World War II, tantalum, and the evolution of modern cranioplasty technique

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Cranioplasty is a unique procedure with a rich history. Since ancient times, a diverse array of materials from coconut shells to gold plates has been used for the repair of cranial defects. More recently, World War II greatly increased the demand for cranioplasty procedures and renewed interest in the search for a suitable synthetic material for cranioprotheses. Experimental evidence revealed that tantalum was biologically inert to acid and oxidative stresses. In fact, the observation that tantalum did not absorb acid resulted in the metal being named after Tantalus, the Greek mythological figure who was condemned to a pool of water in the Underworld that would recede when he tried to take a drink. In clinical use, malleability facilitated a single-stage cosmetic repair of cranial defects. Tantalum became the preferred cranioplasty material for more than 1000 procedures performed during World War II. In fact, its use was rapidly adopted in the civilian population. During World War II and the heyday of tantalum cranioplasty, there was a rapid evolution in prosthesis implantation and fixation techniques significantly shaping how cranioplasties are performed today. Several years after the war, acrylic emerged as the cranioplasty material of choice. It had several clear advantages over its metallic counterparts. Titanium, which was less radiopaque and had a more optimal thermal conductivity profile (less thermally conductive), eventually supplanted tantalum as the most common metallic cranioplasty material. While tantalum cranioplasty was popular for only a decade, it represented a significant breakthrough in synthetic cranioplasty. The experiences of wartime neurosurgeons with tantalum cranioplasty played a pivotal role in the evolution of modern cranioplasty techniques and ultimately led to a heightened understanding of the necessary attributes of an ideal synthetic cranioplasty material. Indeed, the history of tantalum cranioplasty serves as a model for innovative thinking and adaptive technology development.
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KEY WORDS • cranioplasty • World War II • history • neurosurgery • tantalum • cranial defect

CRANIOPLASTY, the surgical repair of skull defects, has a long and rich history with much diversity not only regarding the breadth of materials that have been used in the procedure, but also in the techniques that were developed, modified, and discarded. The World War II era represents a pivotal point in the history of the cranioplasty procedure. The surge in traumatic cranial defects and deformities spurred an evolution in cranioplasty materials and surgical techniques. Tantalum represented a major breakthrough in synthetic cranioplasty implants. In fact, it became the material of choice for cranioplasty during World War II. There are several interesting historical facets and lessons that arose from tantalum's use in the wartime era. During this time, there was a rapid evolution in implant fixation techniques. The experience of neurosurgeons with tantalum for cranioplasty also refined their appreciation of the attributes of an ideal synthetic material for cranioplasty. While tantalum plates did not enjoy an enduring use as cranioprotheses, their use did change the way neurosurgeons, at the time, thought about the procedure. Hence, the story of the rise and fall of tantalum use serves as a lesson in innovation and innovative thinking.

Abbreviations used in this paper: EEG = electroencephalography; PMMA = polymethylmethacrylate.

Evolution of Cranioplasty

Early Development

Substantial evidence suggests that cranioplasty was performed in ancient and possibly prehistoric civilizations. While trephination was much more common, some cranioplasties are believed to have been performed by Incan surgeons using materials such as gourds, shells, and gold and silver plates during 3000–2000 BC.⁴ It is also speculated that skull fragments, known as “rondelles,” may have been used by ancient Europeans for cranioplasty.⁵³ Fallopius (1523–1562) is credited with the first true description of a cranioplasty. In his description of the management of cranial fractures, he recommended the removal of bone surrounding a cranial fracture in cases of dural violation and replacement with a gold plate.⁵⁹ In the 16th century, various materials as diverse as ox horn, hard rubber, and sheet mica were used for cranioplasty, each with varying rates of success.⁷⁶ The earliest instance of a cranioplasty utilizing a bone graft was performed in Moscow. The story was reported by Job Janszoon van Meekeren in 1668. A portion of the skull from a deceased dog was used to successfully repair a cranial defect in a nobleman.⁵⁹ The graft was successful, and the patient returned to normal health. However, the graft was later

removed because of the opposition by the church citing that the use of an animal's bone was marring God's image.^{27,51} Aside from some cranioplasties performed by the native South Sea populations using coconut shells, few cranioplasties were recorded for more than 200 years after van Meekeren's report.¹⁸

Autograft Cranioplasty

In the mid-19th century, Ollier (1859) and Macewen (1873) described and popularized the use of autograft for cranioplasty.^{27,39,59} In 1890, Müller generated a single flap of scalp, pericranium, and outer table calvaria from the region adjoining a cranial defect.⁴⁷ Later that year, König refined this method by describing the use of twin flaps.^{33,60} The Müller-König method became the most used cranioplasty technique for about a decade (Fig. 1). The main shortcoming of this technique was poor cosmesis from both the rotation of scalp flaps and the depression overlying the outer table donor site. In 1903, von Hacker improved the scalp cosmesis of the Müller-König method by only shifting the periosteum and outer table from the bone surrounding the cranial defect (Fig. 2).⁷⁶ In the 1900s, the von Hacker technique quickly became the most popular method of cranioplasty.

Soon after local autograft became popular, various authors attempted to obtain free autograft from various sources such as the sternum, scapula, ribs, ilium, and tibia.^{15,47,58,59} By 1909, osteoperiosteal grafts from the tibia were the most common method of cranioplasty (Fig. 3). In several papers Villandre reported a total of 130 cases

of autograft cranioplasties from various donor sites and concluded that the best results were obtained from osteoperiosteal tibial grafts.²⁷ In 1920, Delangenire published a series of 104 cases of cranioplasty with osteoperiosteal tibial grafts with only two failures.⁷⁶ Around the early 20th century, it became general neurosurgical opinion that autograft cranioplasty was superior to available allografts.⁵⁹

Search for a Suitable Synthetic Material

Although autograft cranioplasty was most prevalent, the added time, blood loss, and donor site morbidity led many to continue to search for a suitable synthetic material for cranioplasty. The most common synthetic material used during the early 20th century was celluloid followed distantly by gold and aluminum. Celluloid, created from nitrocellulose and camphor among other compounds, was first described in 1870. Because celluloid was readily available and easily malleable, several surgeons attempted to use it for cranioplasty. The first cranioplasty with celluloid was described by Fraenkel in 1890.²⁰ In 1939, Ney reported 300 cases of celluloid cranioplasty with very good results.^{48,76} However, most other reports were less enthusiastic due to a substantial inflammatory reaction around the implant and subsequent fluid accumulation that required frequent aspiration.^{54,59,76} Gold and, to a lesser extent, platinum were used for cranioplasty, but their use was limited by high cost.²⁷ Lead cranioplasty was attempted but resulted in significant tissue toxicity.⁵ Reports of aluminum cranioplasty were marred by high infection rates.¹¹ The ideal synthetic material was malleable, strong,

Fig. 1. The Müller-König method. **a:** An S-shaped incision made around the cranial defect (1) to create a second flap (2) containing scalp, periosteum, and outer table. **b:** This flap is then rotated to cover the cranial defect. **c:** The final appearance after closure. **d:** Cosmesis was generally suboptimal. From Woolf: *Int Abstr Surg* 81:1–23, 1945. Reproduced with permission from *Journal of the American College of Surgeons* (formerly *Surgery, Gynecology & Obstetrics*).

History of tantalum cranioplasty

FIG. 2. The von Hacker modification of the Müller-König technique. A single scalp flap is elevated and an osteoperiosteal graft containing outer table only is harvested from the region adjoining the cranial defect (**left**), rotated into the defect, and sutured (**right**). From Woolf et al: *Int Abstr Surg* 81:1–23, 1945. Reproduced with permission from *Journal of the American College of Surgeons* (formerly *Surgery, Gynecology & Obstetrics*).

inert, radiolucent, readily available, and economical.² Despite numerous attempts, cranioplasty utilizing synthetic materials did not gain widespread use because a suitable synthetic material had not yet been discovered.

In the late 1930s, the interest in synthetic cranioplasty was resurrected with the introduction of Vitallium.^{9,26,52} Experimental and clinical evidence demonstrated little tissue reaction when used in cranioplasty.^{9,26,52} However, there were a few key limitations to Vitallium. First, the Vitallium alloy was associated with a corrosion-induced release of highly toxic chromium salts. Second, Vitallium was not malleable and, therefore, often required an operation to create a “cast” that could be used to shape the Vitallium prosthesis *ex vivo* and a second operation for implantation of the prosthesis.¹²

Discovery of Tantalum

Swedish chemist and mineralogist Anders Gustaf Ekeberg (1767–1813) is credited with the discovery of the tantalum in 1802.⁷⁴ The previous year, the element niobium (then called columbium) was discovered by English chemist Charles Hatchett. Due to their high degree of chemical similarity and tendency to be found together, it was not until 1864 that tantalum and niobium would be unequivocally confirmed as separate chemical elements.⁴³

Tantalum (chemical symbol Ta, atomic number 73) is a very dense yet malleable metal. Unlike most metals, tantalum is very resistant to corrosion.¹ The name tantalum is derived from the Greek mythological figure Tantalus, son of Zeus. His punishment for sharing the gods’

secrets with mortals is a famous one. In the underworld, he was made to stand in a pool of water up to his neck. Whenever he would lean down to quench his thirst, the water would recede before he was able to take a drink. Accordingly, Ekeberg named his newly discovered element tantalum because upon its submersion in acid, it did not absorb or react with the acid.^{13,28}

Experimental Evidence

The *in vivo* corrosion of metallic implants occurs as a result of the constant presence of new oxygen molecules in vascularized tissues. Oxidative corrosion of metallic implants used for cranioplasty can cause tissue necrosis primarily due to the liberation of metallic ions from the metal’s surface. Therefore, for the purpose of implantation in humans, it appeared critical to find a metal that would either corrode extremely slowly or in a manner that was not injurious to the patient.¹² In a preliminary report in 1940, Burke began to test the biological inertness of tantalum by placing pieces of the metal in Ringer’s solution at body temperature for a 3-month period. The appearance and weight of both the metal and the solution remained unchanged.¹² In their next experiment, tantalum plates and screws were implanted on the tibia and femur of 6 dogs and rabbits and removed between 3 and 12 weeks later without any noticeable signs of bone or soft-tissue reaction.¹² Shortly thereafter, Pudenz confirmed the relative inertness of tantalum by performing experimental tantalum cranioplasties in 11 cats.⁵⁵ One important finding in this animal series was the formation of a

Fig. 3. Osteoperiosteal graft from the patient's tibia is placed in the cranial defect and sutured to the surrounding periosteum. From Woolf et al: *Int Abstr Surg* 81:1–23, 1945. Reproduced with permission from *Journal of the American College of Surgeons* (formerly *Surgery, Gynecology & Obstetrics*).

connective tissue capsule around the implant. This was actually thought to be a significant advantage at the time because onlay or inlay implantation techniques without fixation were common. Therefore, scar tissue formation could theoretically help prevent implant migration. In none of the cases was the scar tissue compressive, nor did the implant interfere with spontaneous bone regeneration. Most importantly, the tantalum implant remained intact without corrosion.

Clinical Experience

War Applications

World War II began in 1939 and the US entered the war after the attack on Pearl Harbor on December 7, 1941. It was estimated that 5.9% of American World War II casualties were due to head injuries.⁷⁵ The grand scale of the war greatly increased the need for cranioplasty procedures. The clinical problem was aptly described by the neurosurgeon Lieutenant Commander O. Hugh Fulcher in 1943:²²

Cranial defect in military surgery represents a most important problem because of the frequency of occurrence and because it renders a man unfit for military duty unless it can be adequately repaired. Therefore an adequate method of repair is urgent, one which can be performed by the general surgeon as well as by the neurologic surgeon in any ordinary general hospital wherever it may be located. Moreover, the repair should render protection to the intracranial structures against blows, changing atmospheric pressures and changing bodily positions, which should approximate that afforded by the normal cranium. The convalescence following the operative procedure should be brief to keep 'as many men at as many guns as many days as possible'.

Unlike autograft and Vitallium, tantalum greatly simplified the cranioplasty procedure by allowing a single-stage repair in which the implant could be easily cut and shaped with basic instruments. The first recorded use of tantalum for cranioplasty was in the fall of 1941 by Fulcher in the US Naval Hospital in Washington, DC.²²

The operation was successful, and the patient returned to duty 2 months after the operation. After this initial operation, more than 1000 cases of tantalum cranioplasty were performed in the subsequent 5 years.^{36,67}

The majority of published case series describing tantalum cranioplasties occurred in the military population (Table 1). A total of 402 patients underwent tantalum cranioplasty in published series alone during World War II. For uncomplicated bony defects, a sheet of tantalum could be molded by the surgeon intraoperatively or molded over a standard skull model preoperatively, followed by minor adjustments intraoperatively.⁷⁵ Hemberger et al. described an elaborate technique for implant formation using various molding materials shaped over the depression in the scalp corresponding to the defect. This "cast" was then used to shape the tantalum plate preoperatively.³⁰ For complicated bony defects particularly involving the orbital ridges, the repair was performed in 2 stages. A sterile dental mold was created in the first operation, from which a custom made implant was produced and implanted during a second operation.

Implant Fixation Technique

Initially, tantalum implant migration was occasionally observed after cranioplasty.^{14,23,30} Loose or migrated plates were also associated with scalp erosion.⁷³ Originally, tantalum plates were placed in an onlay fashion and secured by suturing adjacent periosteum or pericranium over the plate.^{21,22} Lewin et al. published the largest clinical series of tantalum cranioplasties (130 cases), performed at the Oxford Military Hospital for Head Injuries. The authors sutured adjacent pericranium or periosteum to perforations made in the plate.³⁷ In some cases, they covered the plate with an additional layer of fascia lata that was sutured to surrounding pericranium. They noted that this method was often insufficient for frontal cranioplasties, likely due to the added effect of gravity. In these cases, they used tantalum wire to secure the implant to the calvaria. Many authors adopted 30-gauge tantalum or stainless steel wire instead of suture for such purposes (Fig. 4).^{30,38,40,42,44,56}

Before wire and screws became readily available, more involved inlay techniques were also developed to minimize the risk of implant migration (Fig. 5). Simple inlay involved drilling the outer table for a few millimeters beyond the defect to allow the plate to sit in the ledge.¹⁴ Others bent the edges of the tantalum plate 90° and seated this ledge into cancellous bone via a groove made through the outer table.^{30,44,56,75} The "inlay with groove" technique was sometimes insufficient alone to prevent migration.⁵⁶ Therefore, this technique was commonly supplemented with tantalum triangular wedges, in which the point was seated into the cancellous bone exposed in the groove and the base was folded over the plate (Fig. 5).^{30,44,56,75} With the various aforementioned techniques, plate migration was relatively uncommon, ranging from 0% to 5%.^{30,56,75} These studies generally lacked long-term follow-up, so the true incidence of implant migration is not known.

Tantalum screws were generally not available to US military surgeons during World War II. However,

TABLE 1: Tantalum cranioplasty clinical series*

Authors & Year	No. of Patients	Patient Population	Implant Technique & Fixation†	Plate Thickness (in)	Clinical Outcome	Hospital
Robertson, 1944	26	military	1-stage (92%), 2-stage (8%); inlay w/ groove technique w/ wire suture or tantalum wedges	0.015 & 0.020	100% successful repairs; 0 infections, 1 (4%) CSF leak, 1 early revision for plate migration	Brooke General, Fort Sam Houston, TX
Hemberger et al., 1945	42	military	single perforation in plate; inlay only (14%); inlay + tantalum wire (14%); inlay w/ tantalum wedges (71%)	0.015	1 early plate migration before wires or tantalum wedges; no other outcomes reported	Walter Reed General, Washington, DC
Woodhall & Spurling, 1945	79	military	single perforation in plate; frequently used 2-stage repair w/ cast molds; inlay w/ groove technique + tantalum wedges	0.015 & 0.020	46% returned to duty, 54% discharged (28 neuro deficit, 6 EEG epileptogenic focus, 5 convulsions); 2 (3%) infections, 1 plate migration, 1 extradural pneumatocele (frontal sinus)	Walter Reed General, Washington, DC
Mayfield & Levitch, 1945	20	military	multiple perforations in plate; inlay w/ groove technique + tantalum wire; preop scalp mold used to facilitate 1-stage repair	0.0125 & 0.025	2 (10%) returned to duty, 10 (50%) discharged, 8 (40%) under observation; 2 (10%) infections	NA‡
MacKay & Russell, 1946	25	military	devised a spherical mold matching generic bilat frontal & parietal curvatures w/ equal radii to make ready-made implants; inlay (72%) or onlay (20%) technique w/ tantalum wedges, wire, or ribbon	0.015	successful cosmetic results in all cases; complications not reported	US Naval Base Hospital, Guam, Marianas Islands
Bakody, 1946	40	military	multiple perforations in plate; inlay w/ groove technique + tantalum triangular wedges	0.015 & 0.020	3 known failures: 1 seroma requiring reoperation & insertion of perforations in the plate; 1 necrotic wound requiring revision; 1 motor vehicle accident requiring plate reshaping	US Naval Hospital, Great Lakes, Illinois
Gardner, 1946	8	civilian	perforated plates; onlay method w/ tantalum screw fixation	NA	6 recoveries, 2 implant removals & subsequent deaths	Cleveland Clinic, Cleveland, Ohio
Lane & Webster, 1947	NA	military	various	NA	survey of 116 hospitals: 52 tantalum plates required removal; 26 (50%) involved frontal region & 18 (35%) involved frontal sinus	116 different Veterans Hospitals
Lewin et al., 1948	128	military	1-stage simple defects, 2-stage w/ cast molding for complex contours; onlay method (96%) + silk sutures to pericranium	0.015	11/130 (8%) plates removed (5 infection, 2 cosmesis, 4 intracerebral complication); 1 operative death from postop status epilepticus; local irritation in 7%	Oxford (United Kingdom) & Camps in Northwest Europe
Fulcher, 1948	12	military	multiple perforations in plate; simple inlay technique; perosteum folded & sutured over plate w/ silk	0.025	11 (92%) good outcomes, 1 (8%) failure in an unperforated plate	NA§
Weiford & Gardner, 1949	106	civilian	nonperforated plates; onlay technique + tantalum screws; 10 epilepsy cases, dura replaced w/ a tantalum plate	0.020 (early), 0.007	8 (8%) implants removed (4 infection, 4 scalp erosion); 1 operative death; 10 epilepsy cases: seizures better (1), unchanged (8), worse (1)	Cleveland Clinic, Cleveland, Ohio
Makela, 1949	30	military	onlay technique + tantalum screws or wires	0.015	improvement in headache (56%), vertigo (59%), & epilepsy (53%); new cold sensitivity at implant (41%); 1 removed; 1 infection (3%).	Finnish Red Cross Hospital, Helsinki, Finland

* Case reports of clinical series with fewer than 5 patients excluded. NA = not available; neuro = neurological.

† See Figure 5 for description of inlay techniques.

‡ Although not mentioned in the paper, Dr. Frank H. Mayfield was Chief of Neurosurgery at Percy Jones General Hospital (Battle Creek, MI) from 1942 to 1945.

§ O. Hugh Fulcher was a Professor of Neurosurgery at Georgetown University in 1948 at the time of publication. The location at which he performed his clinical series during World War II was likely at the US Naval Hospital, Washington, DC.

FIG. 4. Tantalum plate secured with stainless steel wire threaded through perforations in the plate and the outer table. Reproduced with permission from Lockhart et al: *J Neurosurg* 9:254–257, 1952.

shortly after the war, tantalum screws with a simple onlay technique supplanted all prior implantation/fixation techniques due to the speed and ease by which screws could be placed in addition to the superior rigidity they provided.^{71,73}

Tantalum Plate Thickness

During the tantalum cranioplasty era, there was much disagreement regarding the optimal thickness of tantalum plates. Mayfield and Levitch reported that plates 0.125–0.250 inches in thickness were easily molded and possessed sufficient strength.⁴⁴ Several surgeons believed 0.015 inches was the ideal thickness of a tantalum plate.^{41,65,75} In contrast, Fulcher^{21,22} and Bakody⁷ believed 0.025 inches was necessary to protect the brain. Oscar A. Turner studied the mechanical response of tantalum plates to impact.⁶⁸ He claimed that the extent of trauma to cranioprostheses had been underplayed in the literature and proposed that a thickness of less than 0.010 inch was insufficient to protect patients against even minor blows (Fig. 6).⁶⁸

On the contrary, Gardner progressively decreased the thickness of the tantalum plates he used from 0.020 to 0.007 inches in his published series of 106 tantalum cranioplasties.⁷¹ He believed 0.007 inches to be the optimal thickness because it was less expensive, more malleable, and most importantly, decreased the plate's radiopacity enough to allow pneumoencephalography and angiography (Fig. 7).²⁴

a Simple Inlay

b Inlay with groove

c Triangular wedge

FIG. 5. Inlay techniques. **a:** Simple inlay: the outer table extending several millimeters beyond the cranial defect was removed to allow the plate to sit in the trough. **b:** Inlay with groove: a groove through the outer table was chiseled to allow the bent edges of the plate to sit in the groove. **c:** Triangular wedge: a supplementary fixation technique using triangular wedges with the point driven into the cancellous bone and the base folded over the plate.

Clinical Outcome and Complications

For studies reporting on infection rates (5 studies, 283 patients), the overall infection rate was 3.5%.^{37,42,44,56,75} Two studies reported on return to duty outcomes after tantalum cranioplasty.^{44,75} The larger of the two studies (79 patients) reported that 46% of soldiers returned to duty and 54% were discharged from the military, most commonly due to neurological deficits or either clinical seizures or the presence of an epileptogenic focus on electroencephalography (EEG).⁷⁵ One study in Finland reported on symptomatic outcomes in 30 patients.⁴² Improvements were observed in preoperative headache (56%), vertigo (59%), and epilepsy (53%) after tantalum cranioplasty. However, 41% of patients experienced new cold sensitivity at the implant site, with one patient requiring implant removal for this reason. The high thermal conductivity of tantalum leading to cold or heat sensitivity was a shortcoming of tantalum that was likely underreported in the literature.

Civilian Applications

The success neurosurgeons experienced with the use of tantalum for cranioplasty during World War II naturally carried over to the civilian population after the war. W. James Gardner, chief of neurosurgery at the Cleveland

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Fig. 6. Removed tantalum plate (0.007 inch) with marked indentation after repeat trauma. Reproduced with permission from Turner: *J Neurosurg* 9:100–103, 1952.

Clinic, was one of the strongest proponents of tantalum. Gardner, along with Wieford, published the largest civilian population case series (106 patients) of tantalum cranioplasty.⁷¹ He used tantalum cranioplasty in 26 old cranial defects, 12 contaminated traumatic defects (Fig. 8), 55 clean operative defects, and 13 infected operative defects. It was generally believed that the indications for cranioplasty for old cranial defects were syndrome of the trephined (headache, dizziness, difficulty concentrating, and fatigue), brain protection, cosmesis, and painful pulsating defects.^{6,14,25,27,71} Traumatic epilepsy was a controversial indication for cranioplasty. Some authors found that repair had no effect,⁴⁴ whereas others found the opposite.⁷¹ Gardner reported that 9 of 10 patients with traumatic epilepsy had reduced seizure frequency or were seizure free postoperatively.

Interestingly, Gardner attempted to perform tantalum cranioplasty in 10 patients with nontraumatic Jacksonian epilepsy. In prior tantalum cranioplasties done for other indications, he noticed that postoperative routine EEG demonstrated a reduction in voltage potential. This, combined with the reduction of seizure frequency after tantalum cranioplasty in the traumatic epilepsy population, led Gardner to believe that the tantalum metal possibly had a grounding effect.⁷¹ In 10 cases, he performed a large frontoparietal craniotomy, resected the dura, and fastened a tantalum plate to the inner table such that when he replaced the bone flap, the plate came into contact with the cortical surface (Fig. 9). Unfortunately, 8 of 10 patients had no change in seizure frequency, and 1 patient actually had more frequent seizures. Postoperative EEG demonstrated a reduction in voltage potential but no change in abnormal delta waves. Gardner concluded that the plate simply caused electrical interference rather than having any effect on cortical electrical activity. He subsequently abandoned this technique.

Two additional applications of tantalum in civilian neurosurgical procedures are worth noting. In 1948, Lester A. Mount described the use of tantalum discs to cover bur holes made with the Hudson brace.⁴⁶ This represented an original form of the bur hole covers commonly used today. The tantalum discs had tabs that were folded down into the bur hole to help prevent the disc from migrating (Fig. 10). Another important application of tantalum in neurosurgery was the use of tantalum dust in craniotomy. Whitcomb and Scoville were the first to report the use of tantalum dust in nervous tissue, which they used to mark the plane of a lobotomy on postoperative radiography.⁷² However, the more common indication for tantalum dust was to diagnose recurrent subdural hematoma using a technique first described by Vieth and colleagues.⁶⁹ After surgical evacuation of a subdural hematoma, tantalum dust was sprinkled over the cerebral cortex and a tantalum clip was placed on the dura. The distance between the tantalum dust and clip on an anteroposterior radiograph then served as a measure of the subdural space (Fig. 11).

The Importance of Plate Perforations

The original tantalum cranioplasty implants consisted of a smooth nonperforated sheet of metal. The

Fig. 7. Pneumoencephalogram with air-filled ventricles (**left**) and angiography with diodrast-filled vessels (**right**) easily visualized through a 0.007-inch tantalum implant. Reproduced with permission from Gardner: *J Neurosurg* 7:590–591, 1950.

FIG. 8. Civilian gunshot wound from Gardner's case series. **Upper Left:** Preoperative radiograph demonstrating comminuted left frontal fracture with intraparenchymal shrapnel. **Upper Right:** Intraoperative appearance during debridement. **Lower Left:** Nonperforated tantalum plate using onlay technique secured with tantalum screws. **Lower Right:** Postoperative radiograph demonstrating the radiopaque nature of a 0.020-inch-thick tantalum plate. Reproduced with permission from Weiford et al: *J Neurosurg* 6:13–32, 1949.

advantage of this design was that a smooth encapsulated sheath would form around the plate and prevent adhesion to the underlying cortex or dura. This characteristic made it easy to remove the implant when reoperation was nec-

essary. However, numerous authors described several advantages of placing multiple perforations in the plate prior to implantation. Before implant fixation techniques were refined, plate migration was a major concern. The use of

FIG. 9. Gardner's method of tantalum dural replacement for intractable cortical epilepsy. **Left:** A craniotomy is performed, the dura is resected, and a tantalum plate is fastened to the inner table of the free bone flap. **Right:** The bone flap is then replaced. Gardner hypothesized the tantalum metal may function to ground aberrant cortical electrical activity. However, after 10 cases, Gardner concluded this method was ineffective. Reproduced with permission from Weiford et al: *J Neurosurg* 6:13–32, 1949.

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Fig. 10. Upper: Tantalum disc with tabs cut to the width of the bur hole. Lower: Postoperative radiograph with a tantalum disc used to cover the frontal bur hole. Reproduced with permission from Mount: *J Neurosurg* 5:208–210, 1948.

perforations promoted scar tissue formation between the dura and galea, which helped secure the implant.⁷³

The major advantage provided by plate perforations was to simplify the management of postoperative infection. A few authors reported that some postoperative infections could be treated without plate removal by a combination of subgaleal fluid aspiration(s) and both subgaleal and intravenous antibiotics.^{7,21,25,44,70} Perforations in the plate allowed the epidural and subgaleal fluid to communicate. Therefore, one could aspirate any fluid underneath the plate.⁷³ Additionally, soft tissues grew into the perforations during wound healing, which increased the blood supply to the infected area. This also had the advantage of allowing increased antibiotic delivery to the area around the plate.^{7,21,44,70} In fact, some neurosurgeons observed that perforated plates became infected less frequently.^{44,45} Although not known during the tantalum cranioplasty era, it is now known that certain bacteria such as *Staphylococcus epidermidis* can form biofilms on metal implants that can prevent the penetration of antibiotics.^{8,29,34,35,50} Perforations would also serve to decrease the surface area on which biofilms could form. Today, most

titanium cranioplasty implants are either perforated or in a mesh-like pattern.

The Demise of Tantalum and Rise of Acrylics

Despite its widespread use for cranioplasty during World War II, tantalum use in cranioplasty declined precipitously in the early 1950s. Acrylic (polymers based on acrylic acid) was the primary successor of tantalum for cranioplasty. Research on acrylic cranioplasty began during the early tantalum era in the early 1940s. Prior to the war, acrylic resins were used for dental implants with no observed adverse tissue reactions.⁷⁵ In the decade after World War II, experimental and early clinical reports of acrylic cranioplasty demonstrated a promising safety and efficacy profile.^{3,10,16,17,19,32,40,49,57,64,66} However, it was Spence's report in 1954 that made a strong case for using acrylic rather than tantalum for cranioplasty.⁶⁴ Spence convincingly detailed the personal, economic, and medical shortcomings of metal plates. First, there existed a significant social stigma associated with having metal in one's head. Second, tantalum was very costly to manufacture. Third, several authors hypothesized that postoperative headaches and local heat or cold sensitivity could be due to the high thermal conductivity of tantalum.^{5,42,73} Finally, the radiopacity of tantalum remained at least a moderate hindrance to meaningful postoperative diagnostic imaging. Acrylics overcame all these limitations.

Spence reported favorable results with polymethylmethacrylate (PMMA).⁶⁴ Unlike metals, PMMA facilitated the filling of cranial defects, which Spence believed prevented brain herniation into the dead space of the cranial defect. Although initially seen as an advantage, the radiolucency of PMMA actually presented a clinical dilemma. In cases of repeat trauma, radiography could not be used to diagnose implant fracture or the displacement of fragments.³¹ Eventually, a small amount of barium was added to the commercially available PMMA mixtures to allow adequate imaging of the implant while maintaining sufficient radiolucency to avoid interference with angiographic imaging.³¹

Polymethylmethacrylate did have its limitations, such as the inhibition of bone growth, and some interest in metals remained. Some authors favored stainless steel because it was also malleable, yet was less than 1% of the cost of tantalum.^{61,62} Titanium, first used for cranioplasty by Simpson in 1965, eventually became the metal of choice and completely halted the production of tantalum cranioprotheses.⁶³

Conclusions

The World War II era heralded a renaissance for cranioplasty. The enormous scale of the war greatly increased the demand for cranioplasty procedures. Tantalum provided a major breakthrough in synthetic cranioplasty as it was strong, readily available, malleable, and biologically inert. This enabled military neurosurgeons to repair cranial defects expeditiously in a single stage without the donor site morbidity of autograft. The surgical technique, particularly in regard to implant fixation, was refined during the war. These developments represent a lasting con-

FIG. 11. **A:** Postoperative anteroposterior radiograph obtained after subdural hematoma evacuation. Tantalum dust is sprinkled onto the cortical surface, and tantalum clips are placed onto the dura to approximate the dimensions of the subdural space. **B:** After several months, a decrease in subdural space is evidenced by decreasing the distance between the tantalum dust and clips. Reproduced with permission from Vieth et al: *J Neurosurg* 24:514–519, 1966.

tribution to the field of neurosurgery. Finally, the limitations of tantalum further defined the attributes of the ideal synthetic material for cranioplasty and pushed scientists and neurosurgeons to search for better materials.

The lessons learned from this historical vignette can inform modern innovation in cranioplasty materials and techniques. We must learn from those who preceded us, lest we become doomed to repeat their mistakes.

Disclosure

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

Author contributions to the study and manuscript preparation include the following. Conception and design: Kshetty. Acquisition of data: Kshetty, Flanigan. Analysis and interpretation of data: Kshetty, Flanigan. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Kshetty. Study supervision: Benzel.

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