Cranioplasty

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Abstract

Calvarial defects are commonly encountered after neurosurgical procedures, trauma, and ablative procedures of advanced head neck cancers. The goals of cranioplasty are to provide a protective barrier for the intracranial contents, to restore form, and prevent syndrome of the trephined. Autologous and alloplastic techniques are available, each with their advantages and drawbacks. A multitude of materials are available for cranioplasty, and proper timing of reconstruction with attention to the overlying skin envelope is important in minimizing complications.

Keywords
- cranioplasty
- cranial reconstruction
- pediatric cranioplasty
- alloplastic
- autologous

Cranioplasty is defined as reconstruction of the skull to protect the underlying cerebrum and restore the cosmetic appearance of the calvarium. The first archeological evidence of cranioplasty dates back to 7000 B.C., but the first successful description of cranioplasty was by Fallopius in the 1500s.[1] While some consider cranioplasty to be an elective, cosmetic procedure, significant functional gains can be realized in properly executed reconstruction. The syndrome of the trephined is a well-known phenomenon that can occur after craniectomy, partial removal of the skull; it is characterized by neurological deterioration with sensorimotor deficits. Syndrome of the trephined is theorized to arise from atmospheric pressure against the cerebral structures leading to alterations in cerebrospinal fluid (CSF) dynamics and cerebral blood flow.[2] Proper cranioplasty is important after craniectomy to prevent not only cosmetic deformity but also to prevent syndrome of the trephined and, in general, protect the brain and calvarial contents.

Timing of Cranioplasty

The underlying cause of disease ultimately leading to craniectomy dictates the timing of ideal repair. Cranioplasty may ideally be delayed, for example, after craniectomy for cases of severe, acute, trauma-related brain swelling to allow resolution of swelling. Contrastingly, reconstruction after a partial craniectomy for skull base access or removal of a malignancy is often performed during the same surgery or soon thereafter. In cases of elevated intracranial hypertension, however, a decompressive craniectomy is indicated, but the ideal timing for cranioplasty in these cases is controversial. Traditionally, "early cranioplasty," considered earlier than 3 months after craniectomy, was avoided due to concern for increased infection risk. Recent trends have led to earlier cranioplasty after decompressive craniectomy, however, as some studies have demonstrated improved outcomes without an increased infection risk compared with delayed approaches.[3–6] Proponents of early cranioplasty argue that the benefits of improved CSF dynamics can expedite neurological recovery. Alkhaibary et al noted the timing of repair is of less significance than other factors including age, defect size, alloplastic material, and storage or fixation techniques.[7] The optimal timing is thus variable by case, and most importantly, the neurological status of the patient must be sufficiently stable before cranioplasty is attempted.

In cases of intracranial infection with devitalized bone, craniectomy is generally performed to remove infected bone and cranioplasty is delayed due to concern for hardware or bone graft infection. Although case reports have demonstrated successful immediate reimplantation of titanium mesh in a small case series, surgeons should be cautious of implanting alloplastic material particularly when infection has not been adequately controlled.[8]

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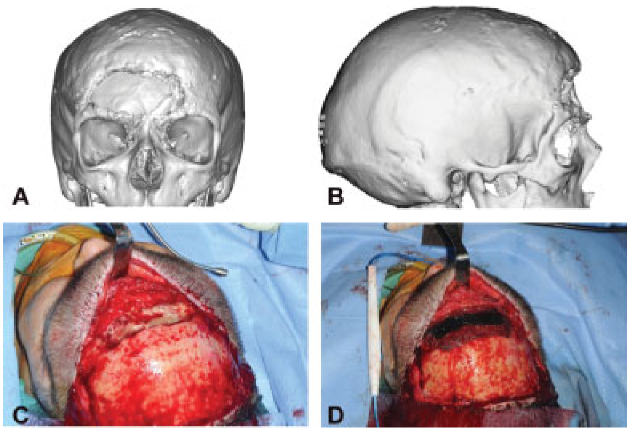

Fig. 1 (A–D) Three-dimensional computed tomographic reconstructions of a patient after partial frontal bone resection—coronal and sagittal views. Intraoperative views of the patient defect and initial titanium mesh reconstruction.

As mentioned above, immediate reconstruction of calvarial defects generally is indicated after ablative procedures for neoplasms that have invaded the calvarium. In these cases, the senior author (Y.D.) prefers reconstruction with titanium mesh followed by a staged definitive custom polyetheretherketone (PEEK) implant several weeks later (►**Figs. 1** and **2**).

Cranioplasty Materials

Autologous Bone

Autologous bone is considered by many to be the gold standard material for cranioplasty due to its high biocompatibility, strength, osteoconduction, and resistance to extrusion. Donor sites include the unaffected calvarium, ribs, and iliac crest.[9] Bone grafts integrate into the cranial defect over time by osteoconduction and require a healthy blood supply and close proximity to adjacent bone. Autologous bone is not always ideal, however. Bone grafts are prone to resorption in large cranial defects, sometimes losing around 20% of their volume.[4,10] In addition, autologous bone grafts have donor site morbidity and can be difficult to shape, thus leading to a poor cosmetic outcome.[11]

Titanium

The use of titanium has been promoted for its low rate of infection, minimal inflammatory reactivity, and ability for osteointegration (►**Fig. 1**). Although there were concerns of the cost of utilizing this material, titanium alloys now exist to produce a lightweight, strong, biocompatible construct with minimal added cost.[12] It has been highly advocated for its use in secondary cranioplasty of large cranial defects with a satisfactory complication profile.[13] In addition, titanium mesh can be used as a scaffold and mixed with other synthetic material for an improved cosmetic result.[14,15]

Polyetheretherketone

PEEK implants consists of a light-weight, inert, and durable material that has shown success in reconstruction of craniectomy defects (►**Fig. 2**).[14] These can be customized to the defect with a high degree of accuracy, especially in those with large defects requiring a greater degree of protection.[16] It has also been successfully used in reconstructing frontal bone defects where there may be concern for communication with the nasal cavity.[17] In addition, the material is radiolucent and does not interfere with radiographic imaging. Disadvantages of PEEK implants include the high cost of the material and lack of osteoconductivity, possibly increasing the risk of infection.[18,19]

Polymethylmethacrylate

Polymethylmethacrylate (PMMA) implants are considered an inexpensive, strong, radiolucent, and nonconductive reconstructive option with excellent cosmesis. It exists in powdered form and is mixed intraoperatively with benzoyl peroxide causing an exothermic reaction, which slowly cools into a malleable putty that has strength similar to bone.[20] However, PMMA implants are at risk of postoperative infection as well as implant fracture due to its brittle nature.[21,22] In addition, its use is limited in the pediatric population due to limited osteoconduction and an inability to accommodate growth of the cranium.[23]

Calcium Phosphate/Hydroxyapatite

Like PMMA, calcium phosphate bone cement exists as a powdered form that can be mixed to form a malleable

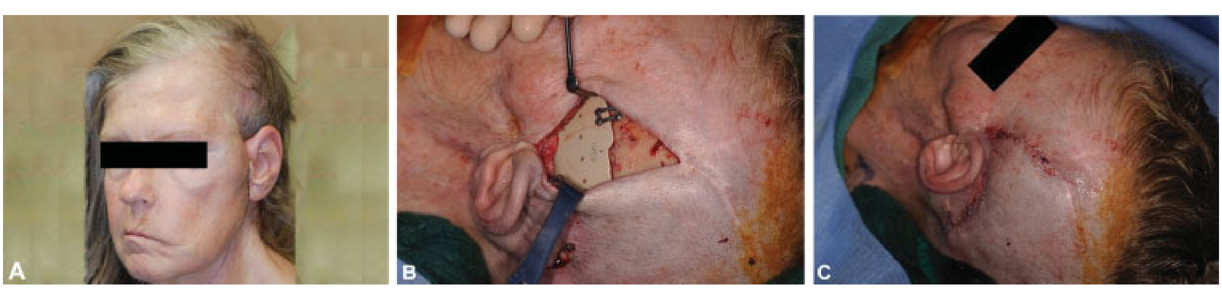

Fig. 2 Patient with a temporal bone defect. (A) Preoperative appearance. (B–C) Intraoperative view of polyetheretherketone patient-specific implant placement.

substance and molded into the calvarial defect. It is highly biocompatible, having a similar chemical and structural composition to human bone. Additionally, it has expansion properties and can be osteoconductive, allowing its use in pediatric cranioplasty.[18,23] Despite these advantages, use of hydroxyapatite has been limited due to its high infection rate and fragility.[24]

Operative Technique

Soft Tissue Exposure

Integrity of a well-vascularized soft tissue envelope is essential for successful cranioplasty, and proper planning can reduce the risk of implant exposure and postoperative infection. Preoperative intravenous antibiotics are administered, and the patient is positioned appropriately to allow full exposure to the area of interest. Blood supply of the scalp is considered, especially when there has been previous surgery or trauma disrupting some sources of nutrient supply. When possible, a coronal incision is made to approach the calvarium, and an extended pericranium flap is raised and banked with the anterior scalp flap in the event vascularized tissue that is needed for reconstruction of the skull base. In cases where prior incisions are present, those same incisions can be used for access. It is preferable to avoid making incisions over the anticipated cranioplasty site, as this can increase the risk of wound dehiscence, implant extrusion, and postoperative infection. In ablative cases where an adequate soft tissue covering is not available, regional or free tissue transfer may be necessary to allow for adequate closure of the cranioplasty site. Closure should ideally be completed in a layered fashion without tension. The senior author routinely places flat drains in the subpericranial space via separate incisions to collect blood and serous fluid from the wound during the early postoperative healing phase.

Autologous Bone Grafting—Calvarium

Harvest of the outer table for autologous grafting can be safely performed along the parietal bone. Depending on the graft size needed, an incision directly over the parietal scalp can be used to obtain a small graft; this incision is well hidden in the patient's hair. Otherwise, the parietal bone can be approached with a coronal incision. Care is taken to avoid harvesting along the midline due to risk of injury to the sagittal sinus. A round burr can be used to drill through the outer cortex laterally, thus defining the border of the graft. This allows for placement of an oscillating saw or osteotomes, with harvest proceeding from medial to lateral within the diploic space harvesting a large amount of the parietal outer table for grafting. In cases where a craniotomy is necessary, the entire calvarium can be harvested, the inner table then separated from the bone flap as bone graft. The outer table is later replaced with miniplate fixation.

Autologous Bone Grafting—Rib

The size of the calvarial defect dictates the choice and number of ribs. In the case of fifth, sixth, or seventh rib harvest, an inframammary incision is made and the desired rib is exposed. A subperiosteal dissection minimizes the risk of injury to the underlying pleura and is performed circumferentially around the rib using either a periosteal elevator or Doyen rib dissector. The rib is sharply separated from the osteochondral junction and cut posteriorly using bone cutting forceps. After harvest of the rib graft, it can be split transversely. The advantage of splitting the rib graft includes increased surface area for the reconstruction of the calvarial defect, improved flexibility of the rib grafts, and exposure of the cancellous portion of the rib that may improve graft survival. If additional rib is needed, it is suggested to harvest alternating ribs to minimize the chest wall contour defect. After rib harvest, the donor site is flooded with saline and Valsalva is performed to confirm the pleural integrity. The chest incision is closed in a layered fashioned. The split rib grafts are then fashioned to the calvarial defect and fixated with miniplates.

Autologous Bone Grafting—Iliac Crest

An incision is made ~1 cm posterior to the anterior superior iliac spine and 2 cm inferior to the iliac crest. Monopolar dissection is carried down to the bone. The inner aspect of the iliacus is elevated and retracted. A reciprocating saw is then used to harvest the necessary amount for cranioplasty.

Fixation Methods

Suture and wire fixation of bony flaps and alloplastic material are outdated, lack strong stabilizing ability, and are prone to dislocation and localized scalp pain. Miniplates are low profile titanium constructs with stronger stabilization compared with wires and sutures. These have become the standard for open reduction internal fixation of various cranioplasty materials. The low profile makes them difficult to palpate over even thin scalps. There is an inherent risk of hardware extrusion particularly in the irradiated patient or in skin envelopes with vascular compromise.

Perioperative Considerations

Osteomyelitis at the cranial defect poses a significant challenge, and high recurrence rates have been reported with earlier reconstruction, concomitant chemotherapy treatment, and composite defects requiring scalp reconstruction at the time of cranioplasty. Kwiecen et al report a 10% risk reduction for reinfection with every month cranioplasty was delayed.[25] Other studies have reported lower infection rates with earlier reconstruction (4% incidence with reconstruction as early as 3 months) in smaller adult cohorts ($n = 25$).[26] Further discussion regarding the treatment of perioperative surgical site infection is beyond the scope of this article; however, infection at the craniotomy site should prompt a infectious disease consultation and delay of reconstruction.

Pediatric Considerations

The goals of cranioplasty are the same in the pediatric population. This population is more challenging, however, due to their unique anatomy and continued dynamic bony growth not found in adults. Children experience rapid calvarial growth in the first years of life continuing up to 7 years of age.[27] Understanding the relationship between the pediatric brain and cranium size is important in predicting expected growth with age. Studies show 70% of the adult brain weight is achieved at 18 months, 80% at 3 years, 90% at 5 to 8 years, and ~95% at 10 years with a similar growth pattern of head circumference.[28]

Autologous Grafts and Alloplastic Materials

Prior to 4 years of age, autologous grafting from the calvarium can be limited due to an underdeveloped diploic space; other sources may be considered as described previously.

In a systematic review, Abu-Ghname et al demonstrated fresh autologous bone grafts and titanium mesh have the lowest surgical site complications including seroma, hematoma, wound dehiscence, and flap or skin necrosis. Surgical-site infections were also lower in contrast to banked bone, which had the most issues and highest infection rates.[29] Autologous reconstruction is typically preferred in the pediatric population, when possible, as evidenced by the 439 autologous cases compared with 201 alloplastic cases. The inherent advantages of autologous reconstruction include osteointegration and remodeling with pediatric brain and bone growth. Limitations of the review include variable follow-up time (range: 1–10 years) for alloplastic reconstructions such as titanium mesh due to combining data from 20 studies. In the experience of the senior author, titanium mesh complications include scalp thinning and ultimate hardware exposure that may occur several years after initial implantation.[30] Banked autologous bone had a 40% resorption rate, and thus alloplastic options may be a suitable alternative when autologous cranioplasty is insufficient in defect repair.

Given the rapid growth of the calvarium, fixation methods need to be considered that will not interfere with bony growth. In cases where rigid fixation is used for cranioplasty, resorbable plates can be a suitable option. Many studies have demonstrated resorbable plates to be safe in pediatric craniomaxillofacial surgery, although some reports of foreign body reaction have been described.[31,32] When rigid fixation with titanium plates is used, following osteointegration of autologous grafts hardware removal may be necessary to accommodate for pediatric calvarial growth.

Complications

Complications following cranioplasty include bone resorption, surgical site infection, seroma, hematoma, wound dehiscence, flap or graft loss, seizures, and hydrocephalus, with reported overall complication rates of up to 40.4%.[33] Long-term complications of alloplastic implants include thinning of the overlying skin with impending hardware exposure, which can be particularly challenging in radiated patients.

The most common complication following cranioplasty for autologous reconstruction is bony resorption with rates up to 17% reported in the adult literature, particularly in banked bony flaps.[34] It is theorized that resorption occurs due to irreversible devitalization of bone without adequate vascular ingrowth from surrounding native bone. The pediatric patient population is particularly at risk with reported rates as high as 57%.[29,35,36] In cases where significant bony resorption occurs, additional autograft or alloplastic cranioplasty may be necessary for adequate reconstruction of the resulting calvarial defect.

Surgical site infection has been reported to be up to 20% in some studies and can lead to significant morbidity including the need for revision cranioplasty.[37] Risk factors associated with increased infection risk include prior infection, inadequate obliteration of intracranial content from the upper aerodigestive tract, devitalized scalp flap, inadequate obliteration of dead-space leading to persistent intracranial or extracranial collection, and revision surgery. Le et al found lower complication rates in cranioplasty with a perioperative bundle to include vancomycin as well as topical chlorhexidine cleansing of cranioplasty incision from postoperative day 4 to 7. With implementation surgical site infection dropped from 24 to 3% and revision cranioplasty from 19 to 0% with limitations of the study being retrospective and nonrandomized with relatively small sample size.[38] In cases where the soft tissue envelope is too devascularized and scarred, free tissue transfer may be necessary to replace unhealthy tissue and allow for adequate coverage of cranioplasty materials to prevent recurrent infection.

Seizures and hydrocephalus may be complications secondary to underlying brain parenchymal injury necessitating subsequent craniectomy. In cases of intracranial hemorrhage and trauma, there are higher rates of perioperative seizures. Loss of brain parenchyma can lead to subdural collections when the brain cannot adequately re-expand to fill the calvarium. Dural tacking sutures can be utilized during cranioplasty to eliminate this potential dead-space. Brain atrophy can result in hydrocephalus as the size of ventricles increases, and ventriculoperitoneal shunts may be indicated secondarily.

Future Direction

The perfect cranioplasty material is one that is osteoinductive, easily molded, of a reasonable cost, and of limitless supply. Computer-designed implants have revolutionized the accuracy of implant shape to achieve premorbid calvarial contours; however, the lack of osteointegrative properties of implants such as PEEK makes restoration of bone challenging. As advances are made in tissue engineering, eventual bioresorbable custom implants with osteoinductive properties may allow for eventual replacement of a temporary scaffold with new calvarial bone, which would be the most personalized and ideal reconstruction.

Note

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Conflict of Interest
None declared.

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