

Autogenous Bone Cranioplasty: Review of a 42-Year Experience by a Single Surgeon

Nicole C. Cabbad, M.D.,
M.B.A.

Mark W. Stalder, M.D.

Aaron Arroyave, B.S.

Erin M. Wolfe, B.S.

S. Anthony Wolfe, M.D.

Miami, Fla.; and New Orleans, La.



Background: Autogenous bone is frequently espoused as the gold standard material for cranioplasty procedures, yet alloplastic cranioplasty continues to persist in the search, presumably, for a simpler technique. Although short-term outcomes can be successful using foreign materials, long-term follow-up in these patients often demonstrates increased rates of failure because of exposure or late infection. Autogenous bone grafts, however, integrate and revascularize, and are thus more resistant to infection than alloplastic materials.

Methods: This is a retrospective review of all patients that underwent reconstructive cranioplasty for full-thickness defects, as performed by the senior author (S.A.W.) between 1975 and 2018. All procedures were performed with autogenous bone.

Results: One hundred fifty-four patients met criteria for inclusion in the report. Cranioplasties were performed for both congenital and secondary indications. Split calvaria was used in 115 patients (74.7 percent), rib graft was used in 12 patients (7.8 percent), iliac crest graft was used in 10 patients (6.5 percent), and combinations of donor-site grafts were used in 17 patients (11.0 percent). In the entire series, none of the patients suffered from complications related to infection of either the donor site or transferred bone graft. None of the patients required secondary operations to fill in defects created by the postoperative resorption.

Conclusions: Although autologous bone is widely considered the gold standard material for cranioplasty procedures, some argue against its use, mainly citing unpredictable resorption as the purported disadvantage. However, it is less susceptible to infection, and results in fewer long-term complications than alloplastic materials. There is no alloplastic material that has matched these outcomes, and thus autogenous bone should be considered as the primary option for cranioplasty procedures. (*Plast. Reconstr. Surg.* 143: 1713, 2019.)

CLINICAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, IV.

Cranioplasties have been performed since the beginning of known human civilization. Thousands of years ago, the Incans used disks of silver and gold to repair trephination defects.¹ The choice of defect fill material has advanced from these precious metals to autologous bone, and now to three-dimensionally

printed synthetic materials. The advances in craniofacial surgery, championed by Dr. Paul Tessier, came because of our increased understanding of

Disclosure: *The authors have no financial disclosures related to this research article.*

From the Department of Plastic and Reconstructive Surgery, Nicklaus Children's Hospital; the Herbert Wertheim College of Medicine, Florida International University; and the Division of Plastic and Reconstructive Surgery, Louisiana State University Health Sciences Center.

Received for publication November 12, 2017; accepted November 13, 2018.

Copyright © 2019 by the American Society of Plastic Surgeons

DOI: 10.1097/PRS.0000000000005677

Supplemental digital content is available for this article. Direct URL citations appear in the text; simply type the URL address into any Web browser to access this content. Clickable links to the material are provided in the HTML text of this article on the *Journal's* website (www.PRSJournal.com).

bone grafts, including their harvest, their contouring, and their survival.

The late 1800s to early 1900s saw the first studies on the successful use of autogenous bone as fill material for cranial defects, with Axhausen in 1916 reporting on 27 successful osteoperiosteal grafts from the tibia.²⁻⁶ Delagenière later performed 104 cranioplasties using osteoperiosteal grafts from the tibia with only two failures, a primary success rate of over 98 percent in the preantibiotic era.⁷ In another article, Manson et al. reported on a series of frontal cranioplasties performed at Johns Hopkins Hospital using both autogenous bone and methylmethacrylate.⁸ There were no infections in the alloplastic group ($n = 25$; length of follow-up is not provided) and four infections (23 percent) in the autologous group ($n = 17$). In an invited commentary on the article, the senior author of this article commented that this ran counter to his own experience,

However, synthetic materials continue to be preferred by most surgeons. In 1943, Gurdjian et al. reported the first use of methylmethacrylate, which can be contoured to any shape by means of an exothermic polymerization.⁹ Titanium mesh, hydroxyapatite, and polyetheretherketone have also become popular alloplastic materials.¹⁰⁻¹⁴ With the availability of three-dimensional printers, custom-made implants of polyetheretherketone and other materials are now widely used in many institutions.¹² The increase in use of alloplastic materials is likely attributable to their ease of use, the perceived dissolution of donor-site morbidity, and the unfamiliarity of many in working with autogenous bone. This study evaluates 42 years of work from the senior author (S.A.W.) to evaluate the complication rate when using autogenous bone for cranioplasty repair.

PATIENTS AND METHODS

This is a retrospective review of all patients that underwent reconstructive cranioplasty for full-thickness cranial defects performed by the senior author between January 1, 1975, and January 1, 2018. Three independent reviewers, one of whom was the senior author, evaluated the operative schedule and office records in the specified time frame to determine eligibility for the study. Inclusion criteria included patients who underwent secondary cranioplasties. Excluded were patients who underwent primary cranioplasties and those without full-thickness defects. Procedures classified as primary cranioplasties were those that were performed for the correction of deformities of congenital cause, such as

cranial vault reconstruction for fibrous dysplasia, Treacher-Collins syndrome, and other conditions. Procedures classified as secondary cranioplasties were those in which established calvarial defects—typically resulting from traumatic or neoplastic causes—were treated. Demographic information collected included age at the time of surgery, sex, time to last follow-up visit, and procedure performed. It is not the practice of the senior author to use cold-stored bone flaps; therefore, all cranial bone grafts were freshly split grafts obtained at the initial reconstructive operation unless otherwise specified. A complication was defined as the need for an additional surgical intervention not in the initial treatment plan, such as reoperation for infection or resorption. The study design was examined by the institutional review board and was determined to qualify for an exemption.

RESULTS

Two hundred twenty-five patients were identified to have undergone cranioplasty reconstruction. After excluding patients who underwent primary cranioplasty, there were 154 patients (68.4 percent) who met criteria for inclusion in this study (Fig. 1). Sixty-nine (44.8 percent) were female patients and 85 (55.2 percent) were male patients. Mean age at the time of surgery was 24.9 years, with a range from 1 to 79 years. Seventy-one of the patients (46.1 percent) were pediatric as defined by age of 21 years or younger, and 83 of the patients (53.9 percent) were adults (Table 1). Minimum follow-up time was 0.5 year, with a maximum follow-up time of 32 years. All patients except for one had autogenous bone used as the reconstructive material for the cranioplasty defect, for a total of 153 patients (99.4 percent). The cause of the defects varied between traumatic, ballistic, infectious, and neoplastic origin. More recently, an increasing amount of the defects were attributable to decompressive craniectomy. Donor sites for bone grafts used to perform the cranioplasties included split cranial bone in 115 patients (74.7 percent), split rib grafts in 12 patients (7.8 percent), iliac crest graft in 10 patients (6.5 percent), and a combination of donor sites grafts in 17 patients (11.0 percent) (Fig. 2). Of note, use of split rib graft did not become popular until it was described by Dr. Tessier in the 1980s. One patient, because of advanced age, had titanium mesh used instead of autogenous bone to fill a postparietal cranial defect. Eight patients (5.2 percent) had bone morphogenetic protein (BMP) used in combination with autogenous bone. Twenty-seven patients (17.5 percent)

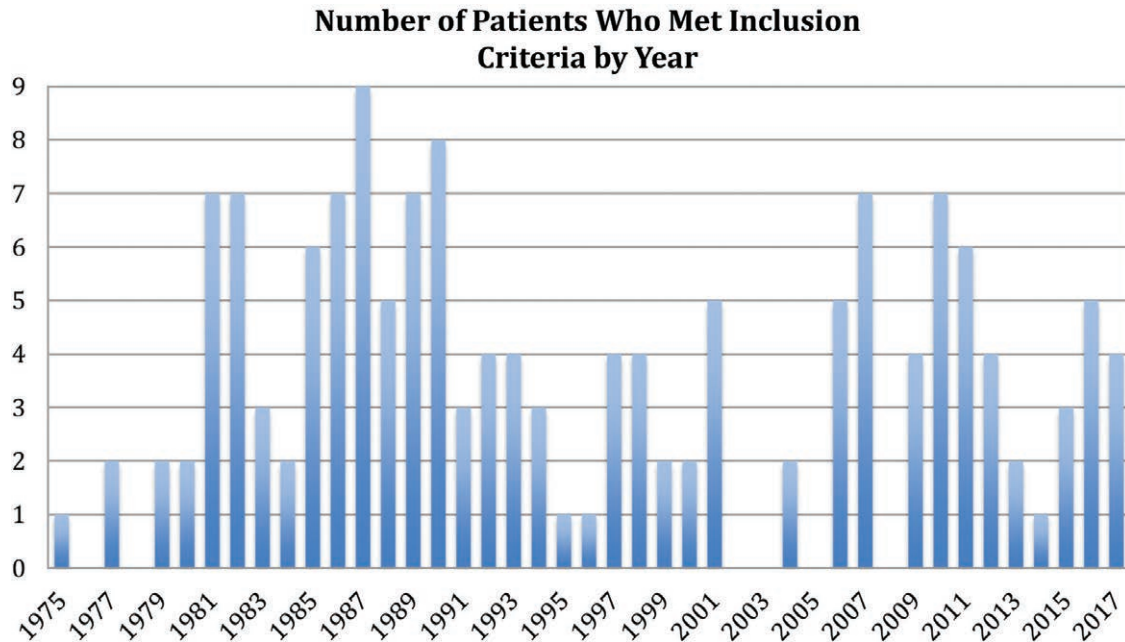


Fig. 1. Patients who met inclusion criteria (secondary cranioplasties) per year from 1975 to 2017.

Table 1. Breakdown between Primary and Secondary Cranioplasties, Sex Distribution, and Pediatric versus Adult Patients

Characteristic	No. (%)
Total no. of patients	225
Type of cranioplasty	
Primary	71 (31.6)
Secondary	154 (68.4)
Sex	
Male	85 (55.2)
Female	69 (44.8)
Age group	
Pediatric (<22 yr old)	71 (46.1)
Adult	83 (53.9)

had multiple operations that included staged cranioplasty because of microsurgery, multiple donor sites, and reconstruction of different areas. None of the patients suffered from complications related to infection of either the donor site or the transferred bone graft.

There was one patient in the combined autogenous plus BMP cohort who developed a seroma after the use of recombinant BMP-2 at the graft harvest site that required reoperation for evacuation of the seroma with placement of dural suspension sutures (Fig. 3). The authors consider this a complication of the use of BMP and not a complication of the autogenous bone because the complication was at the harvest site where the BMP was placed. Given the small numbers of autogenous plus BMP patients in this cohort, the relative risk of adding BMP to the reconstruction is still not known. All

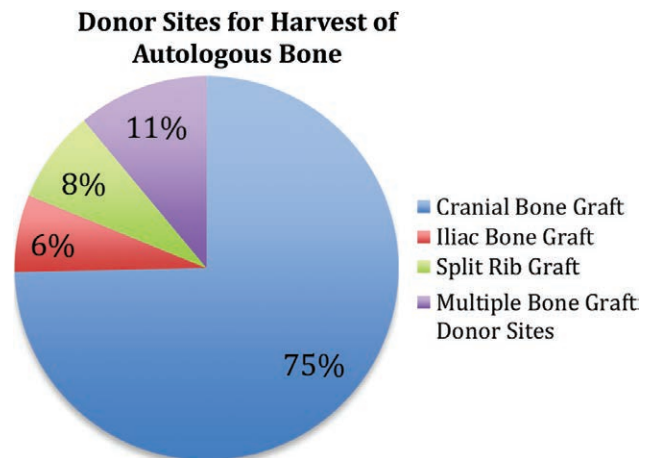


Fig. 2. Donor sites for harvest of autogenous bone grafts.

of the cases requiring multiple operations for bone harvest were because of planned procedures based on the size of the defect at the time of initial operation. None of the patients required secondary operations to fill in defects created by postoperative resorption. Figures 3 through 6 demonstrate several patient case examples of the senior author's technique and results, including one case where BMP was used without adverse effect.

DISCUSSION

In the literature, the complication rate for cranioplasty varies from 2 to 40.8 percent, encompassing everything from the more serious findings of infection, extrusion, and reabsorption, to the less



Fig. 3. An 11-month-old boy was attacked by a dog and lost 50 percent of his skull, including the underlying dura (*above, left and center*). A switch cranioplasty was performed to cover the injured area with BMP, and freeze-dried bone was used to cover the donor site under a pericranial patch (*above, right*). The child healed completely (*below*). The patient is shown 18 months after the procedure; he is now aged 8 years with intact skull on both sides. It is unclear whether the BMP was responsible for the excellent ossification at the donor site or whether this would have occurred regardless because of the regenerative ability of the skull at this age.

common outcomes of hematoma, hydrocephalus, seizure, chronic pain, or thermal sensitivity.^{11,15–20} These comprehensive data are often packaged into a single series of patients treated with an assortment of techniques to attain larger clinical numbers for effect but, in the process, loses a significant component of clinical relevance. Complication rates for autogenous bone cranioplasties are reported as ranging from 0 to 53.3 percent, whereas those reported for alloplastic cranioplasties range from 4.8 to 63.6 percent.^{16,18,20} This might lead surgeons to conclude that the complication rates among the different techniques are essentially equivalent in the treatment of full-thickness cranial defects. However, these data do not offer an adequate clinical picture. Specifically, the most commonly reported issues with autogenous

cranioplasties relate to graft resorption and cosmetic contour deformities, a data point vulnerable to a significant degree of subjectivity.^{11,20,21} In contrast, the most commonly reported issues with alloplastic cranioplasties involve the more morbid complications of infection, extrusion, and graft failure.^{11,14,22}

In 2003, Moreira-Gonzalez et al. conducted a large study analyzing the clinical outcomes in long-term follow-up between autogenous bone, methylmethacrylate, and hydroxyapatite.¹¹ Again, the principal complications seen with autogenous bone were contour irregularities. Infection and exposure were the most common complications seen with methylmethacrylate and hydroxyapatite, and occurred in 13.3 and 22.4 percent of the cases, respectively.¹¹ In comparison, the rate of

infection and exposure seen with autologous bone was lower at 7.1 and 1.3 percent, respectively. The study concluded that autogenous bone is still the most reliable, safe, and cost-effective material for use in reconstructive cranioplasty. Another study in 2010 by Chang et al. found that infection was more common after use of alloplastic material compared with autogenous bone (18.9 percent versus 4.6 percent).¹⁷ Overall, the available literature supports the notion that infection is more common with alloplastic materials when compared with autogenous bone cranioplasties, with infection rates ranging from 0 to 24.8 percent for autogenous bone procedures and from 4.8 to 44.5 percent for alloplastic materials.^{11,17,18,22–26} Likewise, reported rates of extrusion of alloplastic materials are as high as 60 percent; in contrast, Reddy et al. analyzed 195 patients treated with alloplastic or autogenous bone and found that extrusion occurred exclusively in patients treated with alloplastic material.^{18,22,27}

The most comprehensive recent investigation to date regarding the use of autogenous bone for cranioplasties was recently published by Fearon et al. in *Plastic and Reconstructive Surgery*.²⁸ Their 14-year series of 96 patients had zero incidents of postoperative infections resulting in loss of the cranioplasty graft, all of which were performed with split calvaria. Only one patient experienced clinically significant graft resorption that required operative revision. In addition, their extensive review of the literature concluded that alloplastic cranioplasty grafts demonstrated a nearly five-fold higher infection rate relative to autogenous bone grafts. They also noted that should infection occur with an autogenous graft, it can often be treated with drainage alone, as opposed to the nearly universal need to remove an alloplastic implant under similar circumstances.

The latest alloplastic material being used by cranioplasty surgeons is polyetheretherketone. This substance is biocompatible, inert, and reported to have similar mechanical properties to bone. It can be formed to precise measurements preoperatively based on three-dimensional computed tomographic scans. Advocates point to decreased operative times, improved aesthetic outcomes, and with the benefit of no donor site. Early results seem to indicate better outcomes than with other alloplastic materials, but clinical series are limited in scope (between five and 38 patients) and follow-up times are inadequate (from 6 to 24 months).^{29–34} Nevertheless, there is still an implant failure rate of up to 27 percent reported with polyetheretherketone, typically because of exposure and/or infection.^{29,30,33,35} A few direct comparison

studies with polyetheretherketone cranioplasties have suggested a lower complication rate relative to autogenous bone; however, these were small series with short follow-up times.³⁶

The proponents of alloplastic materials claim that autogenous bone grafts undergo resorption. This is certainly the case if a large decompressive craniectomy has been performed and the bone flap refrigerated for subsequent reintroduction. Indeed, it is the complication most commonly reported, with rates of resorption varying wildly among available studies, anywhere from 2 to 32 percent in adults and 20 to 81.8 percent in pediatric patients.^{11,15,16,20,21,23,25,37–42} The fact remains that many thousands of craniotomies are performed by neurosurgeons annually, and if the bone flap is replaced properly—with good contact with adjacent bone and rigid—no significant resorption should be noted. Adverse outcomes reported in the literature may be attributable to variations in surgical technique or surgeon experience. Variance in the reported rate of complications may be from disparate determination techniques to assess the severity or clinical relevance of resorption, or variable follow-up times. In our study, where “fresh” bone graft was obtained, we had zero evidence of resorption as determined subjectively by both the senior author and the patients. We did not have experience with cold-stored bone flaps except for one case where it was used to cover the harvest site (Fig. 3). Once primary healing has taken place, an autogenous cranioplasty becomes vascularized and fully integrated. There have been no reports of secondary infection developing in autogenous bone graft. In contrast, late infection is the primary reason for failure of alloplastic cranioplasty implants. There were no infections in our entire series, either early or late.

Fewer complications can be achieved through better training on the techniques used for bone harvest. The senior author prefers the techniques for bone harvest described by Paul Tessier in his 2005 Supplement to *Plastic and Reconstructive Surgery*⁴¹ on the tools and techniques of harvesting autogenous bone. In addition, the senior author demonstrates his method for harvesting autologous bone through another case example. (See **Video 1, Supplemental Digital Content 1**, which demonstrates the splitting of a large parietal bone flap to be used for reconstruction in an adult patient who had a temporoparietal defect caused by loss of a bone flap after epilepsy surgery, available in the “Related Videos” section of the full-text article on PRSJournals.com or, for Ovid users, available at <http://links.lww.com/PRS/D484>.)



Video. Supplemental Digital Content 1 demonstrates the splitting of a large parietal bone flap to be used for reconstruction in an adult patient who had a temporoparietal defect caused by loss of a bone flap after epilepsy surgery, available in the “Related Videos” section of the full-text article on PRSJournals.com or, for Ovid users, available at <http://links.lww.com/PRS/D484>.

This series was begun in 1975; thus, for at least some of the patients, the follow-up is over 30 years. Long-term follow-up is essential in these patients to accurately convey surgical outcomes. There are many patients who undergo alloplastic cranioplasties with acceptable results, only to return years later with extruded or infected implants. Most series using alloplastic materials have follow-ups of between 1 and 12 years. In addition, staged procedures cannot be performed over or through alloplastic materials. In contrast, once vascularized, bone segments can be built on, osteotomized, and moved as desired. For a very large defect, the entire contralateral skull can be harvested and split in an adult. If this is decided against, three ribs at 20×2 cm, when split, will provide coverage of 240 cm^2 . If additional graft is needed, the patient can return to the operating room in 3 to 4 months where additional rib can be harvested from the contralateral thorax to complete the reconstruction. The impact of BMP could not be determined because of the small sample size. Although there was one case in the study where the patient developed a seroma that required reoperation, there were several cases where the BMP had no adverse effect and might have even improved the outcome (Fig. 3).

Limitations of the study are related to the longevity of the retrospective review. Electronic medical records did not exist until recently. Several of the institutions where the procedures were performed earlier in the study no longer exist. This

limited the ability to calculate operative time, transfusion rates, or length of stay. However, the longevity of the senior author’s practice shows that autogenous bone grafts hold up to the test of time. With the advent of better record-keeping, future studies can more definitively analyze the long-term costs of the ease of alloplastic materials versus the infection-resisting—albeit more challenging to harvest—autologous material.

There is a learning curve associated with autologous calvarial bone harvest and fixation that may be addressed through cadaver laboratory workshops and residency training programs, similar to the way that microsurgery has been demoted from a superspecialized art to a more standard skill taught in every residency training program. The senior author regularly uses Rainey clips and Gelfoam (Pharmacia & Upjohn, Kalamazoo, Mich.)-thrombin to minimize bleeding while exposing the scalp harvest site. Neurosurgery assistance is available in the case of full-thickness cranial bone harvest, and any dural tears if noted are repaired by the neurosurgical team. A patch of pericranium can be used if needed. Rigid fixation is achieved using wires. If intraoperative bleeding is extensive, a drain is left overnight for removal the following day. A course of postoperative antibiotics is used to minimize the chance of infection. Contraindications to autologous reconstruction include extensive comorbidities, extreme bleeding disorders, or a large defect in a frail patient who cannot tolerate a lengthy procedure. A video of the senior author’s technique is included in the digital supplement portion of this article (**see Video 1, Supplemental Digital Content 1**, <http://links.lww.com/PRS/D484>).

CONCLUSIONS

This study, with an extensive long-term follow-up, demonstrates the reliability of autogenous bone with a 0 percent complication rate for the bone graft harvest and a 0 percent reoperation rate for infection of either the donor site or the autogenous bone graft. Although most authors do agree that autogenous bone is indeed the gold standard material for cranioplasty procedures, there are still some that actively argue against its use, suggesting that its propensity for resorption results in an unacceptably high complication rate.^{12,16,20,21,42} This assertion, however, turns a blind eye to the most obvious problems with alloplastic materials and the significant advantages of autogenous bone elucidated in this study. It is clearly less susceptible to infection, results in



Fig. 4. A 27-year-old woman after a gunshot wound to the right fronto-orbital region (*above*). She was treated with multiple débridements before presentation in our clinic, and arrived with a drain in the right frontal abscess cavity. She underwent staged reconstruction with initial excision of a craniocutaneous fistula, pericranial patch, and a free latissimus dorsi muscle flap to fill the frontal dead space with the aid of microsurgeon Jaime Flores, M.D. Several months later, the orbital roof and supraorbital ridge were reconstructed using iliac bone graft. In a separate procedure, split cranial bone from the contralateral side was used to reconstruct the cranial defect (*below*). Now 4 years postoperatively, the patient has no evidence of bony resorption (*center*). She has undergone multiple additional procedures aimed at adjusting the eyelids and orbit.



Fig. 5. A 15-year-old boy was injured in an accident involving a motor vehicle and a bicycle, and suffered a fractured skull and epidural bleeding treated with a decompressive craniectomy. Before arrival at our office, he had undergone failed replacement of the frozen bone flap, infection and removal of a methylmethacrylate cranioplasty, and symptomatic displacement and subsequent removal of a second methylmethacrylate cranioplasty. He presented to us 6 months later with significant contour deformity of the right calvaria, consistent with the prior craniectomy (*above*). He underwent cranial reconstruction with split rib grafts (*below, left*), resulting in satisfactory restoration of the premorbid contour (*center*). Five years after this procedure, there are no signs of graft resorption either clinically (*center*) or on imaging (*below, right*).



Fig. 6. A 58-year-old woman with metastatic breast cancer was treated with removal of a frontal mass and full-thickness frontal craniectomy, with reconstruction by means of titanium mesh cranioplasty. Subsequently, she underwent radiation therapy, and ultimately developed breakdown of the overlying soft tissue with exposure of mesh, bone, and pulsatile dura (*above, left*). Our initial treatment consisted of débridement, removal of titanium mesh, removal of residual frontal sinus and damaged soft tissue, and a free latissimus flap with a skin paddle to provide adequate coverage. Six months later, she underwent split-rib cranioplasty to reconstruct the frontal defect (*center and below*). Eight months postoperatively, the patient has maintained the bony contour, and has intact soft-tissue coverage (*above, right*). Jaime Flores, M.D., performed the microsurgery for this reconstruction.

fewer long-term complications than alloplastic materials, and confers the benefits of integration and cooperation with the growing skull that are so important in the pediatric population.^{43,44} There is yet to be an alloplastic material that can best, or even match these outcomes, and thus autogenous bone should be considered as the primary option for cranioplasty procedures. Let us not forsake the advantages of bone grafting for the expediency of a computer-generated alloplastic material whose long-term infection rate is not fully determined.

S. Anthony Wolfe, M.D.

Nicklaus Children's Hospital
3100 SW 62nd Avenue, Suite 2230
Miami, Fla. 33155
drwolfe@santhonywolfemd.com

PATIENT CONSENT

Patients, parents, or guardians provided written consent for the use of patients' images.

REFERENCES

- Carod-Artal FJ, Vázquez-Cabrera CB. Neurological paleopathology in the pre-Columbine cultures of the coast and the Andean plateau (II): The history of cranial trepanations (in Spanish). *Rev Neurol*. 2004;38:886–894.
- Körlof B, Nylén B, Rietz KA. Bone grafting of skull defects: A report on 55 cases. *Plast Reconstr Surg*. 1973;52:378–383.
- Seydel H. Eine neue Methode, grosse Knochendefekte des Schädels zu decken. *Centralbl Chir*. 1889;12:209.
- Müller W. Zur Frage der Temporären Schädelresektion an Stelle der Trepanation. *Centralbl Chir*. 1890;17:65.
- König F. Der knöcherne Ersatz grosser Schädeldefekten. *Centralbl Chir*. 1890;17:497.
- Axhausen G. Die histologischen und klinischen Gesetze der freien Osteoplastik auf Grund von Thierversuchen. *Arch Klin Chir*. 1909;88:23.
- Axhausen G. Zur Technik der Schädelplastik. *Arch Klin Chir*. 1916;107:551.
- Manson PN, Crawley WA, Hoopes JE. Frontal cranioplasty: Risk factors and choice of cranial vault reconstructive material. *Plast Reconstr Surg*. 1986;77:888–904.
- Gurdjian ES, Webster JE, Brown JC. Impression technique for reconstruction of large skull defects. *Surgery*. 1943;14:876–881.
- Williams L, Fan K, Bentley R. Titanium cranioplasty in children and adolescents. *J Craniomaxillofac Surg*. 2016;44:789–794.
- Moreira-Gonzalez A, Jackson IT, Miyawaki T, Barakat K, DiNick V. Clinical outcome in cranioplasty: Critical review in long-term follow-up. *J Craniofac Surg*. 2003;14:144–153.
- Zanotti B, Zingaretti N, Verlicchi A, Robiony M, Alfieri A, Parodi PC. Cranioplasty: Review of materials. *J Craniofac Surg*. 2016;27:2061–2072.
- Harris DA, Fong AJ, Buchanan EP, Monson L, Khechoyan D, Lam S. History of synthetic materials in alloplastic cranioplasty. *Neurosurg Focus*. 2014;36:E20.
- Shah AM, Jung H, Skirboll S. Materials used in cranioplasty: A history and analysis. *Neurosurg Focus*. 2014;36:E19.
- Iwama T, Yamada J, Imai S, Shinoda J, Funakoshi T, Sakai N. The use of frozen autogenous bone flaps in delayed cranioplasty revisited. *Neurosurgery*. 2003;52:591–596; discussion 595–596.
- Pochon JP, Klöti J. Cranioplasty for acquired skull defects in children: A comparison between autologous material and methylmethacrylate 1974-1990. *Eur J Pediatr Surg*. 1991;1:199–201.
- Chang V, Hartzfeld P, Langlois M, Mahmood A, Seyfried D. Outcomes of cranial repair after craniectomy. *J Neurosurg*. 2010;112:1120–1124.
- Sahoo N, Roy ID, Desai AP, Gupta V. Comparative evaluation of autogenous calvarial bone graft and alloplastic materials for secondary reconstruction of cranial defects. *J Craniofac Surg*. 2010;21:79–82.
- Gooch MR, Gin GE, Kenning TJ, German JW. Complications of cranioplasty following decompressive craniectomy: Analysis of 62 cases. *Neurosurg Focus*. 2009;26:E9.
- Bobinski L, Koskinen LO, Lindvall P. Complications following cranioplasty using autologous bone or polymethylmethacrylate: Retrospective experience from a single center. *Clin Neurol Neurosurg*. 2013;115:1788–1791.
- Martin KD, Franz B, Kirsch M, et al. Autologous bone flap cranioplasty following decompressive craniectomy is combined with a high complication rate in pediatric traumatic brain injury patients. *Acta Neurochir (Wien)*. 2014;156:813–824.
- Jaberi J, Gambrell K, Tiwana P, Madden C, Finn R. Long-term clinical outcome analysis of poly-methyl-methacrylate cranioplasty for large skull defects. *J Oral Maxillofac Surg*. 2013;71:e81–e88.
- Daou B, Zanaty M, Chalouhi N, et al. Low incidence of bone flap resorption after native bone cranioplasty in adults. *World Neurosurg*. 2016;92:89–94.
- Stephens FL, Mossop CM, Bell RS, et al. Cranioplasty complications following wartime decompressive craniectomy. *Neurosurg Focus*. 2010;28:E3.
- Schoekler B, Trummer M. Prediction parameters of bone flap resorption following cranioplasty with autologous bone. *Clin Neurol Neurosurg*. 2014;120:64–67.
- Goh RC, Chang CN, Lin CL, Lo LJ. Customised fabricated implants after previous failed cranioplasty. *J Plast Reconstr Aesthet Surg*. 2010;63:1479–1484.
- Reddy S, Khalifian S, Flores JM, et al. Clinical outcomes in cranioplasty: Risk factors and choice of reconstructive material. *Plast Reconstr Surg*. 2014;133:864–873.
- Fearon JA, Griner D, Dithakasem K, Herbert M. Autogenous bone reconstruction of large secondary skull defects. *Plast Reconstr Surg*. 2017;139:427–438.
- O'Reilly EB, Barnett S, Madden C, Welch B, Mickey B, Rozen S. Computed-tomography modeled polyether ether ketone (PEEK) implants in revision cranioplasty. *J Plast Reconstr Aesthet Surg*. 2015;68:329–338.
- Thien A, King NK, Ang BT, Wang E, Ng I. Comparison of polyetheretherketone and titanium cranioplasty after decompressive craniectomy. *World Neurosurg*. 2015;83:176–180.
- Ramos CK, Cayci C, Castro-Garcia JA, Feiz-Erfan I, Lettieri SC. Patient-specific polyetheretherketone implants for repair of craniofacial defects. *J Craniofac Surg*. 2015;26:631–633.
- Ng ZY, Nawaz I. Computer-designed PEEK implants: A peek into the future of cranioplasty? *J Craniofac Surg*. 2014;25:e55–e58.
- Jonkerougou J, van de Vijfeijken SE, Nout E, et al. Outcome in patient-specific PEEK cranioplasty; a two-center cohort study of 40 implants. *J Craniomaxillofac Surg*. 2016;44:1266–1272.
- Jalbert F, Boetto S, Nadon F, Lauwers F, Schmidt E, Lopez R. One-step primary reconstruction for complex craniofacial

- resection with PEEK custom-made implants. *J Craniomaxillofac Surg*. 2014;42:141–148.
35. Mundinger GS, Latham K, Friedrich J, et al. Management of the repeatedly failed cranioplasty following large postdecompressive craniectomy: Establishing the efficacy of staged free latissimus dorsi transfer/tissue expansion/custom polyetheretherketone implant reconstruction. *J Craniofac Surg*. 2016;27:1971–1977.
 36. Gilardino MS, Karunanayake M, Al-Humsi T, et al. A comparison and cost analysis of cranioplasty techniques: Autologous bone versus custom computer-generated implants. *J Craniofac Surg*. 2015;26:113–117.
 37. Piedra MP, Ragel BT, Dogan A, Coppa ND, Delashaw JB. Timing of cranioplasty after decompressive craniectomy for ischemic or hemorrhagic stroke. *J Neurosurg*. 2013;118:109–114.
 38. Schuss P, Vatter H, Oszvald A, et al. Bone flap resorption: Risk factors for the development of a long-term complication following cranioplasty after decompressive craniectomy. *J Neurotrauma* 2013;30:91–95.
 39. Sundseth J, Sundseth A, Berg-Johnsen J, Sorteberg W, Lindegaard KF. Cranioplasty with autologous cryopreserved bone after decompressive craniectomy: Complications and risk factors for developing surgical site infection. *Acta Neurochir (Wien)* 2014;156:805–811; discussion 811.
 40. De Bonis P, Frassanito P, Mangiola A, Nucci CG, Anile C, Pompucci A. Cranial repair: How complicated is filling a “hole”? *J Neurotrauma* 2012;29:1071–1076.
 41. Tessier P, Kawamoto H, Matthews D, et al. Autogenous bone grafts and bone substitutes—Tools and techniques: I. A 20,000-case experience in maxillofacial and craniofacial surgery. *Plast Reconstr Surg*. 2005;116(Suppl):6S–24S; discussion 92S–94S.
 42. Grant GA, Jolley M, Ellenbogen RG, Roberts TS, Gruss JR, Loeser JD. Failure of autologous bone-assisted cranioplasty following decompressive craniectomy in children and adolescents. *J Neurosurg*. 2004;100(Suppl Pediatrics): 163–168.
 43. Prolo DJ, Oklund SA. The use of bone grafts and alloplastic materials in cranioplasty. *Clin Orthop*. 1991;268:270–278.
 44. Abuzayed B, Tuzgen S, Canbaz B, Yuksel O, Tutunculer B, Sanus GZ. Reconstruction of growing skull fracture with in situ galeal graft duraplasty and porous polyethylene sheet. *J Craniofac Surg*. 2009;20:1245–1249.