Accepted Article

Journal of Research and Practice on the Musculoskeletal System
JRPMS

Review Article

Reconstruction of Defects of the Cranial Vault

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Abstract

Defects of the cranial vault can be congenital or acquired. Congenital defects include syndromic and nonsyndromic. Acquired defects include defects from tumor, infection and trauma, which can cause loss of the calvarium due to direct trauma or by craniectomy procedure. The diagnostic approach for such cases includes physical examination and imaging techniques (such as plain radiographs, CT, MRI, and ultrasound). The method of reconstruction of cranial defects is tailor made to each individual patient. The method as well as the graft material is based on the patient's overall disease state, long-term prognosis, and medical comorbidities. Reconstruction of these cranial defects has been attempted with the use of different materials which include autografts, allografts, xenografts and alloplastic materials. The reconstruction of cranial defects requires a tailored approach based on the patient's overall disease state, long-term prognosis, and medical comorbidities. Autogenous grafts offer advantages such as integration, vascularity, and lower risk of infection, but have drawbacks including resorption. Allografts, xenografts and alloplastic biomaterials provide alternative options for reconstruction, but there is no ideal material that fulfils all characteristics. The choice of graft material should consider factors such as age, sex, size, and site of the defect.

Keywords: Allograft, Xenograft, Alloplastic biomaterials, Autograft, Cranial vault defects

Introduction

The cranial vault consists of 8 bones including paired parietal and temporal bones, the frontal bone, the squamous part of the occipital bone, the greater wings of the sphenoid bone and the ethmoid bone. These bones protect the brain. The calvarial growth ceases when the bones meet in the fusion area.

Congenital defects include syndromic and non-syndromic. Acquired defects include defects from tumor, infection and trauma, which can cause loss of the calvarium due to direct trauma or by craniectomy procedure and may result in brain injury. The above defects, as well as tumor resections, bone flap infections, and pathological conditions (e.g. fibro-osseous lesions, scleroderma, microphthalmia, or intracranial vascular lesions), can lead to post-traumatic residual defects to the frontal, parietal, temporal, and occipital bones[1-3], as well as brain injury. In 1945, Gardner first mentioned the "syndrome of the trephined", which includes symptoms such as headache, dizziness, irritability, loss of concentration, depression, anxiety, intolerance to noise and vibration, and neuromotor weakness[4]. Similar symptoms were later described as "the sinking skin flap syndrome"[5], caused by "the tenting effect", where, due to atmospheric pressure, the scalp "sinks" into the defect, shaped like a tent held by the defect's margins[6].

Reconstruction of these cranial defects has been attempted with the use of different materials in order to protect the brain and re-establish the continuity of the cranium. These materials can be autografts, allografts, xenografts and alloplastic materials[7]. The characteristics of an ideal material[8] are the following:

1) Biocompatibility: Non-toxic to the living tissue

The authors have no conflict of interest.

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Edited by: *Konstantinos Stathopoulos*

Accepted *19 February 2024*

2) Bio-inertion: Does not cause any reaction in the biological environment
3) Bio-activity: Biologically active to repair or regenerate the tissue or organ
4) Bio-resorption: Naturally degraded or absorbed in the living tissue in order to regenerate or repair the tissue
5) Bio-adoptability: Adoptable to the micro environment and molecular mechanism
6) Sterilizability: Suitable for sterilization

Unfortunately, there is currently no material on the market that has all the characteristics. Therefore, an important property that should be considered is the bio-inertness. Specifically, the material should be inert and not provoke an undesirable reaction. An example of such an undesirable response is the hypersensitivity reaction caused by polymerisation and moulding of PMMA (an alloplast), which can lead to damage of the brain[9]. Damage of the brain can also be caused by thermal conductivity of the biomaterials. Also, the thermal expansion of the graft should correspond with that of the bone. Additional properties of biomaterials include non-interference with imaging techniques, such as computer tomography (CT) and magnetic resonance imaging (MRI). The material should be radiopaque to be visible on images[6]. Damage of the brain can also be caused by thermal conductivity of the biomaterials. Also, the thermal expansion of the graft should correspond with that of the bone. Additional properties of biomaterials include non-interference with imaging techniques, such as computer tomography (CT) and magnetic resonance imaging (MRI). The material should be radiopaque, in order to be visible on images[10].

Two methods of reconstruction of defects of the cranial vault have been more popular among neurosurgeons: 1) Osteoplastic reconstruction with autogenous bone, which includes the calvarial, rib, and iliac grafts, and 2) restoration of the cranial vault with alloplastic biomaterials, including poly methyl-methacrylate, titanium, porous polyethylene and ceramics.

Diagnostic Investigations of Cranial Vault Defects

Physical Diagnosis

Evaluation and Initial Management

The evaluation and initial management of traumatic wounds (eg. gunshot and blast injuries) is significantly different to wounds caused by planned ablative tumor surgery. Injuries caused by ballistic weapons are usually contaminated and unstable on initial presentation. Defects caused by tumor surgery are typically planned and stable. Securing a patent airway is the first and most important step of management of trauma patients, followed by stabilisation of vital functions. Furthermore, management of life-threatening wounds take priority over cranial injuries. Once these acute/urgent life-threatening issues are managed and stabilised, then the initial cranial treatment involves:

1. Wound debridement
2. Structural stabilisation
3. Infection control

Once the trauma wound is stabilised, a delayed repair and replacement of hard and soft tissues is initiated. In tumor patients undergoing resective surgery, these life-threatening issues are not a major factor because the reconstruction is planned before the surgery. In trauma patients, once the wounds are debrided and viable, and the extent and type of the defect is established, the approach to reconstruction is similar. In both the stabilised trauma patient and planned tumor defect patient the approach is similar and involves:

1) Defining and classifying the missing tissue (or unusable scar tissue)
2) Treatment planning to accomplish the replacement and restore form and function

Imaging Techniques

Prior to any imaging, a thorough clinical examination should be carried out including observation, palpation, percussion and auscultation[11]. Careful examination of the cranial region must be performed as well as frontal view, profile view and craniofacial examination. A detailed medical, and family history must be taken in order to proceed to other diagnostic methods.

An image is created by passing X-rays through the section which is in focus. Depending on the consistency of the tissue the X-rays either pass through creating a translucent image or reflect and create a radiopaque image. Plain X-rays have little clinical value in the acute trauma patient but can be useful in the stabilised trauma patients as well as in the tumor patient. Radiographic imaging usually does not reveal soft tissue trauma requiring urgent attention before the definitive reconstruction e.g. brain, ocular, salivary gland or facial nerve injuries. Tomography is the technique where the X-ray source and film move resulting in a clear image of the point of interest and blurred out periphery[12].

Contrast media can be used to visualise lumens of organs or vessels, or cavities in the body. The contrast media introduced to the lumen will have a radiopaque appearance on the image created. For real time visualisation, fluoroscopic imaging or serial radiographs, using contrast media, such as barium sulphate suspensions and non-ionic iodinated contrast agents, are performed. There are some risks when using contrast media and doctors should take a thorough medical history including previous reactions to contrast media, asthma, renal problems, diabetes and metformin therapy[12].

Computerized Tomography (CT) scanning is the gold standard for the evaluation and planning of patients with defects of the cranial vault and the maxillofacial region. It is a method of imaging that is fast and available in most hospitals. A fan of X-rays is sent through the patient, and as they travel through the body, they become attenuated.

These attenuated X-rays are detected. This is repeated while the patient moves through the scanner and the detectors rotate, resulting in an image for diagnostic use. Iodinated contrast medium can be used to get a better image of soft tissues and enhance pathological tissues[12]. CT angiography of the lower extremities can be used for the evaluation of vessels in cases of vascularised free tissue transfer. CT data allows for specific treatment planning, precise measurements and the production of 3D printed or stereolithographic models. CT information also provides for computer-aided design/computer-aided manufacturing (CAD/CAM) based surgical guides as well as intra-operative surgical navigation to resect the tumor appropriately. Furthermore, in vascularised fibula free flap cases, CT data can be used to manufacture CAD/CAM cutting guides which allow for an in situ shaping of the harvested bone while still attached to its vascular pedicle. This results in minimal additional reshaping of the fibula before the flap is inserted into the maxillofacial defect. By using these CAD/CAM guides to treatment plan and shape the bone graft, the ischemic time and overall operative time is decreased and the result is significantly improved with the correctly contoured and usable reconstruction[13].

MRI creates an image based on the behaviour of protons when exposed to a radiofrequency pulse within a magnetic field. There are two types of images formed depending on the pulse that the proton is exposed to. In T1 weighted images fat appears bright and water appears dark. In T2 weighted images water appears brighter. The fact that this method does not use ionising radiation to create an image provides an advantage over CT. However, drawbacks are its poor availability, cost and the longer time required for the procedure[12].

Ultrasound Imaging is done by sending ultrasound waves to the area of interest and measuring the reflection and scattering of the waves caused by acoustic impedance. Ultrasound does also not require ionising radiation, has a low cost compared to the other methods of imaging and readily available. However, it is operator/practitioner dependent and requires experience. A gel is used on the skin to reduce the air interference between the skin and the ultrasound probe. Air will scatter the wave signal and result in a 'white out'. When tissues reflect the wave, they are called echogenic. Bone will convey a small amount of wave signals causing a black hole. Tissues like bone are hypo-echoic. Color and power Doppler are used to examine the flow of either a vessel and a pathological structure such as the vascularity of a tumor. Ultrasound can be combined with sampling techniques such as fine needle aspiration biopsy or core biopsy which is very useful in the diagnosis of tumors.

Graft Options and Materials

Defects that need reconstructive surgery can be the result of oncologic ablative surgery, trauma, or congenital anomalies and can affect the patient's quality of life tremendously. As the reconstructive surgical techniques advance, the decrease in functional and aesthetic complication is impressive. The fact that we have a wide variety of surgical techniques allows the surgeon to tailor the different flaps to the individual patient's reconstructive needs, tolerance for donor-site morbidity, and general physical and psychological state. In every case we have to consider the patient's overall disease state, long-term prognosis, and medical co-morbidities.

Autogenous Grafts

The autogenous grafts are often preferred due to their integration and vascularity, viability, and therefore lower risk of infection, as well as the psychological effect on the patient, as they do not feel that their defect is reconstructed with a foreign material. Another advantage is that their radio-sensitivity makes them visible on radiographic images. However, the drawbacks are that the result may be absorption of the graft and loss of structure, possible unfavorable aesthetic result, the availability of the desired quantity of graft material, the susceptibility to fracture, and the surgical intervention on both donor site as well as cranioplasty[1].

Free Bone Grafts

Free bone grafts have been used based on the concept of osteoconduction, osteoinduction and osteogenesis. Osteoconduction refers to the phenomenon when the bone graft acts as a template for new bone growth maintained by the native bone. Osteoinduction is when chemical signals such as BMP (bone morphogenic protein) stimulate the osteoprogenitor cells to differentiate into osteoblasts that will create the new bone. Osteogenesis occurs when the surviving osteoblasts from the original graft form new bone in the region the graft is placed along with the other two mechanisms mentioned. A commonly used graft in this category is the cortico-cancellous block graft, by taking part of the iliac crest for reconstruction of the defect. When using this method of reconstruction, a key to success is the correct positioning and stabilization/rigid fixation of the graft as to gain re-vascularisation, which will lead to resorption and deposition of new bone. This process is called "creeping substitution". There are two important limiting factors that should be mentioned.

1) The size of the defect: >6-9 cm will have poor osteointegration and excessive resorption
2) Insufficient blood supply: in cases where the tissue has undergone irradiation, scarring or infection[14].

The calvarial graft has a similar embryological origin to the host's bone, an important factor which is mentioned above and is the reason it is often preferred to other grafts. Other reasons include donor site proximity, the possibility to harvest an adequate amount of material for small defects, minimum deformity of the donor site and high tensile strength. Full or split-thickness grafts can be used and are harvested from the parietal and a smaller quantity from the frontal bone, excluding pathologically affected bone, infected bone, multiple fragmentation or bone that has been subjected to prolonged exposure. The graft is fixated by titanium mini screws and microplates[6]. However, there is a 3-12% incidence of graft resorption[15,16].

Reconstruction of defects of the cranial vault with split rib grafts was first done by Brown in 1917[2]. Split rib grafts are preferred in cranial vault defects in children due to the adaptation of growing skeleton, and adequate protection of brain. Other advantages include accessibility and availability, regeneration capacity, and minimal blood loss during the procedure. Even though a split rib graft has greater elasticity[17], the shape of ribs makes it difficult to form the correct calvarial contour, resulting in an irregular surfaced reconstructed area, with depressions, causing a "washboard effect"[6]. At the donor site, complications such as hemothorax, pneumothorax or flail chest are considered an emergency, adding to morbidity[18]. Other problems include limited graft availability for large defects, and the unfavourable aesthetic result due to scaring[19].

A popular and often preferred graft for reconstruction of the maxillofacial region, including the cranial vault, is the iliac graft. The size and shape of this bone makes the procedure easier for the surgeon in terms of bone availability, contourable graft, and healing properties, which lead to a successful and symmetrical result. However, complications of grafting this region include gait disturbances, post-operative pain, blood loss during surgical procedure, land slide hernia, and delay or impediment of growth in young individuals, as well as resorption of the graft due to the fact that it is an endochondral bone.

Vascularised Grafts

Vascularised cranioplasty is currently the gold standard of reconstruction due to its acceptable functional reconstruction, especially in irradiated or infected bone and in case of re-intervention of recipient site. In these cases, osseointegration of a non-vascularised graft is less probable, leading to nonunion or osteonecrosis[20]. Based on a prospective study[14], a reconstructed irradiated mandible using free vascular bone graft had 90% success after 10 years. Skilled expertise is needed for reconstruction of a complex composite defects with microvascular bone graft. Although iliac crest free vascular flap, with the deep circumflex iliac artery is the most common microvascular flap, its small pedicle is a limiting factor. Fibular flap on the other hand provides bone as much as 30cm together with adequate vascularity, providing the patient does not have preexisting peripheral vascular disease. The scapula is another commonly used donor site with the subscapular artery, as well as the rib thoracodorsal vessel. The superficial temporal artery is the vessel used on the recipient site[6].

Alloplastic Biomaterials

Acrylic resin is a material with great plasticity, long-term stability and good tissue compatibility, which is used among neurosurgeons since World War II. This alloplastic material can be used for restoration of large defects, does not produce a shattering or paramagnetic effect, is generally well tolerated, and has satisfying aesthetic results. No adverse effects have been reported. The plate is fabricated after an indirect impression is taken, and undergoes overnight cold sterilisation. Holes are made through the plate in order to promote fibrous ingrowth, ensuring the stability and trimmed so that the margins of the plate contact and rest on the surrounding bone, to prevent it from sinking in and to perfectly restore the defect. Thereafter, the plate is fixated with screws or wiring. Disadvantages of this material include fragility, heat generation and, and tissue necrosis or implant failure due to residual monomer[2,21-23]. However, the use of computer-aided design/manufacturing (CAD/CAM) technique and fabrication of customised craniofacial implants (CCI), supplied in a sterile package, can prevent these undesirable effects, and provide improved hard tissue adaptation[24]. There is a 5 to 25% complication rate, with a 5 to 20% infection rate, of cranioplasty with PMMA[3].

Properties of the nonferrous metal titanium, such as biocompatibility, corrosion resistance thermal expansion which matches that of the bone, and radio-density which makes it visible on imaging, make it a very acceptable alloplastic material, and shows no major degradation on computer tomography or magnetic resonance imaging[2,25-27]. It is a light metal, but also strong, and malleable enough to be shaped in a "die-counter-die" system, and hardens with handling 1. It can be used in various ways and forms, including mesh, custom-made plates, and as a reinforcement with other materials used for reconstruction such as cements, ceramics, and hydroxyapatite[28]. In order to increase the tissue acceptance of the prosthesis, it is anodised in a solution made of 80% phosphoric acid, 10% sulphuric acid, and 10% water[29]. Utilisation of this metal has great functional and cosmetic results, and can be used in paediatric patients[30].

Prefabricated anatomical shapes of a porous network created by sintering polyethylene microspheres, in order to form a framework used for reconstruction of cranial vault defects, which will promote ingrowth of bony and soft tissue fibers, as well as vessels. This material has long-term stability and is non-resorbable and insoluble in tissue fluids[31]. It is used for specific small, craniofacial defects, and should be avoided in weight-bearing regions. These implants are prone to exposure and infection[32]. For the above reasons, porous polyethylene implants have limited use.

Ceramic implants can either be hydroxyapatite (HA) or calcium sulphate. The latter's properties are similar to bone in terms of mineral phase and structure[2], whereas the former has great mechanical and osteoconductive properties and is used for reconstruction of large craniofacial defects[33-35].

Their porosity though, increases colonisation of bacteria[36] and therefore risk of infection, and reduces density which makes it brittle. Reinforcement of HA with titanium mesh increases the tensile strength and is used when restoring large cranial vault defects.

Criteria for Choice of Autogenous graft vs Alloplastic Material

The age of the patient is an important consideration when deciding on the method of reconstruction and the material to be used. The skull reaches 75% of its thickness by the age of 5 and its full thickness by the age of 17. Therefore, the skull of a patient younger than 4 years old is not mature and has not completed its diploic differentiation. This fact makes alloplast materials inappropriate for paediatric patients, while autologous rib grafting is preferred in such cases due to its capacity to osseointegrate and grow with the paediatric skeleton[2,21,37]. In patients younger than the age of 2, the dura and pericranium have the osteogenic capacity to heal the defect without surgical repair. Therefore, surgical intervention in such cases is avoided. On the other hand, patients older than 60 years undergo sclerotic changes in the diploic space, leading to difficulty harvesting the split calvarial graft[18].

The defect can be classified based on[3]:

- Size of defect:
1. Class 1 (small): <25 cm^2
2. Class 2 (medium): 23-100 cm^2
3. Class 3 (large): >100 cm^2
- Anatomic involvement:
1. Simple: involving single bone
2. Compound: involving 2 adjoining bones
3. Complex: involving 3 or more adjoining bones

For Class 1 defects the autogenous calvarial grafts are preferred, but not appropriate for the other classes. Class 2 and 3 are rather reconstructed with PMMA or titanium. Class 3 defects require an extended surgical exposure, longer operative time, and consideration of blood loss[3]. Grafts are harvested 1.5 cm from the midline as a safety zone to avoid trauma to the superior sagittal sinus, and above the temporal line, staying away from the thinner part of the skull and therefore avoiding injury to the middle meningeal artery in the pterion zone. However, if the defect involved the pterion region, resin material and fourth generation custom cranial implants (CCI) can be used to add bulk and disguise the persistent temporal hallowing (PTH) that is formed from such defects[38]. In defects that include the paranasal sinuses, alloplasts are not used due to their high rate of infection, foreign body reaction, and implant rejection[22]. Autografts are preferred owing to their greater immunity to infection[2].

Genetic and racial influences do play an important role in the determination of grafting material. A male's calvarial donor thickness is 2mm more than a female's, and a female skull is rounder and more vertical. These facts affect the anthropometric values that have to be taken into consideration. Other considerations should include males' pattern of baldness. Infra-mammary line, and iliac prominence in order the disguise the surgical scar.

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