used for decompression of the proximal C5–T1 nerve roots, as occurs in the thoracic outlet/anterior scalene syndrome.

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Fig. 15.1 Traditional exposure used to access the supraclavicular brachial plexus, showing extension of the incision inferiorly, along the delto-pectoral groove, to access the infraclavicular plexus. (Photo: by author)

Traditionally, this exposure starts proximally in the neck, with an incision along the posterior border of the sternocleidomastoid muscle (SCM), extending down to the level of the medial clavicle, and then turning laterally along the border of the clavicle to the delto-pectoral groove. Extension of this incision along the delto-pectoral groove will provide additional access to the infraclavicular brachial plexus. This incision does not respect Langer's lines and often results in a very noticeable scar (Fig. 15.1).

An alternative, more cosmetically appealing approach uses a transverse incision, one finger breath above the clavicle, running transversely from the medial border of the SCM and laterally to the acromial process. This incision runs along Langer's lines and tends to heal very cosmetically. The extent of supraclavicular exposure required can be increased or decreased depending on the required length of exposure. This approach exposes, after incising the platysma muscle, the posterior border of the SCM medially, and the supraclavicular fat pad centrally. In most instances, the clavicular fibers of the SCM must be taken off the clavicle, leaving a small cuff of fascia for reinsertion at the end of the case. Careful dissection through the supraclavicular fat will then provide visualization of the omohyoid muscle, which serves as a landmark to the underlying location of the brachial plexus. The omohyoid muscle can be easily mobilized and rarely requires transection. Care must be taken to not disrupt lymphatic drainage, particularly the thoracic duct on the left (Fig. 15.2).

Anterior Infraclavicular Approaches

Exposure of the brachial plexus in the infraclavicular space is often less cosmetic. The incision can be partly hidden in the skin crease of the delto-pectoral groove, which extends inferiorly into the proximal bicipital groove of the arm. Exposure of

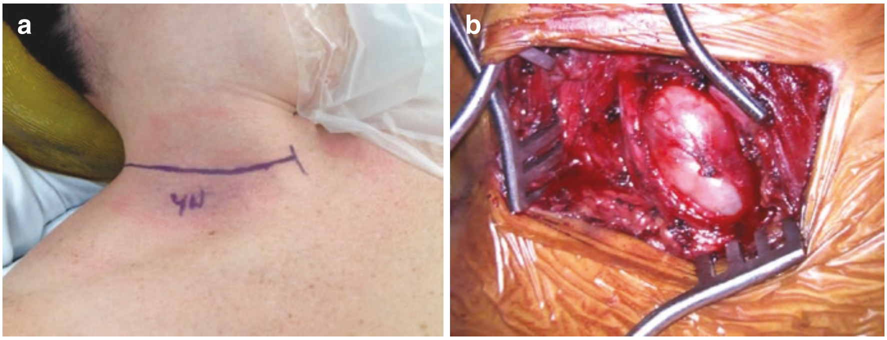

Fig. 15.2 (**a**) The transverse supraclavicular approach to the upper brachial plexus. (**b**) Exposure of an upper trunk brachial plexus schwannoma. (Photos: by author)

the lower brachial plexus is accomplished by splitting the fibers of the pectoralis major muscle and, depending on the location of the lesion, often requires sectioning of the pectoralis minor muscle. Once the pectoralis minor muscle is divided, there is little need to repair it. This approach tends to be less cosmetic because of the need to follow the course of the plexus. Lesions in the distal brachial plexus can often be accessed through an opening along the proximal bicipital groove, extending superiorly along the anterior axillary line, and into the distal delto-pectoral groove. The pectoralis minor muscle can often be retracted superiorly and does not have to be divided.

Combined Supra- and Infraclavicular Approaches

The combined supra- and infraclavicular approach, as shown in Fig. 15.1, is not very cosmetic. This approach, which is most commonly used for exploration following pan-plexus stretch injuries, is rarely used today. Most of these injuries are now treated with nerve transfer procedures, no longer requiring direct exposure of the brachial plexus in the region of the injury.

Suprascapular Nerve Exposures

Decompression of the suprascapular nerve at the level of the scapular notch is commonly performed for suprascapular neuropathy. Compression of the suprascapular nerve at this level results in weakness of the supra and infraspinatus musculature, with weakness in eversion of the shoulder. This approach tends to be cosmetically pleasing and involves making a transverse incision one finger breath above the scapular spine, as shown in Fig. 15.3a. The incision is carried down to the scapular spine, where the trapezius muscle is then detached from it. A natural plane is subsequently developed between the underbelly of the trapezius and the posterior surface of the supraspinatus muscle. Using finger dissection, this plane is developed superiorly to expose the superior surface of the scapula, following

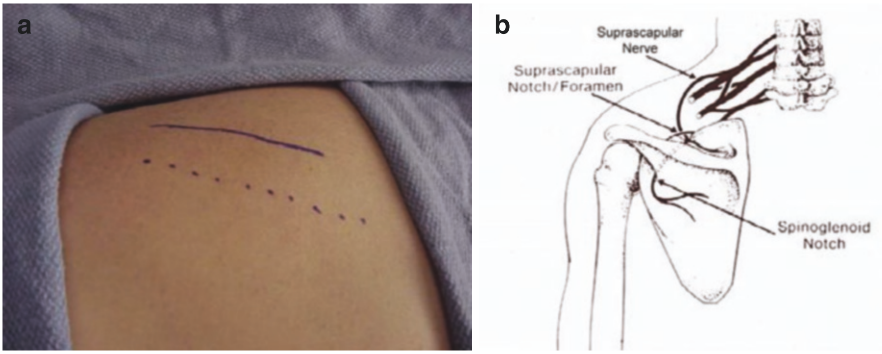

Fig. 15.3 Left-sided suprascapular nerve decompression. (**a**) Transverse incision (solid line) made one finger breath above the scapular spine (dotted line). Photo: By author. (**b**) Anatomy of the suprascapular nerve as it runs through the suprascapular notch. (Used with permission of Elsevier Science & Technology Journals, from Focal Peripheral Neuropathies, JD Stewart, 1987, fig. 8.2, p. 123; permission conveyed through Copyright Clearance Center, Inc.)

which the characteristic groove of the suprascapular notch can be palpated (Fig. 15.3b). This approach is more reliable and less confusing than dissecting directly through the fibers of the trapezius muscle. With closure, the trapezius muscle is re-attached to the scapular spine and the soft tissues are closed in layers, using a subcuticular skin closure.

Posterior Upper Arm/Shoulder

This approach is commonly used for middle triceps to axillary nerve transfer, in patients with isolated axillary nerve injuries. Although the incision, as shown in Fig. 15.4, is along the posterior aspect of the shoulder, it does not follow Langer's lines and will result in a noticeable scar. The incision in this procedure needs to be quite long, extending approximately one-third of the way down the arm and then curving superiorly and medially along the posterior aspect of the shoulder. This approach allows visualization of the axillary nerve in the quadrangular space, along with the nerve to the middle head of the triceps muscle, coming off the radial nerve below the teres major muscle.

Exposure can be extended further down the posterior aspect of the arm for exploration of injuries of the radial nerve, as it runs through the musculospiral groove of the humerus. These lesions can be accessed only through a longitudinal incision, not allowing for a very cosmetic postoperative scar. A radial nerve injury, following instrumentation of a traumatic mid-shaft humerus fracture, is shown in Fig. 15.5. The radial nerve was inadvertently caught beneath the upper aspect of the plate (Fig. 15.5c). This was repaired with sectioning of the nerve, followed by a primary end-to-end anastomosis (Fig. 15.5d). The patient experienced a complete recovery of function.

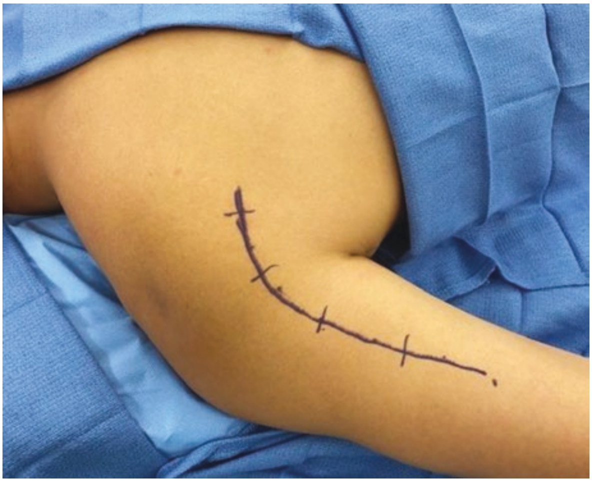

Fig. 15.4 Incision outlined for a left middle triceps nerve to axillary nerve transfer procedure. (Photo: by author)

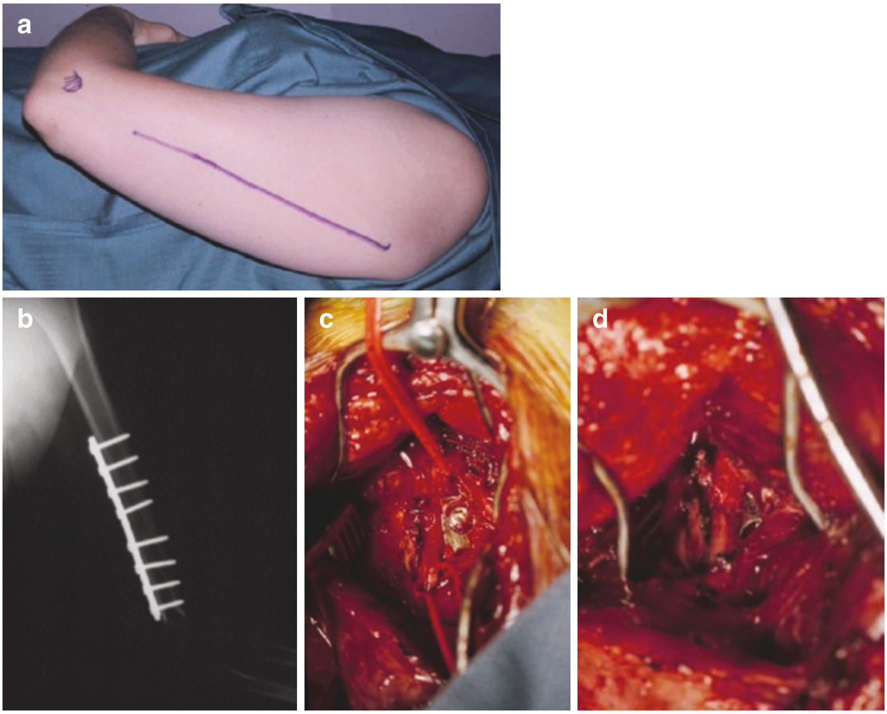

Fig. 15.5 Patient with a radial nerve injury from a mid-shaft humerus fracture, in the region of the musculospiral groove. (**a**) Longitudinal incision for exposure of the radial nerve in the musculospiral groove. Photo: by author. (**b**) Fixation plate placed for repair of humerus fracture. (**c**) Visualization of the radial nerve caught below the superior aspect of the plate, with vessel loops placed around the superior and inferior aspect of the nerve. (**d**) Primary end-to-end nerve repair. (Photos: by author)

Upper Arm/Bicipital Groove

Exposure of the ulnar and median nerves within the bicipital groove is useful both for primary injuries to these nerves and for nerve transfer procedures. The Oberlin and modified Oberlin procedures have become the author's most common nerve transfer procedures performed, primarily for reconstruction of upper trunk brachial plexus injuries. Exposure requires a vertical incision along the bicipital groove extending two-thirds the way down the medial arm (Fig. 15.6). This incision does

Fig. 15.6 Incision made along the bicipital groove of the arm, extending superiorly into the anterior axillary line. Extension of the incision can be made more superiorly, along the delto-pectoral groove, to access the inferior brachial plexus. (Photo: by author)

not follow Langer's lines but, due to its position along the medial surface of the arm, the scar is often difficult to visualize. The most common transfer consists of a dual transfer of a branch of the median nerve to the biceps branch of the musculo-cutaneous nerve (supplying the biceps muscle), along with a branch of the ulnar nerve to the brachialis branch of the musculo-cutaneous nerve (suppling the brachialis muscle), thus giving the potential for recovery of anti-gravity elbow flexion.

Distal Arm/Elbow

Ulnar nerve in the cubital tunnel—Incisions in the distal arm and elbow region can be quite variable depending on the nerve being accessed. The incision for lesions of the ulnar nerve is typically made along the course of the ulnar nerve extending from approximately 4–5 cm above the cubital tunnel to approximately 5 cm below the tunnel (Fig. 15.7). This incision can be shorter for simple ulnar nerve decompression in situ. However, care must be taken during ulnar nerve transposition, to avoid proximal kinking of the nerve in the region of the triceps tendon and distally between the two heads of the flexor carpi ulnaris muscle. This extended incision, along the course of the nerve, does not follow the classic Langer's lines. Again, due to the location of the incision along the medial aspect of the elbow, it is often difficult to visualize. Care should be taken, however, not to have the incision cross directly over the medical epicondyle as this could be a source of postoperative discomfort.

Median nerve—Exploration of the median nerve at the level of the elbow often requires exposure above and below the flexor crease (Fig. 15.8a). As a rule of thumb, any incision which crosses a flexor crease, such as at the elbow, wrist, or popliteal fossa should be done with a z-shaped incision to avoid crossing the crease directly. This requires making a segment of the incision parallel to the crease, which minimizes the chance of creating a scar contracture across the joint. Depending on the extent of required exposure of the median nerve, the incision can be tailored to provide exposure of the nerve in the proximal forearm only (Fig. 15.8b) or by using

Fig. 15.7 Incision for ulnar nerve exploration at the elbow. Incision made along the course of the ulnar nerve, posterior to the medial epicondyle (*). (Photo: by author)

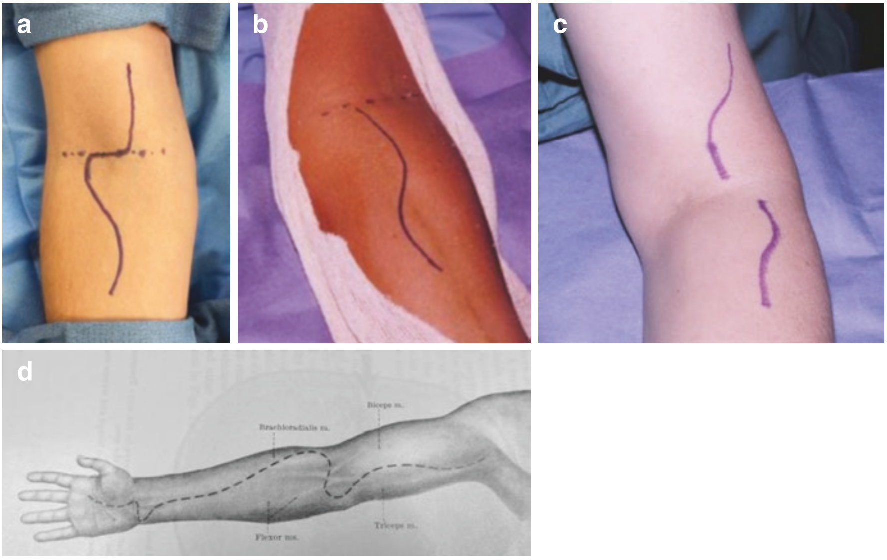

Fig. 15.8 Exposure of the median nerve in the region of the antebrachial fossa. (**a**) Incision crossing the flexor crease of the elbow, exposing the median nerve proximal and distal. (**b**) Incision used for exposure of the distal median nerve, starting at the inferior aspect of the flexor crease, and following an S-shaped course distally. (**c**) Exposure above and below the elbow using two separate incisions, avoiding crossing the flexor crease directly. Photos: by author. (**d**) Surgical exposure of the entire median nerve in the upper extremity. (Reprinted by permission from Springer Nature: Springer Nature, Surgery of Peripheral Nerves, edited by Ludwig G Kempe, 1970)

two separate incisions, above and/or below the crease, thereby avoiding crossing the joint directly (Fig. 15.8c). Figure 15.8d shows the exposure of the median nerve through the entire right upper extremity. As a rule, Langer's lines run transversely around the arm and, except for short transverse incisions used for resection of a small schwannoma, following these lines is difficult. In working below the elbow, a lazy S-shaped incision, as shown in Fig. 15.8b, can often be more cosmetically satisfactory.

Radial nerve—The radial nerve at the level of the elbow lies in a deep groove between the brachialis muscle medially and the brachioradialis muscle laterally. An incision along the ventral-lateral aspect of the elbow, as shown in Fig. 15.9, follows the groove between these two prominent muscle bellies and lateral to the flexor crease. Because of its position just lateral to the flexor crease, a single lazy S-shaped incision can be used without the need for a Z-plasty. The distal limb of the incision should be made along the medial border of the brachioradialis muscle, giving access to the superficial radial nerve and the deep branch of the radial nerve (posterior interosseous nerve) distally. Exposure of the deep radial nerve as it passes through the supinator muscle often requires extending the incision distally and working

Fig. 15.9 Incision for exposure of the radial nerve along the ventro-lateral aspect of the elbow. (Photo: by author)

more laterally over the brachioradialis muscle. For radial nerve lesions below the elbow, in the proximal forearm, a second incision between the brachioradialis medially and the extensor carpi radialis longus muscle laterally is more advantageous. This allows visualization of the deep branch of the radial nerve as it enters the supinator muscle, often a site of potential nerve compression (Fig. 15.9).

Hand

Decompression of the median nerve as it traverses the carpal tunnel can be approached in a variety of ways. The classic approach is through a longitudinal mid-palmar incision, running from the distal wrist crease to a point in the mid-palm, parallel with the base of the thumb (Fig. 15.10). The incision is made along a line running from the mid-palmer crease to the interspace between the middle and ring fingers. For access to the nerve above the flexor crease, a Z-shaped incision is used, crossing the flexor crease into the distal medial forearm. Alternatively, many surgeons employ a transverse wrist incision for both microscopic and endoscopic median nerve decompressions. Unlike the mid-palmar incision, this incision is far more cosmetic (follows Langer's lines) and often results in less postoperative pain. With this approach, however, great care must be taken to protect the palmar cutaneous branch of the median nerve, with possible long-term painful neuroma formation. This can be avoided by staying medial to the palmaris longus tendon.

Access to the ulnar nerve, as it runs through Guyon's canal, requires an incision, similar to that described above, along with a Z-shaped extension running medially above the wrist, lateral to the palpable pisiform bone of the wrist and over the course of the ulnar nerve (Fig. 15.11).

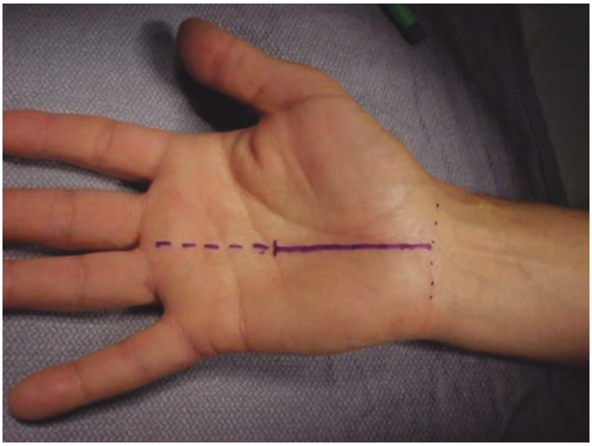

Fig. 15.10 Classical incision used for a carpal tunnel release of the median nerve at the wrist. (Photo: by author)

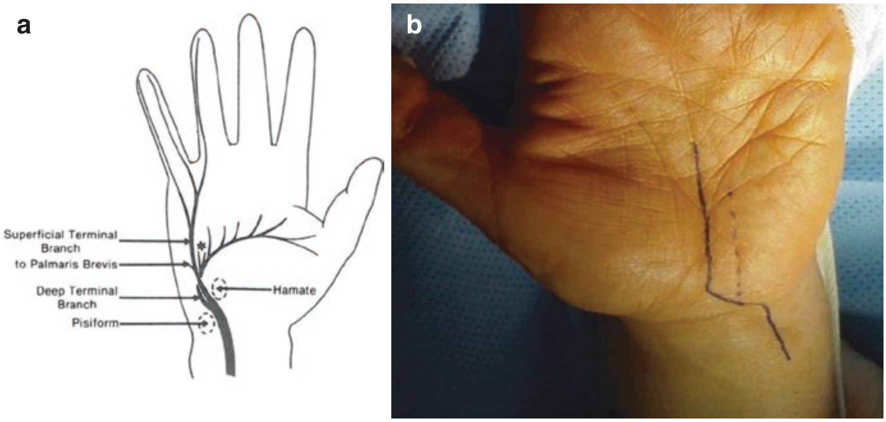

Fig. 15.11 (**a**) Diagramatic representation of the course of the ulnar nerve as it passes through the wrist. Note its course lateral to the Pisiform bone and medial to the Hamate. (**b**) Z-shaped skin incision used to cross the flexor crease. (Photo: by author)

Anterior Thigh/Groin Region

The two most common indications for nerve exploration of the anterior thigh and groin region are for lesions involving the femoral nerve and decompression of the lateral femoral cutaneous nerve for meralgia paresthetica. A transverse incision (Fig. 15.12), approximately one finger breath below the lateral extent of the inguinal ligament, and below the level of the anterior superior iliac spine is made for decompression of the lateral femoral cutaneous nerve. This incision is made transversely, following Langer's lines and parallel to the inguinal ligament. The fascia lata inferior to the ligament is then opened transversely. The nerve lies deep to the fascia, along the medial aspect of the anterior superior iliac spine and just below the fibers of the inguinal ligament. Occasionally the nerve may pierce through the lateral fibers of the inguinal ligament. This incision heals nicely with good cosmesis.

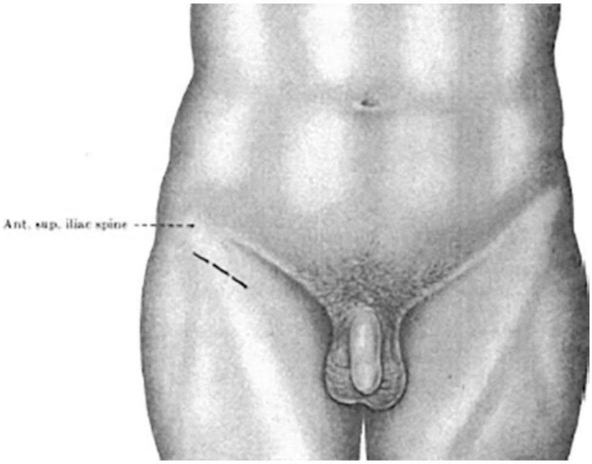

Fig. 15.12 Skin incision used to access the lateral femoral cutaneous nerve for treatment of meralgia paresthetica. (Reprinted by permission from Springer Nature: Springer Nature, Surgery of Peripheral Nerves, edited by Ludwig G Kempe, 1970)

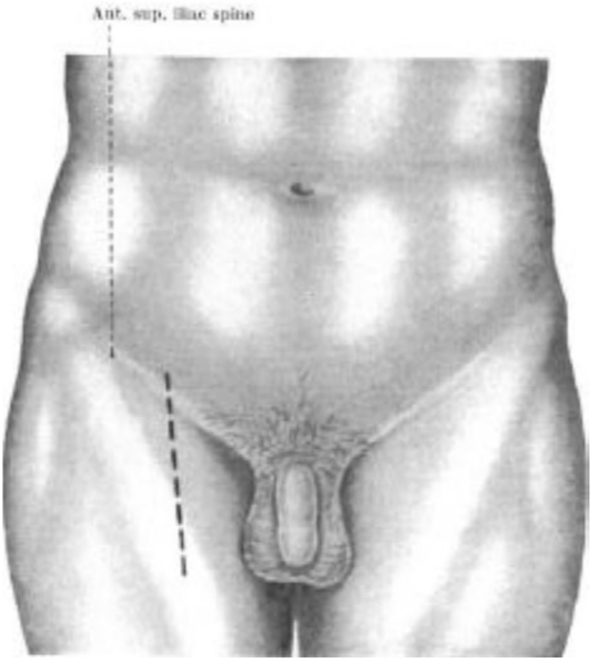

Fig. 15.13 Skin incision used to access the femoral nerve in the region of the femoral triangle. (Reprinted by permission from Springer Nature: Springer Nature, Surgery of Peripheral Nerves, edited by Ludwig G Kempe, 1970)

The scar for exposure of the femoral nerve, however, is not as cosmetic. The femoral nerve arises retro-peritoneally from the posterior divisions of the second, third, and fourth lumbar nerves and runs under the inguinal ligament and lateral to the femoral artery in the femoral triangle. Within the femoral triangle, the nerve lies deep to the iliacus facia in a groove between the psoas muscle medially and the iliacus muscle laterally. At this point, the nerve divides into a rete of terminal branches. The vertical skin incision, as shown in Fig. 15.13, starts at the mid-position of the inguinal ligament and runs along the medial border of the sartorius muscle. If access is required proximal to the inguinal ligament, a Z-shaped extension should be used, incorporating a limb running laterally along the flexor crease and then superiorly up over the lower abdomen.

Posterior Thigh/Buttock

Exploration of the sciatic nerve as it exits from the sciatic notch proximally is most commonly performed for injuries to the sciatic nerve or for tumors involving the proximal sciatic nerve. Occasionally, this exposure is performed for surgical decompression of the nerve as may occur in the "piriformis syndrome." The sciatic nerve can be accessed through a question mark-shaped incision, allowing medial reflection of the gluteus maximus muscle and exposing the sciatic nerve as it exits the sciatic notch. It then runs under the piriformis muscle and crosses over the obturator internus and gemelli muscles. The incision starts superiorly at the posterior superior iliac spine and then forms an arc along the iliac crest superiorly and laterally. The incision then turns inferiorly and follows the lateral aspect of the gluteus maximus muscle and the iliotibial fascial band, staying just posterior to the greater trochanter. The incision then follows the gluteal fold inferiorly to the mid-thigh, where it turns inferiorly to run vertically along the mid-portion of the posterior thigh (Fig. 15.14). Depending on, where the sciatic nerve needs to be explored, any portion of this incision can be used. For sciatic nerve lesions at the level of the inferior buttock/proximal thigh, an incision along the midline thigh, up to and incorporating the gluteal fold, may be sufficient. Despite the extent of the full incision, the incision tends to heal nicely along the inferior gluteal fold running parallel to Langer's lines.

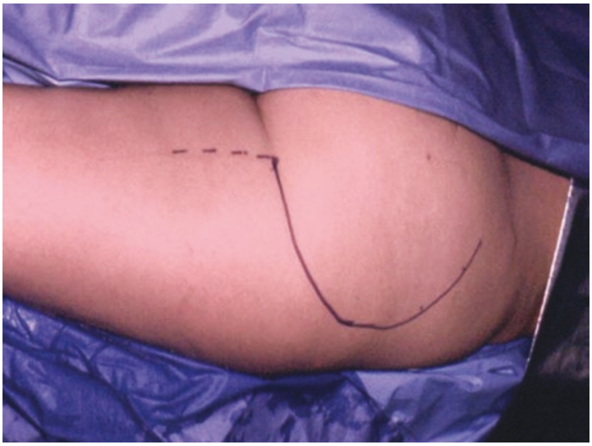

Fig. 15.14 Surgical incision used to access the proximal sciatic nerve in the buttock region. (Photo: by author)

Lateral Knee/Common Peroneal Nerve

Decompression of the common peroneal nerve at the level of the fibular head is one of the most common nerve procedures performed in and around the knee. This is most often performed for alleviation of compression of the common peroneal nerve by the fibrous posterior ligamentous border of the peroneus longus muscle. Decompression of the nerve includes external neurolysis of the common peroneal nerve, with decompression and external neurolysis of both the superficial and deep peroneal nerves as they branch off the common peroneal nerve. The incision must allow access to the common peroneal nerve at and above the level of the fibular head, as well as the distal superficial and deep divisions of the peroneal nerve. If more proximal visualization of the nerve is needed in the region of the distal thigh, the incision is carried into the popliteal fossa, with a Z-shaped extension running parallel to the flexor crease and then superiorly up onto the thigh (Fig. 15.15). Simple decompression of the common peroneal nerve at the fibular head requires only exposure below the popliteal flexor crease.

Another option, used by many nerve surgeons, is an oblique transverse incision running just below the fibular head (Fig. 15.16) [1]. This incision, running parallel to Langer's lines, allows greater access to the nerve in the anterior compartment but less ability to follow the nerve posteriorly into the lower thigh.

Popliteal Fossa/Posterior Tibial Nerve

Exposure of the posterior tibial nerve at the level of the popliteal fossa is often required for traumatic injuries, nerve compression due to a Baker's cyst, or a nerve sheath tumor. The nerve is accessed through a Z-shaped incision crossing the

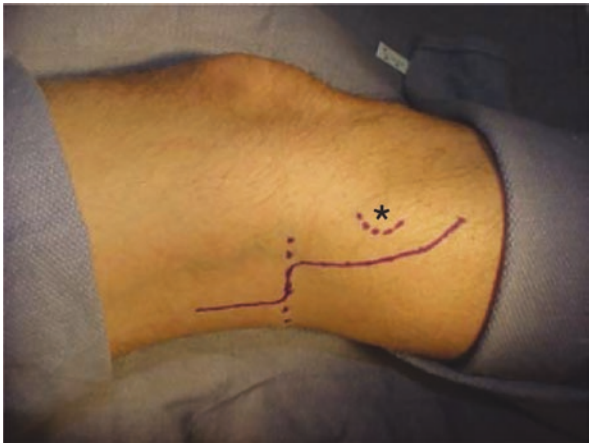

Fig. 15.15 Surgical incision used for exposure of the common peroneal nerve at the knee. Only the distal portion of the incision (to the right), below the flexor crease, is required for nerve decompression in the region of the fibular head. (* Fibular head). (Photo: by author)

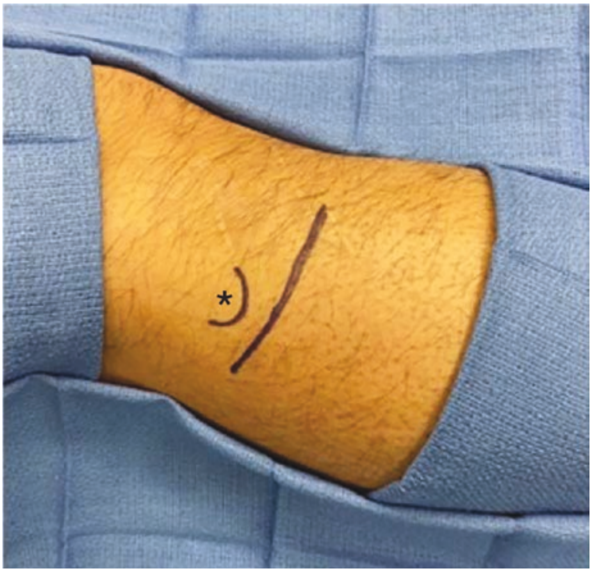

Fig. 15.16 Alternative transverse incision used for peroneal nerve decompression at the fibular head. (* Fibular head). (Photo: by author)

popliteal crease. The horizontal limb of the incision is made transversely along the flexor crease. The proximal extension is made vertically along the mid-thigh and parallel to the hamstring tendons, with the distal extension running vertically down the proximal calf, on its lateral aspect. Exposure of the posterior tibial nerve is then accessed by vertically opening the popliteal fascia, taking care to not injure the more superficial posterior femoral cutaneous nerve. The Z-shaped incision across the popliteal crease prevents future scar contracture across this region.

Tarsal Tunnel

The posterior tibial nerve runs through the tarsal tunnel along the medial aspect of the ankle. Exposure is most commonly performed for nerve compression secondary to trauma with scar formation, inflammatory disorders, and occasionally mass occupying lesions. Surgery is performed with the patient in the supine position under either general or spinal anesthesia. The incision is made along the course of the nerve, starting approximately 3–4 cm above the medial malleolus. The incision continues down behind the malleolus, between the malleolus and calcaneus, and then curving gently forward to stop just before the plantar surface of the foot (Fig. 15.17). The incision should be made well posterior to the medial malleolus to avoid injury to the terminal branches of the saphenous nerve. The posterior tibial nerve is released as it passes through the tarsal tunnel, which is formed by the flexor retinaculum superficially and the tarsal bones on the deep side. Within the tarsal tunnel run the posterior tibial nerve, the posterior tibial artery and vein, and the tendons of the tibialis posterior, the flexor digitorum longus, and the flexor hallucis longus

Fig. 15.17 Skin incision used for exposure of the posterior tibial nerve through the region of the tarsal tunnel on the left. (* Medial malleolus). (Photo: by author)

muscles. Because of the dependent nature of the lower extremity, wound healing is often a concern. Sutures should be left in place for a minimum of 2 weeks with elevation of the leg in the postoperative period. Some surgeons advise non-weight bearing for a period of 1–2 weeks.

Reference

1. Humphreys DB, Novak CB, Mackinnon SE. Patient outcome after common peroneal nerve decompression. J Neurosurg. 2007;107(2):314–8. https://doi.org/10.3171/JNS-07/08/0314.

Part III

Plastic Neurosurgery for Cranial and Craniofacial Disorders

16 Nonsyndromic Craniosynostoses

Ken Rose Winston and Lawrence L. Ketch

Synostosis of a cranial suture restricts cranial expansion in the direction perpendicular to the fused suture, in response to normal growth of brain. Compensatory expansion at other sutures tends to accommodate growth of brain, as listed in Fig. 16.1.

The volume of the human brain at birth is about 25% of the volume of an adult brain and continues to increase until approximately 20 years of age. The calvarium achieves its near-adult size by approximately age 16 years; however, its circumference continues to increase for a few more years as the bone thickens and remodels. Most individuals with craniosynostosis come to neurosurgical attention within a few months from birth. Surgical complications occur more often in surgeries for multisutural synostosis and in reoperations [1].

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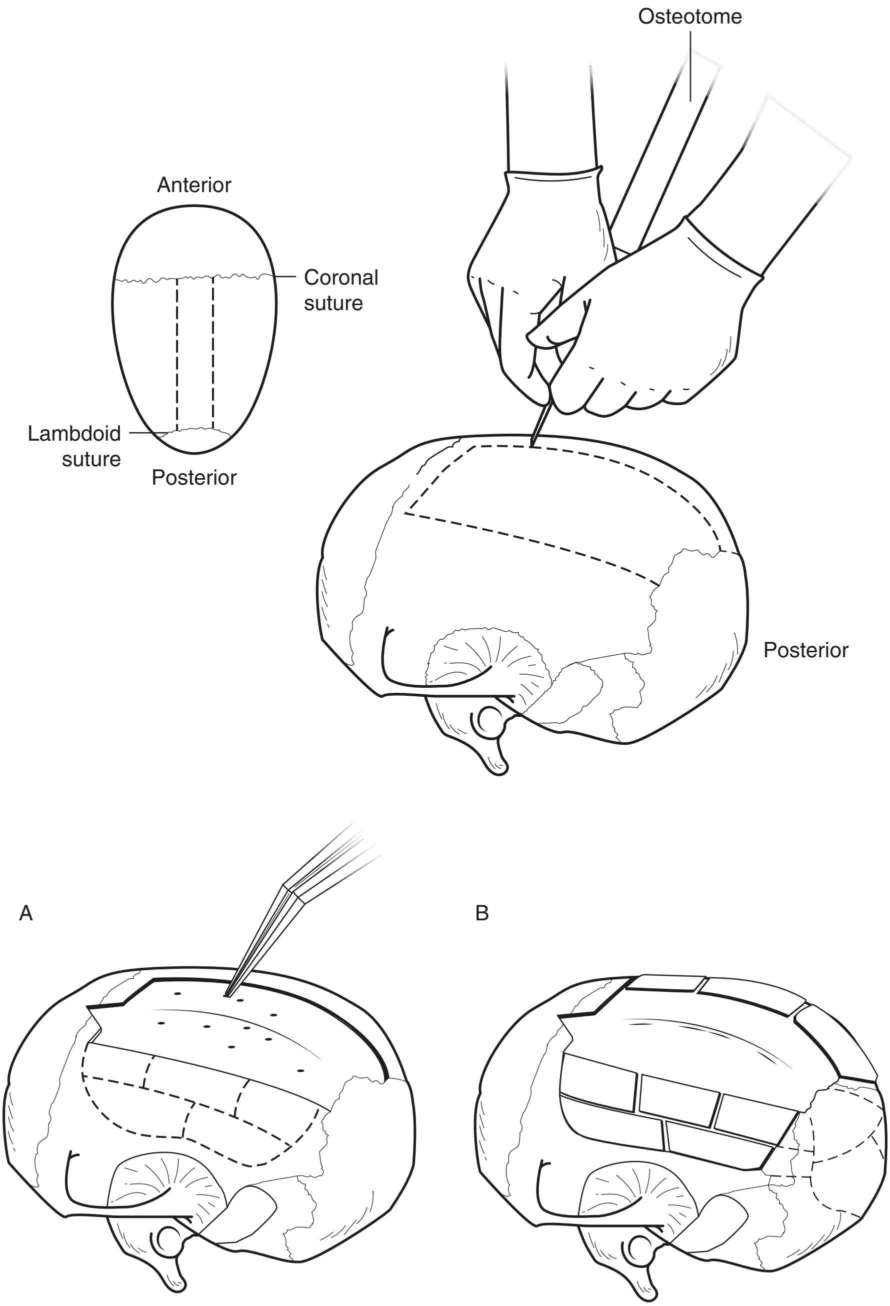

Fig. 16.1 Parasagittal osteotomies being made for sagittal craniectomy. (**a**) Bipolar coagulation for hemostasis on exposed dura. (**b**) Bilateral expansion of brain and enveloping dural envelope after biparietal morcellattion. [Published with permission from Green CS, Winston KR. Treatment of scaphocephaly with sagittal craniectomy and biparietal morcellation. *Neurosurgery.* 1988;23(196):202. doi: 10.1227/00006123-198808000-00012]

Open Versus Endoscopic Surgery

Open surgery exposes both the synostosed suture and cranial surface. This exposure allows resection of synostosed sutures, and correction or improvement of the abnormal contour of cranial bones. The improved contour is immediately apparent after surgery or as edema resolves. A molding helmet is not often required. Endoscopic surgery allows exposure along the synostosed sutures and the resection of synostosed sutures with a few mm of bone on each side. Improvement in contour is not present at the conclusion of surgery but occurs over the following months from physiologic recontouring of bone and physiologic alteration in the brain volume. This is a consequence of brain growth and remodeling directed by the helmet, which is usually required for a few months after endoscopic surgery. Compliance and proper use of the helmet is a significant undertaking by parents and requires commitment; and the helmet must be refitted several time at considerable expense [1].

There are pros and cons for open and endoscopic surgery to correct nonsyndromic craniosynostosis, and decisions are influenced by age, severity of cranial dysmorphia, and parental preference. Endoscopic surgery is associated with shorter scars, less blood loss, shorter operative times, and shorter hospitalizations [2]. The greater transfusion volume associated with open surgery may be, in part, a consequence of surgeons and anesthesiologists being less tolerant of a slow downward drift in hematocrit in these patients. Open surgery is usually more appropriate for syndromic synostoses, multisutural synostosis, and patients older than 6 months. Opinions and recommendations among surgeons vary greatly, with some surgeons believing that open surgery results in better cosmetic outcome. Parents often prefer endoscopic surgery because of the perception that it is less invasive, less likely to require transfusion, and the scars will be shorter. The rate of complications is not significantly different for open versus endoscopic surgery. Deaths did occur in the early days of endoscopic surgery for craniosynostosis but have been rarely if ever reported in the last few decades. However, various complications, including death, remain as risks.

Positioning

Supine Position

Supine positioning is required for most surgeries for correction of craniosynostoses. However, if there is significant occipital bossing, the bossing tends to cause cervical flexion and soft padding will be required to elevate the shoulders.

Prone Position

Prone positioning is required for access to the posterior cranium, for example for correction of lambdoid synostosis and in some patients with sagittal synostosis who have occipital bossing. This is most often done with the face against a softly padded horseshoe head holder, which must be adjusted to prevent pressure against and eyes and to prevent gradual settling between the two arms of the device. It is important to prevent the padding from becoming soaked. The surgeon must gently raise the head clear of the head holder every 10 min to prevent prolonged pressure against the face, which impairs facial perfusion. Failure to do this risks infarction of portions of skin.

The anesthesiologist must provide sealed protection of the eyes before the patient is turned into the prone position and, when securing the endotracheal tube, must anticipate the surgeon's raising the head every 10 min to allow perfusion of the face.

Sphinx (Swan-Dive) Position

Sphinx (swan-dive) position is often used for extensive cranial vault remodeling/reconstruction in older infants and children with scaphocephaly, posterior plagiocephaly, kleeblattschädel, and oxycephaly.

Postoperative Care of Patients with Nonsyndromic Synostosis

Decisions on postoperative care must be made on an individual basis; however, the traditional practice is for all patients, following discharge from the PACU (postanesthesia care unit), to spend one or more days in a pediatric intensive care unit. This level of care is extremely important for patients in whom there is concern, by surgeon or anesthesiologist, for cardiac or respiratory instability or for loss of blood from persistent oozing. However, the vast majority of patients are reliably stable with respect to cardiac and respiratory functions, and management of pain does not require an intensive care setting. It is the authors' opinion that most infants do not require the high level of monitoring that is available in an intensive care unit, with its associated cost [3].

Pain following surgery for craniosynostosis is less than intuitively believed and excessive dosing with opiates is common and *must* be avoided. The length of scalp incision and knowledge on extent of craniofacial osteotomies are not reliable indicators of pain and therefore should not be used for dosing of analgesic medications. Postoperative facial edema, particular periorbital edema, is the cause of much of postoperative fussiness and crying, by patients of all ages.

Scaphocephaly (Sagittal Synostosis)

Scaphocephaly (*Greek: boat shape PLUS_SPI head)* is the term used to describe a long narrow head usually caused by premature synostosis of the sagittal suture. It is the most commonly diagnosed isolated type of craniosynostosis, accounting for 40−60%. It occurs approximately once in 2000–2500 newborns with a male-to-female ratio of 3.5 to one, possibly related to an androgenic effect [4, 5]. Patients typically have biparietal narrowing, a palpable bony ridge along the fused sagittal suture, frontal and/or occipital bossing, and usually an elevated head circumference. Most patients with scaphocephaly have fusion of most or all of the sagittal suture, but a few have fusion of only the posterior third or midportion of the sagittal suture.

The elongated cranium results from compensatory expansion to accommodate normal brain volume in the directions available—i.e., frontal and occipital. The frontal and occipital bossing associated with sagittal suture craniosynostosis becomes progressively worse with age, and for this reason, surgical correction at 3–6 months is recommended. Most patients come to surgical attention as newborns or infants but only rarely as teenagers or adults.

The dysmorphology of scaphocephaly is significant and can become a serious psychosocial concern for children as they grow older and into adulthood. The most common primary indication for surgical correction of scaphocephaly is cosmetic deformity which is occasionally associated with elevated intracranial pressure. Some physicians believe a possible adverse impact on intelligence can be an indication for surgery. Most parents choose to have surgery done within the first few months of postnatal life. Surgery reduces the anterior–posterior dimension of the cranium, increases the transverse dimension of the parietal vault, and corrects bossing of forehead and/or occiput, when significant. This modification of the cranial vault allows the brain, which is at least 85% water, to immediately expand passively in the lateral directions and, if frontal or occipital bossing is corrected, to have a reduced anterior–posterior length.

Leptocephaly (*Greek: thin PLUS_SPI head*) is a variation of scaphocephaly in which the entire cranial vault is extremely narrow and tall [6].

Plastic neurosurgical concerns

- Choose surgical technique.
- Camouflage of scalp incision.
- Correction of biparietal narrowness.
- Correction of frontal bossing, if significant.
- Correction of occipital bossing, if significant.
- Cranial reconstruction (depending on surgical technique chosen).
- Cosmetic closure of scalp.

There are several accepted, but not equally popular, surgical techniques, all of which address the sentinel abnormality, biparietal constriction. These include sagittal strip craniectomy with biparietal morcellation, endoscopic strip craniectomy, pi procedure, reverse pi procedure, cranial vault reconstruction, spring-assisted cranioplasty, strip craniectomy, and broad frontoparietal craniectomy. The often-associated abnormalities of frontal bossing and occipital bossing will be addressed separately. Neuroplastic concerns are a major issue in the execution of all surgeries for scaphocephaly.

Positioning and Immobilization

The position required for surgery to correct scaphocephaly depends on the extent of abnormality and the surgical technique to be used. The supine position is satisfactory for correction of the biparietal constriction and frontal bossing (not always needed). The prone position allows correction of biparietal constriction and occipital bossing. The sphinx position is preferred by some surgeons because it provides the exposure required for correction of biparietal constriction and both frontal and occipital bossing. The author does not recommend the sphinx position because of risk for air embolism and concern for cervical spinal cord injury from hyperextension.

Sagittal Strip Craniectomy with Biparietal Morcellation [7]

(Author's preferred technique for patients under approximately 10 months of age.)

Scalp

The scalp should not be shaved. Open surgery for scaphocephaly is accomplished via a zigzag coronal incision in scalp. If surgery will address only the parietal component of scaphocephaly, the scalp and pericranium are reflected anteriorly across the coronal sutures and posteriorly across the lambdoid sutures. However, if frontal bossing will also be corrected, the scalp reflection must also expose the entire frontal bone down to the supraorbital rims. And if occipital bossing will be corrected, the occipital bone down to the level of transverse sinuses must be exposed.

Bone

The left and right posterior edges of the anterior fontanelle are cleared of dural attachments, using a curette and Penfield dissectors. This clearance of attachments must be continued across the midline. If the anterior fontanelle is sufficiently closed to prevent dissection with a curette, it will be necessary to make a small burr hole on one or both sides of midline of the frontal bones, immediately behind the coronal sutures. A straight parasagittal line is marked with ink approximately 10–15 mm on each side of the parietal midline. In infants under 4 months of age, this line should be approximately 2 cm from midline but, in infants 6–12 months of age, the width of the craniectomy should become progressively narrower. Osteotomies are made along the marked lines, starting at the lateral edge of the anterior fontanelles, and extending posteriorly to, but not across, the lambdoid sutures. A Penfield dissector is then passed transversely beneath the anterior portion of the midline strip of bone and quickly pushed posteriorly to separate the strip of bone from all attachments to dura. The strip of bone is grasped by hand and folded posteriorly as an assistant applies wet cottonoids over bleeding sites on dura and applies gentle suction. The hinged flap of bone is then dissected free along the lambdoid sutures. As cottonoids are removed, bleeding sites can be controlled by bipolar coagulation, but occasionally a small piece of Gelfoam® is required. Bone dust (swarf) should be pressed into the raw edges of bone to assist hemostasis. Bone wax should be used sparingly as it impairs healing. See Fig. 16.1.

The edge of the occipital bone at the end of the craniectomy site must be cleared of attachments to dura. A broad Kerrison rongeur or Leksell rongeur is used to extend the cranial opening for approximately 1 cm into the occipital bone. An Inca bone, if present, can be disregarded.

A U-contoured line that encompasses most of each parietal bone is marked with ink and then a straight anterior–posterior line is marked along the midsection of each parietal bone. Osteotomies are made along the marked lines, resulting in each parietal bone being in two large fragments. Osteotomies are then made to further morcellate each fragment. If the two fragments have relatively smooth contour, the lower fragment is divided into half and the upper fragment into thirds. It is important to attempt to not separate these bone fragments from their dural attachments, but this is not always possible. Any loose fragment is repositioned and a large piece of Surgicel® is laid over the entire parietal bone and irrigated to maintain the fragments in their correct positions. The same subroutine is repeated on the contralateral side.

Following the biparietal morcellation, the parietal dura may bulge outward if the intact frontal fossa is narrow, thereby causing sharp angulation of dura and brain along the raw edge of bone behind the coronal suture. If this is quite minor it can be ignored, but if this bone is causing a pinched-in appearance, three or four anteriorly directed osteotomies of 3 or 4 cm length should be made across each of the coronal sutures and into the intact frontal bone. The resulting peninsular flaps of bone are then molded or fractured outward to alleviate the dural indentations. This will relieve the constriction caused by a narrow bifrontal diameter.

Correction of Bilateral Frontal Bossing [8]

Symmetric frontal bulging is often associated with scaphocephaly. The determination of severity of bossing, and hence the need for surgical correction, is subjective. Mild-to-moderate bossing of the forehead in infants with scaphocephaly will self-correct over several months following the biparietal correction and therefore does not require correction; however, severe bossing will not adequately self-correct and requires surgical correction.

Immediately after the sagittal strip craniectomy and *before* morcellation, a bifrontal craniotomy is marked with ink. The lower edge of the craniotomy is marked as a straight line approximately 1 cm above the supraorbital rim, and the upper edge marked approximately 1 cm anterior to each coronal suture. The adhesions along the anterior edges of the anterior fontanelle are cleared from dural attachments with a curette. An osteotomy is made along the marked lines with a craniotome. If there is a bony keel in the supraorbital midline, it can be easily disrupted with a small osteotome. Midline attachment of dura to bone can be easily separated with a periosteal elevator. The bifrontal bone flap is then removed.

The bulge in the exposed frontal dura is reduced by desiccating several lines across the dura with electrocautery. Care must be taken to prevent thermal injury to underlying brain, by using low power cautery and constantly moving the tip. Correction of severe bulging should not be attempted with this technique but must be accomplished by imbricating fusiform strips of dura with nonabsorbable 4–0 silk sutures.

The free frontal bone flap is remodeled to allow posterior tilting of the forehead and correction of the contour (i.e., increase the radius of. curvature). It is often necessary to make radial osteotomies along the lateral sides of the flap and bend the tongues of bone outward to avoid indentation of the dural envelope, and to produce a smooth cranial contour when the flap is replaced. Triangular segments of bone must be resected to allow smooth seating of the over the frontal convexity. The edge of the remodeled bone flap must smoothly abut the intact supraorbital rim on each side. Four holes then are drilled in in the supraorbital rim on each side of the midline and matching holes in the bifrontal bone flap. The flap is secured in place with tightly tied 2–0 Vicryl® sutures. Occasionally, a suture may be required on the sides of the flap to assure alignment and prevent overlap.

Correction of Occipital Bossing

Symmetric bulging of the occiput is often associated with scaphocephaly but must not be confused with bathrocephaly. Mild-to-moderate occipital bossing in infants with scaphocephaly will often self-correct over several months and therefore not require correction. Bossing which makes lying supine on a flat surface awkward, difficult, or impossible requires surgical correction. The determination of severity is subjective. When occipital bossing is to be corrected, the biparietal correction should precede correction of occipital bossing.

The patient should be in the prone position when occipital bossing is to be a component of the correction of scaphocephaly. A semicircular osteotomy is made on each side, passing just posterior to each lambdoid suture and then transversely 5–7 mm above the transverse sinus. The midline is approached but not crossed with the osteotome because of risk of venous bleeding from emissary veins. The midportion can usually be manually cracked but may require use of a small osteotome. There is often a prominent near midline, emissary vein that is disrupted as the bone flap is removed. The bleeding must be quickly stemmed with Gelfoam® and cottonoid and then controlled with bipolar electrocautery. The bulge of the occipital dura must be reduced by desiccation with electrocautery, while avoiding the superior sagittal sinus.

Multiple radially oriented of 2–3 cm length are made into the free, roughly circular occipital flap and the flaps are then bent with Tessier forceps to produce greenstick fractures across their bases. This flattening maneuver expands the diameter of the flap which must then be trimmed with an osteotome or scissors to fit the craniectomy site. This remodeled bone fragment is then returned to its home site and can usually be held in place by only the pressure of overlying scalp, but the surgeon may wish to secure the flap with one or two absorbable sutures placed through holes drilled for this purpose.

The usual postoperative supine positioning of the head will maintain satisfactory positioning, as the adjacent bone along the lambdoid sutures prevents inward displacement against brain.

Restoration and Closure

The galea is closed with absorbable sutures, usually 3-0 Vicryl® 2-. A vacuum drain, for example Jackson–Pratt type, is placed in the subgaleal space and through a puncture in scalp, to prevent the accumulation of blood and serum. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. Incisions in which the alignment scalp edge is difficult can be approximated with staples. The drain should be removed after 12–24 h.

Endoscopic Strip Craniectomy

A transverse incision of approximately 4 cm length is made at the posterior edge of the anterior fontanelle and approximately 2 cm anterior to lambda. Through the anterior incision, a burr hole is made on one side of the fused suture and, through the posterior scalp incision, a second burr hole is made on the opposite side of the closed suture. Bone is dissected from underlying dura across the midline at each site, using the footplate of a Kerrison rongeur and a blunt nerve hook. The strip of bone overlying the midline is removed with a Kerrison rongeur. Dura is then separated across the superior sagittal sinus from midline bone, using a #2 Penfield dissector and endoscope, with caution to protect the superior sagittal sinus. The latter allow visualization of sites of venous bleeding, which can be controlled by bipolar coagulation or application of FloSeal®. A scissor is used to blindly make a parasagittal osteotomy at approximately 2 cm on each side of midline and the free fragment of bone is removed, but this may require reduction in size. Surgeons may add bilateral coronal parietal osteotomies from the sagittal craniectomy down toward the squamosal suture to facilitate lateral expansion. The dura along the site of craniectomy and along the raw edges of bone must be reviewed with the endoscope for active bleeding and for dural laceration. Some surgeons prophylactically apply coagulation along the raw edges of bon. A dural laceration must be repaired with sutures and this usually requires extension of the scalp incision.

Pi Procedure [9–13]

The pi procedure, named for the Greek letter π, is a popular technique for correcting scaphocephaly. This includes a strip craniectomy 2–3 cm from each side of the sagittal suture, leaving the synostosed suture intact. A transverse strip craniectomy passes along the anterior ends of the parasagittal craniectomies. Several variations of the pi procedure have been described [14].

Reverse Pi Procedure

The reverse pi procedure, also named for the Greek letter, consists, as the name implies, of parasagittal strip craniectomies, leaving the synostosed suture intact, followed by a transverse craniectomy passing along the posterior ends of the parasagittal craniectomies.

Cranial Vault Reconstruction [11, 15, 16]

Infants older than 1 year usually require cranial vault reconstruction. Most of the cranial vault is removed—extent and details depending on the cranial morphology. The fragments of bone are modified as needed and reassembled to form a vault of more normal contour. The fragments are secured with sutures or titanium plates; however, in infants there is a strong tendency for both screws and plates to migrate through bone and penetrate dura, as a result of normal osteoclastic and osteoblastic activity. Cranial vault reconstruction is only rarely required in young infants with scaphocephaly. Blood loss is greater than that associated with the simpler surgeries and the overall risks of complications are greater. When reossification occurs, there will rarely be any cranial sutures, and therefore, there is risk of development of pancraniosynostosis, which will likely require reoperation.

Spring-Assisted Cranioplasty [17–19]

Spring-assisted surgery for sagittal synostosis consists of sagittal craniectomy followed by insertion of one or more stainless steel spring which apply force against the edges of the craniectomy for several (approximately 6) months. This technique is less invasive than most open surgeries for scaphocephaly and has low blood loss. A problem with the technique is selection of springs which are most appropriate for a given patient.

Strip Craniectomy Alone (Not Recommended)

The historical surgeries of removing one narrow midline strip or parasagittal strips of parietal bone allow some lateral expansion of the vault but is very commonly followed by rapid reossification. Several decades ago, the edges of bone along strip craniectomies were wrapped with polyethylene film which were secured in place with steel clips with intent to delay early reossification. This maneuver had minimal effect on reossification because the progenitor cells for bone lie in dura and pericranium and less along the edges of raw bone. Also midline or parasagittal craniectomies do not alter the curvature of the relatively flat parietal bones.

This surgery was later improved by "barrel staving," which consisted of making three or four narrow, coronally oriented cranieotomies in each parietal bone, usually with outward greenstick fracturing each stave.

Broad Frontoparietal Craniectomy (Not Recommended)

Broad frontoparietal craniectomy which includes most of the frontal convexity and a large amount of both parietal bones, if done within a few months after birth, can result in reossification with satisfactory cosmetic result; however, this surgery far too often results in one or more large areas of failure of reossification, particularly if done after approximately 4 months of age [20–22].

Delayed Complications of Surgery for Scaphocephaly

Early Re-synostosis

Early resynostosis may occur within a few postoperative months following surgery, regardless of surgical technique. Often the resynostosis is confined to the sagittal suture but may soon involve many or all cranial sutures, resulting in pancraniosynostosis.

Vertex Bulge

Vertex bulge is a complication that can become apparent a few months after surgery to correct either nonsyndromic or syndromic craniosynostosis, most often scaphocephaly. This occurs because of early multisutural synostosis plus intracranial hypertension resulting from normal expansion of a growing brain expands or, less commonly, by hydrocephalus. The most important indication for surgery is the alleviation of intracranial pressure but correction of the cosmetically undesirable midline bony bulge is also important.

Progressive bulging of cranial vertex can become apparent a few months after surgery to correct nonsyndromic or syndromic craniosynostosis, most often scaphocephaly [23, 24]. Usually, this is a consequence of resynostosis of multiple sutures and causing intracranial hypertension with upward expansion of bone at the location of the anterior fontanelle from normal brain growth. If not covered with bone, the bulge is an encephalocele caused by the same pathophysiology.

The most important indication for surgery is the alleviation of pressure, but correction of the cosmetically undesirable bony bulge is also important. The bulge in bone at the vertex is a manifestation of the elevated intracranial pressure and resynostosis. Correcting the deformity alone will not alleviate or have any beneficial effect on intracranial hypertension.

A bilateral frontoparietal craniotomy that extends beyond the limits of deformity by 1–3 cm on all sides is required. The bulging dura can usually be adequately reduced with desiccation by electrocautery. It is important that the dural desiccation not be done near the superior sagittal sinus. It is often necessary to make several coronal or parasagittal osteotomies to allow expansion of the cranial vault in response to intracranial hypertension. The contour of the free concave bone flap must be improved by radial osteotomies and of tongues of bone with a Tessier bone bending forceps. It may be necessary to divide the flap into several pieces. It can then be secured in place with titanium plates. Correcting the dural bulge by compressing it inward with a snugly secured bone flap is commonly followed by failure. Regardless of technical details, it is important that the superior sagittal sinus not be left in a compressed or kinked position.

Late Correction of Scaphocephaly

None of the techniques used in infants are appropriate for correction of scaphocephaly in patients over approximately 2.5 years of age. The following technique has been used successfully by the author in older patients. A coronal fusiform craniectomy extending approximately 1 cm below the squamosal sutures is made immediately behind the coronal suture. The amount of reduction in anterior–posterior dimension determines the width of the midpoint of the fusiform craniectomy. Parasagittal osteotomies, each approximately 1.5 cm from midline, are made from the posterior edge of the fusiform craniectomy to the lambdoid sutures. The sagittal bone flap is freed from dura, without fracturing or separating its posterior end, using a #2 Penfield and hemostasis is established. Each partial bone is morcellated into approximately five pieces, as described for ***sagittal strip craniectomy and biparietal morcellation***. Two holes are drilled through the anterior end of the intact posterior sagittal bone and corresponding holes near the posterior edte of the midline frontal bone. A 2-0 silk suture is passed through each pair of holes and used to shorten the anterior–posterior dimension of the cranium over a period of 20–60 min. The morcellated parietal bones allow compensatory lateral expansion. If the patient has a shunt, CSF can be drained as the cranium is shortened.

Over 10 Years of Age (Approximate)

Patients over 10 years of age who require correction of scaphocephaly require cranial vault reconstruction to achieve a satisfactory cosmetic result. This surgery can be a long and tedious.

Dolicocephaly

Dolicocephaly (*Greek: long PLUS_SPI head*) is an anthropological term used to describe a long narrow head and, unlike scaphocephaly, is not caused by synostosis and does not imply abnormality. Many ethnic groups around the world have dolichocephalic heads. Also, dolicocephaly may develop in premature babies following prolonged periods of postnatal lateral positioning. Dolicocephaly is *not* a synonym for scaphocephaly but is occasionally incorrectly so used.

Brachycephaly (Bilateral Coronal Synostosis)

Brachycephaly (*Greek: short PLUS_SPI head*) is the term for a cranium that is abnormally short in the anterior–posterior dimension, caused by bilateral coronal synostosis but also used by anthropologists for all crania that are short in the anterior–posterior dimension. Brachycephaly is caused by bicoronal craniosynostosis and is the second most common form of craniosynostosis (20–30%), with an incidence of one in 16,000 in male and one in 8000 in female births [4, 5].

The cranium is short in the anterior–posterior axis and wide in the transverse axis, quite often with vertical elongation. There is broad flattening of the forehead and supraorbital rims with a short anterior–posterior dimension of cranial vault. The anterior skull base is short and supraorbital rims retropositioned. Prominent frontal and bitemporal bossing are common. Extreme cases may have turribrachycephaly. The dysmorphology of brachycephaly is significant and can become a serious psychosocial concern for children as they grow older and into adulthood. Coronal synostosis is a common feature of many craniofacial syndromes, particularly Muenke syndrom (*FGFR-3*). The deformity becomes worse with age; therefore, early surgical attention (3–5 months) is recommended (Table 16.1).

The indications for surgical correction of brachycephaly are the need for expansion of the cranial vault to alleviate intracranial pressure and cosmesis. Prolonged intracranial hypertension can impair intelligence. Most parents choose to have surgery done within the first few months of postnatal life. Surgery expands the anterior–posterior dimension of the cranium, reduces the transverse diameter, and corrects dysmorphology of forehead. This expansion and alteration in shape of the cranium allow the brain, which in an infant is approximately 85% water, to immediately expand passively in the anterior direction [25]. There are several accepted surgical variations. Neuroplastic concerns are a major issue in the execution of all surgeries for brachycephaly. There are two categories of surgery for correction of brachycephaly: open and endoscopic.

Positioning

Surgeries to correct brachycephaly are done with the patient in the supine position.

Table 16.1 Dysmorphology associated with craniosynostoses

Craniosynostosis	Synostosed suture	Direction of growth restriction	Direction of compensatory expansion
Scaphocephaly	Sagittal	Transverse frontal–parietal	Anterior, posterior or both
Brachycephaly	Bilateral coronal	Anterior	Transverse
Anterior plagiocephaly	Unilateral coronal or fronto-sphenoid	Ipsilateral frontal	Contralateral frontal
Posterior plagiocephaly	Lambdoid[a]	Ipsilateral parietal–occipital	Contralateral parieto-occipital
Trigonocephaly	Metopic	Bifrontal	Biparietal
Oxycephaly	Lambdoid, coronal, and often sagittal	All except upward	Upward
Kleeblattschädel	Multiple	All	Frontal and bitemporal
Pansynostosis	All sutures	All directions	None

[a]Most often caused by positional deformation, not synostosis

Open Technique

This technique immediately expands the volume of the anterior cranial vault and addresses the associated morphological abnormalities.

Plastic neurosurgical concerns

- Choice surgical technique.
- Camouflage of scalp incision.
- Position of osteotomies.
- Reduction in bifrontal cranial width.
- Facilitate frontal cranial expansion.
- Reduction of frontal verticality.
- Reconstruction of supraorbital rim and forehead complex.
- Correction of bitemporal bossing.
- Restoration of ipsilateral temporal muscle.
- Cosmetic closure of scalp.

Scalp

The scalp should not be shaved. Open surgery for brachycephaly is accomplished via a zigzag coronal incision in scalp. Scalp, with pericranium, must be dissected over the entire frontal convexity, across both supraorbital rims, and medially across the frontonasal sutures.

Muscle

The anterior two-thirds of each temporalis muscle must be dissected downward and posteriorly to expose the frontozygomatic sutures and the bulging squamous portions of the temporal bones.

Bone

A broad bifrontal craniotomy is marked with ink with its straight transverse supraorbital border approximately 1.5 cm above the supraorbital rims to provide a frontal bandeau. The upper limit of the craniotomy is marked about 1 cm anterior to the coronal sutures. If the anterior edges of the anterior fontanelle cannot be exposed with a curette a small burr hole is made approximately 1 cm from midline and just anterior to one of the fused coronal sutures. The dura exposed through the burr hole is separated from bone across the midline using Penfield and freer dissectors. A craniotome is used to outline the bifrontal bone flap. If there is a supraorbital midline bony keel, this must be disrupted with a small osteotome. A #2 Penfield dissector is used to separate any attachments of midline dura to bone. The frontal bone may be removed in a single piece or in two pieces, depending on the status of the metopic suture.

The anterior edge of the crista galli and floor of the frontal fossa can be cleared with freer and Penfield dissectors back to the midpoint of the crista galli. There are no significant attachments of bone to dura along the anterior floor of the frontal fossa, except over the crista galli. The cribriform plates should not be disturbed.

Removal of Supraorbital Rim

Periorbitum can be easily dissected from the roof of each orbit with Penfield dissectors. Medially this dissection is continued across the frontonasal sutures, without disrupting the medial canthal ligaments. Laterally, the dissection is continued down and across each fronto-zygomatic suture. While gently elevating the frontal dura with a flat brain retractor, osteotomies are made with a narrow osteotome or oscillating saw across the roof of the orbit (floor of frontal fossa) and extended laterally across the sphenoid wings. Osteotomies are then made down the lateral wall of each orbit to approximately 3 mm below each frontozygomatic suture, and each of these sutures is disrupted with an osteotome or oscillating saw. Medially, each frontonasal suture is cut with an osteotome and the lateral end of these osteotomies is connected to the osteotomies across the orbital roofs. The osteotomies at the frontonasal sutures should form a distinct V (apex upward), regardless of the exact orientation of these sutures. Lastly, an osteotome of approximately 1 cm width is positioned in the anterior floor of the frontal fossa, just anterior to crista galli, and driven to a depth of approximately 10 mm. Grasping each orbital rim with thumb and two fingers, each supraorbital rim with bandeau is rotated forward and removed. It may be necessary to extend one or more of the lateral osteotomies with an osteotome to free remaining bony connections.

Remodeling Supraorbital Bar

The free supraorbital bar may initially be a single fragment but, if there is a patent metopic suture, it may be flexible in the midline. Regardless, the frontal bar must be divided, with a craniotome or scissors, into two halves. Approximately 3 mm of bone along the medial edge of each of these halves must be removed with scissors, Leksell rongeur, or craniotome. A wedge osteotomy is made into the far lateral, inner side of each supraorbital bar to allow the lateral extent of each bar to be bent posteriorly into a more normal curvature. Maintenance of this bend often requires a suture through two holes drilled for this purpose. Approximately 3 mm of bone must be removed from the tip of each lateral bony process to allow the supraorbital bar to be tilted posteriorly when repositioned.

Remodeling Frontal Bone Flap

The frontal bone flap is cut in its midline to produce mirror-image fragments. Three to five mm of bone is removed along the medial surface of each flap. While holding the two fragments in their planned position over dura, each is marked for remodeling. Because they will be tilted posteriorly from their original bulged positions, their lower edges must snugly abut the remodeled, resized, and repositioned supraorbital bar. A triangular section of bone must be resected from each lateral side and from each upper edge. Also, remodeling will be required to optimize the contour and ensure a snug fit against the remodeled supraorbital bar producing a more normal frontal angle. Radial osteotomies may be required to facilitate bending of the frontal bone with Tessier bone bending forceps. A generous portion of the anterior lower edge of each frontal bone must be removed with rongeurs. If not done, these edges will protrude far anteriorly after the supraorbital bar is replaced in its new posteriorly tilted position of 10°–15°.

Dura

The bulge in dura in the upper medial frontal and far lateral frontal locations should be shrunk by desiccation with electrocautery until appropriate contour and width are achieved. If the dural bulge is severe or when the patient is a teenager, plication with 4–0 silk or Nurolon® sutures will be necessary.

Reconstruction

Reassembly of Fronto-Orbital Complex

The two halves of the supraorbital bar must be rigidly attached together, using an underlying bone graft of approximately 1.5 by 2 cm (not necessarily rectangular), to reinforce and stabilize the reattached halves. The lower half of this pair is secured to the undersurface of the supraorbital bar by the absorbable sutures which hold the two supraorbital fragments together, using holes drilled for this purpose. The upper half of the graft should extend above the supraorbital bar.

Four holes are drilled through the upper portion of each supraorbital bar and corresponding holes through the inferior edge of each free frontal bone fragment. Also, 3 or 4 matching holes are drilled along the medial sides of the two frontal bone flaps. Absorbable sutures of 2-0 Vicryl are passed through the paired holes and tagged with hemostats. Assembly of these fragments requires two pairs of hands. One person holds two fragments of bone tightly together while the other person tightly ties each suture. The tying is most efficiently accomplished in the following sequence: (1) secure the supraorbital rim fragments, with underlying reinforcing fragment, (2) starting medially, tie the sutures along the supraorbital rims, (3) tie the frontal convexity fragments together including attachment of the stabilizing bone fragment extending upward from the supraorbital rims.

The reconstructed fronto-orbital complex is placed in its normal location for a trial fitting. It is often necessary to make additional modifications which can include removal of more of the upper edges of the construct or making radial osteotomies to improve contour and fit. It is then secured with a 3-0 or 2-0 absorbable suture across each frontonasal suture. The result is a structure called a *floating forehead*. Plates and screws should not be used in children under approximately 3 years of age depending on thickness of bone.

Correction of Temporal Bulge

Prominent bilateral bulging of the squamous portion of the temporal bones, particularly their anterior portions, is characteristic of brachycephaly but also occurs in patients with anterior plagiocephaly, and kleeblattschädel. Correction is usually required. The temporalis muscle above the zygomatic arch must be separated from all bony attachments, including separation from the lateral orbital wall. The muscle is then cut with a knife, not electrocautery, in a line parallel to its fibers from its upper edge down to the zygomatic arch and reflected downward. An oval osteotomy surrounding the bony bulge is marked with ink. A craniotome is then used to make the required osteotomy, and the free convex bone flap is removed. The bulge in exposed dura must be eliminated by desiccating the dura with electrocautery, being careful to not cause thermal injury to underlying brain. The free flap is remodeled as needed to give it, when inverted, a mildly concave contour. The oval flap is inserted into the cranial defect and rotated sufficiently to allow its edges to lock beneath the edges of intact cranial bone; however, one or two sutures may be required to secure it. This will require drilling of holes in the flap and adjacent bone. If the edges of intact cranial bone surrounding the craniotomy are prominent, these should be remodeled with a burr.

The bulging temporal bone has quite often produced significant compression of the temporalis muscle against the zygomatic arch, thereby impairing development of this muscle and causing atrophy. As a result, the temporalis muscle is commonly very thin at time of surgical intervention. It is important to cover the site of the corrected bony bulge with temporalis muscle. The upper edges of the muscle are reattached to frontal and parietal bone with 3-0 or 2-0 Vicryl® sutures, using holes drilled for this purpose. The muscle should also be sutured to the lateral edge of the orbit.

Closure of Scalp

The galea is closed with absorbable sutures, usually 3-0 Vicryl®. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. Incisions which are under tension—uncommon—or in which edge alignment is difficult can be approximated with staples.

Endoscopic Technique

Plastic neurosurgical concerns

- Placement of scalp incisions.
- Protection of dura.
- Secure hemostasis.
- Cosmetic closure of scalp.

Endoscopic surgery for brachycephaly consists of suturectomy of both coronal sutures, which allows compensatory anterior expansion of the cranial vault and brain and expectation of correction of the dysmorphology over the following few weeks and months. Endoscopic surgery provides no immediate significant improvement and does not significantly correct temporal bulging.

A parasagittal incision of 2.5–3 cm length and centered across each synostosed coronal suture is made approximately 3 cm from midline. A burr hole is made just to one side of each fused suture. The galea is easily separated from pericranium along the coronal sutures down to and across the squamosal sutures, using a #2 Penfield dissector and endoscope. A Kerrison rongeur is used to remove a 1 cm strip of bone across each exposed suture. The synostosed suture is then separated from dura with a #2 Penfield dissector. A scissor is used to blindly make a para-sutural osteotomy approximately 5 mm from each side of the synostosed suture, down to and across the squamosal suture. The strut of bone is removed piecemeal with pituitary rongeurs. The exposed dura and the raw edges of bone are inspected with an endoscope for active bleeding and for dural laceration. Any identified bleeding site on dura is controlled by bipolar coagulation or application of FloSeal®. A small piece of bone wax should be used to halt any bleeding from bone. Some surgeons prophylactically apply coagulation along the raw edges of bone, but this probably serves little benefit.

Anterior Plagiocephaly (Frontal Plagiocephaly)

Plagiocephaly (Greek: twisted or crooked PLUS_SPI head) is a term occasionally applied to almost every type of asymmetric cranial contour; however, craniofacial surgeons, pediatric neurosurgeons, and physicians who commonly deal with birth defects use this term for flattening of the frontal or occipital cranial vault, but most commonly for anterior flattening. Anterior and posterior plagiocephaly are quite different disorders.

Anterior plagiocephaly is strongly associated with *unilateral coronal synostosis* and less commonly with *unilateral frontosphenoid synostosis* [26–28]. Premature closure of other sutures on the involved side, for example, the frontoethmoidal, frontosphenoidal, and sphenoethmoidal, can contribute to the deformity [26, 29]. Anterior plagiocephaly occurs in approximately 1/10,000 live births and is more common in females. Coronal synostosis is characterized by an ipsilateral flat forehead and retropositioned and tilted supraorbital rim with vertical orbital dystopia and contralateral frontal bossing caused by compensatory growth at the contralateral coronal suture. There is a tendency for parents to recognize only the flat retropositioned side as being abnormal. The orbital configuration on the fused side is described as having a Harlequin appearance due to its more vertical oblique orientation versus the more horizontal, normal oblique aperture. The ear appears to be anteriorly positioned. The anterior fontanelle is frequently displaced to the nonsynostosed side, and the nose is often curved into a mild C-contour with deviation to the nonsynostosed side. Quite often there is a temporal bulge on the synostosed side, and the pinna may appear to be anteriorly positioned. The facial midline and lower face typically appear to be displaced away from the side of the unilateral synostosis, likely due to impaired development or translation of tissue across the cranial base during development. Vertical strabismus and *apparent* ipsilateral abducens nerve palsy are common in unilateral coronal synostosis, likely resulting from a retropositioned trochlea [30]. There are two categories of surgery for correction of anterior plagiocephaly: open and endoscopic.

Positioning

Surgeries to correct anterior plagiocephaly are done in the supine position.

Plastic neurosurgical concerns

- Cosmetic scalp incision.
- Position of osteotomies.
- Correction of contralateral frontal dural bulge.
- Correction of contralateral frontal cranial bossing.
- Anterior expansion of ipsilateral frontal fossa.
- Remodeling, advancement, and fixation of lateral ipsilateral orbit.
- Correction of ipsilateral cranial temporal bulge.
- Restoration of ipsilateral temporal muscle.
- Prevention of unilateral temporal hollowing.
- Cosmetic restoration of scalp.

Open Technique

Scalp

The scalp should not be shaved. Open surgery for anterior plagiocephaly is accomplished via a zigzag coronal scalp incision, continuing posterior to the ear or down to the zygoma. The anterior scalp flap is reflected with pericranium across both supraorbital rims, and medially across both frontonasal sutures.

Muscle

The ipsilateral temporalis muscle is dissected from bone, from the superior temporal line, anteriorly across the fronto-zygomatic suture, and down to the zygomatic arch on each side. Some surgeons leave a small intact cuff of fascia and muscle along the superior temporal line for repair.

Bone

The anterior edge of the anterior fontanelle is cleared with a curette of all fibrous adhesions. If the anterior fontanelle is closed, a burr hole is required preferably on the synostosed side anterior to the coronal suture and approximately 1 cm from midline. A broad bifrontal bone flap with a supraorbital bandeaux of approximate 1.5 cm height above the inferior edge of the supraorbital rim is outlined with ink. On the side of synostosis, this should extend two or more cm posterior to the location of the synostosed coronal suture and on the contralateral side approximately 5 mm anterior to the coronal suture. A rectangular extension of bone having 1 cm height and 1.5–2 cm length is inked on the ipsilateral side, and, depending on surgeon's choice, also on the contralateral side.

These tongues of bone extend straight posteriorly from the ipsilateral supraorbital bar. They will allow a tongue-in-groove advancement and fixation during reconstruction. Osteotomies are made along the marked lines with a craniotome. If there is a keel of bone in the supraorbital midline, this should be disrupted with a narrow osteotome. The disconnected frontal bone can then be easily separated from dura with a #2 Penfield dissector and removed.

Dura must be separated posteriorly from the floor of the frontal fossa for approximately 1.5–2 cm. There are usually no significant attachments of dura to the floor of the frontal fossa, except near the midline and over the crista galli. The dura can be easily cleared with freer and Penfield elevators to the midpoint of the crista galli. The cribriform plates and olfactory nerves should not be violated.

Periorbitum is dissected free from the roof of each orbit. Medially, this dissection is continued down below the level of the frontonasal sutures but should not disrupt the medial canthal ligaments. Laterally, the dissection is continued down and across each frontozygomatic sutures. The lateral canthal ligaments are usually disrupted. Attempts should be made to tag each with a suture. If periorbitum is disrupted, it should be immediately repaired with 4–0 chromic suture.

While gently elevating the frontal dura with a flat brain retractor, osteotomies are made across each floor of the frontal fossa (roof of the orbit) with a narrow osteotome or oscillating saw. The authors prefer the former. Laterally, each osteotomy must extend across the sphenoid wings and down the lateral wall of the orbits to approximately 3 mm below the fronto-zygomatic sutures. Each frontozygomatic suture is then disrupted with an osteotome. Medially, each frontonasal suture is disrupted with an osteotome.

It is important that these two cuts of the frontonasal sutures meet to form a distinct V-shape of approximately 90° (apex upward), which may not conform precisely to the orientation of the sutures. The lateral ends of these osteotomies are then extended sufficiently to connect with the medial ends of the osteotomies across the floors of the frontal fossae. Medially, each frontonasal suture is cut with an osteotome and the lateral end of these osteotomies connected to the lower end of the osteotomies on the medial walls. Lastly, an osteotome of approximately 8 mm width is positioned against the floor of the frontal fossa, just anterior to crista galli and driven to a depth of approximately 8 mm.

Grasping each orbital rim with a thumb against each inner surface of the supraorbital rims with bandeau are rotated forward and removed, usually as a single fragment. It may be necessary to extend one or more of the osteotomies with an osteotome to free remaining bony connections.

Remodeling of Ipsilateral Supraorbital Fragment

The free supraorbital bar, with bandeau, may initially be a single rigid fragment; however, if the metopic suture is patent, the flap may be flexible in the midline. Regardless, the frontal bar must be divided in the midline with a craniotome or scissors. Several important remodeling steps are required in the ipsilateral fragment, to correct its contour and accommodate the required anterior rotation of the fragment. This repositioning moves the medial wall of the orbit a few mm laterally and swings the previously lateral wall both anteriorly and medially, which would place it in front of the lateral portion of the globe.

1. Approximately 3 mm of bone along the medial edge of the ipsilateral bone fragment must be removed with a craniotome, Leksell rongeur, or scissors leaving a straight edge which will abut the contralateral frontal fragment during reconstruction.
2. Six to eight mm of the anterior edge of the lateral side of the orbit must be removed. This prevents there being bone anterior to the lateral globe and provides a more normal, anteriorly concave lateral orbital wall.
3. The outward protrusion of bone resulting from rotation of the orbit and supraorbital bar must be corrected by one or two wedge osteotomies into the inner side of the ipsilateral supraorbital fragment. This will allow its lateral portion to be bent (greenstick fracture) by approximately 50°–80° from its original position. Maintenance of this bend usually requires placement of an absorbable suture through two holes drilled for this purpose.
4. The relatively flat supraorbital rim is given curvature with two to three osteotomies into the inner side of the rim and orbital roof to allow its curvature to be molded with Tessier bone bending forceps to give a curvature closely resembling that of the contralateral supraorbital rim. Maintenance of this curvature may also require placement of a suture in a pair of holes drilled for this purpose.

Remodeling of Contralateral Supraorbital Fragment

The contralateral supraorbital fragment usually requires little modification. However, if that orbital rim and bandeau were tilted significantly forward, surgical attention is required. A few mm of bone may need to be removed from the inferior lateral portion of this supraorbital fragment to allow the supraorbital bar to be rotated posteriorly and secured in that position. Less often some modification in the bandeau on this side is required.

Reconnection of Supraorbital Bar

A fragment of bone, approximately 1.5 by 2 cm in size, is harvester from one of the upper portion of a frontal convexity bone for use as a stabilizing or reinforcing graft. This graft is placed across on the undersurface of the site of abutment of the two frontal fragments with half its height extending above the supraorbital bar. Two holes are drilled through the medial ends of each supraorbital fragment and underlying bone graft, and the combination of bones are sutured tightly together with 2–0 Vicryl®.

Remodeling Frontal Convexity Bone Fragments

There are no guidelines for this remodeling because each case is unique and surgical creativity is required. Small technical details can greatly affect cosmetic outcome. The frontal bone flap is cut in its midline, resulting in two dissimilar fragments—the smaller ipsilateral one being relatively flat and the larger fragment from the contralateral side having an excessively convex outer surface. On a trial-and-error basis, the two fragments are rotated and switched in various positions to select the positions in which symmetry and cosmesis will be best served. The most common chosen position is a left-right switch of the pieces with one or both rotated 60°–90°.

Each frontal fragment is marked to indicate sections to be removed. It is always safest to err in the direction of resecting too little. Anticipating reassembly, consideration must be intentionally overlapping the frontal fragments. The originally contralateral convex fragment usually requires a few radial osteotomies to facilitate reduction of its convexity. This will expand the bone flap, thereby necessitating removal of bone along its edges. The originally flat ipsilateral fragment, which will usually be transferred to the contralateral size, always requires remodeling with radial osteotomies and trimming of edges to achieve desired contour and fit.

Because the new forehead construct will be tilted from the original forehead position and because its lower edge must snugly abut the remodeled and repositioned supraorbital bar, additional remodeling may be required to optimize contours and a ensure snug fit.

Assembly of Fronto-Supraorbital Complex

The two frontal fragments are secured together, and to the reassembled supraorbital bar with its reinforcing fragment, using 2–0 Vicryl® sutures through matching holes drilled for this purpose. Three or four holes are drilled along the upper edge of each supraorbital bone fragment, and corresponding holes are drilled holes along the inferior edge of the reconnected bones of the frontal convexity. Sutures of 2–0 Vicryl® are passed through the paired holes and tagged with hemostats.

Tying the sutures to assemble these four fragments requires two pairs of hands. For each suture, one person holds two fragments of bone tightly together while the other person tightly ties the suture. This is most tightly and securely accomplished with the following tying sequence: (1) secure the supraorbital bar fragments together with the underlying reinforcing fragment, (2) starting medially, tie the sutures along the supraorbital bar, (3) tie the frontal convexity fragments together and include the stabilizing bone fragment that is extending upward from the supraorbital bar. Loose or moderately tight ties are unacceptable.

Securing Reconstructed Fronto-Supraorbital Complex

The reconstructed fronto-orbital complex is laid to its correct location for a trial fitting. It is often necessary to make additional modifications in contour with removal of more of the upper edges of the construct or making additional radial osteotomies to improve contour and fit.

When the fit is satisfactory, the completed bony construct is secured in place with one 3–0 or 2–0 absorbable suture across each frontonasal suture, using holes drilled for this purpose. The ipsilateral bony tongue is positioned anteriorly and secured with one or two sutures through bone, in order to rigidly fix the previously retropositioned lateral orbit in its new anterior location. The contralateral tongue of bone, if present, will also require attachment to bone with absorbable sutures. The contralateral frontozygomatic suture must be correctly aligned and immobilized with a single suture. Also the ipsilateral frontozygomatic suture may require suture fixation.

Alternative Open Techniques

After the initial frontal craniotomy is marked with ink, another cranial site having an acceptable contour for a new forehead, usually biparietal, is marked to the appropriate size with ink. This bone flap is harvested and placed in saline. A bifrontal bone flap and supraorbital rims are removed, and the supraorbital rims are remodeled and secured in place, as described above. The large bicoronal fragment is modified as needed and used to reconstruct a forehead [31]. The biparietal defect is repaired with fragments of bones from the resected bifrontal convexity.

Dura

The bulge of dura in the contralateral frontal region should be reduced by desiccation with electrocautery, until it approximately matches the contralateral side, but *perfection should not be sought*. Care must be taken to avoid thermal injury to underlying brain. In older children with extreme contralateral bulging, an ellipse of dura approximately 2 cm in width can be harvested from the bulging side and sutured into a durotomy on the ipsilateral. This is rarely required.

Bone

Older Infants and Children

For patients of 9–12 months of age or older, the bone is thicker, less malleable, and less spontaneous remodeling will occur in the weeks and months following surgical correction. Therefore, reconstruction is more tedious and requires more fragmentation and more secure reassembly. A coronal bandeau can be harvested and used to achieve a supraorbital contour which can be securely fixed at each end to supraorbital rims, forming a new frontal convexity bone. The bone of teenagers can be expected to undergo minimal spontaneous remodeling and therefore the location of fragments of bone and their contours should be expected to be visible and possibly permanent following the conclusion of surgery.

Temporal Hollowing

Ipsilateral temporal hollowing is often present in patients after the osseous correction of anterior plagiocephaly is completed. The overlying hypoplastic muscle contributes greatly to this deformity; also, poor bony reconstruction can be a contributing factor. Although this deformity can usually be anticipated and prevented, it may only come to attention in the months following surgery. It is best corrected by a plastic surgeon, usually with an onlay of a synthetic material plus forward rotation of temporalis muscle.

Other Concerns

Tilted Nose

The tilted nose is often less noticeable in infants after correction of the anterior plagiocephaly. Regardless, it commonly improves over the following months and only rarely requires surgical correction. However, if the initial surgery is done in teenagers, the nasal abnormality should be surgically corrected at time of initial surgery.

Apparent Abducens Nerve Palsy

Apparent abducens nerve palsy may be present in the ipsilateral side of patients with anterior plagiocephaly. This is thought to be caused by a retropositioned trochlea, not abducens nerve palsy. This problem should be addressed by an ophthalmologist after the surgery for correction of the anterior plagiocephaly.

Closure

Scalp

The galea is closed with absorbable sutures, usually 3–0 Vicryl® in infants and young children. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. The postoperative coronal incision line often appears askew due to the changes in underlying bony configuration. Incisions which are under tension or in which edge alignment is difficult should be approximated with staples.

Endoscopic Technique [32–34]

Endoscopic surgery removes the synostosed suture but does not alter associated deformities such as the retropositioned ipsilateral supraorbital rim and forehead, nor the contralateral bulging forehead. A parasagittal incision of approximately 3 cm length is made about 1 cm above the midpoint of the fused coronal suture. A burr hole is made on or immediately adjacent to the fused suture. Bone is separated from underlying dura between the sagittal suture, or posterior edge of anterior fontanelle, to the squamosal suture with Penfield dissectors. A scissor is used to blindly make two parallel osteotomies along each side and approximately 5 mm from the path of the synostosed suture. The strip of bone is removed piecemeal with pituitary and Kerrison rongeurs, making certain that the craniectomy extends across the squamosal suture. Dura and raw edges of bone should be inspected with an endoscope to allow identification of sites of venous bleeding and dural lacerations. Bleeding from dural sites can be controlled by bipolar coagulation or application of FloSeal®. Swarf (small bits of removed bone) can be packed into the edge of the osteotomies to control bleeding from bone. Some surgeons prophylactically apply coagulation along the raw edges of bone.

Frontosphenoid Synostosis

A rare cause of anterior plagiocephaly is frontosphenoid synostosis, and this is easily mistaken for unilateral coronal synostosis [31, 35]. This entity most often comes to medical attention in patients with anterior plagiocephaly in whom unilateral coronal synostosis is not present. Neuroimaging is required for accurate diagnosis, but even with neuroimaging the diagnosis is easily missed.

The steps necessary for remodeling of the cranial vault are the same as those described above for anterior plagiocephaly caused by unilateral coronal synostosis, but the surgery *must* also include removal of the synostosed frontosphenoid suture.

Posterior Plagiocephaly (Occipital Plagiocephaly)

Posterior plagiocephaly may be caused by positional deformation or by lambdoid synostosis [36–38]. The former is much more common.

Positional Deformation

Positional deformation is the most common cause for posterior plagiocephaly but is often mistakenly diagnosed as lambdoid synostosis. It occurs from a disproportional amount of time that a newborn spends in the supine position with the head rotated, most often on the right side. This may simply reflect an infant's preference to rotate the head toward a source of light - e.g., window - or in the direction of expected arrival of parents or nurse. The parieto-occipital flattening can be present at birth, in which case it can be diagnosed within hours; however. in most cases, it is not recognized until days or weeks later, when the child quickly develops a strongly preferred sleep position.

Positional deformation has an association with torticollis and strabismus and may occur in one of triplets. The head often has a parallelogram contour with ipsilateral occipitoparietal flattening and ipsilateral frontal bossing. The ear often appears to be positioned anteriorly. A classification of positional plagiocephaly based on severity has been proposed, but is not in common use [30]. Oddly the facial asymmetry, which if prominent, has occasionally led to the misdiagnosis of posterior plagiocephaly as anterior plagiocephaly.

The diagnoses of positional deformation increased when pediatricians recognized a relationship between sudden infant death syndrome (SIDS), also known as crib death, and sleeping in the prone position. The death rate decreased greatly following the change to recommending that infants sleep in the supine position, and the occurrence of positional deformation increased. (*Safe to Sleep Campaign*, formerly the *Back to Sleep Campaign*).

Historically, posterior plagiocephaly in infants having a radiographically visible lambdoid suture was mistakenly thought to have a pathologic suture, often referred to as a “lazy or sticky lambdoid.” This hypothesized pathology, in which agency was attributed to the suture, resulted in many infants undergoing surgery for what is now understood to be positional deformation, and which rarely requires surgical correction.

Nonsurgical Therapy

A recent “pragmatic randomized controlled trial found no evidence of a significant or clinically meaningful difference in improvement in skull contour at 2 years of age between infants who were treated with helmet therapy and those in whom the natural course of skull deformation was awaited” [39]. Mild-to-moderate posterior plagiocephaly very commonly improves spontaneously, particularly if the infant can be prevented from sleeping on the flat area. Mild posterior plagiocephaly is usually not noticeable in adults, if scalp is covered with hair that has not been closely clipped. Some surgeons and rehabilitation physicians recommend molding helmets for treatment, and the cranial contour very often improves significantly. However, the observed improvement is likely due, in part, to the reduction in time spent lying on the flat region and to the passage of time. There is disagreement on the effectiveness and efficacy of helmet therapy for positional skull deformation. In a randomized controlled trial in the treatment of moderate-to-severe skull deformation of otherwise healthy infants, helmet therapy has been shown to add nothing, other than an increase in the costs, when compared to infants in whom the natural course of skull deformation was allowed time to resolve. In summary, surgery is rarely required; however, extremely severe cases, particularly if untreated for many months, can benefit from surgery for cosmesis.

Surgery for Positional Deformation

Surgical correction of posterior plagiocephaly caused by positional deformation is rarely if ever necessary except in severe cases which have not undergone satisfactory spontaneously improvement. The details of surgery are analogous to those described below for posterior plagiocephaly caused by unilateral lambdoid synostosis.

Synostotic Occipital Plagiocephaly (Unilateral Lambdoid Synostosis)

Posterior plagiocephaly, characterized by unilateral flattening of the parieto-occipital region of the cranium, is most often caused by positional deformation, *not lambdoid synostosis*. Much of the published information, particularly from three or more decades ago, on posterior plagiocephaly is difficult to navigate because positional plagiocephaly was so often misdiagnosed as lambdoid synostosis.

Unilateral lambdoid synostosis is present in one of 150,000 live births and accounts for approximately 3% of cases of craniosynostosis. There is unilateral occipital flattening, causing the head to have compensatory contralateral frontal bossing, thereby causing the head to have a trapezoidal contour. A bony ridge is often palpable over the path of the fused suture. The ipsilateral mastoid has a bulging appearance with the pinna displaced inferiorly and the posterior hairline is oriented obliquely. Most of these features do not occur with positional deformation [40]. These characteristics are opposite the findings in patients who have positional molding with open lambdoid sutures

The cranial deformity associated with lambdoid suture synostosis is progressive and becomes worse with age. However, surgical correction is often not required for cosmesis in mild and many moderately severe cases, particularly if the deformity is well covered by hair. Extreme cases usually undergo surgical correction. Aesthetics is usually the major concern in the correction of posterior plagiocephaly.

Plastic neurosurgical concerns

- Careful positioning to protect facial skin and eyes.
- Camouflage of scalp incision.
- Positioning of osteotomies.
- Correction of ipsilateral occipital flattening.
- Correction of contralateral occipital bulge.
- Symmetric remodeling of occipital-parietal bone.
- Rigid fixation of newly constructed bioccipital bone flap.
- Secure reattachment of occipital muscles (if separated during surgery).
- Cosmetic closure of scalp.

Positioning and Immobilization

Surgical correction of posterior plagiocephaly is done with the patient in the prone position with the forehead and face on a well-padded horseshoe head rest. The asymmetric occiput and frontal bossing can induce the surgeon to unintentionally position the head in mild rotation, which can adversely influence the surgery. The sagittal plane of the head should be positioned perpendicular to the plane of the surgical table.

Attention must be given to protection of eyes from pressure and from chlorhexidine which, in the prone position, can flow beneath the protecting cover of the eyes. The head should be lifted every 10 min and held suspended for 1 min or longer to relieve pressure on the forehead and face and allow the skin to be perfused—sometimes referred to as “giving the face a drink of blood.” Failure to do this can result in ischemia and infarction of skin of the forehead or face.

Scalp

The scalp should not be shaved. Open surgery for craniosynostosis is accomplished via a zigzag coronal incision across the posterior parietal scalp with passage behind the pinnae to expose occipital bone from above the normal site of lambdoid sutures and down to approximately 1 cm below the location of transverse sinuses. The pericranium should be reflected posteriorly with the scalp flap.

Muscle

The nuchal muscles usually do not require being disturbed in patients in whom the posterior plagiocephaly is moderately severe; however, in severe cases, the nuchal muscles must be separated from bone down to approximately 2 cm above the foramen magnum. Older children and teenagers who comes to surgery tend to have severe deformities and require separation of these muscles from bone.

Bone

There are several techniques for the osseous correction of posterior plagiocephaly and include the following: transposition, ipsilateral radial osteotomies with remodeling, and total occipital remodeling.

Transposition–Rotation Technique

A large *bilateral* parieto-occipital bone flap is marked with ink and a parasagittal line is then marked on the bulging side of the planned flap approximately 1.5 cm from midline. The flap must encompass the relatively flat appearing bone on the ipsilateral side and an area of the same size on the bulging contralateral side, and must pass across the asteria and up across the transverse sinuses. Some surgeons use a tongue-in-grove technique, and this requires that a tongue be marked into the high contralateral parietal bone [41]. An osteotomy is made with a craniotome along the marked line on the contralateral (bulging) side, including along the parasagittal line. Care must be taken to avoid violation of the transverse sinuses. The contralateral bone flap is then easily removed. A #2 Penfield dissector is used to clear the dura on the flat ipsilateral side from attachments along the venous sinuses. A craniotome is used to make an osteotomy around the ipsilateral side and the bone flap is removed.

Dura

Dura on the bulging side is shrunk by desiccation with electrocautery or by plication but should is not necessary to strive for perfection. Thermal injury to underlying brain must be avoided.

Reconstruction

The two bone flaps are inspected, sides switched, and each rotated as needed. The flap from the contralateral side is modified by making multiple radial osteotomies and the resulting tongues of bone are molded as needed with Tessier bone bending forceps. The edges of the flap are trimmed as needed to fit into the cranial defect on the ipsilateral side. The relatively flat flap from the ipsilateral side requires more extensive remodeling and often must be cut into several pieces to repair the defect on the contralateral side.

The newly modified bone flap for contralateral side is secured in place with 00 Vicryl® sutures. The fragments of bone used to reconstruct the ipsilateral cranial defect may be connected and stabilized in place with 00 Vicryl® and thin titanium plates. Small fragments of bone removed in remodeling the flaps are positioned in gaps between fragments. Most small fragments do not require rigid attachment; however, their dislodgement during manipulation and repair of scalp can be prevented with an overlying piece of Surgicel®.

Closure

The galea is closed with absorbable sutures, usually 3–0 Vicryl® in infants and young children but 2–0 Vicryl® for teenagers. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. Incisions in which edge alignment is difficult should be approximated with staples. The surgical scar may have a skewed appearance because of the surgical change in the underlying bony architecture.

Bilateral Lambdoid Synostosis

Bilateral lambdoid synostosis produces symmetric abnormal flattening of the occiput. This entity is sometimes confusingly designated as oxycephaly, perhaps because it has a peaked upward cranial expansion.

Plastic neurosurgical concerns

- Careful positioning to protect facial skin and eye.
- Camouflage of scalp incision.
- Positioning of osteotomies.
- Remodeling of occipital-parietal bone to correct occipital flattening.
- Rigid fixation of newly constructed occipital-parietal bony construct.
- Secure reattachment of occipital muscles (if separated during surgery).
- Cosmetic closure of scalp.

Positioning

Surgery is done with the patient in the prone position and on a well-padded horseshoe headrest.

Scalp

The scalp should not be shaved. A zigzag coronal incision across the posterior parietal scalp and passing behind the pinnae is required. The scalp with pericranium is reflected posteriorly and downward for several cm below the insertion of the nuchal muscles.

Muscle

Muscles must be widely separated from occipital bone as far downward as surgical correction of the deformity is required and laterally to the asteria, typically 2–3 cm or, in severe cases, to within 1 cm from the foramen magnum. It is usually not necessary to split the muscle mass in the midline. There is no need to leave a cuff of musculofascial tissue on bone to facilitate repair, because the underlying bone will likely be significantly modified and repositioned.

Bone

Extensive remodeling of the entire occipital and posterior parietal cranium is necessary and there is no agreed upon best technique. Osteotomies must be planned to facilitate expansion and a stable reconstruction. In severe cases, the beaten copper (fingerprinting) on the inner surface of the supratentorial bone can hinder smooth passage of a craniotome and increase the risk of violating dura.

A large bilateral craniotomy is required, and this is most often accomplished in two supratentorial flaps and one infratentorial flap. A large symmetric bilateral occipital-parietal flap is marked with ink. This flap should, depending on the upward extent of the deformity, extend above the fused lambdoid sutures and down below the transverse sinuses for the full extent of the deformity. A continuous straight line is marked aoximately 1.5 cm above both transverse sinuses. A parasagittal line is marked approximately 1.5 mm to one side of the parieto-occipital midline, ending at the above-described transverse line. A craniotome is used to make osteotomies along the marked lines which do not cross the sinuses and the two free flaps of bone are removed. A #2 Penfield instrument is used to clear attachments of dura over the superior sagittal sinus and a craniotome is used to cut along the marked lines on the second side. Followed by removal of that bone flap. After dura is separated from bone over the transverse sinuses and confluens sinuses, an inverted U-contoured line is re-marked on the remaining occipital, mostly infratentorial, bone. The arms of the U-contoured line should pass posterior to the asteria, and arc lower across the midline of the squamous part of the occipital bone. A craniotome is used to cut along the marked line and the bilateral occipital flap is removed.

Dura

The usually upward bulging supratentorial region of the dural envelope can be reduced in verticality by plication of fusiform sections of dura or by desiccation with electrocautery. Care must be given to not causing thermal injury to brain or compromising the superior sagittal sinus or transverse sinuses. It is not safe to strive to correct the contour of the dural envelope to normality. The brain will expand posteriorly, in the weeks and months after the bony constriction has been removed and greatly improve the contour of the dural envelope. No action is taken to posteriorly expand the dural envelope.

Reconstruction

Close attention is required to construct a structurally stable and symmetric posterior cranial vault. The new vault must posteriorly expand the region of preoperative flatness—i.e., posterior cranial vault and lower region of the supratentorial vault. Also, the region of preoperative posterior parietal bulging where the dural envelope has been shrunk should be reduced.

There is no agreed upon best technique for reconstruction. On a trial basis, the large bone fragments can be repeatedly positioned to optimize the positions and orientations which achieve the desired occipital expansion and the reduction in the abnormal upward extension of the vault. Often the bone from the parietal region is most useful, after trimming and radial osteotomies, in constructing an expanded occipital region. Remaining fragments are used to complete the osseous repair. Their edges will require revision to allow snug fitting into the bilateral parieto-occipital defect. The larger fragments must be securely attached to surrounding intact bone and to one another with 2–0 Vicryl® and, if 2–4 years of age or older, thin plates. The bone fragment originally covering the transverse sinuses and posterior fossa requires extensive remodeling to achieve a relatively normal curvature. It must then be securely attached to the inferior edges of the upper fragments of bone. The reconstructed cranium, at time of repair, will enclose dead space which will rapidly disappear as brain expands over the next few days.

Nuchal muscles which have been disconnected from bone must be reattached to bone with sutures.

Closure

The galea is closed with absorbable sutures, usually 3–0 Vicryl® in infants. The edges of scalp can be approximated with running 4–0 Vicryl Rapide® suture. Incisions which are under tension or in which edge alignment is tenuous can be approximated with staples.

Oxycephaly

Oxycephaly (*Greek: pointed PLUS_SPI head*) is a term most commonly used to describe a symmetric cranium which has a prominent conical or peaked upward expansion with short anterior–posterior cranial dimension; however, some authors use, confusingly, this term for the flat occiput that results from bilateral lambdoid synostosis. Oxycephaly is caused by synostosis of the sagittal suture, particularly its posterior portion, and coronal sutures. Some patients have lambdoid synostosis without coronal synostosis. Other sutures are occasionally closed. Intracranial hypertension is common. Surgery is required to expand the cranial vault and to provide cosmetic benefit [42].

Acrocephaly (*Greek: high PLUS_SPI head*) and *turricephaly* (*Greek: tower PLUS_SPI head*) are terms which emphasize cranial height and are inconsistently used as synonyms for oxycephaly. Acrocephaly is also used as a term for any tall appearing head or forehead and does not necessarily imply pathology or even abnormality. Turricephaly is a term for a tall tower-like cranium.

Plastic neurosurgical concerns

- Careful positioning.
- Camouflage of scalp incision.
- Positioning of osteotomies.
- Reduction of upwardly expanded dural envelope.
- Protection from buckling or other compromise of superior sagittal sinus.
- Bifrontal and biparietal expansion of cranial vault.
- Reduction in cranial verticality.
- Insufficient bone for complete repair (common).
- Cosmetic closure of scalp.

Positioning and Immobilization

The sphinx position may be the best position because it provides access to the entire calvarium; however, this position has a significant risk for compromise of airway and, if there is a Chiari I deformity or significant skull base deformity, risk of spinal cord injury. The surgery can be done in the prone position, but this limits anterior access and has risks of causing ischemia to forehead and face. Both of these positions require that the abdomen and chest be prone, and this elevates intracranial venous pressure in the presence of already existing intracranial hypertension.

Scalp

The scalp is opened with a zigzag coronal incision and reflected anteriorly to the supraorbital rims and posteriorly well beyond the lambdoid sutures. Pericranium is reflected with scalp.

Bone

Extensive remodeling of most of the cranial vault is necessary and there is no agreed upon best technique. The osteotomies must be planned in a pattern that will facilitate advancement of the supraorbital rims and reconstruction of the forehead. The beaten copper (fingerprinting) on the inner surface of much of the cranial bone and the presence of lacunae can greatly influence the marking of osteotomies and their execution without dural disruptions. For these reasons, the following described osteotomies should be understood as generalizations, not precise recommendations. Each oxycephalic patient is unique.

The retropositioned supraorbital rims must be advanced (see descriptions above in *Brachycephaly* and *Trigonocephaly*) and a new supraorbital bar and forehead fashioned from available bone. A bifrontal craniotomy is required and should extend down to the supraorbital rim. If a bandeau is planned for constructing a new supraorbital rim, this must be harvested along a coronal arc either behind or in front of the coronal sutures if these sutures are present. If the contour of the bifrontal bone flap is not satisfactory for revision and returning to the original site, a new fragment must be harvested from one of the parietal bones. Most if not all of the remaining frontal and parietal bone should be removed in the largest fragments safely possible. It is also necessary to remove the squamosal occipital bone, with the fused lambdoid sutures.

Dura

The tall dural envelope can be mildly reduced in verticality by bilateral plication of longitudinal fusiform areas of parietal dura; however, perfection should not be the goal. The superior sagittal sinus must not be buckled or in any way compromised. It is not safe to strive to correct the contour of the dural envelope to normality. The brain with its enveloping dura will expand posteriorly, in the weeks and months after the bony constriction has been removed.

Reconstruction

Complete calvarial reconstruction is rarely if ever possible with autologous bone. Reconstruction of the supraorbital region, including the frontal convexity, and coverage over the previously bulging vertex should have priority. This may be achieved with a harvested bandeau or other large fragments of cranial bone. The occipital reconstruction must be sufficiently sturdy to allow the patient to lie supine. The remainder of the calvarium should be covered to the extent possible with available fragments of bone which can be secured to intact bone and to one another to optimize the contour. A few radial osteotomies and bending of tongues of bone may be required to contour large fragments of bone. *Under no circumstance* should the upward expansion of the dural envelope be corrected by pressing it downward with bone or other material that is fixed in place.

Closure

The galea is closed with absorbable sutures, usually 3–0 Vicryl® in infants and 2–0 Vicryl® in teenagers. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. Incisions which are under tension or in which edge alignment is difficult should be approximated with staples. Normal pressure against the back of the head when in the supine position can displace fragments of bone, and therefore, a helmet is commonly prescribed protect the brain until bony union occurs.

Bathrocephaly

Bathrocephaly *(Greek: shelf PLUS_SPI head)* is a cranial deformity in which there is an outward convex step-like bulge of the midportion of the occipital bone and it is not caused by synostosis [43–45]. The probable cause is persistence of the mendosal sutures which normally close during fetal life or early in infancy. Occasionally, an interparietal bone, o*so inca*, develops within an open mendosal suture and this is a normal variant. Bathrocephaly often comes to clinical attention in a newborn. No intervention is required.

Sloped Forehead

A prominent posteriorly sloping forehead can, rarely, develop following surgery to correct oxycephaly, after any bifrontal craniotomy in which the bone flap was poorly fixed, or as a consequence of postsurgical resorption of bone after bifrontal craniotomy. A severely posteriorly tilted forehead occurring as a postcraniotomy complication usually requires surgical correction for cosmesis. The bone flap must be mobilized and re-secured in normal alignment, using plates and screws. If there has been significant resorption of bone, synthetic materials may be required. When a sloping forehead is a complication of craniofacial surgery, it is usually well healed by the time it comes to surgical attention. The frontal bone flap, usually along with some of the adjacent cranial bone must be removed, remodeled, and securely reattached in a more normal configuration.

A **sloping** forehead presenting as an isolated cosmetic concern is rarely if ever related to craniosynostosis; however, an exceedingly high hairline in a teenager or adult may bring the forehead to attention. These patients should be managed by a plastic surgeon.

Trigonocephaly

There are two categories of surgery for correction of trigonocephaly: open and endoscopic.

Open Surgery

Open surgical correction of trigonocephaly immediately expands the anterior cranial vault and corrects the morphological abnormalities, whereas endoscopic surgery releases the bony constriction to allow physiologic expansion and recontouring.

Plastic neurosurgical concerns

- Camouflage of scalp incision.
- Positioning of osteotomies.
- Recontouring of lateral supraorbital rims and orbits.
- Advancement and fixation of supraorbital rims and orbits.
- Remodeling of forehead.
- Correction of bilateral temporal bulging.
- Restoration of temporal muscles.
- Prevention of bilateral frontotemporal hollowing.
- Cosmetic restoration of scalp.

Scalp

The scalp should not be shaved. Open surgery for trigonocephaly is accomplished via a zigzag coronal scalp incision extending down to 5–10 mm above the zygoma on each side. Scalp is reflected forward with pericranium and freed from bone across the supraorbital rims.

Muscle

Both temporalis muscles are separated from bone the zygomatic arches. Some surgeons avoid dissection of the temporalis muscles because of concern for increasing the severity of postoperative temporal hollowing; however, this obviates correction of temporal bulging and does not relieve compression of the temporalis muscles.

Bone [46]

A broad bifrontal craniotomy having a straight transverse supraorbital line approximately 1.5 cm above the inferior edge of the supraorbital rims is outlined with ink. The upper extent of the craniotomy is marked about 1 cm anterior to the coronal sutures. If the anterior edges of the anterior fontanelle cannot be exposed with a curette, a burr hole is made about 1 cm from midline, and a craniotome is used to circumscribe the bifrontal bone flap. A supraorbital midline keel can be safely disrupted with a narrow osteotome. A #2 Penfield dissector or periosteal elevator is used to separate bone from dura along the midline. The bifrontal flap of most infants is then easily removed; however, a parasagittal osteotomy will usually be requird in older patients to facilitate removal in two pieces.

Dura is easily separated across the floor of the anterior fossa, except in the midline. The anterior portion of the crista galli must be cleared with freer and Penfield dissectors. Prominent downward displacement of the medial floor of the frontal fossa, which is characteristic of patients with metopic synostosis, can make the medial dissection of dura from bone difficult. It is important to not disrupt dura or dissect over the cribriform plate which would injure the olfactory nerves. Any rent in dura must be repaired with 4–0 Vicryl®.

Removal of Supraorbital Rims

Periorbitum is dissected from the roof of each orbit. Medially, this dissection is continued down across the level of the frontonasal sutures, but without disconnecting the medial canthal ligaments. Laterally, the dissection is continued down and across the frontozygomatic sutures, which disconnects the lateral canthal ligaments. Attempts should be made to tag each with a suture.

While gently retracting the subfrontal dura upward with a flat brain retractor, osteotomies are made with a narrow osteotome or oscillating saw across each floor of the frontal fossa (roof of orbit). Each of these osteotomies is extended laterally across the sphenoid wing. Osteotomies are then made down the lateral orbital walls to approximately 3 mm below the frontozygomatic (known to plastic surgeons as zygomaticofrontal) sutures and each of these sutures is disrupted with an osteotome or oscillating saw. Medially, each frontonasal suture is disrupted with an osteotome and the lateral end of these osteotomies is then connected to the lower end of the osteotomies on the medial orbital walls. It is important that the two cuts of the frontonasal sutures form a distinct V-shape of approximately 90°, which may not conform precisely to the orientation of the sutures.

Grasping each orbital rim with thumb and two fingers, the supraorbital rims, with frontal bandeau, is rotated forward and removed. It may be necessary to extend one or more of the osteotomies with an osteotome to disrupt remaining bony connections. The free supraorbital bar is then removed. Any disruption of periorbitum must be repaired with 4–0 chromic gut.

Remodeling Supraorbital Rims with Bandeau

Cranial bone becomes more brittle and less tolerant of bending with advancing age. Bending or greenstick fracturing of bone of patients older than 12 months often requires focal weakening by making shallow kerfs or V-contoured troughs on concave inner surfaces. Remodeling of the supraorbital bar is complex and is critical for satisfactory cosmetic results. The required remodeling will be described in steps.

1. *Correct frontal angle* The free single supraorbital bar with bandeau is either divided into the midline with a craniotome or greenstick fractured in that site.
2. *Bend lateral wings posteriorly* The lateral end of each half of the supraorbital bar, when reconnected, will be extending far laterally from their straight posterior direction. Each must be bent posteriorly by 30°–50° to approximate a normal position. This requires making one or more vertical V-contour d grooves into the inner side of each side to prevent fracturing. Stabilization of this bend requires drilling a hole on each side of the bend and using a 2–0 absorbable suture to lock the angle until healing begins.
3. *Recontour lateral orbit* Rotation of the supraorbital bar swings the lateral edge of each orbital wall antero-medially and in front of the lateral side of the globe. This requires removal of 5–8 mm of the bone that will be medially rotated bone and giving it a C-contour to match the opposite side.
4. *Recontour roof of lateral orbital* Approximately 2–3 mm of the bone of each lateral orbital roof should be removed with a burr.
5. *Shorten anterior interorbital distance* When the two halves of the supraorbital bar are rejoined to form a normal frontal angle (approximately 104°), the medial side of each orbit will have been moved laterally by a few mm. This is corrected by removing 1–2 mm of bone along the medial edge of each half of the supraorbital bar.

The hypotelorism often present in patients with metopic synostosis is not corrected by the surgery described above; however, its severity rarely if ever requires surgical correction. Correction of hypotelorism requires, among other steps, that a bone graft of appropriate maximum width and having the contour of a truncated pyramid be interposed in the midline. This surgery is done by a plastic/craniofacial surgeon and is outside the scope of this text.

A bone graft of approximately 1.5 by 2 cm is harvested from either of the frontal flaps is required to stabilize the contour across the frontal midline. The lower half of this graft is secured to the undersurface of the supraorbital bar by absorbable sutures through holes drilled for this purpose and the upper half extends above the supraorbital bar.

Remodeling Frontal Bone Flap

The free frontal bone flap is divided into the midline and various positions for the fragments are considered for reconstruction. The best frontal contour is most often achieved when each frontal fragment is rotated 60°–120° and switched to the contralateral side. Each fragment will require remodeling to optimize contour and fit against the remodeled supraorbital bar. Radial osteotomies are often required to facilitate achieving the desired convexity by bone fragments, using Tessier bone bending forceps.

Reassembly of Fronto-Orbital Complex

A fragment of bone if approximately 1.5 by 2 cm is harvested from the upper edge of one of the frontal fragments for stabilizing and reinforcing the site of junction the four fragments of bone. This graft is held with a hemostat beneath the juncture of the two supraorbital fragments and secured snugly with two sutures of 2–0 Vicryl® which also pass through the graft. The two frontal bone fragments are secured to one another with three or four absorbable 2–0 sutures, often with overlap in the midline and burring of the overlapping ledge. The reassembled bones of the frontal convexity are then snugly secured to the supraorbital bar with four 2–0 absorbable sutures on each side of midline, and the two most medial sutures also pass through the bone graft.

Attachment of Reassembled Fronto-Orbital Complex

The reassembled complex is placed in the cranial defect to assess contour and fit. Multiple posteriorly directed osteotomies across the coronal sutures into the parietal bone may be required, and occasionally into the posterior edge of the reassembled frontal convexity bones to achieve an acceptable smooth contour. The reassembled fronto-orbital complex is then positioned, with careful attention to alignment and to forward expansion of the base of the frontal fossa. The complex is secured with one absorbable suture across each frontonasal suture and to the midline bone graft, if being used. Often a suture across each frontozygomatic suture will be necessary to achieve alignment and stability. The result is designated as a *floating forehead*.

Closure

Scalp

The galea is closed with absorbable sutures, usually 3–0 Vicryl® in infants and 2–0 Vicryl® for teenagers. The edges of scalp can be securely and safely closed with running 4–0 Vicryl Rapide® suture. Incisions in which edge alignment is difficult can be approximated with a few staples.

Endoscopic Technique [34]

A scalp incision of approximately 3 cm length is made across the midline and just anterior to bregma. If the anterior fontanelle is open, the edges of the frontal bones are cleared with a curette, but if co-closed or its anterior edges cannot be cleared, a small burr hole is made in the frontal bone adjacent to the fused suture to facilitate bilateral clearing of the edges. The galea is separated from pericranium along the fused metopic suture down to the nasion, using a #2 Penfield dissector and an endoscope. Starting at the burr hole or edge of the freed frontal bone, a Kerrison rongeur is used to remove bone across the midline. Dura can then be separated from midline bone with a #2 Penfield dissector and the endoscope. A scissor is then used to make a parasagittal osteotomy at approximately 5 mm on each side of midline and down to nasion. The midline strut of bone is removed piecemeal with pituitary rongeurs. The dura along the site of craniectomy and along the raw edges of bone is inspected with the endoscope for active bleeding and for dural laceration. Any identified bleeding site on dura is controlled by bipolar coagulation or application of FloSeal®. Bleeding from bone is controlled with bone wax. Some surgeons prophylactically apply coagulation along the raw edges of bone.

Closure

Galea is closed with interrupted 3–0 absorbable sutures and skin is closed with 4–0 Vicryl Rapide™ sutures.

Metopic Ridge

The presence of a metopic ridge alone does not requiree removal; however, some parents or older patients may request removal on the basis of cosmetic concern. The author discourages surgery except when the ridge is a significant cosmetic issue.

Surgical correction can be done via an open or endoscopic technique. The open technique requires a zigzag coronal scalp incision behind the hairline to allow sufficient forward reflection of scalp to expose the metopic ridge. A burr is used to remove the midline ridge of bone and establish a normal curvature across the midfrontal convexity. Scalp is closed in two layers in the usual manner.

Endoscopic removal of the ridge of bone requires two short transverse parasagittal incisions to accommodate the burr and the light. Curvature of the forehead can restrict visualization of the lowest part of the bony prominence.

Kleeblattschädel [47–50]

Kleeblattschädel *(German: cloverleaf skull)* is the name for a trilobar contour d cranium (coronal plane) with shortened anterior-posterior dimension of anterior fossa, large bitemporal protuberances, shallow orbits with exophthalmos, often frontal bossing, bilateral temporal bulging, and a relatively flat occiput. It is associated with synostosis of coronal and lambdoid and sutures, craniocerebral disproportion, hindbrain herniation, hydrocephalus, and venous hypertension. The sagittal and squamosal sutures are not commonly synostosed. All patients have elevated intracranial pressure, usually without ventriculomegaly, and few if any cranial sutures are identifiable. Kleeblattschädel may occur independently or as a component of a syndrome, most often Pfeiffer syndrome. Veins in the scalp are often prominent. Surgery is required to correct the cranial contour and relieve intracranial hypertension by expansion of the cranial vault. CSF diversion is commonly required.

The surgical correction of kleeblattschädel requires extensive remodeling of almost the entire cranial vault. Because the pathologic anatomy is quite variable, there is no standard or agreed upon best technique. Surgery to alleviate the intracranial hypertension resulting from cranial constriction with preliminary remodeling is often done within the first 3 months of life. Midface advancement and further remodeling of the cranium is delayed for several months for reasons of surgical safety. If hydrocephalus is present, CSF diversion will be required.

Plastic neurosurgical concerns

- Positioning for surgery.
- Camouflage of scalp incision.
- Design and execution of osteotomies.
- Protection of dura.
- Extensive removal of cranial bone without disrupting dura.
- Recontouring of the dural envelope.
- Expansion of cranial vault.
- Stable reconstruction of calvarium.
- Management of intracranial hypertension.
- Cosmetic closure of scalp.

Positioning and Immobilization

Surgical correction of kleeblattschädel can be done or the supine position with maximum safe cervical flexion or in the sphinx position. The authors prefer the former for reasons of safety. Multiple surgeries are often required, and if staged surgery is planned from the outset, the initial surgery is usually done in the supine position [51]. However, if Chiari I deformity or severe skull base deformity is present, the initial surgery should be done in the prone position to facilitate decompression and avoid possible complications from the sphinx position.

Scalp

The scalp should not be shaved. The scalp is opened with a zigzag coronal incision. Bleeding from veins in scalp may be greater than expected. The scalp with pericranium is reflected anteriorly to the supraorbital rims, posteriorly several cm beyond the lambdoid sutures, and far down on each side with the usually thin temporalis muscles.

Bone

Most of the frontal, parietal, and temporal squamae must be removed in as large fragments as appears to be safe. Cranial bone commonly has a severe beaten copper appearance (fingerprinting) on its inner surface, and this can cause the making of osteotomies, without violating the dura, difficult. The frontal convexity bone can be removed with a coronal osteotomy and a low transverse osteotomy. Attempt should be made to remove each parietal region of bone in a single fragment, but this may not be safely possible. Osteotomies around each temporal bulge will allow removal of the temporal convexity bones; however, the sphenoid wings are often significant impediments. The sphenoid wings, which are usually dense and deeply indenting the dural envelope, must be removed piecemeal with Leksell and Kerrison rongeurs. Often deep ridges of dura-covered bone extending into cerebral sulci greatly impair the smooth progress of a craniotome and violation of dura is common, even when great care is used in making osteotomies and separating dura from bone. There is also risk of injuring brain. The removal of calvarial bone can be a difficult and tedious task.

Blood loss, primarily from emissary veins and from veins on dura exposed during removal of bone, can be more than expected.

Dura

All rents in the dura must be repaired. The usual multiple small areas of dural infolding and bulging should be ignored. Also, the obvious trilobed configuration should be generally ignored. Bleeding from veins in dura can be greater than anticipated. However, areas of severe constriction/indentation along the sites of the resected sphenoid wings should be surgically released. This requires transection or resection of the deeply constricting bands, followed by re-suturing the edges of dura. *It will not be possible to achieve normal contour of the dural envelope nor should this be attempted*. Normal expansion of brain in the weeks and months following surgery the removal of its bony confinement will greatly improve the contour of the contour of dural envelope and hence the cranial vault.

Reconstruction

The cranial vault is reconstructed by first positioning and fixing the larger fragments of bone over the dural envelope in a manner that solidly spans the frontal region with satisfactory curvature. These fragments may require remolding with Tessier bone bending forceps to optimize cosmesis. Other large fragments of bone should be distributed over the remaining exposed dura and connected to one another and to the surrounding intact cranial bone, using absorbable 2–0 sutures. Gaps can be filled to the extent possible with remaining fragments of bone and covered with large pieces of Surgicel® to prevent their displacement during repair of the scalp. Plates and screws should not be used because of the risk for migration through calvarial bone and the possible puncture of dura and brain. It will not be possible to achieve normal cranial contour.

Nuchal muscles, if they have been disconnected from occipital bone, must be reattached in a stretched position, using sutures. The reattachment of muscle to occipital bone is fraught with problems, and if nuchal muscles are not reattached, they will heal in a contracted state and in a low position on the occipital bone. If attempt is made to pull the muscles to their original normal location, there is risk of displacing occipital bone fragments, either during surgery or in the early postoperative period. For these reasons, the author usually does not, in early surgeries, separate nuchal muscles from bone for more than 1–2 cm below their insertion. Temporalis muscles, which are usually very thin, should be secured to bone in as normal positions as achievable.

Closure

Scalp

The galea is closed with absorbable sutures, usually 3–0 Vicryl®. The edges of scalp can be securely and safely approximated with staples. A helmet is required until some bony union occurs in the occipital region.

Pancraniosynostosis (Craniostenosis) [52–54]

Pancraniosynostosis *(Greek: all PLUS_SPI head PLUS_SPI together)*, also known as craniostenosis *(Greek: head PLUS_SPI constriction)*, is the term that reflects tightness or constriction of the brain caused by synostosis of multiple or all of the cranial sutures. This is the cause of craniocerebral disproportion and many, if not all, cases of slit-ventricle syndrome in patients with shunted hydrocephalus and low resistance valves. Patients come to medical attention because of symptoms and signs of intracranial hypertension. The cranial vault is, regardless of head circumference, abnormally small for the contents. The cranial contour has a normal gross appearance—hence the term, normocephalic pancraniosynostosis [55]. Neuroimaging reveals multisutural synostosis. Cranial bone may be abnormally thick, for example in infants with fibrous dysplasia or osteopetrosis, and in children or adults with hydrocephalus who have had long exposure to low-resistance CSF shunts [8, 34, 56, 57]. Newborns and infants with pancraniosynostosis very often have a prominent copper-beaten inner surface of cranial bones (fingerprinting) which produces prominent indentations over the dural envelope. These indentations usually correspond to cerebral sulci, lie along venous sinuses, or irregularly over the cerebellum. Pancraniosynostosis may develop within a few months following surgery for single sutural synostosis, particularly the sagittal suture, and following surgery for multisutural synostosis, and these patients rarely have bony ridges on the inner surfaces of their calvaria.

Surgery is required to expand the cranial volume for accommodation of normal intracranial contents and not to reach a designated head circumference. If high intracranial pressure is recognized shortly after birth, surgery is often necessary as soon as the newborn is able to tolerate the risks—i.e., within the first few weeks of life.

Early surgeries for craniosynostosis were done to prevent or alleviate intellectual impairment in children with pancraniosynostosis secondary to microcephaly, not recognizing that the sutural fusion had occurred from the absence of centrifugal force being exerted by an expanding brain.

Plastic neurosurgical concerns

- Cosmetic scalp incision.
- Design and execution of osteotomies.
- Expansion of cranial vault (usually by distraction osteogenesis).
- Expansion of scalp.
- Minimize postoperative cosmetic deformity.
- Cosmetic closure of scalp.

Positioning and Immobilization

Correction of pancraniosynostosis in infancy is almost always done in the supine position but the sphinx position is occasionally used. Older children and adults undergo this surgery in the supine position.

Age of Patients

Patients Under 1 Year of Age

The crania of such young children with pancraniosynostosis are managed on an urgent basis by strip craniectomies along the multiple synostosed sutures. Regions of calvarial bone with prominent bony ridges on the inner surfaces can be removed, their prominent ridges destroyed with a burr, and returned to their original locations. Cosmesis is of little concern because of the highly active osteoclastic and osteoblastic activity at this age. Rapid reclosure of sutures very often occurs, leading to recurrent pancraniosynostosis.

Patients Over 1 Year of Age

The calvaria of older children and adults must be expanded in multiple directions. This is most easily and safely done by distraction osteogenesis; expansion may be simultaneously done in multiple directions—e.g., anteriorly, posteriorly, laterally, or vertically, but not simultaneously in all directions [54–59]. The directions chosen for expansion can be selected to minimize adverse cosmetic impact. Children, particularly young children, should undergo overexpansion to accommodate expected growth of brain; however, resynostosis is a near certainty and additional surgery will often be required. The amount of expansion for teenagers and adults should not be limited by data on normal crania [55]. Teenagers and adults do not require intentional overexpansion and, if the expansion is done adequately, reoperation will not be required.

Cranial Vault Expansion [60, 61]

Cranial vault expansion can be accomplished by distraction osteogenesis, which requires two or more surgeries, or as a single surgical procedure, but the latter is becoming much less commonly used.

Cranial Vault Expansion by Distraction Osteogenesis

Distraction osteogenesis, also called callus distraction or osteodistraction, was developed in the 1950s by Gavriil Lierop, a Siberian orthopedic surgeon, for lengthening of long bones. This technique has been refined and applied to other bones, including mandible and the cranium. Successful distraction osteogenesis requires stability of the fixator and is benefited by preservation of a vascularized pericranium [56, 57, 62].

The procedure consists of making osteotomies to free one or more sections of bone from all connections to bone and then slowly and steadily distracting the osteotomy sites. The normal healing process results in the progressive deposition of new bone in the gap between the segments, mimicking intramembranous formation of bone [63, 64]. This is the *distraction phase* of distraction osteogenesis and it is continued in a steady controlled manner until the desired amount of lengthening is achieved. During the distraction phase, all soft tissues spanning the site of expansion and those which must expand to accommodate the osseous expansion are placed under tension, and expand in the same direction. This includes nerves, fibrous tissues, scalp, and blood vessels associated with these tissues.

This phase is followed by the *consolidation pha*se in which the separated bone segments remain rigidly immobilized until ossification of the callus occurs.

A 3-D cranial model can be extremely helpful in selective cases during preoperative planning.

Implantation of Distractors

The required coronal incision should be positioned to avoid corresponding to an anticipated osteotomy. The pericranium should not be reflected with scalp except over the area of frontal craniotomy required for midface advancement. Along each osteotomy, there should be minimum separation of dura from bone [57].

Three or four distractors should be used for the translation of each bone fragment. Often the use of only two results in an unwanted tilted or asymmetric advancement, except when one side of the flap is secured with sutures. It is essential that all distractors attached to a single bone flap have parallel orientation of their axes.

Attachment of Hardware to Bone

The footplates of the distractors must be bent to the contour of the surrounding bone and anchored to the surfaces of surrounding nonosteotomized bone with titanium plates.

Shaft Placement

The shaft of each distractor must pass through a puncture in the scalp. These shafts should not exit through the original scalp incision, unless unavoidable. The coronal scalp incision should be repaired in two layers. Staples should be for scalp repair.

Rate of Advancement

The rate of distraction in common use for cranial and facial bones is 1 mm per day (0.5 mm every 12 h) but rates of 2–2.5 mm per day are prescribed. The more rapid distraction rates may allow ingrowth of fibrous tissue with a resulting fibrous union and diminished bony deposition. Slower distraction can result in early bony union with inability to achieve the desired expansion.

How Much Distraction Should or Can Be Achieved?

Two to three centimeters of distraction are common but there have been cranial distractions of 4 cm. There are no guidelines on how much cranial vault expansion is optimal for children. The surgeon must anticipate the continued expansion of intracranial contents, primarily brain, which is age related. Decisions on the appropriate amount of expansion require consideration of age, severity of initial deformity, and recognition that, in patients with pansutural synostosis, no further vault expansion will occur after the completion of the distraction phase. There will be a likely requirement for repeated cranial expansion due to continuing growth of brain.

Asymmetric or Tilted Distraction

This can be achieved by differential rates of advancement of the distractor devices. However, this can lead to locking or jumping of the threads of the screws. When this occurs, it is usually necessary to surgically replace the malfunctioning distractors.

Wound Management

During the distraction phase, the exit sites of the rods should be cleansed with peroxide and antibiotic ointment applied twice daily. During the consolidation phase prevention of trauma to rods and injury of caretakers or others from their protrusion should be avoided.

Removal of Distractors and Remodeling

Reflection of scalp is more time-consuming, more difficult than that of the initial surgical procedure, and is associated with more loss of blood. All implanted hardware must be cleared of soft tissue and overgrown bone to expose the heads of all screws. The distractors are then removed. Irregularities in bone should be removed with a burr. Some revision of edges of scalp may be required before being closed in two layers. The holes in scalp at the distractor shaft locations usually require edge revision before repair.

The scars in scalp usually do not require delayed revision, but this is occasionally necessary.

Pitfalls/Things to Avoid

The most common complication is infection along the percutaneous tracks of the distractor shafts. This must be managed by gentle irrigation with antibiotic solution and local wound care. This may be augmented by carefully passing a hydrogen peroxide cotton swab along the intradermal portion of the rod.

Cranial Vault Expansion in a Single Stage (Now Uncommon)

Historically, expansion of the cranial vault was done in a single stage via monoblock midface advancement. This is a complex and time-consuming surgical procedure that has significant disadvantages and risks. It still has a role in small local vault expansions, but these are relatively rare.

A coronal incision in scalp is made and the scalp, usually with pericranium is reflected anteriorly to the supraorbital rims and posteriorly by a few cm beyond the lambdoid sutures (usually difficult to identify because of synostosis). Most of the frontal, parietal, and upper temporal bone is removed in large symmetric fragments. When possible, the thicker fragments are split to provide more bone for coverage. The many fragments are then re-assembled to form a larger cranial vault with as normal a contour as possible. Fragments of bone are connected with metal plates or wires. Because the dural envelope does not immediately expand to the newly enlarged cranial vault, a “dead” space persists for several days [65].

Expansion of the scalp to enclose the expanded cranial vault and closure of the wound can be technically difficult and predisposes to dehiscence and other serious complications. Anterior–posterior scalp expansion of 2 cm can occasionally be accomplished, but expansion is fraught with technical difficulty and risks. Closure of scalp may be impossible, in which case the amount of cranial expansion must be reduced. Complications associated with single-stage expansion include, but are not limited to, dehiscence of scalp wound, wound infection, epidural abscess, epidural hematoma, delayed bone healing, and unsatisfactory cosmetic results.

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Cranofacial Syndromes and Facial Clefts

17

Ken Rose Winston and Lawrence L. Ketch

There are more than 150 syndromes which may have craniosynostosis as a component [1]. The correct syndromic diagnosis of craniofacial anomalies can be difficult, and errors may adversely affect decisions on therapy [2]. Direct gene testing now often makes definitive diagnoses possible. The nomenclature and classification of these syndromes can be confusing. Many of the common craniofacial syndromes are *acrocephalosyndactylys (Greek: topmost + head + together + fingers),* of which there are several types:

Type 1—Apert syndrome
Type 2—Crouzon syndrome
Type 3—Saethre–Chotzen syndrome
Type 4—(*not in common use*)
Type 5—Pfeiffer syndrome

A related term, *acrocephalo <u>poly</u> syndactyly (Greek: topmost + head + many + together + fingers)*, also has five subgroups, but this term is falling out of common use, except for type 2 which is Carpenter syndrome.

Plastic neurosurgical concerns in correction of craniofacial syndromes

- Calvarial osteotomies.
- Remodel the dural envelope, if needed.
- Remodel and reconstruct cranial vault.
- Assist in remodeling orbits.
- Management of hydrocephalus, if present.
- Cosmetic repair of scalp.

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Apert Syndrome (Acrocephalosyndactyly Type 1)

Apert syndrome is an autosomal dominant disorder caused in about 95% of cases by a sporadic mutation in the fibroblast growth factor receptors, FGFR-2, possibly related to the advanced age of the father [3]. It occurs in one in 185,000–200,000 births and is equally distributed by gender [4–6]. Ninety eight percent of cases arise from new mutations, which has been attributed to low reproductive fitness. Bilateral coronal synostosis causes brachycephaly with high bulging forehead and often an acrocephalic cranial vertex. Midface retrusion, orbital hypertelorism, horizontal groove above the supraorbital ridge, short wide nose, with depression of the nasal bridge, shallow orbits with exorbitism, a concave appearing dysmorphic face with down slanting palpebral fissures, and type 3 malocclusion are characteristic of the syndrome. Severe syndactyly of fingers and toes are consistently present. Hand involvement commonly includes syndactyly of digits two to four (sometimes also 1 and 5), plus complete syndactyly of toes. Other clinical manifestations of Apert syndrome can include hearing loss, hyperhidrosis, and missing hair in the eyebrows.

Plastic Neurosurgical Overview of Treatment

Surgery to address the craniosynostosis is most commonly done between 3 and 6 months of age; however, midface advancement to correct midface deformity, shallow orbits, and simultaneously expand the cranial vault anteriorly is not done until 5–12 years of age [7]. If there is significant orbital hypertelorism, surgical correction may be required for this and to widen the maxilla (see discussion of *Orbital hypertelorism*) [7, 8]. Hydrocephalus may be discovered shortly after birth and will require CSF diversion [9, 10]. Compromise of airway may necessitate early midface advancement; but facial cosmesis will be significantly better if this surgery can be delayed until 8–12 years of age or optimally until cessation of facial growth, as determined by serial cephalometrics. This creates a conundrum with respect to ongoing facial appearance during childhood.

Carpenter Syndrome (Acrocephalopolysyndactyly Type 2)

Carpenter syndrome is an autosomal recessive disorder occurring in approximately once in a million births and is caused by mutation in the *RAB-23* gene, or less commonly the *MEGF-8* gene. The craniosynostosis is variable in type, and severity of sutural involvement may be manifested as acrocephaly, brachycephaly, or even kleeblattschädel. Asymmetric sutural fusion can produce craniofacial asymmetry, and multisutural synostosis can lead to craniocerebral disproportion with intracranial hypertension [11–13]. Facial dysmorphia can include a flat nasal bridge, downslanting palpebral fissures, low-set ears, class 3 malocclusion with an underdeveloped mandible, and either hypertelorism or hypotelorism. Other features of Carpenter syndrome may include cutaneous syndactyly of hands and feet (usually between digits 3–4), congenital heart defects, growth retardation, mental deficiency, cerebral malformations, dental abnormalities, hydronephrosis, precocious puberty, hearing impairment, obesity beginning in childhood, and a few individuals have situs inversus or only dextrocardia. Carpenter syndrome can be confused with Pfeiffer syndrome.

Plastic Neurosurgical Overview of Treatment

Most patients with Carpenter syndrome require early surgery to address the craniosynostosis and relieve the intracranial pressure. The specific surgical correction of craniosynostosis is determined by the details of the syndrome's expression and its severity. Later surgeries are often required to correct facial dysmorphia, abnormalities of hands and possibly other organ systems.

Crouzon Syndrome (Acrocephalosyndactyly Type 2)

Crouzon syndrome is the second most common type of syndromic craniosynostosis after Muenke syndrome. It is an autosomal dominant disorder occurring in approximately one in 60,000 births and is caused by a mutation in the fibroblast growth factor receptor, FGFR-2. Craniosynostosis of multiple sutures is consistent and characteristic of the syndrome with coronal being most common, followed by sagittal and lambdoid. Therefore, many different cranial shapes occur in Crouzon syndrome [7, 10, 14]. Hypertelorism, down-slanting palpebral fissures, exophthalmos related to shallow orbits, midface retrusion, and ***psittichorina*** (beak-like nose) are very commonly present [6]. Some patients have a significantly restricted airway, and about 30% of patients have hydrocephalus [10]. Hearing impairment is present in approximately 50%. Because of the mandibular hypoplasia, a relative class 3 malocclusion is common. Syndactyly is not a characteristic of Crouzon syndrome; however, there is a rare type 2 Crouzon in which partial syndactyly occurs. Vascular abnormalities including patent ductus arteriosus and coarctation of the aorta have been reported. Acanthosis nigricans occurs in 5–10% of patients with Crouzon syndrome and is caused by a mutation in the FGFR-3 gene [15].

Plastic Neurosurgical Overview of Treatment

The surgical correction required for craniosynostosis in Crouzon syndrome is determined by the details and severity of bony and soft tissue abnormality. Adults and teenagers with little orbital or airway involvement, but with significant malocclusion may require only Le Fort I osteotomies for advancement of the anterior maxilla. Midface hypoplasia (retrusion) in adults and teenagers who do not have intracranial hypertension may require only Le Fort III osteotomies and distraction osteogenesis of the midface, which will improve the position of the eyes, nose, and maxilla. Children with intracranial hypertension, exorbitism, and obstructive sleep apnea require monobloc midface advancement. This is best done with distraction osteogenesis, using an external distraction device [16].

For children under 8 months of age, open or endoscopic surgery may be appropriate for relieving the bicoronal synostosis, thus improving the cranial shape and providing room for brain expansion. Fronto-orbital advancement with calvarial remodeling is often done under the same anesthesic in patients of 10 months of age or older. Some surgeons prescribe a helmet to assist in the correction of the cranial shape.

LeFort Osteotomies

These osteotomies, named for the patterns of fracturing described by Rene LeFort in 1901, may be required in correction of various craniofacial abnormalities and repairs of traumatic injuries, but are done by plastic surgeons, orthognathic, or craniomaxillofacial surgeons; however, neurosurgeons involved with surgeries for craniofacial disorders should be knowledgeable on these procedures.

LeFort Osteotomy Type I

LeFort osteotomy type I, also called transverse maxillary osteotomy, extends transversely above the teeth and through the pterygomaxillary junction, avoiding the pterygoid plates. This is a common orthognathic osteotomy most often used to correct dentofacial deformities by moving the upper jaw forward without changing the nose or cheeks, for example in class 3 malocclusion and cleft palate. See the description of technique by Buchanan and Hyman [17].

LeFort Osteotomy Type II

LeFort osteotomy type II is a pyramidal osteotomy that results in a disconnected maxilla and allows forward movement of the maxilla and nose [18–21]. This osteotomy is rarely required but occasionally beneficial in nasomaxillary hypoplasia and Treacher Collins syndrome. Distraction osteogenesis is used to advance the disconnected fragment (see description below).

LeFort Osteotomy Type III

LeFort osteotomy type III (craniofacial disjunction) disconnects the maxillae, nose, and orbital floors. Osteotomies are required through the nasofrontal sutures, along the medial wall of each orbit, and across the medial floor of the orbits to the inferior orbital fissure. Also, osteotomies are required through each frontozygomatic suture, zygomatic arch, and pterygomaxillary junction. Distraction osteogenesis is used to advance the disconnected midface (see description below).

Monobloc Midface Advancement

Monobloc midface advancement, which includes advancement of the forehead and midface as a single unit, was described by Ortiz-Monasterio et al. in 1978. Surgical correction of midface hypoplasia will be described as an independent surgical procedure without addressing surgery for the usually associated craniosynostosis, although the two are commonly done under the same general anesthetic. These surgeries are done jointly by a craniofacial surgeon and pediatric neurosurgeon [22–24]. Postsurgical management commonly involves orthodontists, learning specialists, and speech therapists.

Insertion of a Circummandibular Wire

The orotracheal tube must be secured to the mandible with a circummandibular wire or to the lower incisor teeth to prevent accidental extubation during surgical manipulations [25, 26]. A small puncture incision with a #11 blapde of the midline skin of the chin immediately over or slightly posterior to the mandible. A curved awl is inserted through the puncture and slowly passed upward behind the mandible, as the tongue is manually retracted out of the path of the awl, until it penetrates the oral mucosa immediately behind the lower incisor teeth. Some surgeons prefer to use a #18-gauge angiocath needle, but it does not have the curvature of the awl.

A 26- or 24-gauge wire is inserted through the hole near the tip of the awl and bent to prevent dislodgment. The awl is pulled slowly downward until its tip clears the lower edge of the mandible and then again pushed upward while the lip is manually retracted outward. The oral mucosa is penetrated immediately in front of the lower incisor teeth. The wire is cut and disconnected from the awl and the awl is removed from the patient. The two ends of the wire are twisted together and then wrapped around the endotracheal tube and twisted tightly to secure the tube and prevent extubation.

Temporary Tarsorrhaphy [27, 28]

Temporary tarsorrhaphy (*Greek: flat surface, referring to the rim of eyelid + suture*) is often required to provide protection of the corneas during craniofacial surgery, particularly during correction of orbital hypertelorism and midface advancement. This is accomplished by passing a 4–0 silk horizontally through the margin of the eyelids without violating the inner mucosal lining and similarly through the mid portion of the upper lid, again not violating the mucosa. This must be tied loosely to achieve lid closure. It is critical that the suture does not rest directly on the cornea.

Scalp

A zigzag or sinusoidal coronal incision which extends approximately 5 mm below each zygoma is required. The anterior scalp and pericranium are reflected forward across the supraorbital rims. The full length of each zygomatic arch and the posterior edge of each orbital rim must be cleared of soft tissue. The nasal bones are also cleared down to the nasal aperture. Bilateral circumferential orbital dissections are required. This will include disconnection and tagging of the medial and lateral canthal tendons.

Bone

Bifrontal Craniotomy

A symmetric bifrontal craniotomy is marked with ink. A straight transverse osteotomy is made immediately approximately 8 mm above the supraorbital rims and connected to a vertical arcing osteotomy that crosses the midline at a point that will be 1–2 cm behind the hairline. If this is being done in a patient who has frontal sinuses, the supraorbital osteotomy should cross the sinuses, not couse above them. The bifrontal bone flap is removed.

Osteotomies for Craniofacial Disjunction

Osteotomies Around Orbits

An osteotomy is made across the full width of each orbital roof and laterally across the sphenoid wings, using either an oscillating saw or osteotome. A connecting osteotomy is made down the lateral wall of each orbit and then medially to the inferior orbital fissure, whose location can be identified with a #4 Penfield dissector. In the extreme anterior medial floor of the frontal fossa, in front of the crista galli, an osteotome is driven vertically through the floor of the anterior fossa and until the nasal septum is freed.

Osteotomies of the Pterygoid Pillars

An incision is made in the oral mucosa posterior to the termination of each maxillary arch, and an osteotome is inserted against the upper third of the pterygoid pillar (the lamina of the pterygoid processes of the sphenoid bone). This is usually done by a craniofacial surgeon. Alignment and positioning of the osteotome requires tactile guidance by intraoral digital palpation. The maxillary artery courses near the mid-to-lower portion of the pterygoid pillar, and its laceration can result in severe and difficult-to-control arterial bleeding. Control requires immediate firm packing. Attempts to establish hemostasis with hemostats, surgical clips, or coagulation will fail.

Osteotomies of the Zygomas

Each zygomatic arch must be severed in its anterior third with an oscillating saw (preferred) or craniotome.

Disimpaction of the Face

Left and right Rowe maxillary disimpaction forceps are inserted, each with one blade in a nasal cavity and the opposing blade in the oral cavity, to firmly grasp the palate. While one person manually immobilizes the head, the surgeon rocks the grasped midface from side to side and in the sagittal plane until it is clearly free of all bony connections to the cranium. It is often necessary to extend osteotomies that are incomplete.

After disimpaction of the face, the frontal bone flap must be firmly reattached to the supraorbital rims, using titanium plates, wires, or absorbable sutures. (The authors prefer 2–0 absorbable sutures.) The scalp is closed in two layers, using 2–0 absorbable sutures for galea and staples for scalp repair.

Distraction Osteogenesis [29–31]

Distraction osteogenesis can be accomplished with either internal jackscrew distractors or an external (outrigger) device. The volume of the cranial vault increases during expansion [32, 33]. The former is the most common technique used for monobloc midface advancement and, in the opinions of the authors, simpler and associated with less blood loss. This requires osteotomies to free the facial skeleton from all osseous connections followed by several days of slow distraction of the osseous face from the cranium, during which there occurs progressive deposition of the callus in the gap between the bony segments. This is the *distraction phase* of distraction osteogenesis during which all related soft tissues must lengthen to accommodate the osseous expansion at the same rate and in the same direction. This includes nerves, fibrous tissues, scalp, and blood vessels associated with these tissues. This phase is followed by the *consolidation pha*se in which the separated bone segments remain rigidly immobilized until ossification of the callus occurs.

Distraction with Internal Distractors

Attachment of Distractors to Bone [29]

Internal distraction has the advantage of minimizing external scarring, thus improving cosmesis. Four jackscrew distractors are be used for forward translation of the facial skeleton. One plate is attached to each side of the kerf which is to be expanded. A small puncture is made for the passage of each shaft through the forehead and faces.

Distraction with an External (Outrigger) Device

The outrigger device (Zimmer Biomet or KLS Martin) is attached to the skull, using approximately two screw-pins through each of the four posts. A wire (24 gauge) is used to attach each of the four posts in the facial skeleton to four sites on the distractor apparatus. The screws are tightened to remove all slack in the wires but not to distract the face.

Rate of Advancement

Distraction begins on the third postoperative day. The rate of distraction in common use is 1 mm per day (0.5 mm every 12 h) but rates of 2–2.5 mm per day have been occasionally prescribed. More rapid distraction rates allow ingrowth of fibrous tissue into the bony gap, with diminished bony union. Slower distraction can result in early bony union with inability to achieve the desired expansion.

How Much Distraction Should or Can be Achieved?

Ten to 20 mm of distraction is common, but more is definitely possible if needed. There are no guidelines on how much cranial vault expansion is optimal for children. The surgeon must anticipate the continued expansion of the intracranial contents, which is age related. Decisions on the amount of expansion require consideration of age, starting status and recognition that no further vault expansion will occur after the completion of the distraction phase, although some remodeling will occur over months and years.

Asymmetric or Tilted Distraction

Asymmetric or tilted distraction can be achieved by differential rates of advancement of the distractor devices. However, this can lead to locking or jumping of the threads of the screws, and when this occurs, it is usually necessary to surgically replace the malfunctioning distractors.

Removal of Hardware

All implanted hardware must be cleared of soft tissue and overgrown bone to expose the heads of all screws. The distractors are then removed. The scars in the scalp and face usually do not require delayed revision, but this may be necessary.

Hemifacial Microsomia (Craniofacial Microsomia, First and Second Branchial Arch Syndrome)

Hemifacial (*Greek: half + face*) microsomia (*Greek: small + body*) is a congenital abnormality involving derivatives of the first and second branchial arch. Its incidence is approximately one in 3500–4500 births, and it is the second most common birth defect of the face, after cleft lip and palate. Most occurrences are sporadic, and the syndrome is thought to be due to insufficient local blood supply in utero [34–36]. Unilateral deformity, usually underdevelopment of the soft and bones of the face, external ear, mandible, temporomandibular joint, muscles of mastication, and facial expression are common in individuals with hemifacial microsomia. Less commonly there is a lateral facial cleft. Involvement is usually limited to one side, but bilateral involvement occurs in 10–15% of cases. The facial deformities become progressively worse with age. Also, there may be cardiac, vertebral, and central nervous system defects. Hemifacial microsomia shares many features with Treacher Collins syndrome and is often one of the characteristics of Goldenhar syndrome [36].

Overview of Treatment [37, 38]

Serious aesthetic problems are common and are important indications for surgery, but because of their variability in type and severity, few generalizations can be made. Neonates with compromised airways or difficulties in swallowing may require urgent intervention. Other required surgeries may include lengthening of the mandible, repair of cleft lip or palate, repair or construction of an external ear, eyelid surgery, and correction of soft tissue abnormalities causing facial asymmetry [39–41].

The neurosurgeon's operative role with these patients is usually limited to harvesting the cranial bone needed for reconstruction of the face.

Midface Hypoplasia

Midface hypoplasia *(Greek: under + formation)* is not a distinct syndrome but can be a component of several craniofacial syndromes, including Crouzon, Apert, Carpenter, Pfeiffer, Saethre–Chotzen. It may be present in other disorders, including achondroplasia, or may occur without other recognized abnormalities. Midface hypoplasia usually occurs sporadically but both autosomal dominant and recessive occurrences are reported [42].

There is underdevelopment of the maxilla, orbits, and sometimes forehead. The severity of involvement varies widely and affected individuals can be asymptomatic and therefore require no treatment. However, patients with severe exorbitism (protrusion of the globe due to an abnormally shallow orbit) are at risk of exposure keratopathy with eventual ulceration or infection. In the extreme form, the eyelids may occasionally contract behind the globe, resulting in orbital subluxation. Keratitis can occur if the lids do not close completely during sleep. When the airway is severely compromised, sleep apnea, snoring, and speech impediment can become progressively more severe with age, and a tracheostomy may be warranted. The retruded maxilla, causing class three malocclusion, can make the mandible appear to protrude excessively.

Overview of Treatment

Patients with little orbital or airway involvement may require only Le Fort I osteotomies with anterior maxillary advancement to address malocclusion. Le Fort III osteotomies are appropriate for advancing the upper face, which will improve the position of eyes, nose and upper jaw, and the malocclusion, but does not expand the cranial vault. Malocclusion must be managed by orthodontists.

The neurosurgeon's role with these patients is in the subgroup who require cranial vault expansion [40]. Midface hypoplasia with intracranial hypertension requires monobloc midface advancement. (See above discussion of *Monobloc midface advancement*.) Vault expansion is best accomplished by distraction osteogenesis. Patients whose distraction is done internally have less scaring in the scalp and seem to be more satisfied with their quality of life during distraction and in their decision to undergo surgery.

Pfeiffer Syndrome (Acrocephalosyndactyly Type 5)

Pfeiffer syndrome is the third most common type of craniosynostosis, occurring in about 1 in 100,000 newborns. It is an autosomal dominant disorder thought to be related to gene mutation in FGFR-2, related to the advanced age of the father [3]. This disorder includes synostosis of various cranial sutures, midface hypoplasia with orbital hypertelorism, vertical orbital dystopia (orbits not in the same horizontal plane), exorbitism, a beaked nose, dental abnormalities, possible hydrocephalus, high palate, class 3 malocclusion, broad deviated thumbs (pollex varus) and great toes (hallux varus) cutaneous syndactyly of digits two to four, and often hearing impairment [8, 43–45]. Jackson–Weiss syndrome has the same features as Pfeiffer syndrome but without the abnormalities of fingers.

Pfeiffer Syndrome Type 1

Pfeiffer syndrome type 1, the mildest and also most common type, is usually associated with mutation in the fibroblast growth factor, FGFR2 gene, and less often with mutation in FGFR-1. These individuals have turribrachycephaly. Intelligence is usually normal.

Pfeiffer Syndrome Type 2

Pfeiffer syndrome type 2 is associated with mutation in the fibroblast growth factor, FGFR2 gene, and all mutations are probably new [46]. These infants have a severe form of synostosis, which can include kleeblattschädel, exorbitism and midface hypoplasia. Severe hand and foot anomalies and malformations of the limbs are common, often with ankylosis of the elbows. Individuals often have impaired mental development and may have a compromised airway. Abnormalities associated with the disorder can be life-threatening, particularly during infancy.

Pfeiffer Syndrome Type 3

Pfeiffer syndrome type 3, the most severe type, is associated with mutation in the fibroblast growth factor, FGFR-2 gene, and all mutations are probably new. These infants have features similar to those of type 2 except they do not have kleeblattschädel. Characteristics associated with type 3 include brachycephaly and various visceral anomalies. As in type 2, these individuals often experience impaired mental development and severe neurological problems. The abnormalities associated with the disorder can be life-threatening, particularly during infancy.

Neurosurgical Overview of Treatment

Treatment of Pfeiffer syndrome must be individualized. Compromise of the airway can require early and continuing attention. Intracranial hypertension may be caused by craniosynostosis, hydrocephalus, or both. Craniosynostosis can be managed by open or endoscopic surgery between 3 and 6 months of age, depending on sutures affected and severity. CSF diversion may be required earlier. Often surgery is required to correct midface hypoplasia, facial asymmetry, exorbitism, ear deformities, and malocclusion. If fronto-orbital midface advancement is required, it is best to be done after 9 months of age, but can sometimes be delayed for a few years.

Saethre–Chotzen Syndrome (Acrocephalosyndactyly Type 3)

Saethre–Chotzen syndrome is an autosomal dominant disorder in which there is a mutation in the TWIST-1 gene. It is thought to occur in 1:25,000–1:50,000 newborns. This is one of the acrocephalosyndactyly disorders, many of which have cutaneous syndactyly of digits three and four, relatively short fingers, and often craniosynostosis. Thumbs and great toes are often noticeably broad [37, 47]. Craniosynostosis, when present, is variable but usually includes bilateral coronal synostosis, most often causing acrocephaly. Less often metopic synostosis may result in a metopic ridge or trigonocephaly. Closure of multiple sutures may lead to craniocerebral disproportion with intracranial hypertension. The cranial sutures may fuse unevenly and produce right-left cranial asymmetry.

Many individuals have a broad forehead with a low hairline, ptosis, a beak shaped nose, an unusually broad depressed nasal bridge, unusually broad, midface hypoplasia and a hypoplastic maxilla with relative mandibular prognathism. Ocular abnormalities can include orbital hypertelorism, shallow orbits, strabismus, downward sloping palpebral fissures, ptosis, and lacrimal duct stenosis. Other craniofacial abnormalities include small low-set ears, and a hypoplastic maxilla. Less commonly, musculoskeletal, cardiac, and renal abnormalities are present. Most individuals have normal intelligence.

Neurosurgical Overview of Treatment

The physical characteristics can be so mild that no surgical intervention is necessary and facial appearance tends to improve with age. There is no single treatment for Saethre–Chotzen syndrome. Surgeries and their timing depend on the abnormalities present, their severity and, most importantly how they affect the child. Craniosynostosis, if present, is usually addressed at 3–6 months of age. Reconstructive surgery may be required to deal with abnormalities of eyelids, nose, and hands.

Muenke Syndrome

Muenke syndrome is the most common type of syndromic craniosynostos and is present in one in 30,000 newborns and caused by mutation in the FGFR-3 gene. It is commonly characterized by bilateral coronal synostosis and orbital hypertelorism. However, synostosis of other sutures, all sutures, macrocephaly without craniosynostosis, and even a normal skull may be observed. The bilateral coronal synostosis usually results in brachycephaly with temporal bossing and facial symmetry [38, 48, 49]. These changes can result in an abnormally shaped head and flattened cheekbones. About 5% of affected individuals have macrocephaly. If the coronal synostosis is unilateral. There is plagiocephaly with facial asymmetry, frontal bossing, eyebrow elevation, and anterior placement of the ear. Muenke syndrome patients typically do not develop midface hypoplasia or retrusion of the midface, and abnormalities of hands and limbs are uncommon. Craniofacial findings include: hypertelorism, exorbitism, strabismus, ptosis, and high arched palate often with cleft lip or/palate. Over 70% of patients have some hearing deficit, often sensorineural. Complications such as elevated intracranial pressure and hydrocephalus can occur especially when two or more sutures are fused. Developmental delay is uncommon. People with Muenke syndrome may have mild abnormalities of the hands or feet. Most people with this condition have normal intelligence.

Overview of Treatment

Surgical management typically begins, at 3–6 months of age, with fronto-orbital advancement and cranial vault remodeling to address the specific craniosynostoses present.

Orbital Hypertelorism (Teleorbitism)

Orbital hypertelorism (*Greek: abnormal separation*), often simply called hypertelorism, is not a syndrome, but is a component of craniofacial deformity. It is the condition in which the orbits are abnormally widely separated, causing wide separation of the inner canthi (ICD) and interpupillary distances (IPD) [43, 44, 50]. Orbital hypertelorism can be a component of many craniofacial syndromes, including Apert, Crouzon, Muenke, Pfeiffer, Saethre-Chotzen, frontonasal dysplasia, and the median cleft face syndrome [51–53]. It may occur as an isolated abnormality but does not result from trauma. Orbital hypertelorism (teleorbitism) must be distinguished from telecanthus *(Greek: far + Latin: corner of eye)*, also called pseudo-hypertelorism, which is an abnormally wide distance between the medial canthi but normal interpupillary distance. The lateral walls of the orbits are normally positioned. This may be associated with Down syndrome, other syndromes, tumors, or trauma.

Distance is increased between the two dacrya (junction of the lacrimal bone, frontal process of the maxilla, and frontal bone). The mean normal intraorbital distance is 32 mm in adult males and 28 mm in adult females [45, 54]. The following is Tessier's classification of orbital hypertelorism [55].

Grade I	Mild	30–34 mm
Grade II	Moderate	35–39 mm
Grade III	Severe	>40 mm

Plastic Neurosurgical Concerns

- Move orbits closer.
- Correct orbital dysplasia if required.
- Remove midline bone to narrow nasal dorsum.
- Remove excess midline skin.
- Cosmetic closure of skin.

Correction of Orbital Hypertelorism

There are several operative procedures for the correction of orbital hypertelorism, but the two most common are *orbital box osteotomy* and *facial bipartition*, each of which has variations. Better cosmetic results are achieved if correction is delayed until age 5 years or older. If orbital hypertelorism is associated with midface hypoplasia, the hypertelorism should be corrected under the same general anesthetic in which distraction osteogenesis is initiated for midface advancement.

Orbital Box Osteotomies

Correction of orbital hypertelorism by box osteotomy was described by Paul Tessier in 1967. Each orbit is separated from all bony connections to cranium and facial bones and moved medially after a rectangular region of bone between the orbits is removed. Bilateral orbital dissection is necessary and usually done before making osteotomies. Orbital box osteotomies are done to correct orbital hypertelorism and, with small modifications, to also correct *vertical* and *horizontal dystopias*. There is risk of damaging the maxillary dentition in young children. The box osteotomy procedure, unlike bifacial partition, does not increase trans-maxillary width or alter the palatal or occlusive plane. See Figs. 17.1 and 17.2.

Osteotomies are made across the anterior floor of the frontal fossa (roofs of orbits). Care must be taken to not damage the olfactory nerves.

1. A parasagittal osteotomy is marked on each side of the internasal suture and extending upward across the supraorbital rim. The distance of these marks from midline are determined by the needed medial translation of the orbits. This dis-

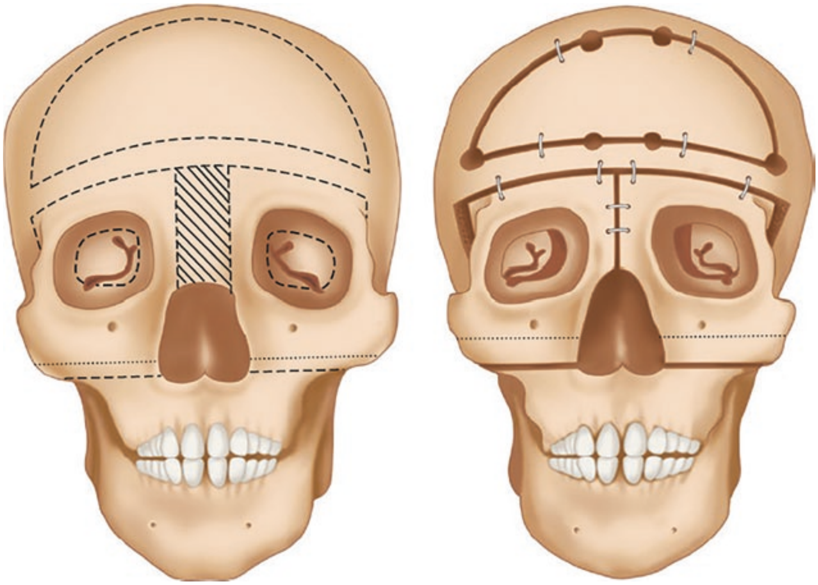

Fig. 17.1 Orbital box osteotomies. (Republished with permission of Springer, from "The Rare Facial Cleft", Cassio Eduardo Raposo-Amaral, Reza Jarrahy, Rizal Lim, Nivaldo Alonso in: Nivaldo Alonso and Cassio Eduardo Raposo-Amaral, eds, Cleft Lip and Palate Treatment: A Comprehensive Guide, 2018; permission conveyed through Copyright Clearance Center, Inc.) Titanium plates are now more commonly used than wires

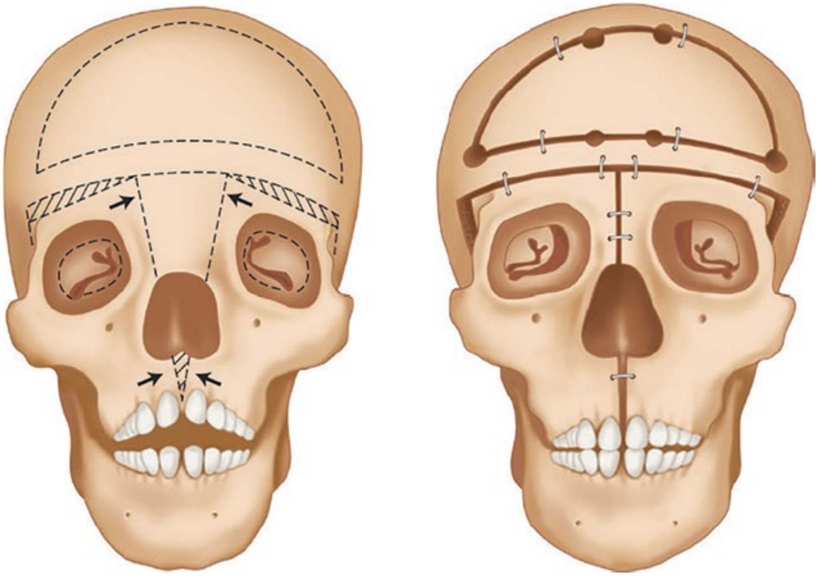

Fig. 17.2 Facial bipartition. (Republished with permission of Springer, from "The Rare Facial Cleft", Cassio Eduardo Raposo-Amaral, Reza Jarrahy, Rizal Lim, Nivaldo Alonso in: Nivaldo Alonso and Cassio Eduardo Raposo-Amaral, eds, Cleft Lip and Palate Treatment: A Comprehensive Guide, 2018; permission conveyed through Copyright Clearance Center, Inc.) Titanium plates are now more commonly used than wires

tance should usually be the same on each side. An oscillating saw is used to make osteotomies along these marks, leaving the medial wall of each orbit intact.
2. Using a narrow osteotome, osteotomies are made down the lateral wall of each orbit posterior to the zygom.
3. Osteotomies are made across the maxilla below the infraorbital rims, from medial and lateral directions and toward or across the inferior orbital fissure, carefully protecting the infraorbital nerves.

Based on intraoperative measurements, a midline rectangle of nasal and ethmoid bone of sufficient width to facilitate the desired reduction in interorbital distance. The two mobile orbits are then moved medially and secured to one-another with wires or plates and also secured to the intact supraorbital bandeau with plates.

It is important to pay close attention to the impact of the newly positioned walls of the orbits on soft tissues within the orbit, particularly when correcting very wide orbital hypertelorism.. There is risk of blindness if an optic nerve is compressed, stretched, or if its blood supply is compromised, and this will not be apparent until the patient awakens from anesthesia.

It is possible to accomplish box osteotomies with medialization of orbits without antecedent frontal craniotomy. This is accomplished by leaving the orbital roofs intact and moving the U-shaped floor and walls of the orbits medially. Although anatomically simpler, the original orbital roofs remain unchanged, and this results in the new orbital roofs having a significantly abnormal curvature.

Facial Bipartition (Median Fasciotomy) [8, 42]

Facial bipartition, described by Jacques van der Meulen in 1979, is a significant modification of box osteotomy. This translates the orbits medially and widens the maxillae. A transverse frontal osteotomy is made above the supraorbital rims. (A frontal bandeau is not required.) The orbits and the midface are disconnected from the skull-base via monoblock osteotomies (pterygomaxillary, septal and palatal). Craniofacial disjunction is accomplished with a set (right and left) of Rowe disimpaction forceps; however, insertion of the nasal blades can be difficult in some children. A triangle of bone, having its base centered across the frontal midline and above the supraorbital rims and its apex between upper incisor teeth is removed from the midface. See Fig. 17.2.

The two halves of the midface are rotated medially and brought together in the midline. The lateral side of each hemiface is tilted outward. These rotations reduce the interorbital distance widen the maxillae and alter the plane of the hard palate and the occlusal plane. The two halves of the facial skeleton are attached with plates to each other and to the bifrontal bone flap, after its replacement. Defects along the lateral edges of the orbits and in the gaps in the zygomatic arches are repaired with autologous bone grafts harvested from the free frontal bone flap or the intact cranial vault.

Secondary Reconstruction After Orbital Repositioning

Patients with orbital hypertelorism have an abnormally broad nose, and therefore the medial translation of orbits produces an undesirable nasal bony structure which results in excessive scalp between the medial canthi [56]. The required correction of these abnormalities is done by a plastic surgeon and is not within the scope of this book. Also, reconstruction is often required for nose, eyelids, and lips. Medial and lateral canthopexies are always necessary. Orthognathic surgery is almost always required.

Complications of Correction of Orbital Hypertelorism

The correction of orbital hypertelorism regardless of technique, has risks for serious complications, which include, infection, CSF rhinorrhea, abnormalities of eye alignment, blindness, large volume blood loss and unsatisfactory cosmetic outcome.

Treacher Collins Syndrome (Mandibulofacial Dysostosis) [57–59]

Treacher Collins syndrome is a congenital disorder that affects the development of bones and soft tissues of the face resulting from dysgenesis of the first and second branchial arches. Clinical manifestations can be minimal, but patients who come to surgical attention tend to have severe abnormalities that typically include a vertically short ramus, small mandible, hypoplastic or absent mandibular condyle, micrognathia, antimongoloid slant of palpebral fissures, and small deformed pinnae. Cleft palate is common as is coloboma and sparse eyelashes. Hearing loss is quite common, and vision can be impaired. Newborns can have life-threatening compromise of airway. Most patients with Treacher Collins syndrome have normal intelligence and can develop into normally functioning individuals.

Overview of Treatment [51, 58]

Management should begin shortly after birth and requires a craniofacial team. Early surgeries may be necessary to maintain a competent airway and/or to protect the eyes, and auditory function. Later surgeries often include reconstruction of the mouth, external ear, and face.

Facial Clefts

Facial clefts are rare congenital malformations in which there exist one or more gaps in the skin and often in muscles and bone. The prevalence and incidence of these rare deformities are not known. The cause of facial clefting is not clear and there is great diversity in expression, even among those in the same named category.

Other anomalies are commonly present. The most common cranial anomaly seen in combination with facial clefts is encephalocele.

Facial clefts are managed by a team with craniofacial surgeon having the leading role. Few neurosurgeons have experience with these disorders. The introductory experience for a neurosurgeon may occur when consulted for harvesting cranial bone for facial grafts, assist in the correction of orbital deformities and frontofacial advancement, or management of intracranial hypertension. Neurosurgeons involved in surgeries for correction of facial clefts should have a sound working knowledge of these complex disorders.

Tessier Classification

The Tessier classification of facial clefts is based on the anatomical location of the cleft, is the most commonly used classification, and is applicable for *all* craniofacial clefts [45]. Clefts are numbered from 0 to 14 with the 0 cleft being in the medial mandibular location. See Fig. 17.3.

It is purely descriptive and applies to both clefts in soft tissue and in bone. The clefts in soft tissue do not always correlate precisely with clefts in bone having the same numerical designation. The numbering system is generally centered on the

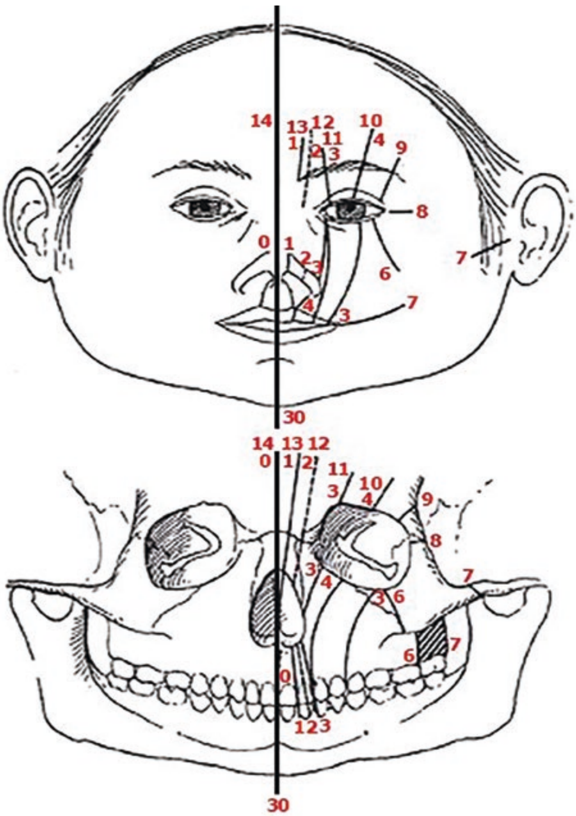

Fig. 17.3 Tessier classification of facial clefts. (Reproduced with permission from: Kawamoto HK Jr., Craniofacial anomalies. In: Grabb & Smith's Plastic Surgery, fourth ed., Smith J, Aston S (Eds), Little, Brown, New York 1991. Copyright © 1991 Lippincott Williams & Wilkins [60])

orbit. Clefts of soft tissue are numbered counterclockwise from 0 to 7 and cranial clefts numbered from 8 to 15. A cleft in the midline of the mandibular symphysis is designated cleft 30. The 15 Tessier clefts, numbered 0 through 14, are commonly considered in 4 groups [52].

Van der Meulen Classification

The classification proposed by van der Meulen is based on location in which developmental arrest is thought to have occurred during embryogenesis. These developmental arrests are divided into four groups [53, 61].

Internasal Dysplasia

This type is caused by a development arrest before the union of the nasal halves and is characterized by a median cleft lip, median notch of the cupid's bow or a duplication of the labial frenulum. Also, there may be underdevelopment of the premaxilla.

Nasal Dysplasia (Nasoschisis)

This dysplasia is caused by a development arrest of one side of the nose, resulting in a cleft. The nasal septum and cavity are usually not involved. Hypertelorism is often present.

Nasomaxillary Dysplasia

An arrest at the junction of one side of the nose and maxilla results in a naso-ocular cleft or, if between the mouth, nose, and orbital floor results in an oronasal-ocular cleft. Neither is associated with an abnormality in development of the lip.

Maxillary Dysplasia

There are two types of maxillary dysplasia. *Median maxillary dysplasia* is the more common type and is caused by a failure in development of the medial portion of the maxillary ossification centers. This results in clefting of the lip, philtrum, and palate. *Lateral maxillary dysplasia* is caused by a failure of development of the lateral part of the maxillary ossification centers, which results in clefting of the lip, palate, and lateral part of the lower eyelid (coloboma).

Overview of Management of Facial Clefts

The surgery required for correction of facial clefts must be highly individualized. The management of facial clefts is complex—surgically and otherwise—and requires a multispecialty team approach led by a craniofacial surgeon, but commonly including a pediatric neurosurgeon, orthognathic surgeon, neurointensivist, psychologist, and other specialists. The role of a neurosurgeon is in the assistance in designing and making cranial and orbital osteotomies and occasionally altering the dural envelope. CSF diversion is not commonly required. Also, the neurosurgeon should have a broad understanding of the surgical plan and never simply act as a technician for making designated osteotomies.

The surgical goal is improvement of function and aesthetic appearance. Because of the diversity in facial clefts and the variations in each category, few generalizations can be made regarding required surgery. Impairment of function mitigates for early surgery, but the best aesthetic outcome is achieved from delayed correction. Timing of surgery varies with severity of the deformity; however, early reconstruction often results in recurrence of deformity, because of growth of the involved bone, and therefore additional surgeries will be required at an older age. The psychological impact of these severe facial deformities can be devastating on a child and therefore influence the timing of surgical corrections. Also, early reconstruction involving the maxilla has significant risks of damaging the tooth buds in the maxilla. Reconstruction of soft tissues can be done at a young age, but careful attention is required for design of skin flaps and location of incisions because these will likely require reuse in subsequent surgeries. Physicians and parents should develop a long-range plan, shortly after birth, a plan of anticipated surgeries, including their timing. This plan will often extend into the late teen years.

Plastic Neurosurgical Concerns

There are plastic neurosurgical concerns for every step in the surgical correction of facial clefts, which involve scalp, facial skeleton, soft tissues of face, and often calvarial bone.

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Special Disorders of Children

18

Ken Rose Winston, Lawrence L. Ketch,
and Charles Corbett Wilkinson

Aplasia Cutis Congenita with Cranial Defect (Aplasia Cutis Congenita Composite Type)

Patients with aplasia cutis congenita composite type who have cranial or cranial plus dural defects must be managed jointly with a pediatric plastic surgeon and pediatric neurosurgeon. Prior experience with management of this birth defect is greatly beneficial. Aplasia cutis congenita involving only the scalp or other regions of the body does not require neurosurgical involvement.

Optimal case management requires a coordinated neurosurgical and plastic surgical team approach. Early surgical management using scalp rotation flaps, when surgically and anesthetically considered to be safe, is the intervention of choice for most patients with composite type cutis aplasia congenita of the scalp.

Neurosurgical and plastic surgical consultations are typically requested on an urgent, if not emergent, basis if there is exposure of the dura. This is a life-threatening birth defect with which most neurosurgeons and plastic surgeons have little or no personal experience and therefore tend to proceed cautiously and delay decision making, which can lead to less than optimal, if not fatal, outcome.

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Plastic Neurosurgical Concerns

- Spontaneous life-threatening hemorrhage
- Prevent desiccation
- Prevent infection
- Establish coverage with the skin

Risks

Threats to the survival of patients with composite aplasia cutis congenita are present immediately after birth and remain high until the scalp is healed. (If the dura is not exposed over the superior sagittal sinus, the risks of both non-surgical and surgical management are relatively low.) Unexpected catastrophe can strike suddenly and inexperienced clinicians, not understanding the risks, may pursue a seemingly "safe conservative" approach, often with a catastrophic outcome. The reported mortality rate of 12.5–55% for composite aplasia cutis congenita is from multiple series having a wide spectrum of severity and case management. Perinatal mortality from bleeding occurs in approximately 20% of cases [1]; however, mortality is probably much lower from more aggressive treatment, particularly in experienced hands.

The exposed venous sinuses and dura must be kept continuously moist with saline-soaked sterile bandages for the hours between birth and wound coverage to prevent desiccation and cracking. Often a crack in the dry dura will extend into a major vein in the dura mater or into the superior sagittal sinus, resulting in sudden massive bleeding [1–3]. Massive hemorrhages are commonly preceded by smaller sentinel bleeds, whose grave significance may not be recognized [4]. A pathophysiologically different cause of life-threatening hemorrhage results from drying of eschar overlying the dura mater [5]. As the eschar contracts, small herald bleeds occur, followed by severe or fatal hemorrhage. Any active bleeding from the superior sagittal sinus or dilated veins in the exposed dura, however small, is a neurosurgical emergency. Manual pressure over the bleeding site, preferably over dry gauze will usually achieve temporary hemostasis [6] and the application of Surgicel® (oxidized cellulose) may be briefly beneficial.

Overview of Management

Controversy persists regarding surgical versus non-surgical management for neonates with calvarial defects, but the tide of opinion has shifted toward early surgical intervention. Early surgical intervention is crucial if the sagittal sinus is exposed and particularly so if there is a dural defect [4, 7, 8]. In these authors' opinion, the safest course usually includes surgical intervention, preferably within 24 h, unless anesthetic or surgical risks are prohibitive [9]. Non-surgical management can be considered for small lesions with intact dura, particularly if the bony defect is small and does not overlie the superior sagittal sinus, but even these lesions are best managed surgically.

A pediatric plastic surgeon, preferably with experience with this disorder, is the lead surgeon in the surgical management of a patient with aplasia cutis congenita.

The exposed dura *must be kept continuously moist* until securely covered with viable tissue.

Large defects usually straddle the superior sagittal sinus. Coverage of the scalp defect with full thickness rotated flaps very soon after birth is the most reliable method of preventing spontaneous hemorrhage and infection.

Non-surgical management has the indisputable advantage of avoiding all risks associated with surgical management. The near constant vigilance required to avoid desiccation of the dura and to be able to respond in emergency to even small amounts of spontaneous bleeding is extremely difficult to organize and continue over weeks or months and the consequences of a brief lapse can be fatal.

Craniopagus

Ken Rose Winston

Craniopagus (*Greek: head + fixed together*) is the term for twins, always of same sex, joined only at their heads; craniopagi is the term for more than one joined pair. (Craniopagus twins is a redundancy.) Approximately 2.3 live births of craniopagi occur in the USA per year, which is about 5.1 occurrences per 100,000 twin deliveries. Eighty-one percent of craniopagi are female. This is considered to be a form of incomplete twinning, as are all abnormalities containing three germ layers, such as parasitic twins, fetus-in-fetu, and teratomas. The classification of craniopagi in most common use today recognizes four types. It is important to know the type when making decisions on separation [10–12] (Fig. 18.1).

Ethics [13–15]

Ethical and legal issues of surgical separation must be considered because of the risks involved and the fact that two individuals are involved, often with different risks. Under what circumstances should the rights of one twin be infringed for the rights of the other twin? Is it ever ethical to sacrifice one twin for the survival or improved outcome of the other? For twins old enough to express opinions, what should be done if the twins disagree on surgical separation?

Plastic Neurosurgical Concerns

Before Separation (One Surgical Team)

- Plan surgery with plastic surgeons, neuroradiologist, anesthesiologists, and nurses
- All surgeons, anesthesiologists, and nurses rehearse the surgery in the planned surgical room(s)

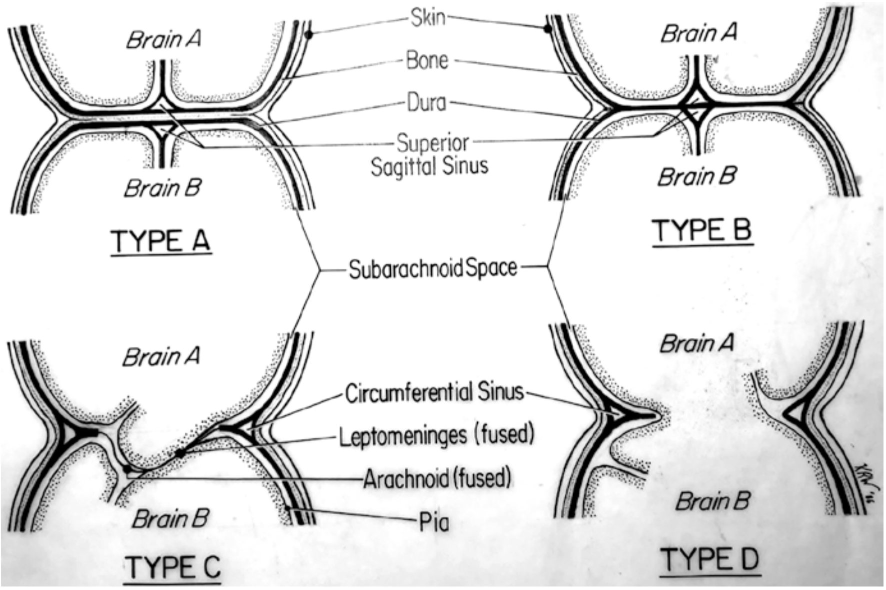


Fig. 18.1 Classification of craniopagi based on extent of intersection and showing deepest shared embryological tissue: type A cutaneous ectoderm, type B ectomeninx, type C endomeninx, and type D neural ectoderm. (Republished with permission of Oxford University Press—Journals, from Craniopagi: anatomical characteristics and classification, KR Winston, *Neurosurgery*, 1987;21(6):769–781; permission conveyed through Copyright Clearance Center, Inc.)

- Position of craniopagus on table
- Choice of scalp incision
- Osteotomies
- Durotomy
- Protect the circular venous sinus
- Anticipate problems with venous separation
- Be prepared for significant loss of blood

After Separation (Two Patients, Two Surgical, and Two Anesthetic Teams)

- Two independent surgeries in the same room or separate rooms
- Reposition each patient
- Repair (patch) dural defect
- Manage cranial defect (usually repaired at a subsequent surgery)
- Closure of the scalp

Surgery

A detailed description of surgical separation of craniopagi will not be addressed. It is the authors' strong recommendation that craniopagi be managed by a team with experience with this disorder. The surgical management of craniopagi requires a team composed of pediatric neurosurgeons, craniofacial surgeons, anesthesiologists, and intensivists. There is a high risk of neurologic damage or death of one or both individuals. The separation of a craniopagus is an extremely complex undertaking and requires extensive neuroimaging, surgical planning, multispecialty involvement, and rehearsal. The details of surgical separation and management of the defects in the dura, bone, and scalp are case specific and require a detailed preoperative planning by neurosurgeons, plastic surgeons, and anesthesiologists [10, 14]. A few medical centers around the world have been the sites of successful management; however, most neurosurgeons and plastic surgeons never see a craniopagus, and those who do, rarely see more than one. Management of shared venous sinuses is critical and extremely difficult [13, 14, 16].

The published mortality associated with surgical separation of craniopagi was greater than 50% through the twentieth century but has significantly improved in the twenty-first century. Staged separation, in some cases, seems to have improved survival [17].

Encephalocele

Most encephaloceles are repaired by pediatric neurosurgeons; however, the skills of a craniofacial surgeon may be required for lesions that are in the frontal or frontonasal locations. Encephaloceles are neural tube defects of the head and consist of herniations of the brain through a congenital deficiency in the dura and cranial bone, occurring almost exclusively in the midline [18–20]. They are most often occipital or frontal in location and only rarely fronto-parietal. Encephalocele is the most common cranial anomaly occurring with facial clefts. The herniated brain is usually covered with skin and attenuated dura but rarely there is exposed brain. The cortex of the herniated brain and surrounding brain is abnormal, but the extent and severity vary greatly. The herniated brain may extend outward for only a few mm or may include half of the cerebral volume. Most herniations are broad based but some are pedunculated. The term ‘encephalocele’ is sometimes confusingly applied to acquired herniations of brain through cranial defects secondary to intracranial pressure following craniotomy or craniectomy.

Surgical repair should be done when newborn, except the few in whom survival is highly unlikely. The goals of surgery are: (1) Elimination of the herniation of the brain, (2) Establishment of an intact dural envelope, (3) Cranioplasty [20, 21].

Plastic Neurosurgical Concerns

- Details of surgical exposure
- Cosmetic fusiform scalp incision
- Repair of dural defect to establish a snug dural envelope
- Repair of cranial defect
- Cosmetic closure of the scalp

Surgery

Peduncular Encephalocele

Peduncular encephalocele is relatively easy to surgically manage because of the narrow tubular bases, relatively small dural and cranial defects, and absence of need to preserve the abnormal cerebral tissue within the sac. Each can be approached with a fusiform, usually midline sagittal, scalp incision that surrounds the encephalocele with attention to preserve enough scalp for repair. The dura of the encephalocele is cleared of soft tissue around the edges of the cranial defect. The superior sinus is usually not precisely in the midline but passes to one side of the herniation. While avoiding the sinus, the dural tube is ligated with 2-0 or 3-0 silk and the sac is resected.

The cranial defect will usually persist but become smaller over several months or years. However, the defect can be repaired early with relative ease. A craniotomy is used to excise an elongated strip of bone having length greater than the width of the defect in the bone. This free fragment is then positioned across the site of congenital defect and secured by tucking its ends beneath the intact bone. It is important that the tucked ends be quite thin to avoid indenting the superior sagittal sinus. The scalp is repaired in two layers.

Sessile Encephaloceles

Sessile encephaloceles that are covered by normal appearing scalp are approached with a curved scalp incision designed to anticipate resection of excessive at time of repair. If covered with attenuated scalp or no scalp, a fusiform incision is most often used. The dura of the encephalocele must be cleared of soft tissue around the edges of the cranial defect. These encephaloceles may have near-normal appearing dura but often have attenuated dura over the dome. The superior sinus is usually not in the midline but passes to one side of the herniation. The sac must be opened to inspect the contents. The herniated brain usually has an abnormal visual appearance and, when so, can be resected. A questionably abnormal brain should not be resected. The herniated dura is examined to identify a line of demarcation between the attenuated and normal dura. A circumferential durotomy is made to remove the attenuated dura and 2–3 mm of normal dura. The dural edge must be cleared of any adhesions to the brain to facilitate repair of the dura, which requires a patch. A sufficient amount of pericranium is commonly available.

The cranial defect can be repaired with strips (barrel staves) of the bone harvested from the cranium. A few strips of the bone covering the patch and part of the intact dura is usually satisfactory. Synthetic materials should not be used at the time of primary repair in newborn children. The scalp is repaired in two layers.

Large encephaloceles may lack coverage with the scalp or scalp over the dome may be severely attenuated. Encephaloceles approaching the size of the cranial vault and very large encephaloceles in microcephalic newborns are severely neurologically impaired and commonly have other birth defects making survival unlikely or impossible. However, if survival appears to be likely, it is reasonable to excise the mass repair the defect to facilitate childcare.

The superior sagittal sinus, sometimes including the torcula (torcular Herophili), may be within the herniated tissue in encephaloceles of the low occipital region and upper posterior fossa. The superior sinus is usually not in the midline but passes to one side of the herniation. Care must be taken to not surgically enter, obstruct or compromise the sinus. The cranial defect can be repaired by making a U-shaped osteotomy in the adjacent bone, transposing the bone flap over the site of resection, and leaving the newly exposed dura, over which new bone will develop. The usual result is an adequately ossified cranial vault. However, if the cranial defect does not ossify, some ossification will occur around the periphery of the defect but often not sufficient for full coverage.

Encephaloceles by Location

Frontonasal Encephalocele

Frontonasal encephalocele widens the distance between the medial orbital walls, resulting in telecanthus; however, orbital hypertelorism is uncommon. The dura may be defective. The nasal skeleton is mobilized and placed in its correct position and the telecanthus is corrected. Skull defects are repaired with bone. Correcting the deformity at an early age is recommended [22].

Frontoethmoidal Encephalocele

Frontoethmoidal encephaloceles occur at the junction of the frontal and ethmoidal bones and are commonly divided into nasofrontal, nasoethmoidal or nasoorbital types, depending on the details of their location; however, there is a considerable overlap and use of these terms [18, 20]. The first two types account for over 85% of frontal encephaloceles. Frontal encephalocele occurs in 1 of 35,000–40,000 births in the West, but in Thailand, it occurs in 1 per 5000 births. The nasoethmoidal type is most common in Southeast Asia and parts of India, whereas nasofrontal encephaloceles dominate in much of the rest of the world. Nasofrontal encephalocele presents with a mass in the nasofrontal region and telecanthus, but uncommonly with hypertelorism. Nasoethmoidal encephalocele shows swelling over the nose, hypertelorism, and abnormalities of the orbits. Patients with orbital encephaloceles present with proptosis.

The required surgical correction for each type of encephalocele is determined by the details of the pathological anatomy and will not be described in detail. Most surgeries include repair of the defect in the dura, nasal reconstruction, and medial canthopexy. Hypertelorism, if present, requires repair [20].

Nasopharyngeal Encephalocele

Nasopharyngeal encephaloceles are often present in infancy with nasal obstruction, CSF rhinorrhea, and occasionally, meningitis [19].

Encephaloceles in the Floor of the Frontal Fossa

These and sphenoidal encephaloceles can often be managed by an endoscopic technique [23].

Expanding Fracture (Growing Fracture)

Ken Rose Winston and Lawrence L. Ketch

The bony defect, the size of the defect in the dura, and the volume of herniated brain steadily increase, and therefore, delay in repair makes the surgery ever more complex and difficult. As the cerebral herniation increases, it becomes kinked around the edges of the bone and dura, often causing injury to the brain. Also, CSF may accumulate in a pocket over the herniated brain, hence the outdated and etiologically missleading term, *leptomeningeal cyst*.

Plastic Neurosurgical Concerns

- Cosmetic scalp incision for wide exposure
- Separate edges of the bone from the brain
- Expose retracted edges the dura with large craniotomy
- Identify edges of dura and dissect free from brain
- Repair dural defect (establish snug and secure dural envelope)
- Redistribute and secure free fragments of bone to cover cranial defect
- Cosmetic closure of scalp

Surgery

The crucial component in managing an expanding fracture is the re-establishment of an intact dural envelope by snugly repairing the defect in the dura. The edges of the dura associated with all expanding fractures, particularly those which have been expanding for months or years, can be expected to have retracted for several cm beyond the edges of the receding bone, and therefore difficult to find [24–26].

Bone must be removed on each side of the defect, often in two or more fragments along the roughly fusiform shaped cranial defect. An expanding fractures of less than 1 cm width may have dural retraction of 1.5–2 cm, and therefore resection of approximately 2.5–3 cm of bone on each side of the axis of the bony defect will be necessary to clearly identify the edges of the retracted dura. The edges of the dura may lie 2–4 cm beyond the edges of the bony defect with large expanding fractures. This sometimes necessitates the inexperienced neurosurgeon to extend the scalp incision and expand the cranial opening, sometimes in multiple increments, much farther than expected to be required.

The brain must be gently separated from the identified margins of the dura for a distance of at least 1 cm. A thin layer of scar tissue can be misinterpreted as attenuated dura and, sewing a patch to this material does not reestablish a dural envelope and allow the defect to continue to expand.

Reconstruction and Closure

Bone

There is consistently insufficient autologous bone for coverage of the cranial defect. The cranial defect in infants and young children can be managed by attaching the larger fragments of bone over the patched portion of the dura, using 2-0 or 3-0 absorbable sutures. Small fragments of bone are placed over the exposed intact dura and covered with Surgicel® to prevent displacement during closure of the scalp. This will result in some areas of dura not having bony coverage. The dura and any overlying pericranium will assist in the formation of new bone within the gaps. If some of the fragments of the cranial bone can be split, these split-thickness fragments are useful in closing the defects. The free cranial fragments of bone which are never of satisfactory size or shape can be distributed in a trial-and-error manner to achieve the maximum coverage of the exposed dura and the larger fragments should be attached securely to the surrounding intact bone and to one another with absorbable sutures.

Dura

Pericranium is an ideal material for patching the dura and there is usually sufficient pericranium for this purpose, perhaps in more than one piece. Synthetic material, for example suturable Duragen®, can be used if there is insufficient pericranium. It is important that the patch be sutured in a manner that establishes a snug dural envelope. A loose or baggy patch will result in failure of the repair.

Reconstruction and Closure of Large Expanding Fracture

It may be impossible to achieve full reduction of the cerebral hernia through a large, expanded fracture. Reducing the volume of the herniated brain with intravenous mannitol or hyperventilation to facilitate closure of the dura can be life-threateningly dangerous, as the brain will re-expand to a normal volume within its newly reduced envelope soon after the closure is completed.

If the hernia is extremely large, it will be necessary to expand the dural opening by removing a large amount of the hemicranial bone and making two or more radial incisions in the sides of the intact dura to alleviate the acute angulation of the brain over the dural edge. This will allow a smoother expansion of the brain; however, this makes repair of the dura more difficult.

In extremely large herniations associated with years of delay before coming to neurosurgical attention, the contralateral cerebral hemisphere may have herniated across midline and become acutely angulated against the edge of the falx. In such a case, a large bifrontal craniotomy is required, followed by a far anterior durotomy and with transection of the falx. This alleviates the acute angulation of the brain against the falx and allows expansion of the contralateral dural envelope, thereby providing space for that hemisphere as it returns toward its normal site of domicile. The dural defect on the side of herniation is snugly repaired with a patch of pericranium, in a manner that shifts the brain in the contralateral direction and at least partially reduces the cerebral herniation. A full translation to a normal position is unlikely without excessive tightness of the ipsilateral closure of the dura. The contralateral dural defect, now expanded to accommodate more brain, will also require a patch which does not have to be very snug.

The bilateral cranial openings are repaired by tangentially splitting the larger fragments of bone and using these with full-thickness fragments of calvarial bone. The scalp is closed in two layers in the standard manner.

Macrocranium

Macrocrania are large crania but most physicians restrict the term to extremely large crania. All patients with macrocrania have an elevated intracranial pressure. Consideration of surgery to reduce the size of the cranial vault is appropriate in extreme cases, usually older infants, and young children. These patients, when supine, often require constant elevation of the trunk to compensate for the occipital expansion, which prevents supine positioning without extreme cervical flexion. Older children are unable to sit independently because of the weight of their heads relative to that of their bodies. Many patients with severe macrocrania are significantly neurologically, including intellectually, impaired [27].

The goal of cranial vault reduction is to improve the patient's quality of life by reducing the mass of the head and making upright posture possible. Reduction cranioplasty can greatly simplify nursing and home care. Nevertheless, not all patients with severe macrocephaly are appropriate candidates for surgery.

Plastic Neurosurgical Concerns

- Cosmetic scalp incision
- Select technique for reduction cranioplasty
- Management of CSF volume and pressure
- Management of sag of the dural envelope and brain
- Reduction of dural envelope
- Prevent kinking or compromising superior sagittal sinus
- Reassembly of cranial fragments into a smaller stable configuration
- Cosmetic closure of scalp

Positioning and Immobilization

The trunk is in the supine position with approximately 10° of Trendelenberg. The head is placed on a horseshoe headrest approximately 30° of cervical flexion. This head is immobilized with pillows and sandbags. The sphinx position has been used but the weight of the head and the extent of cervical extension make this position problematic. Immobilization with 3-point fixation cannot be used because of the surgical requirement for access to most of the cranial surface.

Overview of Surgery

The tactical goal of reduction cranioplasty is the reduction in size, hence, mass of the cranial vault, improvement in cranial contour, and attention to hydrocephalus, if no CSF shunt is present. Surgery to reduce the cranial volume is a long and high-risk adventure. Most patients have severe ventriculomegaly with a thin cerebral mantel, but some patients have small ventricles and a large extracerebral presence of CSF. Most patients who are considered for reduction cranioplasty have a CSF shunt.

Scalp

A coronal incision is made, with preauricular extensions to the zygomas. The scalp is reflected anteriorly to the supraorbital rims and posteriorly by several cm behind the lambdoid sutures (not always easily identified). The surgeons must be prepared to deal with venous bleeding from multiple emissary veins across the cranial vault, which often bleed more vigorously than expected because of the elevated intracranial pressure.

Muscle

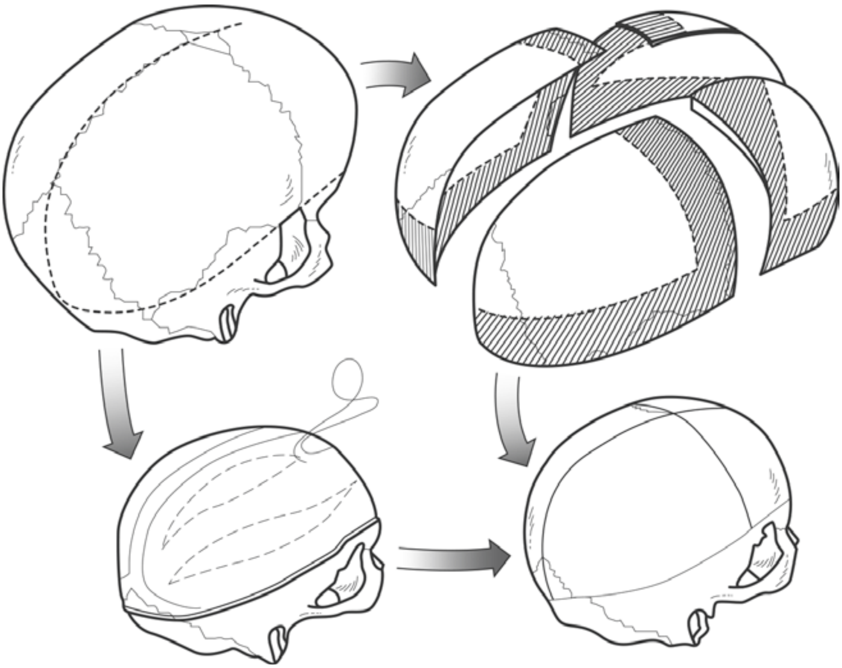
Temporalis muscles are separated from bony attachments and reflected downward. It is not necessary to separate muscle all the way to the zygomatic arches.

Bone

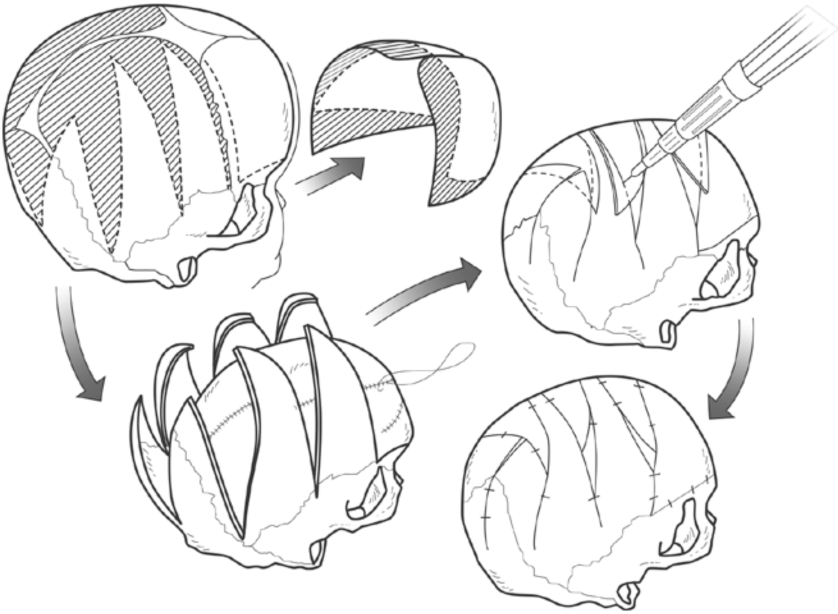
Three techniques are described for cranial vault reduction (see Fig. 18.2).

Quadrantal Plate Technique [28]

This technique can be used for macrocrania of any size or shape but requires rigid bone and therefore is inappropriate for infants and small children with soft cranial bones. The cranial vault is considered in quadrants and marked with ink. Osteotomies are made along the marked lines. The head is rotated as far to one side as appears to be safe to prevent sagging of the dura over the edge of intact bone when bone is removed. The uppermost posterior quadrant is removed and, after CSF is allowed to passively drain, is reduced in size, remodeled as necessary by dividing it into fragments and then reassembled. The now smaller composite is secured to intact cranium with plates or wires. Next the ipsilateral frontal quadrants of bone are removed,



Quandrantal technique



Picket fence technique

Fig. 18.2 Quadrantal plate technique; Picket fence technique; Crossbar technique. (Published with permission from Winston KR, Ogilvy, McGrail K. Reduction cranioplasty. *Pediatr Neurosurg.* 1995;22(5):228–234. https://doi.org/10.1159/000120906)

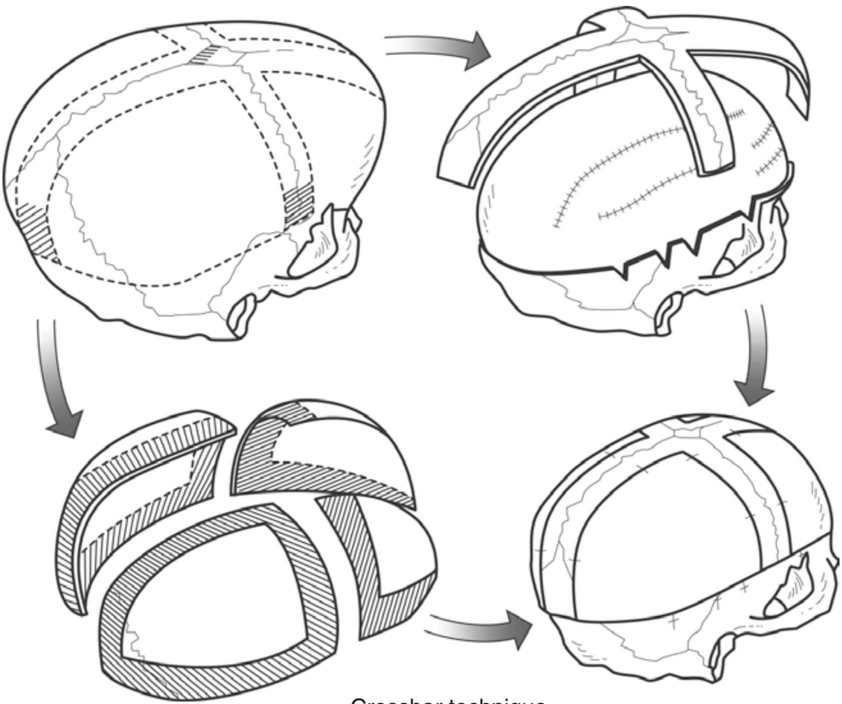


Fig. 18.2 (continued)

reduced in size, and remodeled in the same manner, and secured to intact cranium and to the anterior edge of the posterior quadrant bone with titanium plates or wires. The head is then rotated to the opposite side and the same procedures executed on the posterior and anterior quadrants of bone. It is important that the reconstructed cranial vault have reliable structural stability (see discussion below on management of CSF and dura).

Picket Fence Technique [28]

This technique is appropriate for infants with macrocrania, particularly if there are large fontanelles and open sutures, but inappropriate in older patients whose cranial bones are thick and have little malleability. The planned triangular pickets must be marked in ink on each side of the exposed cranial vault with a plan to facilitate subsequent left-right interdigitation. After all osteotomies are completed, the bone over the vertex is removed. All bony pickets must be separated from the dura and each triangle of bone rendered malleable with Tessier bone bending forceps, without breaking them free from their bases. The dural envelope is reduced in size by drainage of CSF, and the required imbrication of the dura must be completed before approximation of the pickets. The pickets are rendered more malleable, using Tessier bone bending forceps, and then folded across the midline. Abutting edges of the bone are secured with titanium plates or wires. During the surgery, the dural envelope always has continuous lateral and posterior support and therefore has little risk of sagging. The newly constructed vault has excellent structural stability (see discussion below on CSF management and dura.)

Crossbar Technique [28, 29]

This technique requires an intact cranial vault and therefore is not possible in the presence of open fontanelles. Osteotomies are made in the cranial vault and the quadrantal plates of bone (smaller than required for the quadrantal technique) are removed, leaving the four ends of the crossbar attached to the cranial base. The dura must be separate from the undersurface of the crossbar. The dural envelope is reduced in size by drainage of CSF. Each of the ends of the crossbar is sequentially shortened, not necessarily equally, and re-secured to the cranial base with titanium plates or wires. The four ends of the plates are reduced in size, remodeled as necessary and re-secured in their original sites (see discussion below on CSF management and dura).

Ventricular Fluid Management

The CSF shunt must be disconnected, and the ventricular catheter connected to a sterile reservoir for drainage and sterile preservation of the fluid during the surgery. If the patient does not have a CSF shunt, as may be the case in infants and young children, a ventricular catheter must be inserted and sutured to the dura to prevent accidental removal. The drainage of ventricular fluid can be controlled by the position of the reservoir with respect to the head -and by clamping-unclamping the connecting tube. This allows the dural envelope and brain to decompress and moderately sag, in a controlled manner, to allow safe manipulation of the bone. It is not unusual for over a liter of ventricular fluid be drained. After the cranial vault is reduced in size and reconstructed, a sufficient volume of ventricular fluid is slowly returned to the lateral ventricles to re-expand the cerebral mantel and dural envelope.

The external ventricular drain is continued through the early postoperative period to manage the hydrocephalus and hence the intracranial pressure. After a week to 10 days, the CSF shunt must be re-established.

Dura

Redundancy in the dural envelope must be eliminated by imbricating multiple fusiform areas of the dura on each side, with non-absorbable running sutures. The lines of imbrication are chosen to achieve the amount and direction of reduction in size of the dural envelope and they may run in any direction. Care must be taken to avoid injury to the underlying brain or vessels on the brain. The dural envelope can also be reduced by resecting the fusiform sections of the dura; however, the sutured durotomy lines are sites for possible CSF leakage.

The appropriate amount of reduction in the dural envelope and its left–right symmetry can be monitored by allowing the inflow of CSF to re-expand the dural envelope and brain during dural imbrication. It is important that, after the dural envelope is re-expanded, that the new envelope fit *snugly* within the reassembled vault, with a little or no residual extradural dead space. Small dead spaces will not cause problems. However, non-imbricated buckled dura allows persistent hammering of the dura against bone with likely displacement of the overlying bone fragments. Some buckling of the superior sagittal sinus inevitably occurs, and the surgeon must ensure that this occurs far anteriorly and never in its posterior two-thirds to three-quarters, to minimize risk of venous infarction of the brain.

Reconstruction and Closure

Dura

During reconstruction of the cranial vault, the dura must be repeatedly examined, and it may be necessary to remove or imbricate small areas to establish a dural envelope of satisfactory volume and shape. The management of the dura is critical in cranial vault reduction.

Bone

Each of the techniques for cranial vault reduction requires the attachment of bone to other bone to establish a stable cranial vault. Much of this may be done, particularly in infants, with 2-0 sutures, but titanium plates are required for rigidly securing the thicker fragments of the bone. However, titanium screws and often the plates have a strong tendency, in infants and young children, to migrate through the cranial bone from normal osteoclastic and osteoblastic activity.

Scalp

There is temptation to immediately excise the excess scalp to achieve a snug, near normal post-surgical appearance. However, the redundant scalp will contract in the days and weeks after repair, particularly in infants and children and its hair density will therefore increase. As a rule-of-thumb, no more than half of the apparent excess scalp should be resected at the time of repair. After a few weeks, it may be necessary to resect the redundant scalp, but much less will require resection than seemed apparent at the time of initial repair and sometimes no resection is required.

Lipomyelomeningocele

Ken Rose Winston and Lawrence L. Ketch

The goal of surgery in patients with lipomyelomeningocele (*Greek: fat + cord + membrane + hernia*) is, to the extent safely possible, untether the spinal cord by removing the fibrofatty mass arising from the spinal cord. The surgery of lipomyelomeningoceles has been described in multiple texts [30–32].

Plastic Neurosurgical Concerns

- Skin incision and resection that will optimize cosmetic closure
- Maximum safe reduction of lipoma
- Closure of the lumbodorsal fascia

Management of the spinal cord and nerves is not within the scope of plastic neurosurgery.

Positioning

Almost all patients coming to surgery for lipomyelomeningocele are children, most often infants. Patients are placed in the prone position on longitudinally oriented soft rolls in a manner that minimizes pressure against the abdomen. This is done to reduce the venous pressure in the surgical site and minimize blood loss.

Skin

The opening incision should be marked in a manner that anticipates skin closure, which will necessitate a fusiform resection of the excess skin. The skin over a lipomyelomeningocele may contain an area of hemangioma, a dimple or hairy patch and these can be safely removed with the excess skin at the time of closure. An incision is made along one side of this marked incision. The skin flap on each aide, with its own associated adipose tissue is undermined and reflected beyond the different-appearing adipose tissue of the lipoma.

Adipose Tissue

The normal appearing adipose tissue associated with the skin has a different gross appearance from the fat of the lipomyelomeningocele, which contains more fibrous material. The two can usually be visually distinguished and separated by dissection with Metzenbaum scissors. The dissection should be continued around all sides of the fatty mass until lumbodorsal fascia is clearly exposed and then medially across the intact fascia until the edges of the gap in the fascia is identified. The details of dissection of adipose tissue from neural elements is not within the scope of this text.

Fascia and Muscle

Fascia must be incised in the midline in both the cranial and caudal direction from the midline defect in fascia and dissected laterally with paraspinous muscles to expose the subfascial portion of the lipomyelomeningocele and dura. This dissection must extend cranially and caudally along one or more intact vertebral arches; however, this dissection is often made difficult by missing or asymmetrically deformed spinous processes. It may be necessary to separate paraspinous muscles from a spinous process and from the sacrum to achieve adequate exposure.

Bone

Removal of bone is usually not required but, in order to expose the dura, it is sometimes necessary to remove a portion or all of the lowest vertebral arch above the lesion. Occasionally there exists a prominent posteriorly protruding spike of bone from a spinous process and this should be removed to protect the overlying skin when the patient lies supine after closure.

Dura

The dorsal-lateral junction of the dura with lipoma typically consists of the intermingled dura and fibro-adipose tissue, making it difficult or impossible to precisely delineate a discrete border. Using moderate magnification, the thecal sac is entered in both cranial and caudal locations at the sites thought, based on palpation and neuroimaging, to be free from attachment to the underlying neural structures or adipose tissue. It is usually best to start dissection at the caudal end of the mass. Under moderate to high magnification, the dura is slowly dissected from the fibro-adipose tissue, using the blunt and sharp technique. The edges of the dura must be identified and dissected free of adipose tissue and retracted with sutures. The separation of the dura from adipose tissue facilitates closure of the dura. Care must be taken to protect the nerves of the cauda equina, which may be adherent to the dura and often course along unpredictable pathways through adipose tissue to their sites of exit from the thecal sac. There are many anatomical variations, and the dissection and protection of nerves can be painstakingly slow.

Nerves and Spinal Cord

The details of dissection of the nerves and spinal cord are not within the scope of this text.

Closure

Dura

A strong attempt should be made to establish an intact dural envelop. Commonly there is insufficient dura to allow primary closure, and therefore a patch will be required. Tissue adhesive may improve the closure and reduce the risk of CSF leakage. Lumbodorsal fascia can be harvested for this purpose in most patients and only rarely is a synthetic material is required; however, there is disagreement on this. It is important that the thecal sac remain loose and not be stretched tightly across the neural placode and any residual tissue.

Muscle

Muscle should be approximated if it can be accomplished without excessive tension. The forceful tugging of the laterally displaced muscle masses with sutures causes extensive damage and unnecessary scarring within muscle.

Fascia

The edges of fascia can usually be securely approximated; however, it is important that the closure of fascia, regardless of the materials or technique used, not compress the neural tissues or residual lipoma within the spinal canal.

Skin

There is always excess skin in these surgeries. The surgeon must decide whether to resect the excess, and if so, how much, keeping in mind that there will occur some spontaneous contraction of the loose skin over 7–10 days following surgery, which will spontaneously reduce the amount of excess skin. There is no guideline for the optimum amount of skin to resect but the surgeon should strive to err in the direction of less resection.

The redundant skin is usually symmetrically excessive in all directions. It is therefore usually appropriate to resect a biconcave sagittal strip to reduce the right and left excess. The initially marked fusiform-shaped proposed incision with its axis in or near the midline should be re-marked with ink. There is a tendency for the less experienced surgeon to excise too much skin while striving to optimize immediate cosmesis and to unnecessarily extend incisions to correct or avoid standing cones (dogears). These standing cones will become smaller over weeks and months and may never require surgical attention. However, if required for cosmesis, this should be done by a plastic surgeon.

The skin should be closed in two layers, using 3-0 Vicryl® sutures for the dermis and either Nylon or Rapid Vicryl® for the skin. The closed incision should be reinforced with long broad Steristrips™ to minimize tension on the incision line by distributing the tension more broadly.

Cranial Meningocele

Ken Rose Winston and Lawrence L. Ketch

Cranial meningoceles are CSF-filled outpouchings of meninges through a cranial defect. They occur most commonly in the occipital midline but have been reported in many other locations, including the cranial base and even far off the midline. They are covered with the scalp, and in neonates, they can be initially confused with encephaloceles; however, meningoceles do not contain brain tissue but may contain a few neural elements. Most meningoceles have a small base but the mass can be anywhere between a few mm in diameter to the size of the cranium. The brain is often normal in patients with small lesions but severely abnormal in patients with very large meningoceles [33]. Abnormalities associated with cranial meningoceles include unusual malformations of the venous structures and brain [34]. Manual pressure, with a few exceptions, will quickly displace the CSF intracranially and reduce the size of the meningocele. Rarely, there is only a tiny size connection or no identifiable continuity with intracranial CSF, and therefore, these do not reduce in size in response to manual pressure. There is an association with hydrocephalus, but most patients do not have hydrocephalus.

Plastic Neurosurgical Concerns

- Cosmetic fusiform scalp incision
- Repair of dural defect to reestablish a snug dural envelope
- Repair of cranial defect
- Cosmetic closure of the scalp

A fusiform incision in the scalp is made around the meningocele, preferably with its axis transversely positioned. It is important to leave intact enough scalp on the sides of the lesion to facilitate repair with full-thickness scalp. The edges of the cranial defect must be cleared of soft tissue attachments, and the dural connection between the meningocele and the dura of the cranial vault must be clearly exposed. Pedunculated cranial meningoceles often have a connection to the cranial dura of only a few mm in diameter, which makes their repair simple. After the dural connection is identified and cleared, a non-absorbable 2-0 ligature is tied around the base and the distal sac is resected. Meningoceles with wider bases require resection followed by repair of the defect in the dura, which often requires a patch. Small cranial defects close spontaneously over the following weeks and months, but the larger ones, particularly those associated with a dural patch, do not completely ossify. In this instance, it is reasonable to transpose a piece of the adjacent calvarial bone of sufficient size to cover the original defect and secure it in place, often by tucking its edges beneath the intact bone, allowing a new bone to develop in the site of harvest. The repair of the scalp is a straightforward two-layer repair of galea with 3-0 Vicryl® and approximation of the skin with 4-0 Vicryl Rapide™.

Spinal Meningocele

Ken Rose Winston and Lawrence L. Ketch

The management of a patient with a spinal meningocele, regardless of age at presentation, is relatively simple. The presenting complaint is usually the presence of a fluctuant mass, most commonly over the posterior lumbar midline. Much less commonly, pressure over the mass when lying supine can cause headache and impair consciousness caused by a volume of CSF being forced into the thecal sac, and raising the intracranial pressure. The shape is hemispherical and height can vary from 1 to 8 cm. The size can be reduced with manual pressure, but this should only be done briefly to confirm the connection of the external sac to the thecal sac.

Plastic Neurosurgical Concerns

- Secure occlusion of connection of the meningocele to the thecal sac
- Elliptical resection of excess skin
- Cosmetic restoration of the skin

Positioning

Surgery is done with the patient lying prone on two longitudinally oriented soft rolls, which reduce pressure against the abdomen. This reduces venous pressure in the surgical field and therefore reduces blood loss during surgery, although blood loss is typically low in these surgeries.

Skin

The skin incision for a small meningocele can be vertical and approximately 2.5 cm in length. Large meningoceles require a fusiform incision to deal with the excess skin.

Dura and Fascia

The CSF containing dural sac, which is adhered over its convexity to dermis, is usually entered at the time of skin incision. The sac consists primarily of attenuated dura, but the dura near the passage through the fascia typically has the appearance of normal dura. The neck of the meningocele usually has a diameter of 2–10 mm courses in the midline between two spinous processes to connect to the dorsal side of the thecal sac. The fascia is incised along each side of the spinous processes, and the fascia and muscle are retracted aside to allow placement of two ligatures around the neck of the meningocele. The distal neck is cut and the sac removed.

Closure

The fascia is closed across and attached to the spinous processes with absorbable sutures. Depending on the amount of excess skin, a fusiform section of the skin may need to be resected. The dermis is approximated with 3-0 Vicryl® and the skin with 4-0 Vicryl Rapide®.

Myelomeningocele (Spina Bifida Aperta)

Ken Rose Winston and Lawrence L. Ketch

The management of a newborn with myelomeningocele spans many years and involves multiple disciplines. Only the role of plastic neurosurgery is discussed in this chapter. The important roles of other specialists are not within the scope of this text.

Plastic Neurosurgical Concerns

- Decision on closure of the neural placode
- Closure of dura without compression of neural placode
- Approximation of fascia without compression of the neural placode
- Prevention of meningitis
- Cosmetic closure of the skin

Positioning

Surgery is done with the patient lying prone on two longitudinally oriented soft rolls, which reduce pressure against the abdomen. This reduces venous pressure in the surgical field and therefore reduces blood loss during surgery.

Skin

The atretic skin surrounding the placode is separated from the neural placode by making a circumferential incision. The tiny vessels along the junction of atretic tissue and placode can be cauterized and cut. Rarely there exists a single, prominent artery entering one side of the placode from the underside of the skin, and this vessel should be carefully dissected free and protected because significant neurologic injury may result from its disruption. The undermining of lateral skin flaps should be in the plane superficial to the lumbodorsal fascia and never immediately beneath the skin, lest the skin's blood supply be compromised when stretched medially. The skin flaps should be undermined with an index finger for at least 4 cm to allow the distribution of tension. There is a tendency for the novice to undermine the lateral flaps for only a short.

The spontaneous outflow of CSF will allow the placode to lie on the ventral surface of the thecal sac and thus usually below the closure of fascia. The neural placode and all nerves must be freed from most of their adhesions. The details of management of the neural placode, spinal cord, and nerves are outside the scope of this text.

Bone

Surgery for closure of myelomeningoceles does not require any removal of bone unless there is an associated diastematomyelia, which is a rare occurrence (see below discussion of “Split Cord Syndrome”).

Dura

Establishment of a secure dural envelope is important and this requires that it be identified and dissected free around all sides. The lateral edges of the dura can be near the placode or far lateral. Dissection to free the dura as it is folded into the spinal canal may encounter significant venous bleeding which can be controlled with bipolar coagulation.

An intact spinal dural envelope must be established. This can usually be accomplished by approximating and suturing the two sides of the freed dura with absorbable 4-0 running sutures; however, if there is insufficient dura to achieve approximation or if primary approximation will cause pressure against the neural placode, a patch graft will be required. A dural defect of approximately 1 cm or less can usually be patched with lumbodorsal fascia. Harvesting a wider patch of lumbodorsal fascia is not advisable. Otherwise, the defect in the dura must be patched with a synthetic material such as suturable Duragen®. The patch is sutured in place with 4-0 absorbable sutures. Under no circumstance should the dural defect be left open or closed snugly against the neural placode.

Fascia

The lumbodorsal fascia may be left open or closed. Leaving it open is simpler and avoids risk of compression of the neural placode but results in a less strong, one-layer wound closure. Closing the fascial layer reduces the risk of CSF leakage but may adversely affect the strength and function of the underlying muscles. If the lumbodorsal fascia is to be primarily approximated, the edges of lumbodorsal fascia must be undermined for at least a cm to facilitate approximation and suturing with 3-0 absorbable sutures. Care must be taken not to close the fascia in a manner that compresses the underlying thecal sac and neural placode. If it is not possible to approximate the fascia, far lateral relaxing incisions in the lumbodorsal fascia will usually allow the sliding or reflection of sufficient fascia to accomplish approximation. If this is not possible, a synthetic material, for example Duragen®, can be used to patch the defect but two layers of synthetic materials must not lie in contact with one another—e.g., a patch in both dura and fascia. This increases the risk of infection and delay in healing. It is better, in this situation, not to approximate fascia or do so very loosely.

Closure [35, 36]

Skin

Secure and safe closure of the skin is the most critical and often the most difficult component of closing a myelomeningocele. The surgeon should strive for minimal tension across the suture line. The skin flap on each side of the defect must have good blood supply, normal thickness, and be sufficiently loose, when approximated, to avoid compression of the neural placode. Transverse diameters between 4 and 5 cm may or may not be safely closed primarily. A skin defect having a maximum transverse diameter of 4 cm or less can usually be closed primarily. However, primary closure of a 4 cm defect in a newborn with little subcutaneous fat, for example, a premature baby, can be quite difficult to close primarily. Also, 4 cm skin defects centered across the pelvis are difficult to close primarily. Primary closure of defects greater than 5 cm in transverse diameter, if achievable, requires relatively strong traction, which will have a high risk of dehiscence. Regardless of the diameter of skin defect, very tight approximation constricts the abdomen and possibly the lower chest, thereby raising intraabdominal pressure and impairing respiration. Secure and safe closure of defects in the skin of 5 cm or larger requires more complex surgical techniques.

Skin Defects of Less than 5 cm Width

The skin is undermined for 3–4 cm on each side of the defect but for only about 1 cm in cranial and caudal directions. Most skin defects, at the beginning of closure, are oval in shape with their long axes in the midline, but some skin defects have transverse or obliquely oriented long axes.

A midline fusiform incision best serves most closures, but some skin defects require an oblique or Y-shaped closure. Transverse closure is prone to dehisce, because of tension across the incision when the newborn flexes the lumbar spine.

The planned fusiform incision in the skin should be marked with ink. The incision should be made beyond the atretic skin and sufficiently far from its edge to enter full thickness skin with bleeding along the dermal layer. Beginning at either tip, not the middle, of the fusiform wound, the two sides of dermis are approximated with 3-0 absorbable sutures. The edges of the skin are approximated with a non-absorbable material—e.g., nylon sutures. If a ventricular drain or CSF shunt has been inserted under the same anesthetic, the intrathecal pressure can be kept reliably low during the early stages of healing, and therefore the skin edges can be approximated with absorbable Vicryl Rapide®, with a low risk of dehiscence. It is important not to tie the skin sutures tightly. Extension of incisions in the skin to avoid standing cones (dog-ears) should be avoided, because this will result in longer scars; however, with some exceptions, these will disappear over a few weeks and not be a cosmetic problem.

Skin Defects of 5 cm Width or Greater

There are several techniques for closing large skin defects associated with myelomeningoceles that are done almost exclusively by plastic surgeons and these will not be described in detail [36]. These include bilateral rotation of latissimus dorsi and trapezius musculocutaneous flaps, subcutaneous based pedicle flap with bilateral V-Y advancement, lumbosacral fasciocutaneous flaps, muscle flaps using paraspinous, latissimus dorsi, and gluteal muscles, superior gluteal artery and dorsal intercostal artery perforator flaps, and split-thickness skin grafts [37].

Staged Closure with Expansion of the Skin

The following is the preferred technique of the author for closing defects of 5 cm or greater. Coverage is achieved with full-thickness skin, minimal blood loss, a midline scar, and a high rate of success without dehiscence but requires several surgical stages [38].

A circumferential incision is made in the atretic skin surrounding the myelomeningocele, thereby encountering little bleeding. The skin on each side of the defect is undermined by blunt dissection, using the index finger and scissors, but with minimal undermining in the cranial and caudal directions. This subcutaneous dissection must be done far laterally and continue around the abdomen, almost to the abdominal midline. A separate strip of synthetic mesh having a loose weave is tucked beneath the skin on each side of the defect for a distance of approximately 4 cm. The width of each strip should be the same as the sagittal length of the skin defect. The mesh is then sutured to the undersurface of the dermis with approximately four sutures of 2-0 silk, placed in each of two parasagittal rows. These sutures must *not* penetrate or strongly dimple the epidermal surface. A third row of *full-thickness* 4-0 silk sutures is used to attach the unrevised atretic edge of each gently stretched skin flap over the mesh. The left and right strips of mesh are then sutured together in the midline with approximately four sutures of 2-0 silk in a manner that applies moderate tension to the two skin flaps. At this stage, the edges of skin are often separated by a few cm.

At 3-day intervals, the 2-0 sutures holding the two pieces of mesh together are cut and the two flaps of mesh are pulled more snugly together and again secured together with 2-0 silk sutures. Two or three of these tightening procedures are usually required, and these can be done without anesthesia because no incisions or needle punctures of tissue are required. Each tightening procedure brings the edges of the skin progressively closer, without significantly compressing the abdomen or chest, until the undersurfaces of the skin flaps, *not their edges*, abut one another. When approximately 1.5 cm of the undersurfaces of the opposing skin flaps are separated only by the two pieces of mesh, the edges of the skin flap will be protruding outward. After another delay of 3 days, the newborn is placed under general anesthesia and all mesh and sutures are removed. The edge of each skin flap is revised to expose full thickness healthy appearing skin. The dermis can be easily closed with 3-0 Vicryl® and the skin edges are approximated with 4-0 nylon sutures. The wound is reinforced with long broad Steristrips™ to minimize tension across the incision line during healing.

Other Techniques for Closing Large Skin Defects

Lateral relaxing skin incision is an historical technique for closing large skin associated with myelomeningoceles. It consisted of bilateral creation of far lateral, full-thickness incisions in skin of 7–10 cm length. These produce severely disfiguring scars, often fail to achieve satisfactory closures, and there are better ways to achieve closure of large skin defects. The author recommends that that lateral relaxing skin incisions never be used.

Closure of Myelomeningoceles in Older Children and Adults

Rarely older children and even adults present with unclosed myelomeningoceles. Some have well epithelialized bulging defects, but others may present with chronically infected draining wounds occasionally with slow leakage of CSF. The hydrocephalus must first be addressed, usually with external drainage, while the wound is debrided, cleared of infection, and closed. The dura must be closed, followed by mobilization and rotation of skin flaps. Plastic surgical involvement is important. After the myelomeningocele is securely healed, a CSF shunt can be safely implanted.

Risks Associated with Closure of Myelomeningoceles

Complications occur more commonly following the closure of large defects. These include wound dehiscence, CSF leak, wound infection, meningitis, hematoma, necrosis of flap, and fat necrosis [39].

Wound Dehiscence

Wound dehiscence may occur from poor skin closure, tension on the closure, failure to resect the attenuated skin, wound infection, or elevated CSF pressure in the thecal sac. Management of wound dehiscence must begin with addressing its cause. Simply re-suturing a dehisced myelomeningocele wound usually results in repeat dehiscence, regardless of the cause.

Infarction of Skin

The skin along the edge of one or both sides of the wound may infarct as a result of one or more of the following: significant compromise of blood supply during surgical dissection, excessively tight closure, skin sutures tied too tightly, and excessive number of sutures. The infarcted skin or eschar must be resected and the wound reclosed unless the infarction is thought to involve only the epidermis (not common). If skin infarction extends a few cm from the edge of the incision, rotation flaps will be required for closure and a plastic surgeon, if not already involved, should be consulted.

CSF Leak

CSF leakage is usually caused by elevated CSF pressure in the thecal sac—i.e., hydrocephalus—but can be related to defective wound closure. A postoperative CSF leak must be assumed to be associated with bacterial contamination and risk of meningitis. Action is urgently required to address the cause of leakage and the patient must be closely monitored for meningitis. Insertion of a ventricular drain will halt the leakage and allow healing to occur.

Infection

Wound infection is the result of surgical wound contamination or secondary to dehiscence of the wound. Infection often spreads subcutaneously beneath skin flaps and can quickly progress to meningitis. Also, an infected CSF shunt or ventricular drain may be the source of inoculation of the freshly closed myelomeningocele site.

Prenatal Closure of Myelomeningocele

Charles Corbett Wilkinson

Prenatal closure of myelomeningocele has become an accepted treatment due to a lower rate of postnatal cerebrospinal fluid shunting than after postnatal closure [40]. Although prenatal closure may not be the right choice for all patients and families, the standard of care for appropriate candidates should include a discussion of the pros and cons of prenatal versus postnatal closure.

Maternal requirements for prenatal closure include a singleton pregnancy, no previous preterm birth, no previous hysterotomy, and a normal cervical length. Due to increased risk of preterm delivery with obesity, the original Management of Myelomeningocele Study (MOMS) also restricted prenatal closure to mothers with a body mass index (BMI) less than 35 [40]. However, the absolute increased risk is relatively small [41] and it may be reasonable to offer prenatal closure to some mothers with non-morbid obesity. Under an ongoing IRB-approved protocol, we are currently offering prenatal closure to women with BMIs less than 40.

Prenatal closure should be before 26 weeks gestation. We often perform surgery at 23–24 weeks, because of the lower risk of preterm delivery following surgery at this gestational age, compared to that of 26 weeks. Regardless, the possibility and potential morbidity of preterm delivery shortly after surgery should be thoroughly discussed with the patient and family.

All prospective patients undergo a comprehensive evaluation. Radiologic studies include fetal ultrasound, fetal echocardiogram, and fetal MRI. In order to proceed with surgery, there must be a Chiari malformation and the upper border of the myelomeningocele should be lumbar or thoracic. After post hoc analysis of the MOMS data revealed that fetuses with large ventricles still were very likely to need postnatal shunting after prenatal myelomeningocele closure [42], many centers have restricted prenatal closure to fetuses with ventricular atrial diameters narrower than 15 mm. In general, structural abnormalities not related to the myelomeningocele disqualify patients from fetal closure, as do abnormal karyotype or fluorescence in situ hybridization (FISH) results. Prospective patients and families undergo both group and independent counseling by a maternal fetal medicine specialist and neonatologist. They also must undergo psychosocial evaluation.

It is critical to have an experienced multidisciplinary team taking care of patients who undergo prenatal myelomeningocele closure. There must be an anesthesiologist experienced in fetal and maternal analgesia/anesthesia [43]. Uterine tone must be kept low to prevent placental separation and fetal distress. In addition to the pediatric neurosurgeon, the team should include a fetal surgeon, a maternal fetal physician, and an ultrasonographer to monitor the fetal cardiac function during the procedure. At our institution, the ultrasonographer is a pediatric cardiologist with expertise in fetal cardiology.

Surgery

A low transverse maternal incision is made to expose the uterus. The location of the hysterotomy depends upon the location of the placenta. With a posterior placenta, the hysterotomy is anterior. With an anterior placenta, the hysterotomy is posterior or fundal. Regardless of the location of the placenta, the hysterotomy should be at the highest point of the uterus with respect to the operating table. This prevents amniotic fluid loss and keeps the back of the fetus horizontal, making closure easier. Prior to opening the hysterotomy, two monofilament traction sutures are placed through the entire thickness of the uterine wall. The uterus is opened sharply between the sutures, then a uterine stapling device (using absorbable polyglycolic acid staples) is used to create a hysterotomy. Ultrasound is used to localize the hysterotomy over the myelomeningocele and prevent injury to the fetus. Continuous echocardiography is performed throughout the procedure. While the uterus is open, it is continuously infused with warm fluid to replace the lost amniotic fluid.

Closure of the myelomeningocele may be performed using loupe magnification or the operating microscope; we prefer the superior magnification and lighting of the microscope. The first step is to measure the skin defect. If it is too wide—more than 2–2.5 cm—it cannot be closed primarily with the usual postnatal techniques. The postnatal tactic of widely dissecting the skin and bringing the edges together under tension will tear the fetal skin. Most centers use an acellular dermal patch in this situation, although other materials are being investigated. If the team decides to use a patch, it is prudent to have a member of the team cut it to appropriate size and the patch should be smaller than the defect. Even if the edges cannot be brought together primarily, with some undermining they can still be brought closer together. The smaller the patch, the smaller the area that will need to undergo postnatal epithelialization.

The placode is sharply dissected from the arachnoid. The arachnoid in a 23–26-week fetus is extremely transparent, making it very is easy to identify the edges of the placode. There has been concern about postnatal epidermoid cysts after prenatal myelomeningocele closure [1], but the pristine arachnoid helps prevent leaving the cutaneous ectodermal tissue attached to the placode. The transparent arachnoid also makes it quite easy to see and cauterize the underlying vessels before cutting them.

At this point, the placode is untethered. If desired, the placode can be neurulated with a fine interrupted suture, such as 7-0 polydioxanone (PDS). Excess tissue (arachnoid, etc.) is then sharply trimmed back to full-thickness skin. Closure of the open dura is next. If the dura is to be closed primarily, it must be dissected from the underlying soft tissue, but this is more difficult than in postnatal closure. The dura is closed with a fine, non-braided suture such as 7-0 PDS. Prenatal dura has the thinness and friability of postnatal arachnoid. Injection of saline between the dura and underlying fascia helps with elevation of the dura [44]. If the dura becomes shredded during dissection, the defect in the dura can be covered with a collagen matrix graft.

One can also elevate and close the thoracolumbar fascia as well with needle-tip electrocautery and standard microdissection techniques. This fascia has a similar toughness to prenatal dura, and care should be taken not to inadvertently open it. Thicker musculofascial flaps are possible as well. However, the effects of elevating the paravertebral muscle on spinal stability and function of latissimus dorsi are unknown. These effects may be outweighed by a greater likelihood of obtaining a water-tight closure and consequent increased likelihood of reversing hindbrain herniation and decreased need for shunting.

Great care must be taken during dissection required for skin closure to prevent damage. The skin is widely dissected from the underlying fascia in between the hypodermal adipose tissue and lumbosacral-dorsal fascia, preserving the blood supply of the skin to the greatest possible extent. We use a simple running technique with a non-braided absorbable suture, e.g., 5-0 PDS, for primary closure. The same suture is used when sewing in a patch. Often, when closing with a patch, the superior and inferior poles can be closed primarily, allowing use of a patch not only narrower than the defect but also shorter. It is useful to reinforce the closure with fibrin glue or a similar material. If the fascia has been closed, skin closure can be strengthened by passing the cutaneous sutures through the fascia.

Fastidious closure of the hysterotomy is critical to prevent uterine rupture. At our institution, closure is done with 2-0 running PDS through the myometrial edges, interrupted 2-0 full-thickness PDS retention sutures, and a third, imbricating layer to provide serosal-to-serosa apposition [45]. The hysterotomy closure is then covered with an omental patch. The abdominal fascia and skin are closed in a standard fashion.

Post-surgery, magnesium sulfate is infused as a tocolytic (*Greek: childbirth* + *loosening*) for 24 h or more. If the mother is from out of town, she stays in town for 2 weeks. A 2-week follow-up fetal MRI is done prior to returning home and improvement of the Chiari is considered to be an auspicious sign that postnatal shunting may not be necessary. Delivery is by caesarean section and, if the mother desires, is done by her local maternal-fetal/obstetric team. Requirements for local delivery include a neonatal intensive care unit and the availability of a pediatric neurosurgeon. Infants are followed for development of hydrocephalus with sequential measurements of the orbitofrontal circumference and by intermittent ultrasonography of the head.

The scar at the time of delivery, following primary closure of the fetal skin, will usually be closed and have a satisfactory appearance. If a patch was used in closure, the skin will usually not be completely epithelialized; however, rapid epithelialization will usually occur if the site is kept moist and covered.

Risks

The prenatal closure of a myelomeningocele has risks for both mother and fetus; however, these will not be addressed here.

Split Cord Malformation (Diastematomyelia) [46, 47]

Ken Rose Winston

Diastematomyelia (*Greek: split* + *spinal cord*) is a type of neural tube defect (spinal dysraphism) with tethering of the spinal cord caused by a septum or spike of bone that traverses the dural envelope and spinal cord, resulting in two hemicords, each invested in a separate dural sheath—i.e., split cord malformation, type I [46, 47]. Type I has two hemicords with each invested in a dural envelope and the two are separated by a bony or osteocartilaginous septum. Vertebral abnormalities are always present and commonly include fused vertebrae and hemivertebrae. Type II has the two hemicords enclosed in a single dural envelope and bony abnormalities are rare.

Diastematomyelia most often comes to medical attention in the course of workup of patients with scoliosis. Although usually an isolated deformity, this abnormality is occasionally identified during the closure of myelomeningoceles [48].

The surgery for type I split cord syndrome will be described in this text. The goal of surgery in patients with diastematomyelia is to untether the spinal cord by removing the septum of bone passing through the dural envelope and spinal cord.

Plastic Neurosurgical Concerns

- Resection of transfixing bony spike
- Protection of the split spinal cord
- Safe resection of dural chimney
- Closure of dura
- Cosmetic closure of skin

Positioning

Patients are placed in a prone position on longitudinally oriented soft rolls in a manner that prevents or minimizes pressure against the abdomen. This is done to reduce venous pressure in the surgical site and minimize blood loss.

Skin

A midline incision of sufficient length to span at least three spinous processes and centered longitudinal across the radiographically identified bony septum is done. Some patients have a patch of hair overlying the lesion and this can be removed with a fusiform incision.

Fascia and Muscle

A longitudinal incision is made along the midline of the exposed spinous processes and the fascia of each side is separated from these spinous processes. The paraspinous muscles are separated from the spinous processes and laminae on each side and are retracted with two self-retaining retractors.

Bone

Two spinous arches, whose laminae are commonly fused, are removed with Kerrison rongeurs. This will allow safe identification of the anatomy of the posterior attachment of the bony septum, which varies greatly. The shaft of the bone may course vertically or obliquely across the spinal canal and through the thecal sac but only rarely in the exact midline. The shaft always has pericranium which may be fused to the dura at the caudal extent of the straddling dura. The complete removal of the shaft is critical for untethering the spinal cord, and this is done with a combination of small rongeurs, burrs and curettes. The surgeon must be aware that the split spinal cord is tethered tightly against the dura at the inferior edge of the bony septum. A small artery is usually present in the center of the shaft of bone, and bleeding from this vessel will require control with bone wax or cautery [48]. Complete removal of a severely oblique shaft can be quite tedious.

Dura

The thecal sac in type I defects always has two channels, often of unequal size, one passing on each side of the bony septum and each side containing a spinal hemicord. The dura that straddles the shaft, commonly known as the *chimney*, forms a tear-shaped sleeve that straddles the shaft of bone and its distal end is always positioned tightly against the lower end of the divided spinal cord, thereby tethering the spinal cord.

Beginning approximately 1–1.5 cm cranial to the chimney, a straight midline incision is made in the thecal sac above the dural bifurcation and extended caudally along each separate dural channel to the distal end of the chimney. Incision is continued along each dural channel, and the two incisions then meet approximately 1 cm below the chimney. The incision is then continued caudally, as a single incision for 1–1.5 cm. The chimney of the dura must be gently dissected free of the spinal cord under high magnification and resected. The dura always has adhesions to the spinal cord at the caudal end of the chimney and, to a lesser extent along the lateral sides of the chimney. There will be a slight cranial shift of the spinal cord as the tethering is released. Great care must be taken to protect the spinal cord. The chimney is resected under high magnification with microscissors, with attempt to leave sufficient dura for closure of the resulting ventral and dorsal dural defects.

Closure

Dura

The thecal sac is closed in a manner that produces a single channel. Closure of the ventral dural defect of the sac is always tedious because it must be done between the two spinal hemicords. Ideally, the ventral defect in the dural envelope should be sutured, but this is almost never possible without risking injury to one or both hemicords. The defect in the ventral dura can be managed either by placing an onlay patch consisting of a narrow strip of dura, across the defect on the inside of the thecal sac or by sliding a small piece of lumbodorsal fascia around the thecal sac and positioning it across the extradural surface of the ventral dural defect. Closure of the posterior opening in the dura is rarely difficult but, if there is a wide defect, a patch may be required.

Fascia

Closure of the fascia is usually straightforward as is the two-layered closure of the skin.

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