Bone Grafting: Physiology and Techniques

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Craniofacial anatomy represents one of the few places in the body where bony anatomy is truly married to that of soft tissue. As well as providing structural support and protecting sensory anatomy, the skeletal component of craniofacial anatomy is essential in fulfilling perhaps the face's most important role: to look like a face. Given this unique marriage of form and function, the goal of this chapter is to review the principles of bone anatomy, physiology, histochemistry, repair and regeneration, and reconstruction and grafting techniques, as they pertain specifically to craniofacial surgery.

Bone Anatomy

The craniofacial skeleton is made up of a total of 29 bones; 8 comprise the cranium, 14 the facial area, 6 form the auricular ossicles, and finally there is the hyoid. As well as providing protection of vital sensory organs, bone provides structural support and serves as an attachment point to facilitate movement of the facial soft tissues. Bone also serves as a reservoir for growth factors and minerals, although to a lesser degree in the craniofacial skeleton than elsewhere in the body. Bones are often described as either flat or tubular; the craniofacial skeleton is composed primarily of flat bones. These differ from tubular bones in that they do not contain the three distinct regions seen in tubular bones (diaphysis, metaphysis, and epiphysis) and are primarily cancellous with a thin cortical shell.

Bone may be classified either as cortical or cancellous. These differ greatly in terms of density, structure, and metabolic activity. Cortical bone makes up the majority of all bony tissues (~80 %) and forms the outer layer of the skeleton. A dense, fibrous, bilayered membrane known as periosteum covers this shell. A thin layer of connective tissue that lines the surface of the bony tissue that fashions the medullary cavity of long bones forms what is known as the endosteum. Cortical bone is resistant to torsional and bending stresses and is 5–10 % porous, which is what provides it with its compressive strength. Cortical bone is composed of osteons, or haversian units, each of which consist of concentric layers or cortical tissues, or lamellar, of compact bone tissue surrounding a central, or haversian, canal (Fig. 8.1). Perforating holes, known as Volkmann's canals, run perpendicular to the haversian canals within the osteons and interconnect the haversian canals with each other and the periosteum. It is within the haversian and Volkmann's canals that nutrient vessels and nervous tissue tract. Conversely, cancellous bone is 50–90 % porous, which allows it to be compressible, and also has a higher rate of metabolic activity owing to its greater surface area.

Composition

While an understanding of bone composition and function of those components is important for the craniofacial surgeon, detailed histology and discussion of the intricate signaling pathways of the cellular components is beyond the scope of this text.

Bone is made up of inorganic matter, organic matter, and water. The inorganic component, which comprises 60 % of bone, is primarily made up of hydroxyapatite, which is a naturally occurring mineral form of calcium apatite. The inorganic bone matrix therefore sequesters 99 % of the body's storage of calcium. The hydroxyl component may be replaced by minerals such as phosphate, which allows for bone to function as a reservoir. The organic phase, which makes up 30 %, is primarily composed of type I collagen. Other components include proteoglycans, growth factors, and glycoproteins.

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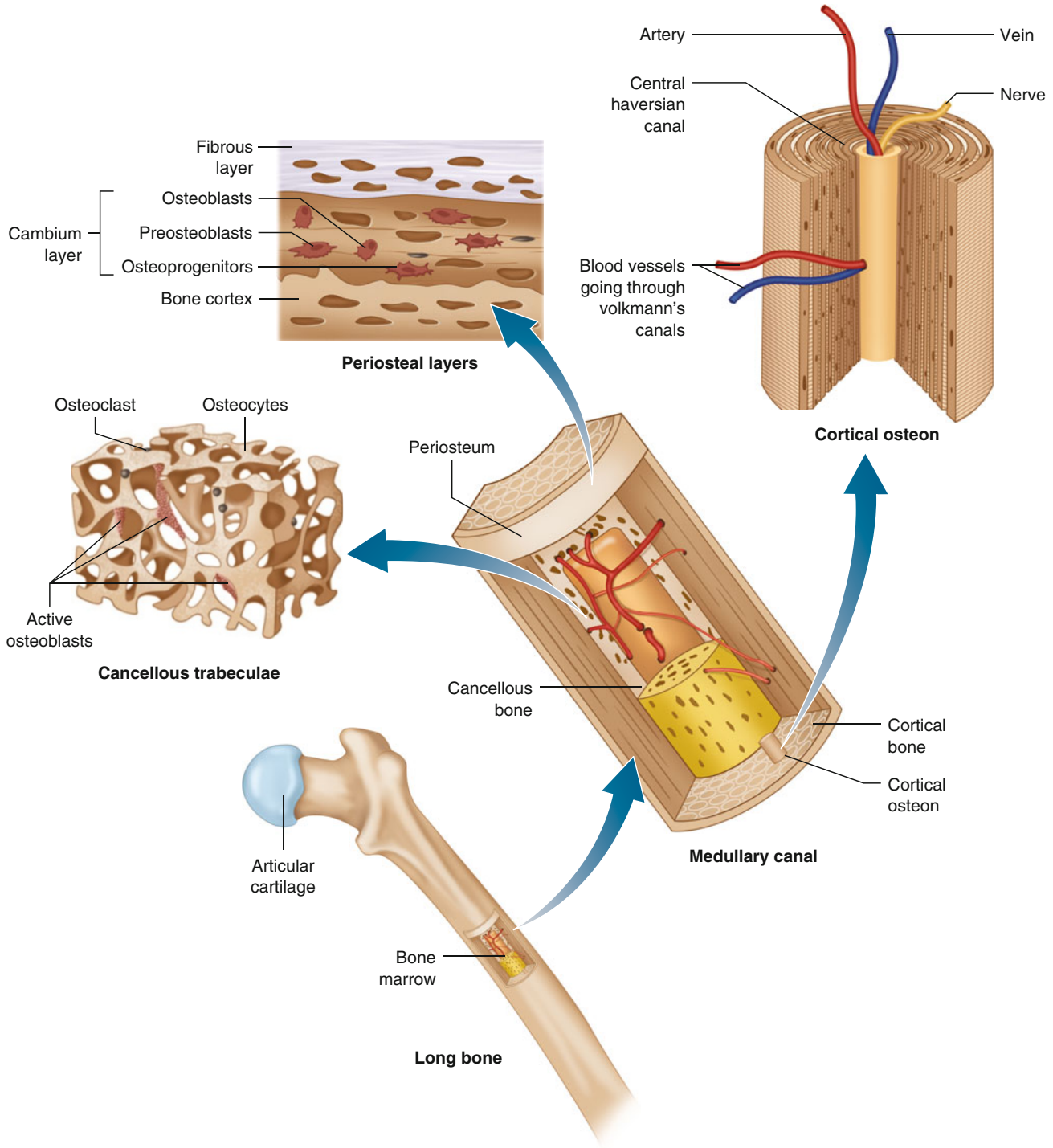

Fig. 8.1 Bone microanatomy. Most bones are comprised of a hard cortical component and a "spongy" cancellous component. Cancellous trabecular packets are arranged to maximize surface area for nutrient diffusion and exposure to circulating cytokines and hormones important in bone and mineral homeostasis. The external surface of bone is covered by a periosteum, which provides additional vascular supply, and osteoprogenitor cells important in the initial stabilization of fracture callus

Cells within bone may be divided into two groups: osteoprogenitor cells and osteoclasts. Osteoprogenitor cells arise from pluripotent mesenchymal stem cells and differentiate to form osteoblasts and osteocytes, whereas osteoclasts arise from hematopoietic cells. Osteoblasts are located on the surface of the bone and form a dense, active, remodeling surface. Osteoblasts are rounded, basophilic cells. When active, they produce bone matrix and in doing so release alkaline phosphatase, which serves as a marker of osteogenesis. Upon activation, they either remain as osteoblasts, terminally differentiate into osteocytes, or revert back to an osteoprogenitor cell.

Osteocytes are embedded within the lacunae, which is akin to a bone corpuscle. These lacunae are connected to one another by canaliculi, which are thin cytoplasmic projections that extend from the osteocyte upon activation. Osteocytes are therefore stellate cells. Osteocytes are essential for mineral homeostasis, particularly calcium, and bone resorption when stimulated by parathyroid hormone.

Osteoclasts are large, multinucleated cells with a ruffled border that are located within Howship lacunae, shallow grooves/pits of endosteal and periosteal that form over the surface of bone. In areas of active remodeling, they form deeper cavities known as cutting cones. Osteoclasts resorb bone, adhering to bone matrix and dissolving it through acidification. This process is of particular importance clinically in instances of pathologic and dysfunctional resorption.

The extracellular matrix is formed primarily by osteoblasts. It is primarily composed of type I collagen, but also contains myriad other collagens, noncollagenous phospho- and glycoproteins, and growth factors. It is this matrix from which bone derives the majority of its strength.

Bone Regeneration

Differing from collagen deposition in the process of scar formation, bone is unique in its ability to heal through cellular regeneration via mineral matrix production and constant remodeling. Much like any other molecular process, there exists an intricate milieu that governs migration, proliferation, and differentiation. Identification of key factors within these cascades, as well as the ability to spatially control their effects, continues to be the basis for much of today's research. The following serves as an introduction to the more prolific of these key factors, with specific craniofacial clinical applications discussed here and in subsequent sections.

Bone Morphogenetic Protein

Bone morphogenetic proteins (BMPs) are members of the transforming growth factor-β superfamily and are essential in the regulation of cellular growth and differentiation. They also serve to attract osteoblasts and mesenchymal cells. With 20 unique isoforms identified, BMPs play different roles at various stages of development. They are critical to skeletogenesis, epidermal induction, and neural crest cell development. BMP is expressed during fracture repair by mesenchymal cells, as well as by osteoblasts and osteoclasts. Many studies have elucidated the role of BMP with regard to the specific aspects of the craniofacial skeleton, including its role in accelerating bone deposition in the mandible during distraction, as well as in the regeneration of cranial defects. Furthermore, BMP is the only signaling molecule capable of singly inducing de novo bone formation. Clinically, rhBMP-2 and rhBMP-7 are the only two isoforms that are currently Food and Drug Administration approved for human application and are most often utilized for spinal and orthopedic procedures. Most notably in the field of craniofacial surgery, BMP has been shown to accelerate mandibular regeneration and therefore may be utilized to augment distraction osteogenesis within the craniofacial skeleton. Its use in alveolar cleft bone grafting has also been documented.

Transforming Growth Factor-Β

Transforming growth factor-β (TGF-β) is also a member of the transforming growth factor-β superfamily and controls proliferation, cellular differentiation, motility, as well as many other functions in a wide variety of cell types. It plays a role in many human diseases, including cancer, heart disease, diabetes, and acquired immunodeficiency disorder. TGF-β is released in three isoforms, with TGF-β1 having been shown to play an important role in bone physiology. TGF-β1 is the primary isoform secreted by bone, and in addition to being critical in inducing mesenchymal cell differentiation to chondrocytes or osteoblasts, it has been implicated in osteogenesis, osteoclastogenesis, and bone resorption and repair.

Fibroblast Growth Factor

Fibroblast growth factors (FGFs) play important roles in all stages of human life. Involved in angiogenesis, wound healing, and embryonic development, they are a heparin-binding glycoprotein and are key in a wide range of aspects of cellular developmental biology. With regard to bone, FGFs regulate prenatal and postnatal bone formation, controlling osteoprogenitor cell replication and osteoblast differentiation and function. While TGF-β and BMP are indirect regulators of angiogenesis, FGF, specifically FGF-2, is a direct regulator and therefore increases this process during fracture repair. Furthermore, dysfunction of FGF signaling has been

implicated in human skeletal dysplasias and cranial suture disorders and therefore may provide a molecular basis for developing clinical therapeutic strategies.

Platelet-Derived Growth Factor

Platelet-derived growth factor (PDGF) is a polypeptide chain, made up of disulfide-bonded dimers, which promotes organogenesis, skeletal development, angiogenesis, and wound healing. PDGF increases chemotaxis of osteoblasts and is secreted by osteoblasts and macrophages during fracture repair, promoting matrix deposition and turnover. PDGF has also been shown to increase the production of osteoprotegerin, an inhibitor of osteoclastogenesis and bone resorption. With specific regard to craniofacial biology, PDGF directly and indirectly increases bone turnover in periodontal tissue in humans.

Bone Healing

Craniofacial bones develop, grow, and heal by direct ossification of mesenchyme rather than preformed cartilage. As such, unlike bones of the appendicular skeleton, cartilage within craniofacial bone only acts as a scaffold and does not act as a bone precursor. This is important for a number of reasons, but in regard to craniofacial reconstruction, one must be cognizant that therapeutics designed for long bone healing may not directly translate to that of the craniofacial skeleton.

As is the case elsewhere in the body, bone repair following fracture repeats the process undergone during skeletogenesis for that particular anatomy. For the majority of bones within the body, this may be either primary healing (direct cortical healing without a cartilaginous intermediate through the deposition of bone by osteoblasts) or secondary healing (callus bone repair whereby a cartilaginous intermediate is formed within the periosteum, soft tissues, and bone marrow). However, similar to its development, bones of the craniofacial skeleton do not heal via a callus model as described above, but rather through a process akin to secondary endochondral bone union whereby preexisting cartilaginous matrix is replaced with osseous precursors which in turn lead to new woven bone formation.

Variables Influencing Craniofacial Bone Repair

Key elements in fracture healing closely resemble elements critical in wound healing, with the exception of the addition of fracture fixation. Adequate blood supply is essential for bony healing. Revascularization may occur through a process known as haversian remodeling. Vascular endothelial growth factor (VEGF) is the prototypical molecule described in the direct regulation of angiogenesis. A dimeric glycoprotein expressed by osteoblasts, osteoclasts, and mesenchymal cells, VEGF increases vascular sprouting, endothelial cell migration, and proliferation adhesion. The therapeutic promise of VEGF continues to be elucidated. The persistence of devitalized bone even in the setting of a well-vascularized environment remains possible. In such cases, devascularized bone is unable to activate remodeling and, over a period of 6–12 months, will transition to become necrotic bone and predispose itself to repeat fracture. An important variable that is often encountered during craniofacial reconstruction is the effect of radiation following the treatment of head and neck cancers. Radiation-induced changes limit options for primary salvage and impair secondary reconstruction by inhibiting bone healing and growth, choking microvascular supply, and decreasing the integrity of surrounding soft tissue.

Fracture fixation, while pervasive today, has a relatively short history in craniofacial surgery. Over the past several decades, there has been a constant evolution and refinement of the principles of craniofacial fixation, resulting in enhanced understanding of its benefits. While the scale of fixation systems has decreased with time, the principles of application remain the same. Critical to the stability and success of bony healing is the reduction in the degree of motion of fracture fragments. At the same time, micromotion at fracture sites has been shown to increase the degree of bone healing through the enhancement of chondrogenesis and osteogenesis. In the setting of insufficient fixation, fibrous tissue is subsequently deposited within the fracture gap, creating a callus that may be visualized radiographically. In some instances, the fibrous tissue provides sufficient stabilization of the bony fragments to result in differentiation of the callus into bone. If this is not the case, which is occasionally the outcome in the craniofacial skeleton where bones are subject to the forces of muscular movement during expression and mastication, cartilage forms within this gap, resulting in nonunion. These same principles hold true for stabilization and survival of bone grafts.

Age brings with it a number of physiologic changes that affect multiple factors ranging from angiogenesis and stem cell function to signaling cascades and periosteal structure, each of which are essential to bone healing and repair. This is evidenced by the observation that pediatric bone heals at a faster rate than adult bone, likely secondary to increased angiogenic potential of younger bone.

Bone Remodeling

Bone and bone grafts regenerate through three mechanisms: direct spontaneous formation (direct osteogenesis), osteoinduction, or osteoconduction. Combinations of varying degrees

of each can occur in a single setting. When implant materials are utilized, a process of osseointegration also occurs, with osteoinduction or osteoconduction occurring in the context of the architecture and composition of the implant.

Osteoinduction

Osteoinduction is the process whereby undifferentiated pluripotent cells are stimulated to transform into bone-producing cells through the release of active factors and thereby form bone in an area previously devoid of it. BMP is the most studied and the most prolific bone-inducing agent, occurring naturally during the genesis of bone or following fracture repair, or via exogenous stimulation. For bone grafts, the architecture of the graft (cancellous versus cortical) dictates the success of incorporation. Cancellous bone graft incorporation tends to be more favorable compared to cortical bone, owing to its open architecture which allows for more rapid revascularization and differentiation of osteoprogenitor cells into bone-forming osteoblasts.

Osteoconduction

Osteoconduction describes bone formation from either adjacent bone or periosteum via the ingrowth of capillaries and osteoprogenitor cells from the recipient bed into, around, and through a bone graft or bioimplant. Therefore, the graft or bioimplant acts as a scaffold for new bone formation. Unlike osteoinduction, this process occurs in an environment already containing bone. Osteoconduction can be more broadly described as the facilitation of bone growth along a scaffold of autogenous, allogenic, or alloplastic materials. In the case of nonvascularized bone grafts, partial necrosis initially occurs, followed by an inflammatory phase where the majority of grafted bone is replaced with new bone, a process described as creeping substitution.

Osseointegration

Osseointegration refers to the direct structural and functional connection between living bone and the surface of a load-bearing artificial implant. Osseointegration of implants results in union without a cartilaginous intermediate. Therefore, the composition and architecture of the implant is integral to its ability to osseointegrate. Implant materials may be classified as either inert or bioactive. Inert materials may generally be used in areas where adjacent soft tissue quality is satisfactory, whereas reconstruction of load-bearing architecture as well as tooth-bearing areas generally requires bioactive materials.

Distraction Osteogenesis

Distraction osteogenesis (DO) is the surgical process of lengthening bones of the body, whereby new bone is formed between two vascularized bone surfaces as those surfaces are slowly mechanically separated. Alessandro Codivilla, an Italian surgeon, introduced surgical practices for lengthening of the lower limbs in 1905. However, like many medical endeavors, early techniques were plagued with high complication rates often resulting in subsequent therapeutic failure. It was not until after the contributions of Gavril Ilizarov, a Russian orthopedic surgeon, that the technique was popularized. Ilizarov's technique was based upon the biology of bone and founded upon the fact that soft tissues regenerate under tension.

Reconstruction of both congenital and acquired craniofacial defects often requires the elongation of facial bones. As such, it was not long before Ilizarov's principles were explored within the craniofacial skeleton. Unique challenges were appreciated with respect to the three-dimensional movement of bone within the face, as well as lower thresholds for cutaneous scarring. Clinical reality was not achieved until 1992, when McCarthy et al. published the first report of gradual mandibular elongation in humans. The same basic principles are adhered to (1) a cut around the perimeter of the bone to be elongated; (2) application of a rigid fixator/distractor; (3) following a short latency period, gradual separation/distraction of the opposing bone surfaces; and (4) consolidation of the newly formed bone. Mechanisms have evolved from external devices with a single vector to both external and internal devices that may move bone in multiple vectors. Most devices are still dependent upon manual turning and are not yet capable of continuous distraction. However, spring-mediated distraction, capable of gradual continuous distraction, has shown promise in craniofacial applications. More so than with long bones, movement of bones within the craniofacial skeleton must be carefully planned. Three-dimensional planning tools are currently available to simulate the entire process of distraction osteogenesis and in doing so calculate the necessary trajectory needed.

Clinical Applications of Bone Grafts

Bone grafting materials may be classified according to origin or architecture. Autografts are taken from the host and are the "gold standard." They are the only grafts that are truly osteogenic, i.e., osteoblasts originating from the bone graft contribute to new bone formation, in addition to bone formation via osteoinductive and osteoconductive processes. Allografts are taken from the same species and are usually cadaveric; incorporation is via osteoconduction, and possibly osteoinduction if osteoinductive cell mediators are still

present in the graft. Xenografts are taken from different species and are usually of bovine or porcine origin. Synthetic grafts are not taken from living donors and have no cellular or protein products; calcium phosphate derivatives such as hydroxyapatite are among the most common.

Indications for Bone Grafting

Bone grafts can be used for (1) the filling of acquired bone defects, such as following tumor extirpation or continuity defects following trauma; (2) surface augmentation, such as placement of bone graft for zygomatic or chin augmentation; and (3) reconstruction of congenital defects, such as bone grafting for alveolar cleft defects or for mandibular ramus reconstruction.

Bone Graft Healing and Graft Survival

Bone graft healing parallels that of fracture repair, as outlined earlier, and as such differs in the craniofacial skeleton versus elsewhere in the body. Osteocyte activity is primarily at the recipient site, as osteocytes of the donor seldom survive following transplantation. Bone viability should be maintained during the harvest. The duration of exposure to air should be minimized. Grafts should be covered in a blood-soaked sponge with a moist saline gauze over top. Graft should be kept below 42 °C, and antibiotic washes used with caution owing to their cellucidal properties. The graft recipient site should be well vascularized, and if it is the case, cancellous grafts should be abutted to a cancellous bed.

Decreased viability secondary to poor technique may result in decreased healing capacity, as well as poorer biomechanical properties of the grafted bone and resulting bone regenerate. Viability is dependent upon the size and thickness of the graft, as well as its application to the recipient site. Onlay bone grafts tend to resorb, whereas inlay bone grafts have more favorable survival, with osteogenesis being favored over resportion.

Techniques of Harvest and Sources of Autologous Bone Graft

Sources of autologous bone run the entire topography of the human body. The choice depends upon quantity of bone desired, as well as desired architecture and shape. Traditionally, the ilium, tibia, calvarium, rib, and mandible have served as the preferred donor sites for craniofacial applications. The importance of using the correct instruments, and for those instruments or be in optimum condition, cannot be stressed highly enough.

Iliac

The ilium is a workhouse donor site for the majority of craniofacial applications. Iliac bone graft harvest may be divided into anterior iliac (AI) and posterior iliac (PI) harvest. Iliac harvest allows for a dual surgical team approach and may provide free bone as well as vascularized bone grafts. Given that most craniofacial procedures require the patient to be supine, the anterior ilium is the site of choice in most cases. Bone may be harvested in a variety of states: cancellous, thin cortical, corticocancellous, and bicorticocancellous (Fig. 8.2). The ilium, therefore, serves all indications for bone grafts for craniofacial procedures. The ilium is also the primary donor site for alveolar bone grafting.

The primary goal, in addition to the harvest of quality bone graft, is preservation of the shape and regenerative ability of the iliac crest and the avoidance of postoperative pain. The approach for AI graft harvest is made by first appropriately positioning the patient either supine or with the hip slightly raised. A skin incision 3 cm lateral to the iliac crest, 5 cm below the lateral femoral cutaneous nerve, is made (Fig. 8.3). The skin and subcutaneous tissue is pulled medially to allow for an incision straight down through the superficial fascia and muscular aponeurosis to the periosteum at the top of the iliac crest. There is no need to elevate the periosteum on the crest ridge. Care should be taken to avoid unnecessary superior dissection, which places the lateral cutaneous branch of the T12 subcostal nerve at risk of being stretched or cut (Fig. 8.4). In adults, the fascia overlying the bone must be separated. In the pediatric population, the crest is padded with a cartilaginous growth area that should be preserved in order to avoid growth disturbances.

With a saw or a chisel, the iliac crest is split into two segments. The medial segment remains attached to the insertion of the abdominal muscles, and lateral segment to the insertion of the gluteal muscles. This split is extended ~10 mm anteriorly and posteriorly through the crest, down to the anticipated graft harvest zone. The marrow may be harvested with a sharp curette from this exposure. For corticocancellous harvest, the dissection continues deeper, with careful subperiosteal elevation of the medial iliac and lateral gluteal muscles; care should be taken to avoid laceration of these muscles. The medial iliac crest segment, having been split in an inferomedial direction, is reflected medially with the abdominal muscles attached, and the lateral part of the crest, having been split posterolaterally, is reflected

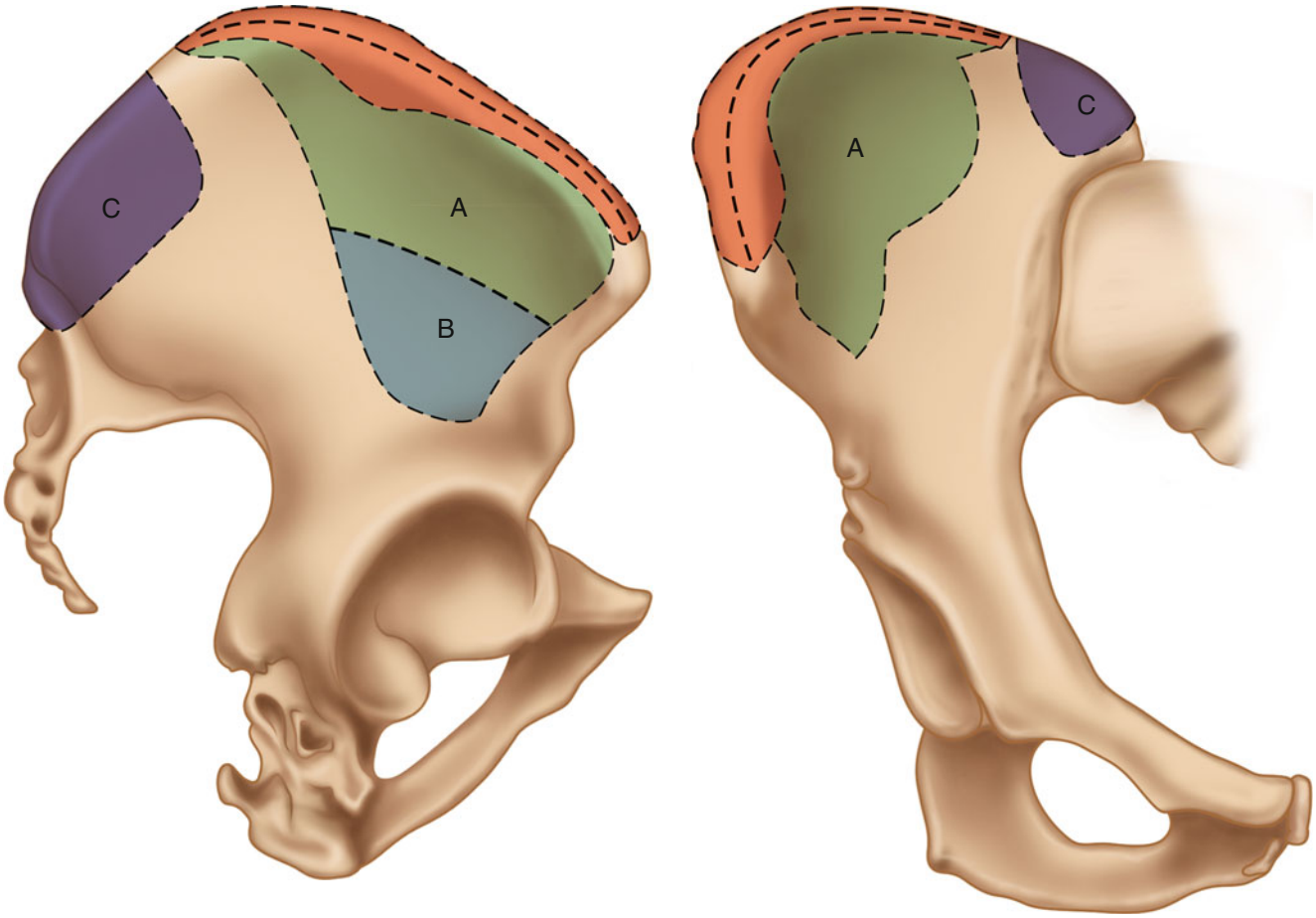

Fig. 8.2 (*Left*) The outer aspect of the anterior and posterior iliac crests, showing (*A*) the large subcrest 5×8 cm corticocancellous graft that can be harvested, (*B*) cancellous bone harvest area down to the cotyloid ridge, and (*C*) the posterior corticocancellous graft donor site. (*Right*) The inner aspect of the anterior and posterior iliac crests, with (*A*) the large 6×10 cm innercorticocancellous donor site and (*C*) the smaller inner table posterior iliac crest donor site

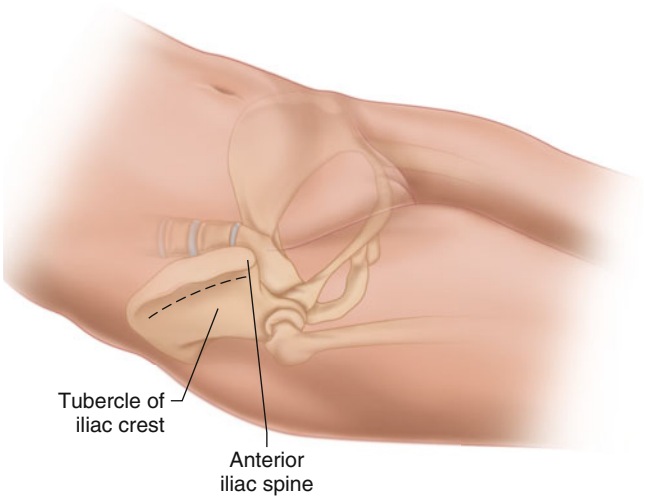

Fig. 8.3 Location of the skin incision 3 cm lateral to the iliac crest. The incision is drawn after marking the locations of (1) the anterior iliac spine and (2) the tubercle of the iliac crest

laterally with the gluteal muscles attached (Fig. 8.5). The lateral dissection can be avoided in the harvest of a medial monocortical graft. Mono- or bicortical grafts can then be harvested using straight or curved thin osteotomes or with a reciprocating saw (Figs. 8.6 and 8.7). Gelfoam is then used to preserve the periosteal pocket of the donor site, and the medial and lateral segments of the split crest are then repositioned and secured with either a sturdy resorbable suture or 26 gauge wires (Fig. 8.8). Harvest from the posterior iliac follows the same tenets. While classically the patient is positioned prone, the patient may be positioned supine following the technique of Tessier et al. The posterior pelvis is raised on a sandbag, with the legs turned to the contralateral side. The skin incision is made on the medial third of the crest, and the exposure is then achieved as previously described (Fig. 8.9). The complication rate for iliac bone graft harvest is reported to be as low as 0.5 %, with postoperative pain being most predominant. This

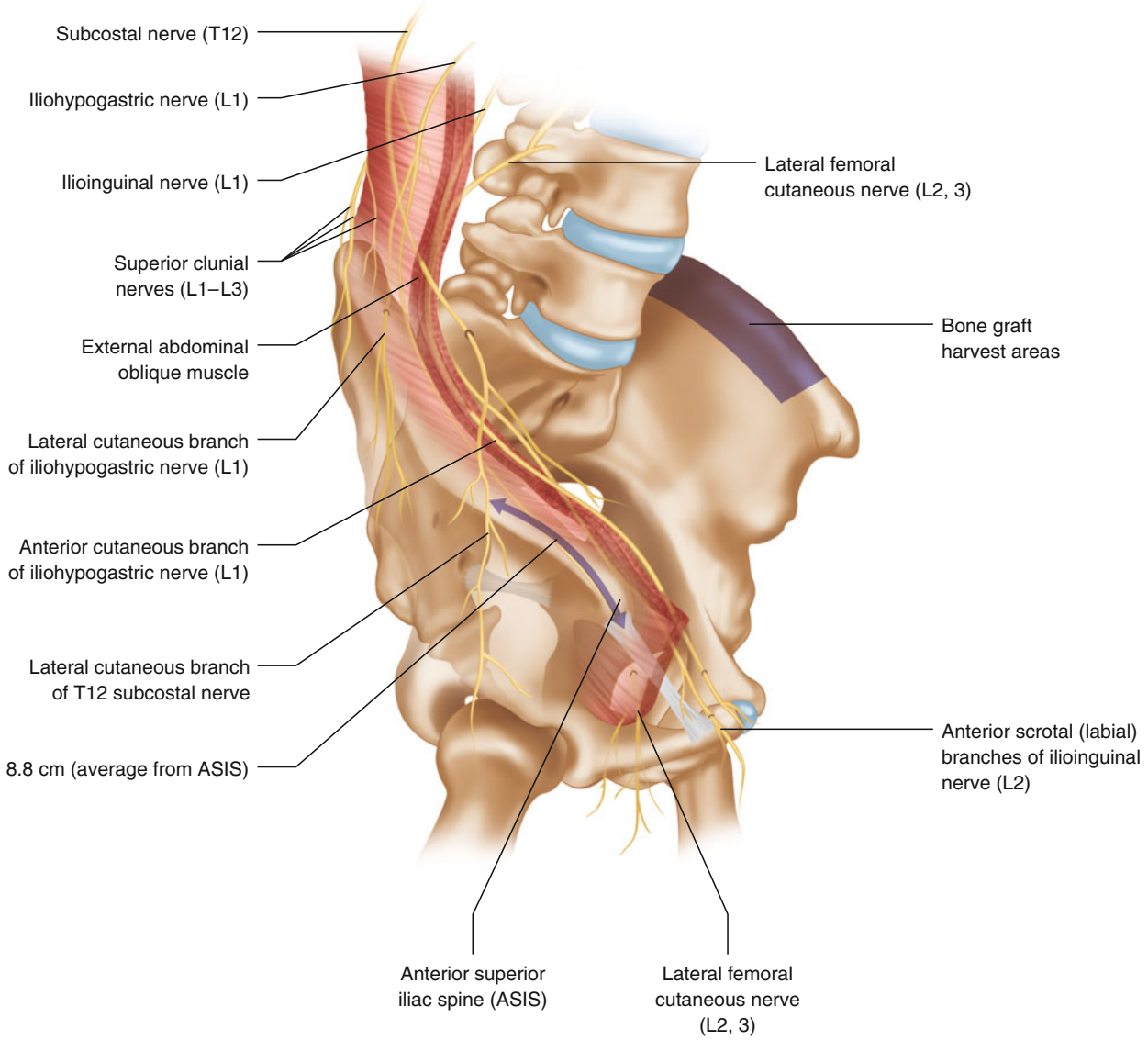

Fig. 8.4 Planned line of osteotomy to split iliac crest, with lateral cutaneous branch of the T12 subcostal nerve at risk for injury at the superior margin and the lateral femoral cutaneous nerve at risk for injury on the lateral and inferior margins

may be reduced utilizing a minimally invasive approach. Percutaneous hollow needle technique has been described to reduce blood loss as well as postoperative pain versus conventional open harvest (Fig. 8.10). Similarly, in comparing a minimally invasive technique utilizing a trephine system versus conventional open harvesting of cancellous bone, the minimally invasive technique was found to be a superior alternative, with shorter operative time, decreased requirement for pain medications, less pain on discharge, and a shorter hospital stay. Placement of continuous release analgesic systems has also been shown to be safe as well as reduce pain scores and time to first narcotic compared to traditional open techniques. Fractures of the leaves of the split crest, hematomas (0.1 %), infection (0.02 %), hernia (0.02 %), parasthesia (0.18 %), and hardware failure (0.14 %) have also been reported among the complications associated with iliac harvest.

Tibia

The proximal tibia has long been used as an excellent source of cancellous bone with minimal morbidity. Cancellous bone volumes equaling or exceeding that of the iliac crest can be harvested. Volumetric analyses of the proximal tibia using three-dimensional imaging reconstruction have shown an average of 77 cm^2 of cancellous bone available for harvest in the proximal tibia, two to three times the accepted

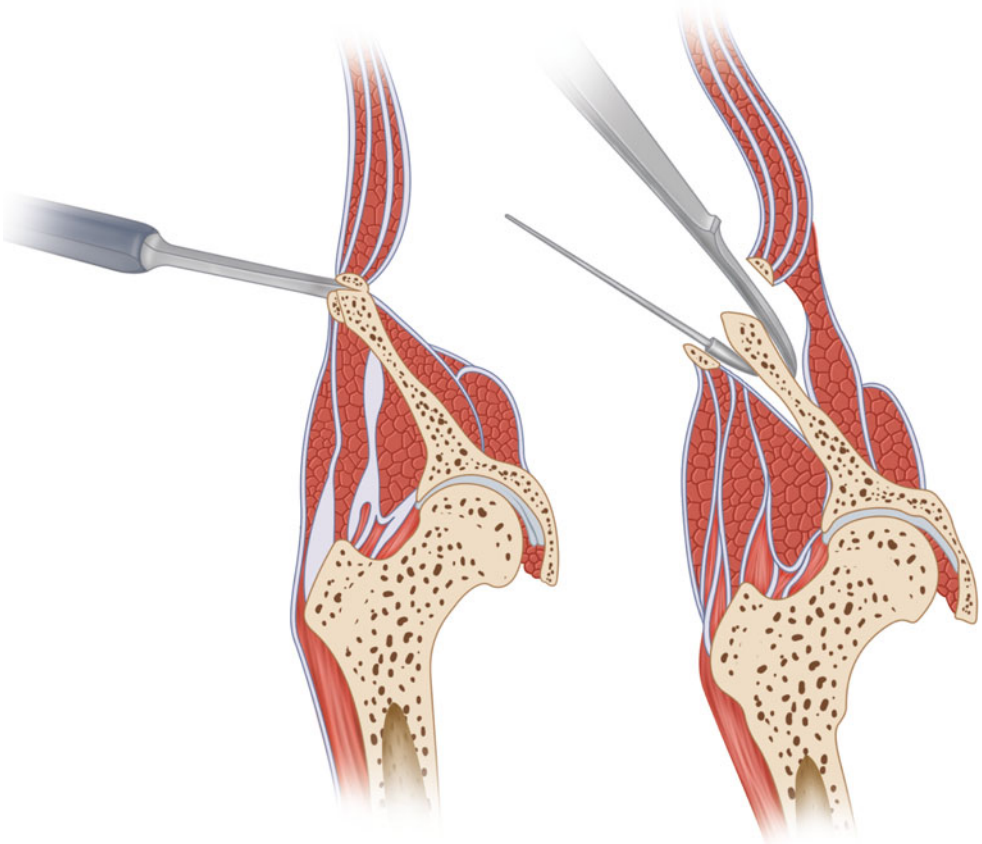

Fig. 8.5 (*Left*) The iliac crest is split medially and laterally, leaving the abdominal muscles attached medially, and the gluteal muscles attached laterally. (*Right*) Subperiosteal dissection can then be performed medially and laterally to allow for the harvest of corticocancellous grafts

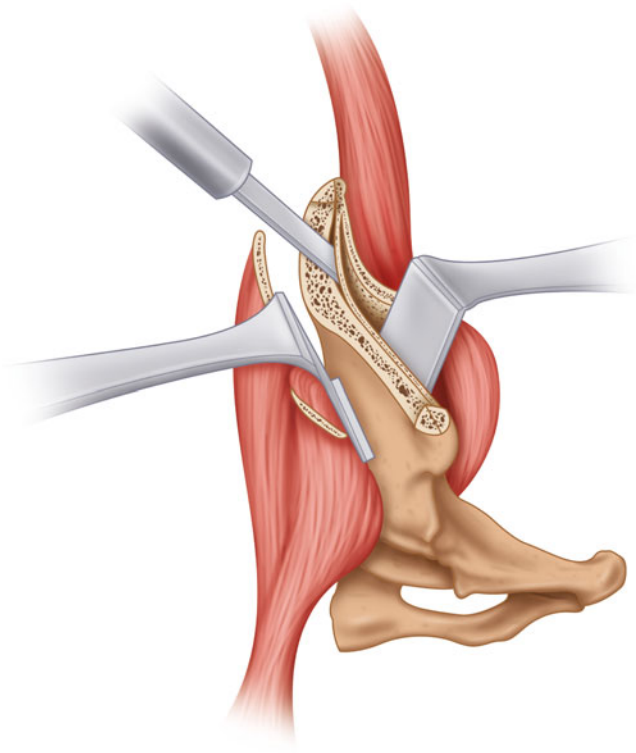

Fig. 8.6 Following splitting of the crest and medial subperiosteal elevation, corticocancellous bone graft can be harvested with osteotomes

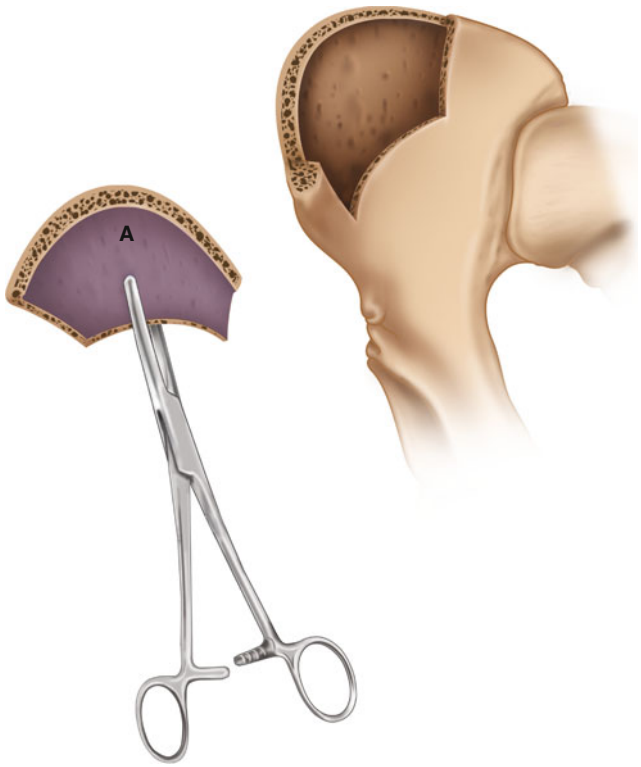

Fig. 8.7 Harvest of a large corticocancellous graft, up to 6×10 cm, can be achieved

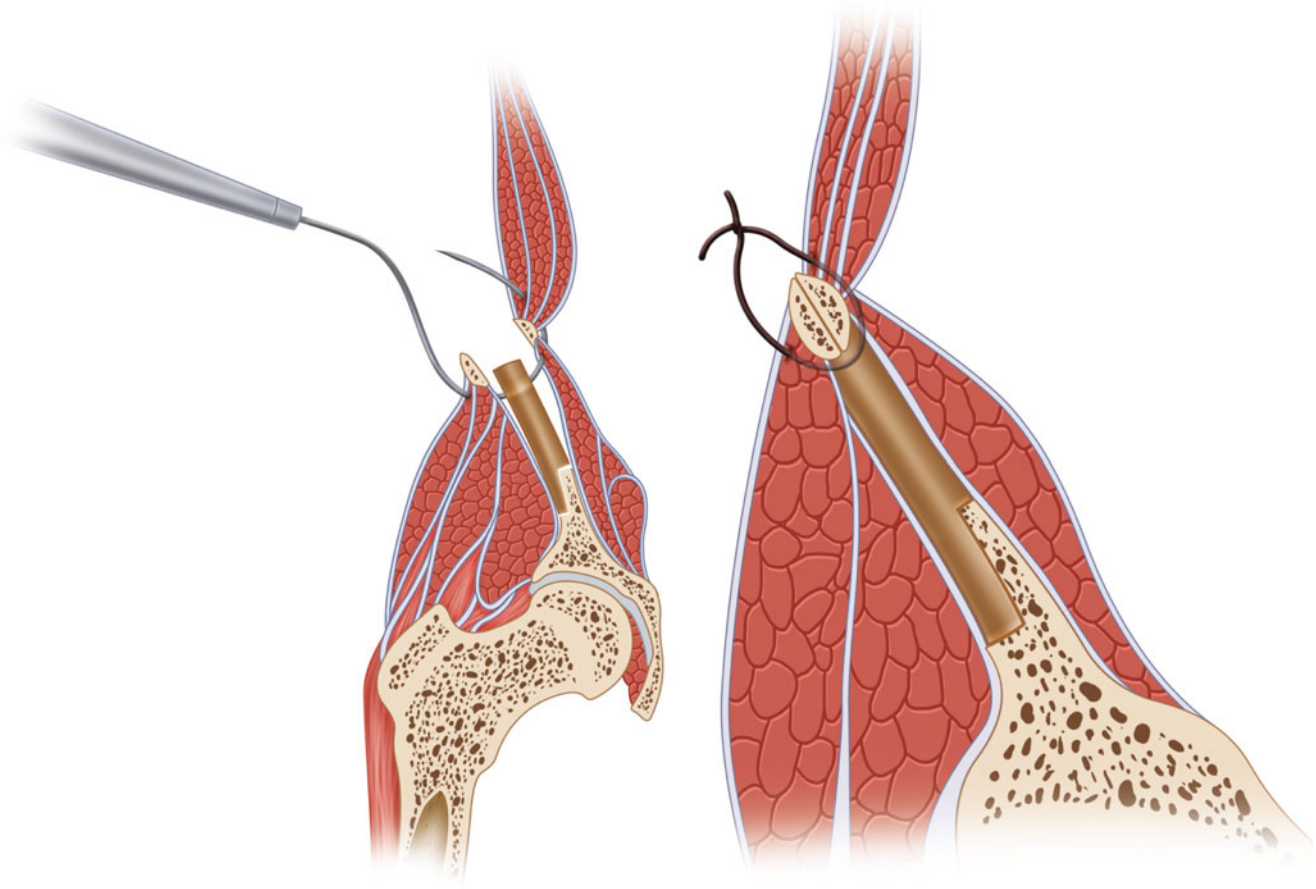

Fig. 8.8 Closure of the donor site is achieved by passing four 26 gauge wires or sturdy resorbable sutures to reapproximate the medial and lateral leafs of the split iliac crest. The reapproximated leaves should rest on the anterior superior iliac spine to provide stability and can be fixed to the ASIS with wire or suture

average. Due to their rigidity, tibial cortical grafts are more difficult to contour than calvarial grafts, but remain a potential source of strong cortical bone graft. With regard to graft harvest, the procedure begins by palpating and marking Gerdy's tubercle. Gerdy's tubercle is the bony protuberance between the patellar ligament (midline) and the head of the fibula, which is palpable 90° laterally (Fig. 8.11). A tourniquet is used for hemostasis, and local anesthetic with adrenaline is also used for vasoconstriction and postoperative pain control. A 3 cm incision is made directly over Gerdy's tubercle, and dissection proceeds through the thin soft tissue layer and periosteum down to the tubercle. A 1 cm^2 cortical window is made using osteotomes, or a circular window using a surgical drill; a circular window has the theoretical advantage of less stress than at the angles of a square or rectangular window in the cortical bone. Curettes are then used to harvest the cancellous bone from the tibial plateau and down the tibial shaft, with great care taken to avoid entering the joint space superiorly (Figs. 8.12 and 8.13). If a 1–2 cm wide strip of cortical bone is required, the approach is modified, utilizing a skin incision that begins under the tibial tuberosity and arcs medially as it courses down the leg, and through the superficial fascia. The fascial edges are reflected to expose the tibia. The periosteum is incised in a slightly larger area than the planned donor site, maintaining a connected edge. A sharp osteotome is then driven into the cortex and used to mark the donor site, and a corticoperiosteal flap pedicled superiorly at the tuberosity is preserved for later closure. Cancellous bone is then extracted from the upper epiphysis using curettes (Fig. 8.14). The donor site may be packed with Gelfoam, and the corticoperiosteal strap unfolded to cover the donor site. Closure is completed in layers, with closed suction drainage and a pressure dressing applied from the toes to the knee.

Complications are few and have been reported as low as 0.3 %. They include transient postoperative pain, hematoma requiring drianage, infection, and fracture of the tibial eminence.

Calvarium

Calvarial bone is extensively utilized in craniofacial reconstruction, with Tessier outlining the use of autologous calvarial bone grafts for facial and cranial reconstruction. Its rich diploic vascular system allows for rapid revascularization

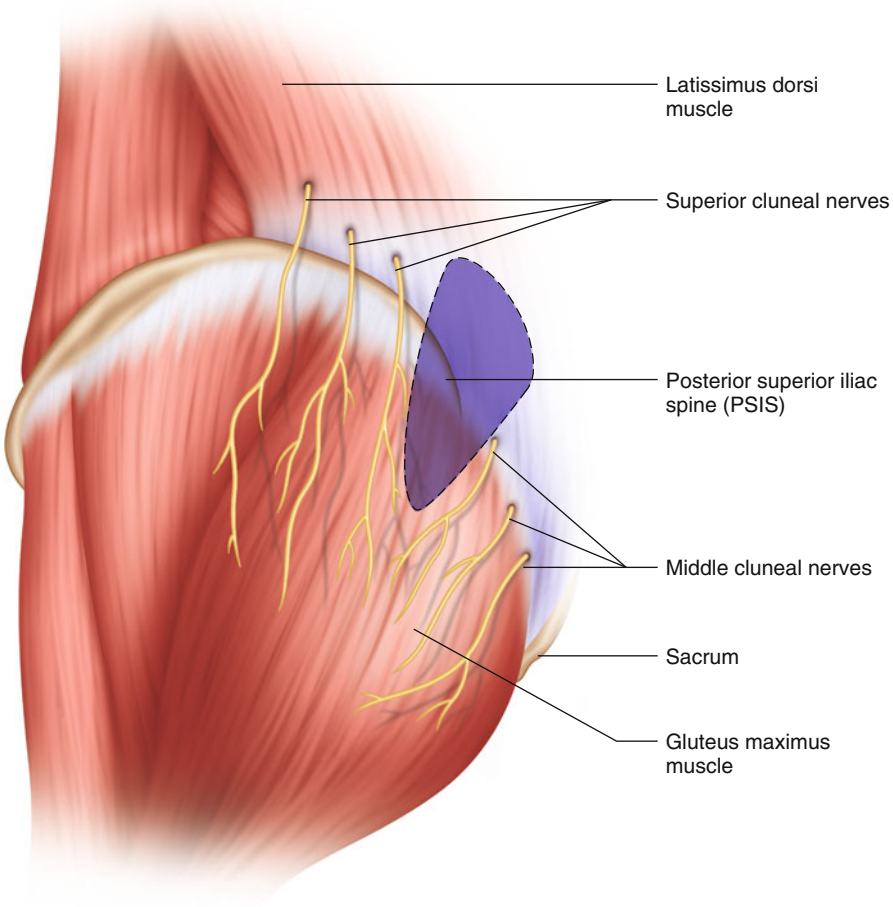

Fig. 8.9 Posterior iliac crest harvest. In order to avoid injury to the superior and middle cluneal nerves during harvesting of a posterior iliac bone graft, a linear incision approximately 2.5 cm anterior to the PSIS and perpendicular to the long axis of the posterior iliac crest is recommended. Subperiosteal dissection over the PSIS on each side of the axis of the incision (2.5 cm on each side) will most likely avoid injury to the superior and middle cluneal nerves

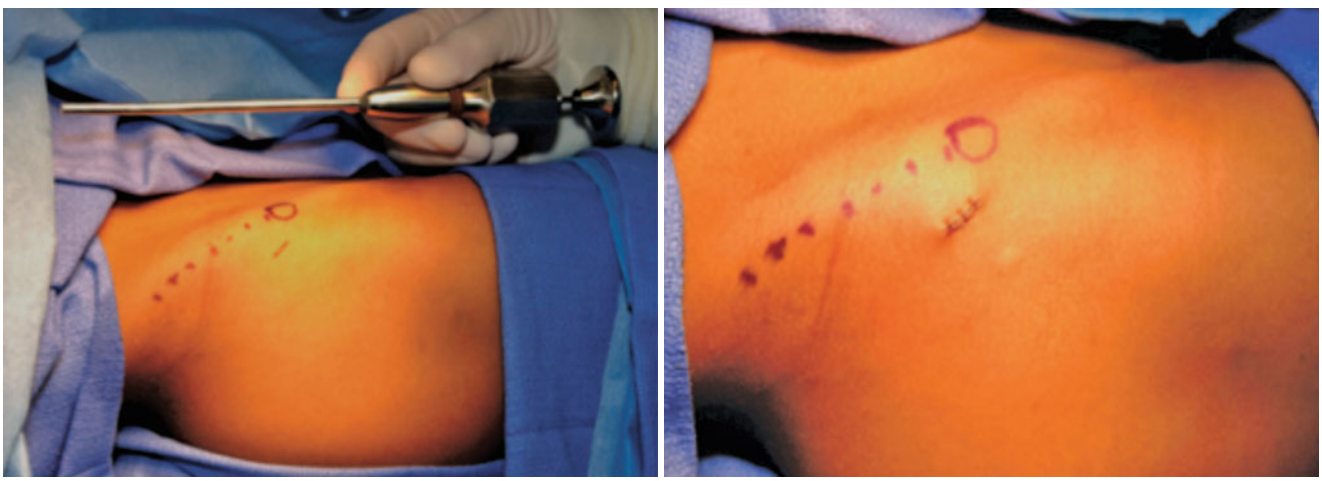

Fig. 8.10 Percutaneous harvest of iliac bone graft. The skin incision is made 3 cm posterior and inferior to the ASIS (marked with a *circle*)

and decreased resorption compared to other corticocancellous grafts. Furthermore, the calvarium is an intramembranous bone, which is thought to undergo less resorption than endochondral bone. Proximity to the recipient site, as well as minimal donor site morbidity, makes these grafts ideal for calvarial, orbital, nasal, and midfacial applications. Calvarial grafts can be selected based upon natural shape, but contour may be improved with bone benders. Attention must be paid to the location of the coronal and sagittal sutures (Fig. 8.15), as well as the posterior perforating vessels, the anterior temporal crest, and the intraosseous lateral vein. A preoperative coronal CT scan is of use in assessing the thickness of the parietal bones for harvesting grafts and of any potential midline abnormalities.

Harvest of calvarial grafts may be achieved through a variety of techniques. A coronal incision is made through the

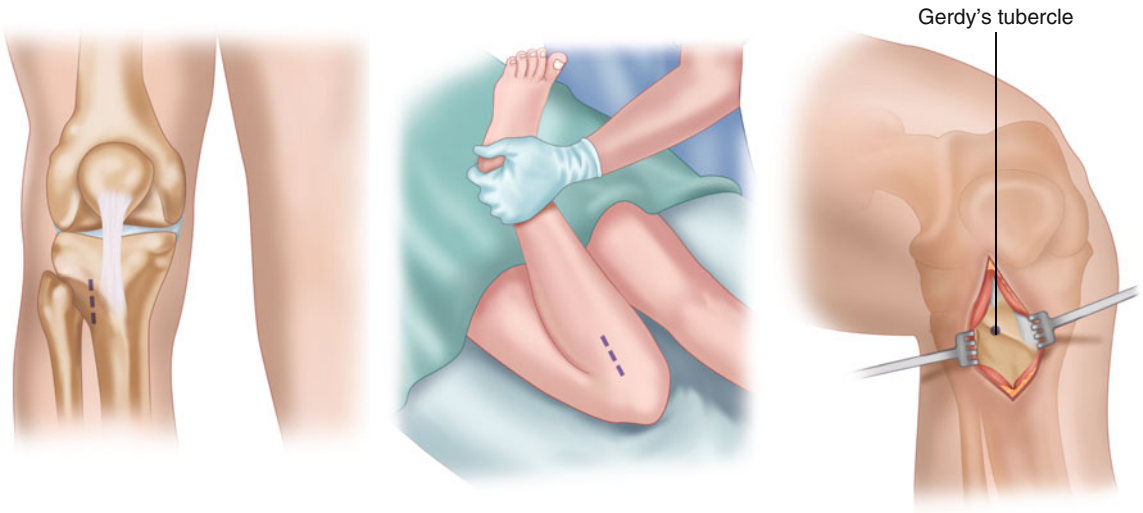

Fig. 8.11 Gerdy's tubercle is the tuberosity on the anterolateral side of the upper end of the tibia giving attachment to the iliotibial tract; it is located between the tibial tuberosity in the midline and the fibular head laterally. As there are no vital structures overlying Gerdy's tubercle, an approach centered over it is safe and effective

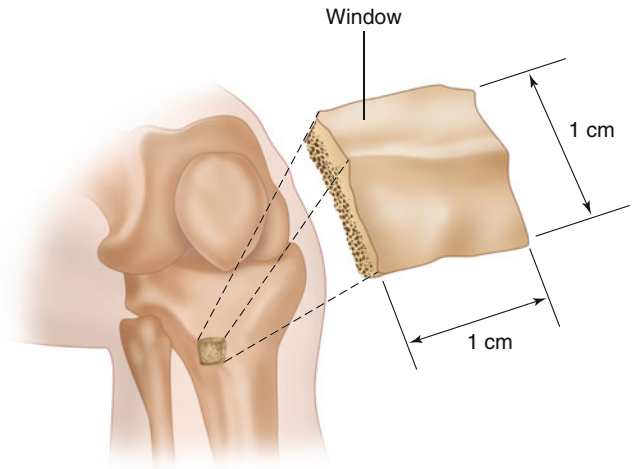

Fig. 8.12 A square or circular 1×1 cm ostetomy is made through Gerdy's tubercle, exposing the cancellous bone

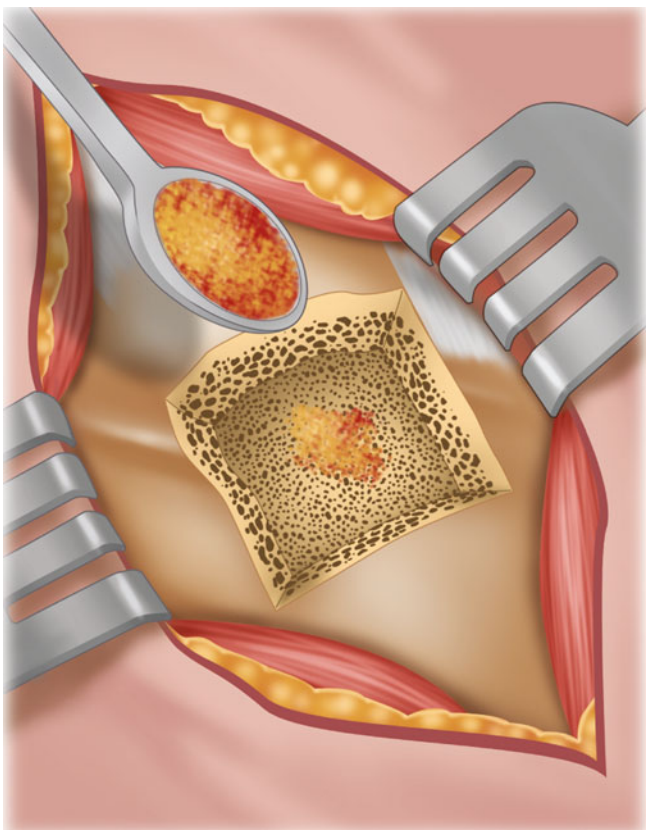

Fig. 8.13 Around 70 cm^2 of cancellous graft can be harvested from the proximal tibia; care must be taken during superior graft harvest to avoid injury to the tibial plateau and entering the joint space

scalp and galea. The pericranium is then incised and elevated with wide Obwegesers, with Gelfoam and bone wax used to help achieve hemostasis. For split in situ grafts, the outline of the donor site is first scribed with a saw or chisel. An oval 6 mm, side-cutting bur is then used to delineate the bone grafts. A narrow anterior strip is scribed and removed in order to allow room to keep the calvarial splitting osteotomes tangential. Alternating straight and curved osteotomes of varying widths are then used to split the bone. Following removal of the cortical segments, the diploe may be removed in sheets with a straight osteotome. This harvest may extend as far back as the lambdoid suture. The donor site may be covered with a large sheet of Surgicel. Closure is completed in layers, with the pericranium sutured over the donor site, the galea approximated, and a closed suction drain placed before final closure of the scalp with sutures or staples (Fig. 8.16).

An intracranial approach may be a better option, especially in the pediatric patient where in situ splitting may not be feasible secondary to a thin or irregular skull. A team approach with a neurosurgeon is recommended in these instances.

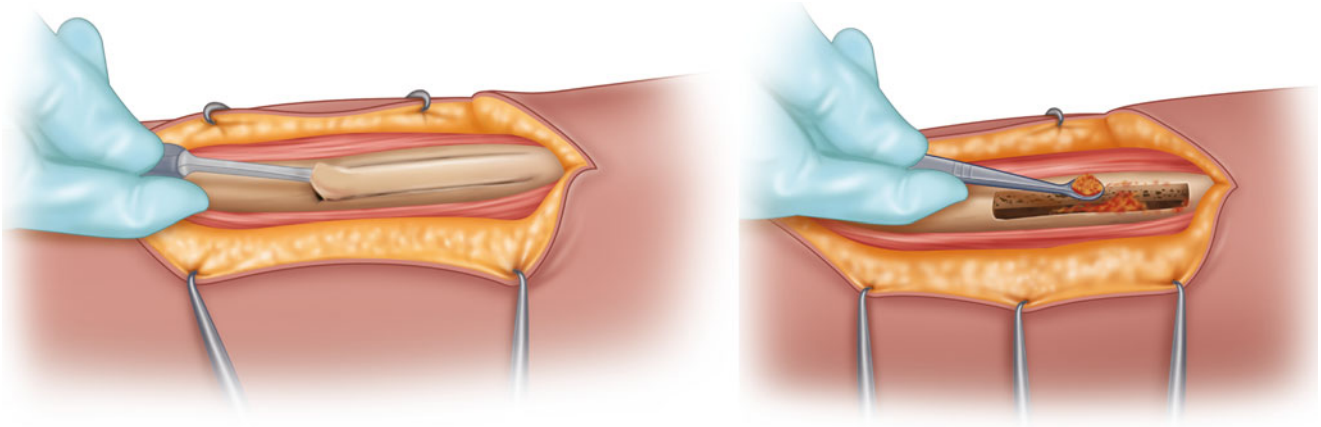

Fig. 8.14 (*Left*) Elevation of the superiorly based corticoperiosteal flap, used for closure, prior to removal of the outer tibial cortex. (*Right*) Following removal of the cortex, cancellous bone can be easily harvested from the upper epiphysis

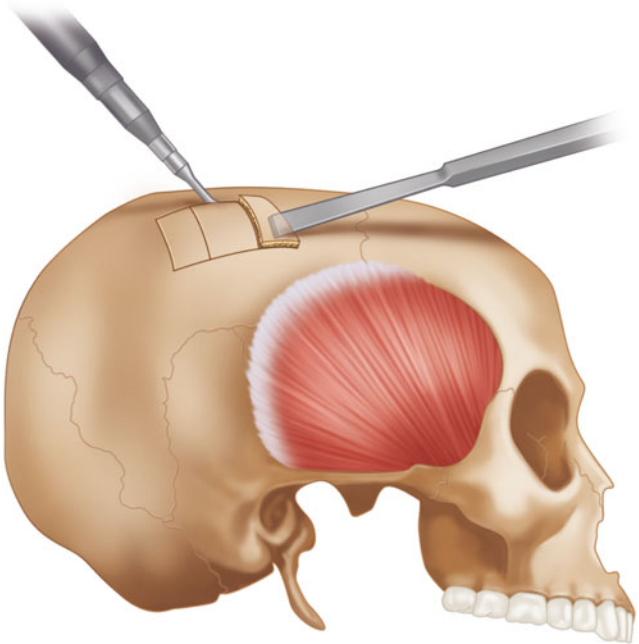

Fig. 8.15 The right side parietal bone donor site. Remain at least 1 cm posterior to the coronal suture and 1.5 cm lateral to the sagittal suture. The lines of osteotomy for bone harvest can be marked with a reciprocating saw or side-cutting bur, and a narrow strip removed first to allow for tangential placement of the larger osteotomes

The complication rate of calvarial harvest is reported to be as low as 0.25 %. Like other donor sites, pain, paresthesia, and bleeding are the most frequent complications. Calvarial irregularities may also occur; however, these are often camouflaged by hair. Alopecia along the scalp incision line may be avoided by minimizing thermal injury along this area.

Rib

Free rib grafts can be harvested in a variety of ways: full thickness, split thickness, and as composite costochondral grafts. They are suitable for reconstruction of the mandible, as well as defects of the zygoma, orbits, and calvarium. They contain little cancellous bone with a thin cortex and are best fixed using wires. Careful microplate fixation, such as in cantilever rib grafts for salvage rhinoplasty, is also a possibility.

Preoperative markings and landmarks are dependent upon the amount of harvest required. Regardless of the extent of harvest, the technique follows the same principles. In the case of single rib harvests, an incision is made directly over the rib to be harvested; if two ribs are being harvested, an incision is made over the rib between those that will be harvested. Skipping ribs when harvesting multiple ribs will help maintain chest wall stability and avoid contour deformities. Incisions are usually made over the fifth, sixth, or seventh rib on the right side of the chest (Fig. 8.17).

These are often hidden within the breast fold of female patients. Costal cartilage graft harvest occurs more medially. Taking advantage of short incisions and appropriate retractors will help avoid unnecessary subcutaneous dissection and will decrease the risk of pneumothorax. Skin and superficial thoracic fascia is first incised, followed by the deep thoracic fascia directly over the targeted rib. The periosteum is incised longitudinally over the lateral surface and an angled elevator used to elevate tissues subperiosteally along the edges of the rib. Ribs should be divided close to the costochondral junction. Once the rib is divided, Semb elevators are used to continue the subperiosteal dissection posteriorly. The use of Semb elevators will reduce the risk of pneumothorax. Retractors should be repositioned as the dissection progresses deeper (Fig. 8.18).

The wound should be irrigated and checked for any air leak. Closure is achieved in a layered fashion: edges of the periosteum, followed by approximation of the deep fascia and muscles, followed by closure of the superficial fascia and skin (Fig. 8.19). A costal cartilage graft, such as those used in microtia repair, requires partial division of the rectus, which must be repaired during the final closure.

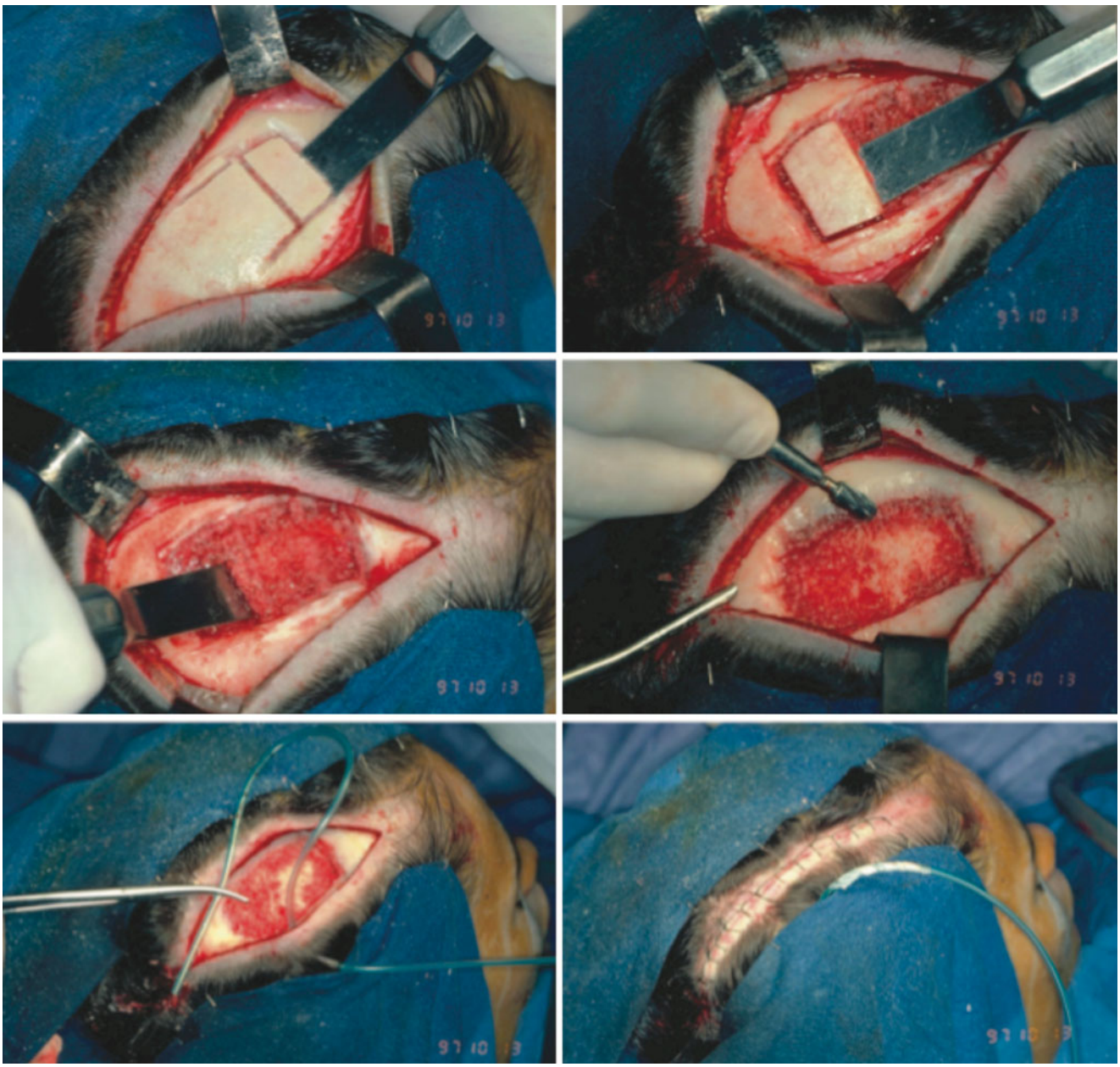

Fig. 8.16 (*Top left*) Following scalp incision, periosteal elevation, and osteotomy line scoring, grafts can be removed with a sharp osteotome. (*Top right*) Removal of the final graft. Grafts can be harvested to within 1 cm of the lambdoid suture. (*Middle left*) Following removal of the corticocancellous graft, diploic cancellous graft can be harvested with curettes or osteotomes. (*Middle right*) The edges of the donor site can be smoothed with a pineapple burr to decrease any step-offs palpable through the scalp. (*Bottom left*) Drain placement to help avoid fluid collection. (*Bottom right*) Closure of the scalp over Gelfoam with either sutures or staples

The overall complication rate for ribs harvested using the above technique is 0.9 %. One of the primary concerns regarding harvest of rib grafts is the risk of pneumothorax. This is a relatively low risk (1 %) when proper technique and tools are utilized. Also, when harvesting multiple rib grafts, skipping ribs will help avoid chest wall contour deformities as well as maintain chest wall stability.

Mandible

The mandible provides a local source of membranous (body and ramus) and endochondral (condyle) bone. As well as the advantage of proximity to the recipient site, bone may be harvested intraorally, which eliminates the morbidity of cutaneous scarring.

Harvest approach and technique is dependent upon the specific mandible donor site. For a mandibular symphysis harvest, one may approach with a vestibular or a sulcular incision, the latter being used in cases of healthy dentition without any crowns (Fig. 8.20).

The vestibular incision is made 1.5 cm from the gingival sulcus and continues through the mentalis muscle while preserving the gingival, periosteal, and mentalis insertion attachments superiorly, similar to an osseous genioplasty approach. For the sulcular approach, an incision is made along the gingiva from second bicuspid to second bicuspid, with oblique relaxing incisions made at the distal buccal line. A full thickness mucoperiosteal flap is then elevated, enabling complete visualization of the symphysis and bilateral mental neurovascular bundles. In either approach, the superior osteotomy should be at least 5 mm below the root apices, as well as 5 mm from the mental foramina, and should penetrate the labial cortex. Depth is dependent upon graft thickness (Fig. 8.21). Closure is achieved in a layered fashion, with care to avoid the complication of mentalis or chin ptosis in the case of the vestibular approach.

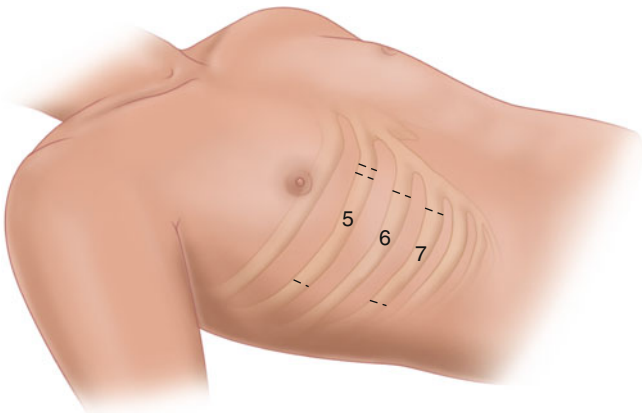

Fig. 8.17 The fifth, sixth, or seventh ribs are most commonly used for either costal or costochondral grafts

When harvesting from the ramus and body, an incision is made distal to the most posterior tooth and continues to the retromolar pad and up the ascending ramus (Fig. 8.22).

Oblique incisions may be made at the posterior extent of the incision. The incision extends along the buccal sulcus opposite the first bicuspid. The temporalis is stripped from the bone with an elevator superiorly, and a full thickness mucoperiosteal flap reflected inferiorly. Three complete osteotomies are made: one superior and two vertical. Another horizontal bone groove is made at the inferior border. The superior osteotomy is created with a small fissure

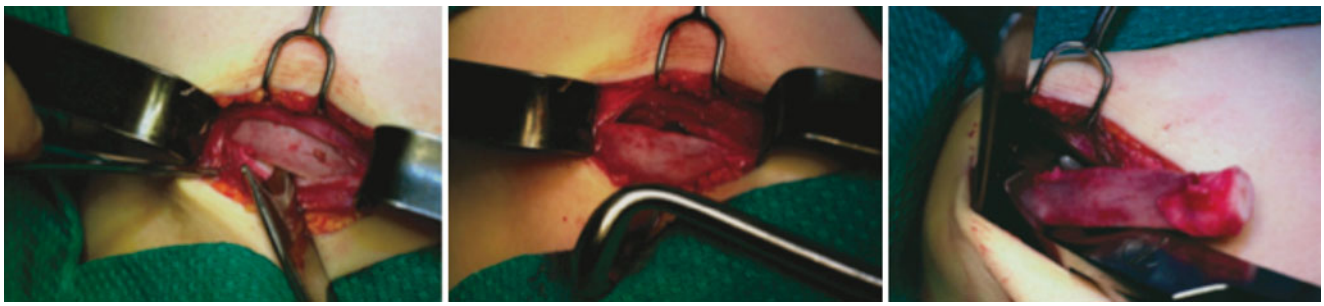

Fig. 8.18 (*Left*) Following dissection straight down to the rib, the perisosteum is incised and elevated from the superior and inferior (pictured) surface of the rib. (*Center*) A Doyen elevator can then be passed from inferiorly to superiorly in the subperiosteal plane and used to free the periosteum from the rib posteriorly. (*Right*) A cartilagenous cap can be left on the medial surface of the rib, as in ascending ramus reconstruction in hemifacial microsomia, and the rib can be divided laterally using a costotome

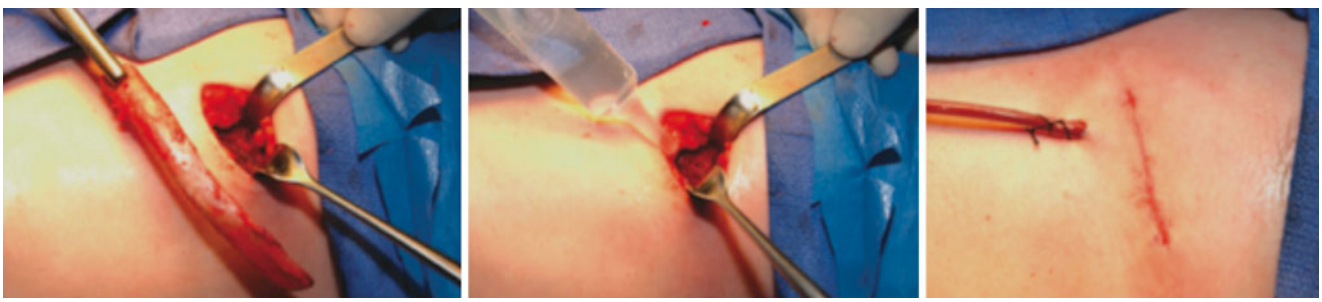

Fig. 8.19 (*Left*) A long section of rib (15 cm) can be harvested through a smaller incision. (*Center*) Prior to closure, the wound should be filled with normal saline and positive pressure breaths given to look for bubbles, which would be indicative of a pleural tear. (*Left*) Closure of the incision (with drain optional placement)

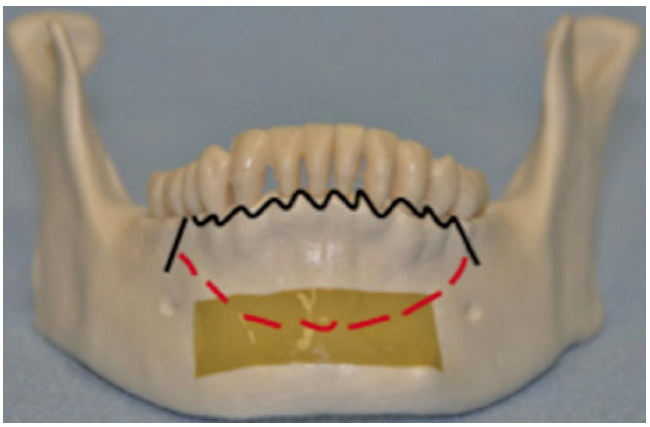

Fig. 8.20 Mandibular symphysis bone grafts can be harvested via vestibular (*dotted red line*) or sulcular (*curvilinear black line*) incisions. The sulcular incision should be reserved for those patients with healthy dentition without anterior crowns

bur 4–5 mm medial to the external oblique ridge. The superior osteotomy begins at the mandibular first or second molar and continues posteriorly along the ascending ramus depending on the required size. Anterior and posterior vertical osteotomies begin at each end of the superior cut and are made 10–12 mm in length in the superoinferior direction. Finally, a groove connecting the inferior aspect of each vertical osteotomy is made using a round bur. The graft is then split at the osteotomies using sharp chisels and is fractured along the inferior groove (Fig. 8.23). Care is taken to avoid injury to the inferior alveolar neurovascular bundle, which is visible 10–12 % of the time. Sharp edges may be smoothed with a large round fissure bur. Following adequate hemostasis, closure is achieved in layered fashion.

Harvest of mandibular bone may be complicated by temporary mental nerve hypersthesia, parasthesia, and altered sensation, with each of these being higher in cases of symphysis

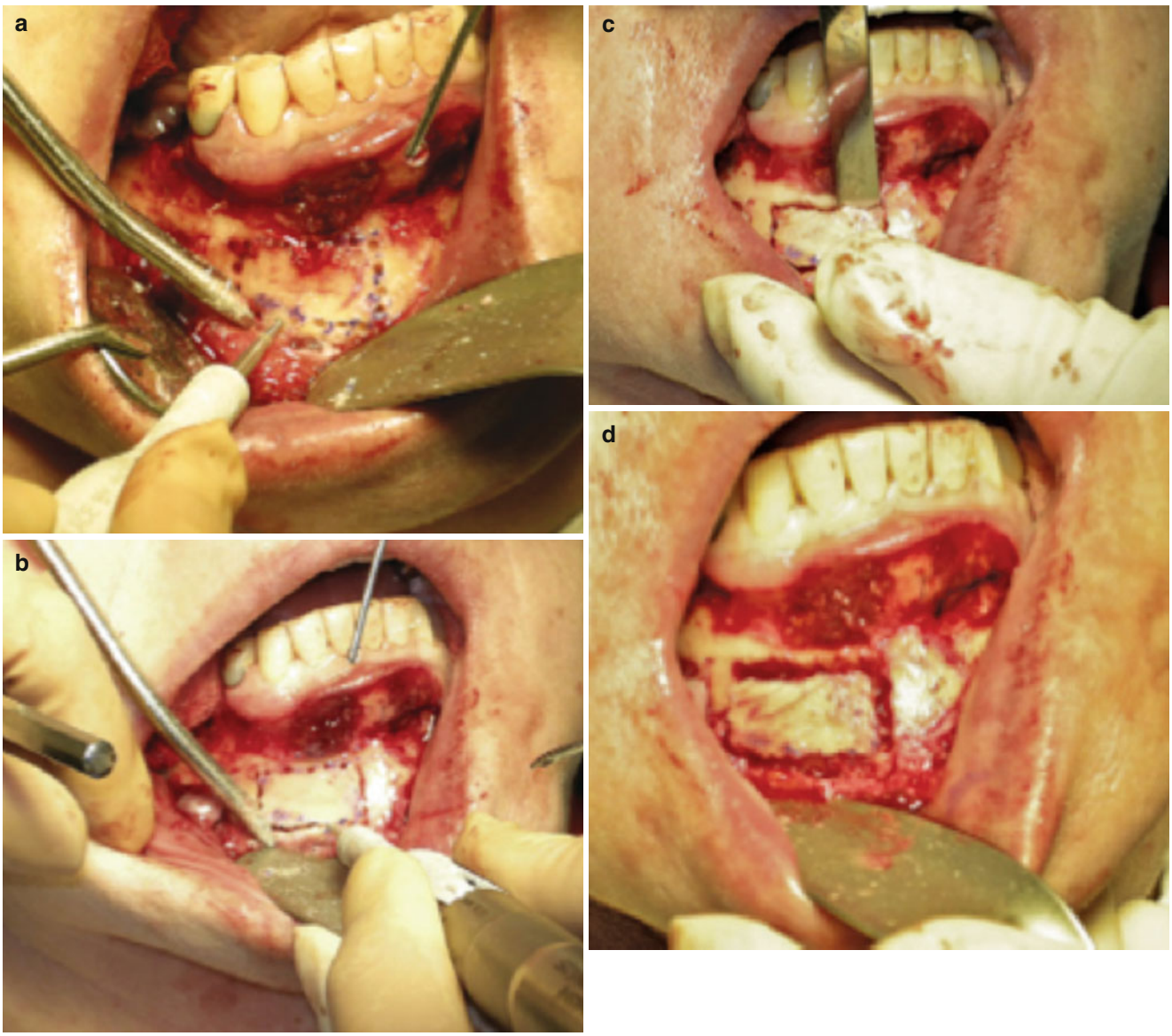

Fig. 8.21 (**a**) Marking the osteotomy of the mandibular symphysis with a marking pen. (**b**) Using a small round bur to incise the labial cortex. (**c**) Harvesting the labial cortex using a small osteotome. (**d**) The freed corticocancellous block harvested from the right mandibular symphysis

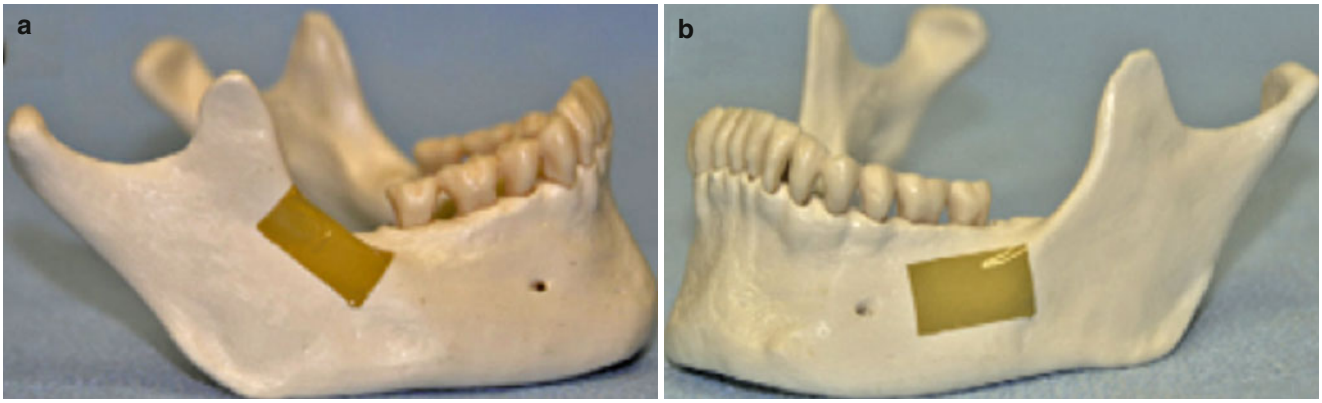

Fig. 8.22 Bone grafts can be harvested from the ascending mandibular ramus (**a**) or mandibular body (**b**)

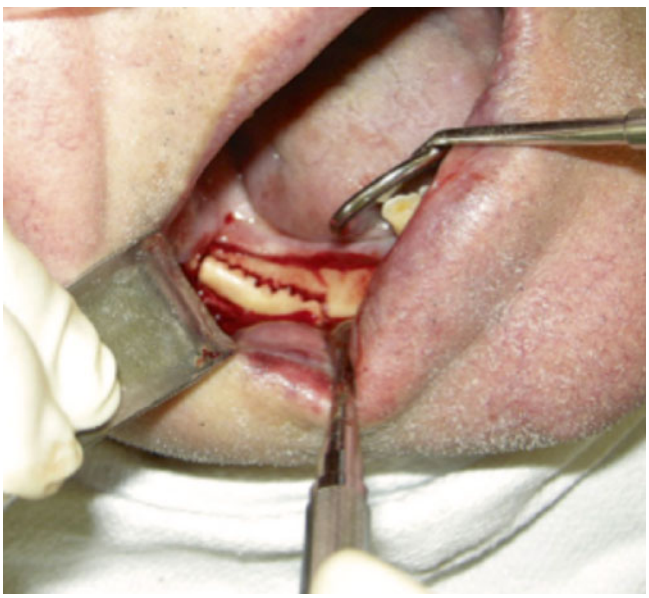

Fig. 8.23 Bone graft harvest from the right ascending mandibular ramus. Care must be taken to avoid injury to the inferior alveolar neurovascular bundle

harvest. Infection rates and permanent neurosensory deficits are reported to be less than 1 %. The vestibular approach for symphysis harvest may also result in chin ptosis, scar band formation, as well as postoperative pain. The ramus/body approach therefore offers the advantages of similar bone stock with decreased risk of neurosensory disruption.

Allogenic Bone Grafts

Allografts are taken from the same species and are usually cadaveric. They may also be harvested from living donors. The ideal allograft would provide a combination of space maintenance, osteoconductive structural guidance for bone regeneration, acceleration of bone remodeling, and may act as a carrier for antibiotics, growth factors, or other tissue-engineering approaches. Allografts retain osteoinductive (they release BMPs) and osteoconductive properties, but lack osteogenic properties because of the absence of viable cells. While these constructs are acellular, there remains concern regarding the association of allogenic material and the risk of transmission of viral diseases, malignancies, systemic disorders, or toxins. The use of allografts has increased recently given improvements in processing and preservation, but this has resulted in a decrease of the osteoinductive properties. Allografts come in a variety of shapes and sizes: complete bone segments, corticocancellous or cortical grafts, cancellous chips, and most commonly, demineralized bone matrix (DBM). Allografts are also not without additional cost. The benefits, however, include abundant supply, potential addition of growth factors, and decreased donor site morbidity.

Specifically for craniofacial reconstruction, allogenic DBM has been used to supplement cancellous autograft. DBM is prepared by pulverizing allogenic bone to a consistent size, followed by extraction of the mineralized phase of bone. This results in a composite of noncollagenous proteins, growth factors, and collagen, which lacks any structural stability. DBM is usually available in a variety of constitutes including putty block form, moldable paste with bone chips, gel form, and an injectable bone paste. DBM application is therefore limited to structurally stable environments. The addition of supplemental DBM allograft and cancellous allograft to iliac autograft in cleft alveolar defects has been shown to be safe and effective, resulting in low morbidity, shorter operative times, and higher rates of bone graft survival when compared to autograft alone. Similarly, a randomized controlled clinical trial comparison of the utility of synthetic biomaterials, bovine-derived bone substitutes, and human-derived allografts to autograft in maxillary sinus augmentation resulted in human-derived allograft providing the second highest rate of de novo bone formation, behind that of autograft. For most all other craniofacial reconstruction applications, however, autograft remains preferred over allograft.

Vascularized Bone Grafts

Vascularized bone flaps are superior to nonvascularized grafts, owing to a lack of dependency on recipient bed vascularity. Indications include irradiated and chronic defects as well as those whose vascularity is compromised by extensive scarring. By bringing with it a robust blood supply, free bone flaps in turn increase blood flow to the recipient site and may be tailored to include skin, muscle, and nerves in addition to bone. Vascularized bone grafts are covered in detail elsewhere.

Xenogenic Bone Grafts

Xenografts are taken from different species and are usually of bovine or porcine origin. These are rarely used in the setting of craniofacial surgery as they are void of growth factors and proteins and therefore are inferior in their utility to autografts and allografts.

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