Surgeons have long searched for an ideal material to use in skull reconstruction. Ideally, it should be widely available, low in cost, and easy to mold during surgery, yet strong and durable in its final form. While autologous bone is widely used and favored in contemporary reconstructive procedures, synthetic alternatives have been used throughout history and are necessary in current practice for select cases when autograft reconstruction is not an option (such as cases with severe bony comminution, bone graft resorption, infection, and limited donor site options). The use of synthetic materials, when necessary, has been functional. Over time, this search has led to the use of metals, ceramics, plastics, and later, resorbable polymers. This paper provides a tour of the materials that have been used and experimented with throughout the history of alloplastic cranioplasty.

**Key Words** • cranioplasty • history • alloplastic materials

### Metallic Bone Substitutes

**Gold and Silver**

The earliest historical cranial reconstructions were performed with locally available materials such as gourds, coconuts, or precious metals. Archeologically, there is much more evidence of trepanation than of cranial repair. One theory is that precious metal prostheses may have been removed before burial, leading to historically underestimated rates of cranial repair. While trepanation was practiced in many ancient civilizations including the Asians, the North Africans, and the Polynesians, very little is written on ancient practices of craniofacial reconstructions. This paper provides a tour of the materials that have been used and experimented with throughout the history of alloplastic cranioplasty.

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Abbreviation used in this paper: PEEK = polyetheretherketone.
inserted into the pockets of unscrupulous practitioners rather than into the skull defect of the patient.28

Gold was found early in the 20th century to have low complication rates, but its high price and softness led to its disuse.21 Silver was also tested as a potential graft material early in the 20th century. Though it was found to be easy to shape and less expensive than gold, it was too soft to provide adequate protection; silver also interacted with surrounding tissue, causing discoloration of the skin as it oxidized.31 Gold and silver were both in use for cranial repair in World War I, but by the midcentury, they were no longer in use.29

Platinum, Lead, and Aluminum
Throughout the early 20th century, platinum, lead, and aluminum were also investigated as potential repair modalities. However, platinum was too expensive to be a widely viable option and lead caused dangerous toxicity.3,31 Aluminum was first applied in the late 19th century to perform cranial reconstructions but was found to be associated with an increased rate of infectious complications and epilepsy.3 For these reasons, use of these three metals in cranial reconstructions was discontinued.

Alloys
Alloys were also investigated as potential reconstructive materials in a search to find a solution that balanced the benefits of using metals for reconstruction (such as strength, availability, and malleability) with some of the downsides (side effects, cost, and radiopacity). Alloys that were commonly used in the mid-20th century included tantalum, Vitallium, and steel. Tantalum, a material named after Tantalus, a character in Greek mythology, was widely used during and after World War II. It is inert, malleable, and noncorrosive, but it fell into disuse because of its expense, limited availability, and thermoconduction.23 Indeed, patients complained of intolerable headaches from the metal heating in the head, especially when they were outside in the sunlight. Vitallium was also found to be noncorrosive, but it was too difficult to shape intraoperatively and thus was not a favored material.6 Stainless steel was used for a time as well. It was found to be similar to tantalum in strength and malleability, and more radiolucent and economical than tantalum. However, certain stainless steel alloys were tissue incompatible and were found to have high failure rates.3 As surgeons were facing difficulties with these alloys, nonmetallic prostheses were being developed, creating another set of options in cranial reconstructions.34

Titanium
Titanium is the only metal currently used in cranial reconstruction. It began to be used for cranioplasty in 1965 and is currently the basis of several modalities of cranial reconstruction.3,31 Titanium plates are used to affix bone in many surgical repairs throughout the body. Titanium mesh is used alone or as a scaffold for cements in cranial reconstruction. Titanium has good biocompatibility with virtually no risk of allergic reaction, good mechanical strength, and low infection rates and is more radiolucent and cheaper than many other metals, which is why it is also used alone to repair cranial defects.3,8 While titanium is hard, it can still be shaped intraoperatively (Fig. 1).14 Technological improvements also have led to the custom shaping of prostheses based on imaging using computer-aided design and computer-aided modeling (Fig. 2).3 Titanium is often used as a secondary repair mechanism after a primary autologous repair has failed.3

Nonmetallic Bone Substitutes
Celluloid
The Industrial Revolution allowed for the cheap production of a wider variety of materials. This opened up the possibilities for a broad range of applications starting with the use of celluloid in cranioplasty, which was popularized in Germany in the late 1800s. Celluloid, generally considered to be the first synthetic plastic, was first used in cranial reconstructions in the late 19th century.2,31 In 1890, Fraenkel discovered that celluloid did not adhere to the dura, preventing the secondary scar formation often seen with other materials.31 Because of its availability and ease of use, celluloid was widely adopted in calvarial reconstruction. However, it later became evident that celluloid tended to react with the tissue, forming a serosanguinous exudate that needed to be aspirated for up to 2 weeks following surgery.28,31 Despite these limitations, there were very few alternatives until acrylic resins and tantalum came into use in the 1940s.

Acrylics
In 1940, Zander was the first physician to implant a methyl methacrylate prosthesis into a patient.28,31 Methyl methacrylate proved to be superior to metals because of its lightness, low cost, malleability, radiolucency, and lack of thermoconduction.31 It became particularly useful in treating the multitude of cranial injuries sustained by World War II veterans.

Preparation of acrylic resin plates initially involved a cumbersome two-stage process where the mold had to

Fig. 1. Titanium mesh contoured intraoperatively for frontal sinus injury reconstruction.
History of synthetic materials in alloplastic cranioplasty

Fig. 2. Customized prefabricated titanium implant.

be prepared and later inserted into the cranial defect. In 1954, Spence developed a one-stage method for preparing acrylic resin plates, allowing more popular use of methyl methacrylate prosthetics. The skull plates were prepared in the operating room by mixing a polymerized methyl methacrylate (PMMA) with a liquid monomer. The resulting reaction allowed the acrylic resin to become malleable and easily shaped to fit the contours of the cranial defect. There were several disadvantages to this process. First, the powder that was used to mix the acrylic resin was not sterile. Second, the process of hardening induced an exothermic reaction, requiring frequent irrigation with cool saline to prevent tissue damage. Brittleness is another limitation of acrylic resins. This can cause fracturing of the plates, which can result in fragments becoming embedded in the skull. In 1967, Galicich and Hovind addressed this problem by incorporating a stainless steel mesh to strengthen the plate. This technique was widely used until Malis in 1989 proposed using a titanium mesh as it had numerous advantages over stainless steel including its lightweight profile, malleability, and nonferromagnetism. Acrylics continue to be widely used in current practice. In recent years, advancements in computer-aided design and computer-aided modeling have decreased the need for intraoperative molding and have improved the use of acrylic resins.

Plastics

Plastics are widely used in current practice, primarily in the form of polyetheretherketone (PEEK) and porous polyethylene. As enthusiasm for celluloid waned, the resurgence of thermoplastics in cranioplasty began modestly in the 1940s. Polyethylene was developed in 1936 and was originally used as an insulator in electrical wires. After World War II, the pioneering pediatric neurosurgeon Franc Ingraham promoted its use in cranioplasty after performing animal experiments with various materials including fibrin film, methyl methacrylate, and tantalum. Ingraham concluded that polyethylene was the most effective due to its biocompatibility. In 1948, Busch reported on the use of polyethylene in humans. However, polyethylene was too soft compared with acrylic resins, and its use was limited to smaller cranial defects.

Polyethylene was not widely used until the recent development of porous polyethylene. Porous polyethylene may allow soft-tissue ingrowth and collagen deposition through pores of 100–250 μm. These features may have some degree of porous ingrowth. Polyetheretherketone implants were originally developed for spinal surgery and hip replacement surgery in 1998. These implants are also used in craniofacial reconstruction. Customized patient-specific implants can be prefabricated using 3D CT scanning (Figs. 3 and 4). Polyetheretherketone has many features including radiolucenty, stiffness, and strength comparable to that of cortical bone. Additionally, PEEK is nonallergenic and inert and has a high heat and gamma ray tolerance, allowing for multiple sterilizations if necessary. It can also be shaped intraoperatively when needed.

Ceramics

Calcium phosphate ceramics have been the cornerstone in the development of modern techniques for alloplastic cranioplasty. Calcium and phosphate compounds were originally thought to hasten bone growth. Plaster of Paris (calcium sulfate) was used as a bone substitute as early as 1892. Since then, many have investigated the use of plaster of Paris in the repair of fractures. Particularly, its use as an alloplastic implant in craniofacial reconstruction was investigated by Beeson in 1981. These implants are also used in craniofacial reconstruction. Hydroxyapatite’s tissue compatibility as well as properties of osteoconductivity and osteoinductivity made it attractive. Yet, it was also brittle and difficult to mold. In the 1980s, Brown and Chow reported on a calcium phosphate cement that is self-hardening when mixed with water at room temperature. This allowed the cement to be easily molded during surgery. The innovations and variety of calcium phosphate cements have since grown, and their use has led to a wide range of applications in craniofacial reconstruction in children and adults.
Resorbable Implants

Resorbable materials are a relatively new modality for cranial reconstruction, yet their benefits have been known for centuries. A notable example is Galen’s use of catgut suture to treat the wounds of gladiators in ancient Greece. Catgut was preferred for its biodegradable properties, thus preventing the higher risk of infection with other foreign substances. Nonetheless, it was not until the 1960s when the concept of resorbable implants in reconstructive surgery arose.

In 1966, Kulkarni envisioned polymers of lactic acid as an ideal substance for resorbable implants. Animal studies were performed using polylactic acid rods to replace nonresorbable stainless steel pins used in the fixation of craniofacial fractures. The results were promising, and interest in resorbable implants grew in response to many of the problems of earlier reconstructive materials such as thermoconduction, radiological artifact, implant migration (especially in the growing skulls of children), and difficulty of a second operation if complications arose. In the 1990s, resorbable plates and screws were introduced into clinical practice using materials derived from a wide variety of synthetic polymers. Resorbable mesh and implants are considered especially useful in pediatric patients, for whom skull growth adds an additional consideration in the selection of material.

These materials, however, are not without complications. While resorbable implants are largely considered to be biocompatible, there have been reports of fistulas, osteolysis, inflammatory reactions, and incomplete resorption. In addition, resorbable materials have a lower tensile strength than metals. Innovations in the design and application of biodegradable materials continue to expand their use in craniofacial reconstruction. New techniques are being developed to use a combination of bone particles, growth factors, and resorbable plates to encourage native bone growth to repair a skull defect.

Future Directions

Alloplastic cranioplasty will continue to make developments toward improved alternatives for reconstructive material when autologous bone is not an option.
centuries, experimentation with materials has ranged from gourds and locally available metals, to modern titanium, methyl methacrylate, and hydroxyapatite. These modern developments have resulted in improved outcomes including improved strength, biocompatibility, coverage, and cosmesis. The story of alloplastic cranioplasty will continue to evolve with ongoing research in bioengineering.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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