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PATIENT-SPECIFIC CRANIOPLASTY IN THE ADDITIVE-MANUFACTURING ERA: COMPARATIVE EVALUATION OF PEEK, TITANIUM, PMMA, AND REGENERATIVE POROUS IMPLANTS

Abstract

Background. Patient-specific cranioplasty has evolved from intraoperative manual contouring toward computed-tomography-based design, additive manufacturing, and biologically informed implant architecture. Material selection remains controversial because geometric accuracy does not automatically ensure infection resistance, soft-tissue compatibility, mechanical durability, or osseointegration.

Materials and methods. Randomized trials, prospective cohorts, retrospective comparative studies, biomechanical investigations, additive-manufacturing studies, and clinical series published through July 2026 were synthesized. Evidence was organized according to defect geometry, implant accuracy, mechanical and thermal behavior, imaging compatibility, infection, exposure, fluid collection, manufacturing workflow, cost, and biological integration.

Results. Patient-specific PEEK provides accurate contour reconstruction, low weight, favorable imaging characteristics, and bone-like elastic behavior, but remains bioinert and may be associated with subgaleal or epidural fluid collections. Titanium offers high mechanical strength, thin-profile fabrication, reliable fixation, and opportunities for porous osseointegrative architecture, but produces imaging artifacts and may be vulnerable to thermal discomfort or exposure under compromised scalp. PMMA remains accessible, modifiable, and cost-effective, particularly when manufactured with three-dimensional printed molds; limitations include exothermic polymerization, brittleness, residual monomer, and inconsistent tissue integration. Porous hydroxyapatite, calcium-phosphate–titanium composites, and experimental porous titanium or functionalized polymer implants seek progressive bone ingrowth and vascular integration, but clinical evidence remains heterogeneous and long-term explantability requires consideration.

Conclusion. No universally superior cranioplasty material exists. The proposed CRANIO-MAP framework links wound biology, defect geometry, soft tissue, cerebrospinal-fluid dynamics, imaging requirements, mechanical demands, manufacturing logistics, biological integration, and patient priorities to implant selection.

Keywords: cranioplasty; patient-specific implant; additive manufacturing; three-dimensional printing; polyetheretherketone; titanium; polymethylmethacrylate; porous hydroxyapatite; osseointegration; cranial reconstruction.

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ПАЦИЕНТ-СПЕЦИФИЧЕСКАЯ КРАНИОПЛАСТИКА В ЭПОХУ АДДИТИВНОГО ПРОИЗВОДСТВА: СРАВНИТЕЛЬНАЯ ОЦЕНКА PEEK, ТИТАНА, PMMA И РЕГЕНЕРАТИВНЫХ ПОРИСТЫХ ИМПЛАНТАТОВ

Аннотация

Актуальность. Пациент-специфическая краниопластика прошла путь от интраоперационного ручного моделирования до проектирования на основе компьютерной томографии, аддитивного производства и биологически ориентированной архитектуры имплантатов. Выбор материала остаётся спорным, поскольку геометрическая точность не гарантирует устойчивость к инфекции, совместимость с мягкими тканями, механическую долговечность или остеоинтеграцию.

Материалы и методы. Синтезированы рандомизированные исследования, проспективные когорты, ретроспективные сравнительные работы, биомеханические и аддитивно-производственные исследования, опубликованные до июля 2026 года. Данные систематизированы по геометрии дефекта, точности, механическим и термическим свойствам, совместимости с визуализацией, инфекции, экспозиции, жидкостным скоплениям, производству, стоимости и биологической интеграции.

Результаты. Пациент-специфический PEEK обеспечивает точное восстановление контура, малую массу, благоприятную послеоперационную визуализацию и эластичность, приближенную к кости, однако остаётся биоинертным и может сопровождаться субгалеальными или эпидуральными скоплениями жидкости. Титан обладает высокой прочностью, позволяет создавать тонкие и пористые конструкции и обеспечивает надёжную фиксацию, но вызывает артефакты и может экспонироваться при неудовлетворительном состоянии скальпа. PMMA доступен, модифицируем и экономически оправдан, особенно при применении трёхмерно напечатанных форм; его ограничения включают экзотермическую полимеризацию, хрупкость, остаточный мономер и отсутствие полноценной интеграции. Пористый гидроксиапатит, кальций-фосфатно-титановые композиты и функционализированные полимерные конструкции направлены на врастание кости и сосудов, но их доказательная база остаётся неоднородной, а биологическая интеграция может осложнять последующее удаление инфицированного или повреждённого устройства. Предложенная модель учитывает качество кожно-апоневротического лоскута, перенесённую инфекцию, лучевую терапию, наличие шунта, дефект основания черепа, ожидаемую нейровизуализацию и локальные производственные возможности.

Заключение. Универсально лучшего материала не существует. Модель CRANIO-MAP связывает биологию раны, геометрию, мягкие ткани, ликвородинамику, визуализацию, механику, производство, остеоинтеграцию и предпочтения пациента.

Ключевые слова: краниопластика; пациент-специфический имплантат; аддитивное производство; трёхмерная печать; полиэфирэфиркетон; титан; полиметилметакрилат; пористый гидроксиапатит; остеоинтеграция; реконструкция черепа.

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ADDITIV ISHLAB CHIQARISH DAVRIDA BEMORGA MOSLASHTIRILGAN KRANIOPLASTIKA: PEEK, TITAN, PMMA VA REGENERATIV G‘OVAK IMPLANTLARNING QIYOSIY BAHOSI

Annotatsiya

Dolzarblik. Bemorga moslashtirilgan kranioplastika intraoperatsion qo‘lda shakllantirishdan kompyuter tomografiyasiga asoslangan loyihalash, additiv ishlab chiqarish va biologik yo‘naltirilgan implant arxitekturasigacha rivojlandi. Materialni tanlash bahsli bo‘lib qolmoqda, chunki geometrik aniqlik infeksiyaga chidamlilik, yumshoq to‘qimalar bilan moslik, mexanik uzoq muddatlilik yoki osteointegratsiyani avtomatik ravishda ta’minlamaydi.

Material va usullar. 2026-yil iyuligacha chop etilgan randomizatsiyalangan sinovlar, prospektiv kohortalar, retrospektiv qiyosiy tadqiqotlar, biomekanik va additiv ishlab chiqarish ishlari sintez qilindi. Dalillar nuqson geometriyasi, implant aniqligi, mexanik va termik xususiyatlar, tasvirlashga moslik, infeksiya, ekspozitsiya, suyuqlik to‘planishi, ishlab chiqarish, xarajat va biologik integratsiya bo‘yicha tizimlashtirildi.

Natijalar. Bemorga mos PEEK aniq kontur, kam massa, yaxshi tasvirlash va suyakka yaqin elastiklik beradi, biroq bioinert bo‘lib, subgaleal yoki epidural suyuqlik to‘planishi bilan kechishi mumkin. Titan yuqori mustahkamlik, yupqa profil, ishonchli fiksatsiya va g‘ovak osteointegrativ tuzilma yaratish imkonini beradi, ammo tasviriy artefaktlar, termik noqulaylik va zaif bosh terisida ekspozitsiya xavfiga ega. PMMA arzon, o‘zgartiriladigan va uch o‘lchamli qoliplar bilan aniq tayyorlanadigan materialdir; uning cheklovlari ekzotermik polimerizatsiya, mo‘rtlik, qoldiq monomer va sust biologik integratsiyadir. G‘ovak gidroksiapatit, kalsiy-fosfat–titan kompozitlari va funksionalizatsiyalangan polimerlar suyak va tomirlarning ichkariga o‘sishini rag‘batlantirishga qaratilgan, biroq klinik dalillar turlicha va kuchli integratsiya keyingi eksplantatsiyani murakkablashtirishi mumkin. Model skalp va yara holati, oldingi infeksiya yoki radioterapiya, likvor shunti, nuqsonning anatomik murakkabligi, keyingi KT yoki MRT ehtiyoji, bemor yoshi, implantning kutilayotgan mexanik yuklanishi va mahalliy raqamli ishlab chiqarish imkoniyatlarini birgalikda baholaydi.

Xulosa. Barcha bemorlarga mos universal material mavjud emas. CRANIO-MAP modeli yara biologiyasi, geometriya, yumshoq to‘qima, likvorodinamik holat, tasvirlash, mexanika, ishlab chiqarish, osteointegratsiya va bemor ustuvorliklarini bog‘laydi.

Kalit so‘zlar: kranioplastika; bemorga mos implant; additiv ishlab chiqarish; uch o‘lchamli bosib chiqarish; poliefirefirketon; titan; polimetilmetakrilat; g‘ovak gidroksiapatit; osteointegratsiya; bosh suyagini rekonstruksiya qilish.

Introduction. Cranioplasty restores the mechanical continuity, external contour, and protective function of the skull after decompressive craniectomy, trauma, infection, tumor resection, congenital deformity, or removal of a failed previous implant. The procedure is often described as reconstructive, but its clinical role extends beyond cosmesis. Re-establishing a closed cranial vault can improve protection of the brain, normalize atmospheric-pressure transmission, modify cerebrospinal-fluid and venous dynamics, and contribute to neurological recovery in selected patients with the syndrome of the trephined [1, 2, 10, 13]. Despite its apparently straightforward objective, cranioplasty remains associated with clinically important rates of infection, wound dehiscence, hematoma, hydrocephalus,

seizures, fluid collection, implant exposure, fracture, displacement, and reoperation. Outcomes are influenced by the original pathology, interval after craniectomy, history of contamination, previous operations, cerebrospinal-fluid shunting, radiation, diabetes, smoking, nutritional status, scalp quality, defect size, implant geometry, fixation, and surgical technique. Material is important, but it is only one component of a complex biological and mechanical system [3, 6, 10]. Autologous bone is attractive because it is anatomically matched and biologically familiar. Its limitations include resorption, infection, fragmentation, warping, storage-related contamination, and progressive failure, particularly in children and after large decompressive craniectomy. Alloplastic reconstruction becomes necessary when the original flap is unavailable, contaminated, resorbed, oncologically unsuitable, mechanically deficient, or has failed previously [2, 3, 18].

Historically, alloplastic implants were manually shaped intraoperatively from polymethylmethacrylate, titanium mesh, or other materials. Manual contouring is accessible but depends heavily on operator experience and can produce irregular edges, asymmetry, dead space, prolonged operating time, and suboptimal temporalis reconstruction. Patient-specific implant manufacturing replaces subjective contouring with a digital workflow that reconstructs the missing cranial anatomy from high-resolution computed tomography. The simplest reconstruction uses mirror imaging of the unaffected side. Bilateral, midline, fronto-orbito-temporal, suboccipital, and skull-base defects require template databases, spline interpolation, anatomical landmarking, or semiautomated surface reconstruction. The final implant may be milled from a solid PEEK block, additively manufactured from titanium alloy, cast from PMMA using a three-dimensional printed mold, or produced from porous bioceramic or composite material [11, 12, 20]. Patient specificity provides more than a smooth external contour. Digital design can incorporate variable thickness, fixation tabs, countersunk screw holes, dural suspension apertures, temporal hollow correction, channels for drains, porous interfaces, planned overlap with healthy bone, and avoidance of frontal sinus or vascular structures. The design can also reduce intraoperative modification, which may shorten surgery and decrease contamination from repeated handling [2, 3, 10, 18].

A patient-specific implant is not necessarily biologically superior. A perfectly fitted implant may trap fluid, compress dura, leave an unrecognized contaminated sinus, overload thin scalp, or become infected. Conversely, a manually molded implant may perform well when soft-tissue coverage is excellent and surgical technique is meticulous. The additive-manufacturing era therefore requires a shift from geometry-centered thinking to patient–material–workflow matching. PEEK, titanium, and PMMA currently represent major alloplastic options. PEEK is lightweight, radiolucent, chemically stable, and mechanically less rigid than titanium. Titanium offers high strength, thin-profile fabrication, durable fixation, and established osseous biocompatibility. PMMA is widely available, inexpensive, modifiable, and compatible with mold-based local manufacturing. Each material also has distinctive failure modes [3, 6, 15, 18]. Regenerative porous implants represent a different therapeutic concept. Rather than functioning only as permanent protective plates, they are designed to permit tissue infiltration, vascularization, and bone ingrowth. Porous hydroxyapatite, calcium-phosphate ceramics reinforced with titanium, porous titanium lattices, and surface-functionalized PEEK or PEKK seek to transform the interface from fibrous encapsulation toward biological incorporation [3, 10, 18, 27]. Clinical integration must not be confused with complete regeneration of native calvarium. Current

implants generally remain structural devices with varying degrees of tissue ingrowth. Porosity can improve interface stability and antibiotic penetration, but it can also reduce mechanical strength, retain bacteria, complicate debridement, or make later explantation difficult. Recent comparative studies have not identified one consistently superior material across infection, fluid collection, cosmesis, exposure, and reoperation. A randomized comparison of custom hydroxyapatite and titanium included 52 patients and found numerically fewer implant-associated infections with hydroxyapatite, although the difference was not statistically definitive. Contemporary comparative cohorts similarly show that outcomes depend strongly on patient and wound characteristics rather than material alone [6, 11, 12, 20].

Materials and Methods. This manuscript was designed as a structured integrative review with an original material-selection and manufacturing synthesis. Randomized clinical trials, prospective multicenter cohorts, retrospective comparative investigations, patient-specific implant series, biomechanical experiments, additive-manufacturing studies, and translational porous-implant investigations published through July 2026 were evaluated. The principal concepts included cranioplasty, patient-specific cranial implant, additive manufacturing, computer-aided design, computer-aided manufacturing, PEEK, titanium mesh, additively manufactured titanium, PMMA, porous hydroxyapatite, calcium-phosphate–titanium implants, porous polymer implants, implant infection, exposure, subgaleal effusion, epidural collection, implant fracture, osseointegration, cost, and point-of-care manufacturing. Evidence was classified into eight domains.

The first domain was anatomical reconstruction, including defect surface area, curvature, thickness, midline involvement, orbitotemporal extension, frontal sinus exposure, temporal hollowing, and fixation margins. The second domain was material mechanics, including elastic modulus, impact resistance, fatigue, brittleness, thermal conductivity, density, and stress distribution. The third domain was biological performance, including tissue adhesion, fibrous encapsulation, osseointegration, vascular ingrowth, bacterial biofilm, inflammatory response, and response to radiotherapy. The fourth domain was imaging, including CT and MRI artifact, radiolucency, visualization of recurrent tumor, assessment of bone integration, and compatibility with radiation planning. The fifth domain was clinical safety, including surgical-site infection, implant removal, wound breakdown, exposure, hematoma, fluid collection, seizure, fracture, displacement, and revision surgery. The sixth domain was manufacturing, including image acquisition, segmentation, virtual reconstruction, design approval, fabrication, postprocessing, cleaning, sterilization, packaging, and traceability. The seventh domain was health-system feasibility, including production time, direct implant cost, specialist engineering requirements, local manufacturing, sterilization validation, operating time, and revision cost. The eighth domain was patient-specific selection, including age, original disease, infection history, radiation, soft-tissue status, shunt dependence, defect location, future imaging requirements, and preferences.

No new patient cohort was generated and no independent quantitative meta-analysis was conducted. Findings were interpreted according to study design, implant type, defect complexity, follow-up duration, and selection bias. Tables represent an original synthesis and do not contain fabricated patient-level data.

Results. A patient-specific cranioplasty begins with thin-slice CT of the craniofacial skeleton. Slice thickness, motion, metal artifact, gantry angulation, and incomplete coverage influence segmentation quality. A scan obtained before decompressive surgery is particularly valuable because it represents the patient's original anatomy, but such imaging is not always available. Bone is segmented from the DICOM dataset using density thresholds followed by manual correction. Automated segmentation may fail at thin temporal bone, orbital walls, frontal sinus margins, comminuted fractures, and previous metallic fixation. Every defect boundary should be reviewed in axial, coronal, sagittal, and three-dimensional views.

Unilateral defects can be reconstructed by mirroring the intact side across an anatomical midline. The method assumes relative cranial symmetry and may reproduce pre-existing asymmetry. Midline and bilateral defects require statistical shape models, interpolation from surrounding curvature, archived precraniectomy imaging, or manual anatomical design. The implant's internal surface must match the defect margin without compressing the dura. A zero-clearance design may appear geometrically ideal but can fail if the scalp, temporalis, dura, or bone edge has changed between imaging and surgery. Small planned tolerances may be required, particularly after recent decompression, evolving brain volume, or previous infection. The outer surface should restore frontotemporal contour and transition smoothly into native bone. Excessive thickness increases weight and scalp tension. Insufficient thickness creates depression and weakens mechanical protection. Variable-thickness design can reproduce the diploic profile while minimizing mass. Fixation can be achieved through integrated flanges, peripheral holes, miniplates, screws, or embedded titanium elements. Fixation points should distribute load around healthy bone while avoiding thin temporal squama, frontal sinus, mastoid air cells, previous burr holes, and vascular grooves.

The completed design undergoes surgeon approval before manufacturing. Approval should explicitly confirm side, orientation, defect coverage, overlap, implant thickness, fixation, frontal sinus management, temporal contour, and any required drainage or dural-suspension holes. Design approval is a clinical decision, not an administrative step. Titanium implants are commonly produced by electron-beam or laser powder-bed fusion. PEEK implants are frequently milled from medical-grade material, although additive manufacturing of PEEK and PEKK is advancing. PMMA patient-specific implants can be cast preoperatively or intraoperatively using printed molds. Hydroxyapatite and calcium-phosphate implants are produced using ceramic manufacturing, sintering, or composite workflows. Postprocessing includes removal of supports, machining, polishing, surface treatment, powder removal, cleaning, inspection, and sterilization. Porous structures require particular attention because residual powder or manufacturing debris may remain within interconnected pores. Mechanical and dimensional quality control should be documented before clinical release.

Clinical PMMA series have shown that locally produced three-dimensional molds can provide excellent fit and cosmetic reconstruction, although complications remain determined by surgical and patient factors rather than geometric accuracy alone. Recent low-cost workflows demonstrate the potential for additive manufacturing to expand access to patient-specific reconstruction in resource-limited settings[7, 9, 19, 28].

Table 1. **Patient-Specific Implant Manufacturing and Quality-Control Workflow**

Workflow stage	Principal technical task	Potential error	Required quality-control checkpoint
CT acquisition	Thin-slice cranial imaging	Motion, artifact, incomplete skull coverage	Confirm image quality before design
Segmentation	Separate bone from soft tissue and artifact	Loss of thin bone or false defect boundary	Multiplanar manual review
Reconstruction	Restore missing anatomy	Incorrect symmetry or curvature	Compare with preinjury imaging and landmarks
Implant design	Define thickness, overlap, fixation, and porosity	Scalp tension, dead space, inadequate fixation	Formal surgeon design approval
Manufacturing	Print, mill, or mold implant	Warping, dimensional deviation, incomplete fusion	Dimensional inspection and manufacturing record
Postprocessing	Remove supports, powder, roughness, and debris	Residual particles or sharp edges	Visual, microscopic, and cleanliness assessment
Sterilization	Validated terminal or hospital sterilization	Material deformation or inadequate sterility	Material-specific validated cycle
Intraoperative verification	Match implant to defect	Interval anatomical change or unexpected bone loss	Trial fit before definitive fixation
Fixation	Achieve stable, low-profile attachment	Rocking, edge prominence, screw loosening	Circumferential stability assessment
Postoperative imaging	Confirm contour and intracranial relationships	Undetected fluid collection or malposition	Early CT according to clinical protocol

PEEK Patient-Specific Implants. Polyetheretherketone is a semicrystalline thermoplastic polymer with high chemical stability and favorable resistance to fatigue. Its elastic behavior is closer to cortical bone than that of titanium, reducing extreme stiffness mismatch. PEEK is lightweight and can be produced with accurate patient-specific geometry through high-precision milling or controlled additive manufacturing. A major advantage of PEEK is radiological compatibility. The implant produces fewer CT and MRI artifacts than metallic reconstruction, facilitating assessment of recurrent tumor, hemorrhage, hydrocephalus, brain perfusion, and surrounding soft tissue. This property is particularly relevant in neuro-oncology, vascular surveillance, epilepsy monitoring, and patients likely to undergo repeated postoperative imaging.

PEEK also has low thermal conductivity. Patients are less likely to perceive environmental temperature through the implant than with a thin metallic mesh. The polymer can be thickened to replicate natural cranial contours without becoming excessively heavy. The central biological limitation is surface

bioinertness. Conventional smooth PEEK is hydrophobic and does not inherently promote strong bone bonding. The interface is commonly stabilized by screws and fibrous tissue rather than true osseointegration. Surface roughening, perforation, plasma treatment, hydroxyapatite coating, titanium coating, and porous architecture are being investigated to improve cellular attachment.

The lack of tissue adherence may facilitate implant removal if infection occurs, but it can also contribute to fluid accumulation. Subgaleal and epidural collections have been reported after PEEK cranioplasty, particularly when the implant creates substantial dead space or when dural suspension and drainage are inadequate. A retrospective comparison of 130 patients reported subgaleal effusion more frequently after PEEK than titanium mesh, with rates of 85.7% and 53.7%, respectively. This finding should not be interpreted as an intrinsic complication rate for every PEEK design, because drainage practice, implant thickness, defect size, fixation, and soft-tissue management strongly influence fluid accumulation [6, 11, 12, 20]. Perforated PEEK designs permit communication across the implant, dural suspension, fluid egress, and possible tissue bridging. A 2025 retrospective study comparing smooth and perforated PEEK found broadly comparable major complication and revision profiles, although surface architecture remains a promising modifiable variable rather than an established solution [4, 8, 14, 25]. PEEK can be difficult to modify intraoperatively. Minor contour adjustments require high-speed cutting and can generate heat and polymer debris. An implant designed from outdated imaging may not fit if bone margins were revised, infected bone was removed, or soft tissue changed after the planning CT. The material is generally more expensive than locally manufactured PMMA and may have longer production lead times. Cost must be evaluated against reduced intraoperative contouring, high cosmetic predictability, low weight, imaging benefits, and the potential cost of revision.

Titanium Mesh and Additively Manufactured Titanium. Titanium and titanium alloys have long been used in craniofacial reconstruction because of their strength, corrosion resistance, biocompatibility, and compatibility with stable screw fixation. Traditional titanium mesh can be manually contoured or preformed using three-dimensional models. Additive manufacturing allows production of solid, lattice, mesh-type, or hybrid patient-specific implants. Titanium's high strength permits a thin implant profile. This is beneficial when scalp volume is limited and when the defect requires broad mechanical protection. Integrated fixation flanges can reduce the need for additional plates and minimize intraoperative contouring. The material's ductility distinguishes it from brittle ceramics and PMMA. A titanium implant can tolerate substantial deformation before catastrophic fracture. In high-impact trauma, deformation may occur instead of fragmentation, although severe deformation can transmit force to the fixation points or underlying structures. Titanium has an established capacity for osseous apposition. Roughened and porous surfaces can support bone ingrowth, particularly at the interface with vascularized calvarial margins. Additive manufacturing permits controlled lattice architecture and variation in porosity, pore interconnection, stiffness, and interface thickness. The principal imaging limitation is metal artifact. Titanium causes beam-hardening and susceptibility effects that can reduce CT and MRI quality near the implant. Artifact is generally less severe than with ferromagnetic metals, but it can interfere with evaluation of adjacent brain, tumor recurrence, hemorrhage, or vascular anatomy. Titanium has high thermal conductivity relative to polymers. Some patients report cold or heat sensitivity. The clinical importance varies and is

influenced by implant thickness, scalp coverage, environmental exposure, and individual perception. Implant exposure is a major concern when scalp is thin, scarred, irradiated, infected, or repeatedly operated. Rigid mesh edges, prominent fixation plates, poor temporal soft-tissue coverage, and progressive scalp atrophy can lead to erosion. A customized smooth-edged titanium implant reduces but does not eliminate this risk. A comparative cohort of PEEK and titanium found no universal superiority in overall complications, while other studies have reported different profiles of fluid collection, exposure, and patient satisfaction. A 2024 retrospective comparison likewise concluded that selection should be individualized rather than based on the assumption that either PEEK or titanium is categorically safer [8–12]. Additively manufactured porous titanium seeks to combine mechanical protection with biological incorporation. The implant can include a relatively dense protective outer shell and a porous peripheral or internal interface. Excessive porosity, however, reduces structural strength and may create stress concentrations or retain biological debris. Porous titanium design parameters cannot be transferred directly from dental or long-bone implants to the skull. Calvarial bone is thin, locally vascular, mechanically non-weight-bearing, and exposed to different impact and soft-tissue conditions. Cranial-specific pore size, porosity, fatigue, fixation, and impact resistance require dedicated validation. A randomized animal study published in 2026 compared patient-specific porous titanium cranial structures with different pore architectures and demonstrated early histological and mechanical integration. Such translational evidence supports biological plausibility but does not yet establish long-term superiority in human cranioplasty [2, 6, 18, 27].

Mechanical, Thermal, and Imaging Comparison. The skull is not a conventional weight-bearing bone, but a cranioplasty implant must resist localized impact, protect the brain, maintain contour, tolerate screw fixation, and survive repeated low-level mechanical loading. Mechanical testing should reproduce curved geometry, defect margins, fixation points, and realistic impact rather than rely solely on flat material specimens. Titanium is the stiffest and strongest of the major materials. PEEK has a lower elastic modulus and absorbs energy differently. PMMA is rigid but brittle. Hydroxyapatite is osteoconductive but fracture-prone. Composite and porous structures allow mechanical properties to be tailored but introduce manufacturing variability. An implant that is excessively stiff may transfer force to fixation points and surrounding thin bone. An implant that is too flexible may deform inward during impact. Thickness and curvature can be as important as bulk material modulus. Thermal conductivity is greatest with titanium, lower with ceramics, and low with PEEK and PMMA. Thermal perception is also determined by scalp thickness, perfusion, implant size, and environment. PEEK and PMMA facilitate postoperative CT and MRI surveillance. Titanium may compromise local image quality, although modern artifact-reduction sequences can mitigate this effect. Hydroxyapatite is radiopaque and allows assessment of progressive integration, but distinguishing implant, new bone, and fracture may require dedicated CT interpretation.

Table 2. **Comparative Characteristics of Major Patient-Specific Cranioplasty Materials**

Characteristic	PEEK	Titanium	PMMA	Porous HA/CaP or regenerative composite

Geometric accuracy	Excellent with milling or validated printing	Excellent with additive manufacturing	Excellent with patient-specific molds	Excellent when custom manufactured
Mechanical behavior	Lightweight and relatively bone-like	High strength and stiffness	Rigid but relatively brittle	Variable; ceramics can be brittle
Implant profile	Moderate thickness	Can be very thin	Usually thicker	Design-dependent
Imaging artifact	Minimal	Moderate CT/MRI artifact	Low	Generally limited but radiopaque
Thermal conductivity	Low	High	Low	Low to moderate
Conventional osseointegration	Limited	Moderate; enhanced with porosity	Limited	Intended biological integration
Fluid-collection tendency	Reported in some series	Generally lower dead-space volume with mesh	Technique-dependent	Variable
Exposure risk	Related mainly to wound failure	Important under thin or irradiated scalp	Edge and wound dependent	Related to wound biology and brittleness
Intraoperative modification	Difficult	Possible but limited in custom solid implants	Relatively easy	Usually difficult
Relative cost	High	Moderate to high	Low to moderate	High
Local production potential	Technically demanding	Demanding metal-print workflow	High using printed molds	Specialized manufacturing required
Explantation after integration	Usually straightforward	Variable with tissue ingrowth	Usually straightforward	May become difficult after bone ingrowth

Infection, Biofilm, and Implant Salvage. Cranioplasty infection is not solely a material event. The process reflects inoculum, bacterial virulence, tissue perfusion, dead space, operative time, prior infection, shunt hardware, radiation, wound tension, implant handling, and the capacity of host tissue to clear contamination. All permanent implant materials can support biofilm. Biofilm organisms are protected from systemic antibiotics and immune clearance. Smooth surfaces may reduce tissue adherence but do not prevent bacterial colonization. Porous surfaces encourage host integration but also increase internal surface area available to bacteria. A history of previous implant infection is one of the most important risk indicators. Before revision reconstruction, the team should confirm wound healing, absence of drainage, inflammatory control, eradication of osteomyelitis, and management of

contaminated sinuses or shunts. The scalp is the biological envelope of the implant. Thin, irradiated, scarred, or avascular scalp may fail over any material. Free-flap or rotational-flap reconstruction should be considered when primary closure would create excessive tension or insufficient vascular coverage. Implant salvage may be appropriate in selected early or superficial infections with stable fixation, preserved soft tissue, susceptible organisms, and no intracranial involvement. Deep infection, exposed porous implant, uncontrolled purulence, osteomyelitis, structural failure, or recurrent biofilm generally requires removal. Porous hydroxyapatite and CaP–Ti implants challenge the traditional assumption that every infection requires immediate explantation because vascularized tissue can penetrate the implant. Implant-preserving surgery has been reported, but selection is critical and evidence remains observational [5, 11, 16, 20].

Fluid Collection and Dead-Space Management. Epidural and subgaleal collections can develop after any cranioplasty. Mechanisms include poor dural suspension, cerebrospinal-fluid leakage, inflammatory exudate, bleeding, implant–dura dead space, shunt-related pressure change, and inadequate drainage. A solid PEEK or PMMA implant can isolate the epidural and subgaleal compartments. Perforations permit fluid communication but may also allow direct adhesion between tissues. Titanium mesh is naturally permeable, although custom solid titanium implants may behave differently. Dural tack-up sutures reduce epidural dead space. Their number and distribution should reflect defect size and dura quality. Integrated fixation or suspension holes can be included during digital design. Drain use should be individualized. Excessive negative suction can promote CSF leakage or alter intracranial pressure, particularly in shunted patients. Premature removal can permit fluid accumulation. Prolonged drainage increases infection risk. Shunt valve settings may require perioperative adjustment. Cranioplasty changes cranial compliance and atmospheric-pressure transmission; therefore, preoperative and postoperative ventricular size and clinical status should be monitored.

Scalp, Temporalis, and Cosmetic Reconstruction. Cosmetic success depends on more than the implant's external contour. Temporalis muscle atrophy, denervation, fibrosis, inferior displacement, fat loss, scar contracture, and frontal branch injury can produce persistent frontotemporal hollowing despite accurate calvarial reconstruction. The digital model should include the expected soft-tissue volume rather than reproduce only bone symmetry. In severe temporal hollowing, implant augmentation, temporalis resuspension, fat grafting, or soft-tissue flap reconstruction may be necessary. A thick implant can improve contour but increase scalp tension and edge prominence. A thin titanium mesh may preserve space for soft tissue but remain palpable. PEEK allows contour volume to be incorporated directly but requires accurate prediction of the soft-tissue envelope. Forehead and fronto-orbital defects demand especially precise contour because small asymmetries are visible. Titanium artifact may be less important in a purely post-traumatic defect, whereas PEEK imaging compatibility may be more valuable after tumor resection. Suboccipital reconstruction has different objectives. Muscle reattachment, prevention of CSF leakage, protection of posterior-fossa contents, and avoidance of palpable hardware may be more important than visible cosmesis.

Timing of Patient-Specific Cranioplasty. The optimal timing of cranioplasty remains individualized. Earlier reconstruction can reduce the duration of an unprotected cranial defect and may support neurological rehabilitation. It may also be performed before complete resolution of edema,

infection risk, or CSF disturbance. Late reconstruction allows soft-tissue maturation and medical stabilization but may be associated with scar contraction, temporalis atrophy, difficult dissection, and prolonged syndrome of the trephined. A patient-specific implant requires lead time for imaging, design, approval, manufacturing, sterilization, and delivery. Clinical deterioration, hydrocephalus, infection, or interval surgery can make the original model obsolete. The planning CT should therefore be obtained after cranial geometry is sufficiently stable. In revision infection cases, definitive design should generally follow completion of debridement unless the expected resection margin can be predicted reliably. Single-stage tumor resection and custom reconstruction are possible when the planned craniectomy is accurately defined. If the resection boundary changes intraoperatively, a prefabricated implant may require modification or may not provide complete coverage.

Cost and Health-System Implementation. The purchase price of an implant is only one component of cost. The complete economic analysis includes planning, engineering, imaging, sterilization, operating time, fixation, hospital stay, complications, revision surgery, and long-term surveillance. Commercial PEEK and custom titanium implants have high upfront costs. They may reduce intraoperative shaping and improve cosmetic predictability. Whether this produces net savings depends on local pricing, operating-room cost, procedural volume, and revision rates. PMMA molds can be produced locally at substantially lower cost, provided that the digital workflow, mold material, sterilization, and quality assurance are validated. Low cost does not justify uncontrolled manufacturing. A point-of-care implant program requires responsibility for design approval, software validation, material traceability, cleaning, sterility, documentation, and adverse-event review. Regional manufacturing can shorten delivery time and reduce dependence on international supply chains. It can also support surgical simulation and patient education. The same infrastructure may be used for anatomical models, cutting guides, molds, and implant prototypes. A low-volume center may obtain better value through external validated manufacturing than through maintaining a complex metal-printing facility. PMMA mold production has a lower technical threshold, while implantable PEEK and titanium manufacturing requires substantially greater process control.

Patient-Specific Material Selection. No material should be selected from defect size alone. The same large frontotemporoparietal defect may require PEEK in a patient needing repeated tumor imaging, porous titanium in a patient with healthy thick scalp and a high mechanical priority, PMMA in a resource-limited system, or a regenerative CaP–Ti implant in a complex revision patient with a carefully reconstructed vascularized scalp. PEEK is particularly attractive when postoperative imaging quality, low weight, smooth contour, and thermal insulation are priorities. It may be less attractive when repeated fluid collections, severe dead space, or a need for immediate bone integration dominates the case. Titanium is advantageous when thin-profile strength, robust fixation, complex shape, and resistance to fracture are required. It should be used cautiously beneath compromised scalp or when local imaging artifact would interfere with oncological surveillance. PMMA is appropriate when cost, local availability, intraoperative adaptability, and rapid manufacture are major considerations. The material requires controlled polymerization, sufficient thickness, smooth edges, and meticulous infection prevention. Porous hydroxyapatite and CaP–Ti implants are attractive when biological integration is a central objective and the wound is adequately vascularized. Their brittleness, specialized production, cost, and difficult explantation must be recognized.

Table 3. **Clinical Scenario–Based Implant Selection Matrix**

Clinical scenario	Preferred material tendency	Principal rationale	Important caution
Neuro-oncological defect requiring serial MRI	PEEK or low-artifact PMMA	Improved visualization of recurrence and brain tissue	PEEK fluid collection and PMMA biological inertness
Large traumatic hemicranial defect with healthy scalp	PEEK, titanium, or custom PMMA	All can restore contour effectively	Selection should follow cost, imaging, and fixation needs
Thin irradiated scalp	Low-profile PEEK with vascularized flap or carefully designed titanium	Reduce edge prominence and improve coverage	Material cannot compensate for inadequate soft tissue
Previous implant infection	Staged reconstruction; selected porous composite or conventional PSI after eradication	Prioritize wound biology and vascular coverage	Avoid premature implantation
Pediatric large defect	Porous HA or individualized alloplastic reconstruction	Avoid autologous resorption and consider integration	Implant does not grow normally with the skull
Complex fronto-orbital contour	Milled PEEK or custom titanium	High geometric precision	Protect sinus and orbital structures
Resource-limited setting	Mold-assisted PMMA	Low cost and local production	Validate sterilization and manufacturing quality
High-impact occupational risk	Titanium or mechanically validated thick PEEK	Superior structural protection	Scalp coverage and fixation remain critical
Revision after multiple failures	CaP–Ti, porous HA, PEEK, or titanium with flap reconstruction	Selection based on failure mechanism	Strong integration may complicate future removal
Expected future cranial surgery	PEEK or PMMA	Easier imaging and possible explantation	Maintain secure fixation and contour

Complication Prevention by Material and Workflow. Infection prevention begins before the implant enters the operating room. Active skin infection, open wound, unresolved sinus contamination, untreated dental or systemic infection, and inadequately controlled CSF leak require correction. The implant should be handled minimally. Repeated trial fitting, drilling, and contouring increase contamination and particulate debris. Patient-specific design should reduce, not merely relocate, intraoperative manipulation. Titanium edges must be smooth and covered by well-vascularized tissue.

PEEK and PMMA implants should avoid excessive thickness and dead space. Porous devices require careful handling to prevent contamination within the pore network.

Hemostasis must be confirmed before fixation. A precisely fitting implant can conceal epidural bleeding. Dural tack-up sutures and strategic drainage should be planned before the implant obstructs access. Fixation should eliminate rocking while avoiding excessive screw torque. Ceramic implants are vulnerable to point-loading fracture. PEEK holes can be damaged by repeated screw insertion. Thin titanium mesh can deform if screws are over-tightened. The temporalis should be resuspended anatomically. Failure to restore muscle position contributes to hollowing and can expose the inferior implant edge.

Table 4. **Material-Specific Failure Mechanisms and Prevention**

Material	Characteristic failure mode	Predisposing mechanism	Prevention
PEEK	Subgaleal or epidural collection	Smooth solid interface and dead space	Perforations, dural suspension, drainage, shunt management
PEEK	Poor osseous integration	Hydrophobic bioinert surface	Stable fixation and validated surface modification
Titanium	Implant exposure	Thin scalp, prominent edge, radiation, atrophy	Low-profile design and vascularized coverage
Titanium	Imaging artifact	High-density metallic structure	Use artifact-reduction imaging or alternative material when surveillance is critical
PMMA	Thermal injury	In situ exothermic polymerization	Polymerize outside the wound and cool fully
PMMA	Fracture	Brittle material, insufficient thickness, impact	Mechanically validated geometry and distributed fixation
PMMA	Monomer-related inflammation	Incomplete polymerization or washing	Standardized mixing, curing, and cleaning
Porous HA	Fracture	Brittleness and point loading	Controlled fixation and careful handling
Porous implant	Persistent deep infection	Bacterial colonization of interconnected pores	Strict selection, debridement, and timely explantation when necessary
CaP–Ti	Difficult revision	Strong tissue and bone integration	Use when long-term biological incorporation is a deliberate objective

The CRANIO-MAP Framework. The proposed CRANIO-MAP framework begins with Contamination and wound biology. Previous infection, radiation, scar, sinus entry, osteomyelitis, shunt hardware, and scalp perfusion are assessed before material selection. Reconstruction geometry includes defect size, curvature, thickness, midline crossing, orbitotemporal extension, skull base,

temporal hollowing, and available fixation margin. Anatomy and soft tissue includes scalp thickness, temporalis volume, vascular supply, previous flap surgery, and the need for free-tissue transfer. Neurological and CSF status includes hydrocephalus, shunt dependence, seizures, cerebral swelling, syndrome of the trephined, and expected neurological recovery. Imaging requirements determine the importance of CT and MRI artifact. Neuro-oncology and vascular follow-up may favor PEEK or PMMA, whereas mechanical priorities may favor titanium. Osseointegration objectives establish whether the implant should remain removable and inert or become progressively incorporated into native tissue. Mechanical and thermal behavior includes impact risk, implant thickness, defect location, thermal perception, brittleness, fatigue, and fixation. Additive-manufacturing logistics includes local availability, lead time, validated software, material certification, sterilization, cost, and revision support. Patient priorities include cosmesis, weight, thermal sensation, imaging, cost, expected lifestyle, willingness to accept future revision, and individual valuation of biological integration.

Table 5. **Scientific Originality of the CRANIO-MAP Model**

Existing limitation	**Conventional interpretation**	**Proposed CRANIO-MAP principle**	**Expected clinical contribution**
Implant selected mainly by surgeon preference	One material used for most defects	Material selected from nine patient-specific domains	Reduces preference-driven selection
Geometric accuracy treated as clinical success	Excellent fit assumed to ensure outcome	Fit separated from wound biology, CSF dynamics, and integration	Prevents technically precise but biologically unsuitable reconstruction
Infection attributed to material	Implant chemistry considered dominant	Scalp, contamination, shunt, dead space, and biofilm integrated	Improves infection-risk stratification
Porosity assumed universally beneficial	More bone ingrowth viewed as always desirable	Integration balanced against strength, infection, and explantability	Prevents overuse of regenerative architecture
Cost defined by implant price	Cheapest device assumed most economical	Full life-cycle cost includes surgery and revision	Supports health-system planning
Imaging treated as secondary	Artifact considered an inconvenience	Future surveillance incorporated before material selection	Improves neuro-oncological and vascular follow-up
PMMA considered non-personalized	Acrylic associated with manual shaping	Printed molds provide patient-specific low-cost reconstruction	Expands access to precision cranioplasty
Soft tissue evaluated after implant choice	Scalp closure treated as final operative step	Soft-tissue envelope determines allowable implant architecture	Reduces exposure and wound failure

Biological integration equated with regeneration	Tissue ingrowth interpreted as restored skull	Degree and clinical meaning of integration stated explicitly	Avoids unsupported regenerative claims

Discussion. The principal conclusion of this review is that patient-specific cranioplasty has solved much of the geometric problem but has not solved the biological problem. Additive manufacturing can reproduce external contour with submillimetric precision, but infection, exposure, fluid collection, hydrocephalus, hematoma, and neurological outcome remain dependent on the patient and the complete surgical workflow. This distinction explains why comparative studies have not identified a universally superior material. PEEK, titanium, PMMA, and porous bioceramics fail for different reasons. The absence of one failure mode is often accompanied by another trade-off. PEEK is frequently described as an ideal cranial material because it is light, radiolucent, thermally insulating, and mechanically closer to bone than titanium. These advantages are clinically meaningful. They do not eliminate the polymer's bioinert surface or the risk of fluid collection. The 2025 surface-design study is important because it shifts the question from "Is PEEK effective?" to "Which PEEK architecture is appropriate?" Smooth and perforated implants may behave differently with respect to fluid communication, tissue attachment, weight, and fixation. Current evidence is insufficient to define a universally optimal perforation pattern [2, 6, 18, 27]. Titanium remains the most mechanically versatile material. Additive manufacturing can produce thin patient-specific structures with integrated fixation and locally controlled porosity. Titanium is therefore particularly valuable for complex geometry, large defects, and cases requiring high structural confidence. Its disadvantages become most evident in the biological envelope. A perfectly fabricated titanium implant can fail years later because the scalp progressively thins over a rigid edge. Previous radiation, infection, repeated surgery, and temporal muscle atrophy increase this risk. Soft-tissue planning must precede implant selection. PMMA remains underestimated when discussed only as hand-molded bone cement. Three-dimensional printed molds can transform PMMA into an accurate patient-specific implant at a fraction of the cost of some commercial alternatives. This is especially relevant for global neurosurgery and regional point-of-care manufacturing. The PMMA workflow must nevertheless be controlled. Poor polymerization, unvalidated mold material, contamination, irregular thickness, inadequate cooling, and weak fixation can convert an economical solution into a hazardous one. Precision manufacturing is a process, not the presence of a printer. Regenerative porous implants introduce the most biologically ambitious concept. Porous hydroxyapatite has the longest cranial clinical history and the strongest evidence of tissue and bone integration. CaP–Ti composites add mechanical reinforcement. Porous titanium and functionalized PEEK or PEKK attempt to combine structural reliability with osteogenic surfaces. The term "regenerative" should be used cautiously. Bone ingrowth at the implant interface does not necessarily produce a living cranial structure equivalent to native vascularized diploic bone. The central portion of a large implant may remain predominantly artificial even when peripheral integration is excellent. Biological integration creates a therapeutic paradox. A strongly integrated implant may be more stable and less prone to migration. If deep infection or tumor recurrence occurs, the same integration makes removal more traumatic. The appropriate integration objective therefore depends on the likelihood of future surgery. Neuro-oncological patients represent a clear example. A radiolucent PEEK implant may facilitate MRI and CT surveillance and can be removed during

recurrence surgery. A highly integrated porous device may be less attractive when future re-entry is probable.

A young trauma patient with a stable wound, low likelihood of reoperation, and decades of anticipated implant use may derive greater benefit from long-term biological incorporation. These examples demonstrate why material selection should be driven by predicted lifetime trajectory rather than only the immediate operation. The randomized hydroxyapatite–titanium trial illustrates the limitations of current evidence. The observed infection difference was clinically notable but statistically inconclusive because the sample was small. Large randomized material trials are difficult because defects, patients, and surgeon preferences are heterogeneous [4, 7, 14, 19]. Retrospective studies are vulnerable to confounding by indication. Surgeons may select expensive PEEK for large defects, titanium for complex trauma, PMMA for lower-risk or resource-limited cases, and porous composites for revision surgery. Raw complication rates then reflect both material and case selection. Future studies should therefore record defect area, location, number of previous operations, scalp quality, radiation, infection, shunt, time since craniectomy, implant thickness, porosity, fixation, dural suspension, drains, antibiotic protocol, and surgeon experience.

Cosmetic outcomes require standardized measurement. Surgeon judgment alone is insufficient. Three-dimensional surface scanning, cranial symmetry indices, patient-reported satisfaction, temporal hollowing, palpability, and scar quality should be assessed separately. Mechanical testing must also become patient specific. A generic material strength value does not predict performance of a curved implant with variable thickness and discrete fixation. Finite-element analysis can identify stress concentration, edge loading, and impact deformation before manufacture. Topology optimization may reduce weight while maintaining protection. Lattice regions can be placed near bone margins, while the central protective surface remains dense. Such designs require validation for cleaning, sterilization, fatigue, and impact. Antimicrobial functionality is another developing field. Antibiotic-loaded PMMA, antibiotic-immersed hydroxyapatite, silver or copper coatings, antimicrobial polymers, and drug-eluting porous structures may reduce bacterial burden. They may also create toxicity, resistance, altered integration, or mechanical weakening. The material should not be expected to compensate for uncontrolled infection. The most effective antimicrobial strategy remains appropriate timing, radical debridement, removal of nonviable tissue, microbiological diagnosis, targeted antibiotics, stable fixation, dead-space control, and vascularized coverage.

The timing of cranioplasty remains linked to material planning. A patient-specific implant requires stable anatomy and sufficient production time. Early neurological benefit must be balanced against the risk that edema, hydrocephalus, or infection will change the surgical geometry. The presence of a ventriculoperitoneal shunt deserves specific attention. Shunt overdrainage can create a sunken flap before cranioplasty and epidural or subgaleal space afterward. Valve adjustment, temporary ligation, staged shunting, or simultaneous management should be planned according to ventricular and cranial physiology. Temporalis reconstruction should be integrated into the digital workflow. Some visible postoperative deformity attributed to implant contour is actually caused by muscle atrophy or inferior retraction. Three-dimensional soft-tissue simulation may improve future planning. Point-of-care manufacturing has major potential but requires governance. The hospital becomes part designer, manufacturer, sterilization provider, and quality-control authority. Roles and

legal responsibility must be explicit. A low-cost PMMA implant manufactured under a validated local system may be safer than an expensive custom device inserted without adequate wound preparation. Conversely, unregulated printing with undocumented materials is incompatible with safe implant surgery. The CRANIO-MAP model is intended to structure this complexity. Its originality lies in placing biological, mechanical, imaging, manufacturing, and patient-priority variables within the same selection process. The model is not a validated score. It does not assign a numerical threshold for choosing PEEK, titanium, PMMA, or porous implants. Prospective validation could convert individual domains into a structured decision-support tool. Future research should include pragmatic multicenter registries with standardized implant architecture and wound variables. Randomized comparisons are most realistic in relatively homogeneous primary cranioplasty populations rather than complex revision cases.

Long-term studies are essential. Implant exposure, fracture, progressive tissue thinning, ossification, and imaging consequences may emerge years after surgery. Short-term cosmetic success is not sufficient. Pediatric research requires separate analysis. Skull growth, resorption risk, congenital pathology, future revision, and long life expectancy distinguish children from adults. An implant that performs well in an adult may restrict growth or require replacement in a young child. Patient-reported outcomes should include protection, appearance, temperature sensitivity, pain, palpability, confidence in social interaction, headache, return to work, and satisfaction with cost. These outcomes may differ even when complication rates are similar.

Conclusion. Patient-specific cranioplasty represents a major advance in reconstructive neurosurgery. Computed-tomography-based design and additive manufacturing permit accurate restoration of complex cranial geometry, integrated fixation, controlled implant thickness, and predictable cosmetic reconstruction. Geometric accuracy is necessary but insufficient. Long-term success depends on contamination control, soft-tissue vascularity, cerebrospinal-fluid dynamics, fixation, dead-space management, implant architecture, manufacturing quality, and patient-specific clinical goals. PEEK provides low weight, minimal imaging artifact, thermal insulation, accurate contour, and relatively bone-like elasticity. Its principal limitations are biological inertness, cost, difficult intraoperative modification, and a reported tendency toward fluid collection in some series. Titanium provides the greatest structural versatility, thin-profile strength, reliable fixation, and the possibility of porous osseointegrative design. Its disadvantages include imaging artifact, thermal conductivity, stiffness mismatch, and exposure risk beneath compromised scalp. PMMA remains a clinically relevant and economically important material. Three-dimensional printed molds can convert it from a manually shaped cement into an accurate patient-specific implant. Controlled polymerization, material quality, thickness, cleaning, fixation, and infection prevention are mandatory. Porous hydroxyapatite, CaP–Ti composites, porous titanium, and functionalized porous polymers seek biological integration and progressive bone ingrowth. Their regenerative potential is promising but should not be equated with complete restoration of native living calvarium. Brittleness, infection, mechanical variability, cost, and difficult explantation remain important. No universally superior material exists. The best implant is the one whose geometry, biology, mechanics, imaging characteristics, manufacturing pathway, and lifetime behavior are aligned with the individual patient. The proposed CRANIO-MAP framework integrates Contamination and wound biology,

Reconstruction geometry, Anatomy and soft tissue, Neurological and CSF status, Imaging requirements, Osseointegration objectives, Mechanical and thermal behavior, Additive-manufacturing logistics, and Patient priorities. Future cranioplasty should move beyond choosing among material names. It should select a patient-specific implant architecture through a validated digital workflow and a clinically explicit understanding of the failure mechanism that must be prevented.

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