Original Article

Additively manufactured vs. conventionally pressed cranioplasty implants – an accuracy comparison

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Abstract

This paper compared the accuracy of producing patient-specific cranioplasty implants using four different approaches. Benchmark geometry was designed to represent a cranium, and a defect added simulating a craniectomy. An 'ideal' contour reconstruction was calculated and compared against reconstructions resulting from the four approaches – 'conventional', 'semi-digital', 'digital – non-automated' and 'digital –semi-automated'.

The 'conventional' approach relied on hand-carving a reconstruction, turning this into a press tool, and pressing titanium sheet. This approach is common in the UK National Health Service (NHS). The 'semi-digital' approach removed the hand-carving element. Both of the 'digital' approaches utilised Additive Manufacturing (AM) to produce the end use implant. The geometries were designed using a non-specialised Computer Aided Design (CAD) software; and a semi-automated cranioplasty implant-specific CAD software. It was found that all plates were clinically acceptable, and that the digitally designed and AM plates were as accurate as the conventional implants. There were no significant differences between the AM plates designed using non-specialised CAD software, and those designed using the semi-automated tool.

The semi-automated software, and AM production process, were capable of producing cranioplasty implants of similar accuracy to multi-purpose software and AM, and both were more accurate than handmade implants. The difference was not of clinical significance, demonstrating that the accuracy of AM cranioplasty implants meets current best-practice.

Keywords

Additive Manufacturing, Rapid Prototyping, Implant, Surgery, Accuracy, Co-ordinate Measurement, Cranioplasty, Computer-Aided-Design

Introduction

Cranioplasty is a common procedure across the world, including within the UK National Health Service (NHS). Patient-specific cranioplasty implants (Figure 1) are used to replace absent portions of cranium – usually following the removal of diseased anatomy [1], or a decompressive craniectomy procedure to relieve pressure on a patient's swelling brain [2]. The viable size of decompressive craniectomy following severe traumatic cranial and brain injury has increased in recent years [3], making the design and production of cranioplasty plates more challenging. Technologies, including Computer Aided Design (CAD) and Additive Manufacturing (AM) have the potential to improve the accuracy of, and access to, both large and small patient-specific cranioplasty implants. This paper reviewed the accuracy of cranioplasty implant outputs from four different UK production methods. Two were based on more typical, craft-based, hospital-laboratory approaches, and two were based on CAD and AM techniques. Each approach incorporated design *and* fabrication activities – and the important translation stages between them. A literature review was undertaken to evaluate previous work on accuracy, and to highlight relevant key factors from beyond the featured production methods and materials.

TAKE IN FIGURE 1

Figure 1 – Typical Cranioplasty Implant Fixed to Anatomical Model of Partial Cranium

Broadly, in the UK NHS, patient-specific cranioplasty implant production can be classified according to the degree of digital technology involvement as: conventional production (hereafter: "Process A"), semi-digital production (hereafter: "Process B"), and digital production (hereafter: "Process C") [4]. Because the most expensive and time-consuming of the three approaches was found by Peel and Eggbeer [4] to be the digital route, (requiring multiple software packages and a specialist design engineer), this investigation introduced a fourth classification for comparison, semi-automated digital (hereafter: "Process D"). This new route involved a single software package which can be used by a surgeon directly, or by laboratory staff, to rapidly specify, design, and verify a custom cranioplasty implant design prior to direct AM of the end-use titanium (Ti6Al4V – equivalent to grade 23) part.

Literature Review

Across a broad range of surgical applications, digitally planned procedures and AM devices have been shown to offer a more accurate device fit [5, 6], improved viability for complex procedures [7], improved predictability [8, 9], a reduced need for two-stage surgeries [10], and shorter duration surgeries [11]; when compared to off-the-shelf implants which are intraoperatively adapted [12], or to more traditional autologous reconstruction techniques using bone [13]. Additionally, positive secondary effects can be reasonably inferred but not yet explicitly and consistently proven; such as reduced infection risks and blood loss [14], and accelerated recovery [10]. The new semi-automated AM implant workflow therefore sought to reduce the amount of design time and specialised human resources required when digitally designing simple cranioplasty implants, without sacrificing accuracy, and the other established CAD/AM benefits.

Previous Work - Accuracy

Previous published cranioplasty studies have assessed the quantified accuracy of: automated die design for hydroforming [15]; differences between cast and machined polymethyl methacrylate (PMMA) [16]; an algorithm for implant design based on combining low-resolution diagnostic Computed Tomography (CT) scans with high-resolution surgical-planning scans [17]; an algorithm for reconstructing cranial defects with depressed contours to ease wound closure [18]; and the degree of compliance of a conventionally-pressed titanium plate with the edges of defective anatomy [19]. In many studies however, the evaluation of cosmetic outcomes was based on subjective judgements by patients and / or clinicians, either in person or via imaging [20-24]. No published literature was found with quantified accuracy comparisons between NHS laboratory and CAD/AM production techniques. This paper established initial quantified benchmarks for laboratory accuracy, and compares them with the two fully digital CAD/AM approaches mentioned above (and described in detail in the 'Methods' section). This was to capture the fundamental difference between the high-skill, artisanal nature of the current laboratory and non-automated digital methods [4, 15, 23] and the comparatively de-skilled, potentially more accessible, new semi-automated digital method. This was especially relevant when the relative uniqueness of UK hospital-laboratory capabilities were considered. The authors defined implant accuracy as: the degree to which the final implant form matched a pre-defined 'ideal' result. The ideal result was known prior to design and fabrication, by basing the investigations on an artificial defect modelled on healthy donor cranium scan-data (as opposed to a real defect where the precise original form is unknown).

Clinical Background - Craniectomy

When medical management (including temperature control, sedation, and coma) fails to relieve elevated intracranial pressure following a traumatic brain injury, a surgical intervention may be made in the form of a decompressive craniectomy [2]. After removing a portion of the cranium, and creating extra space for the brain to swell into, the bone flap can be replaced immediately (craniotomy) or left off (with only the soft tissues covering the brain) pending further recovery [2]. Other indications for craniectomy (or procedures resulting in similar defects) include resections of cranial lesions [25]; together with benign bone pathologies such as fibrous dysplasia [26], and needing access to the brain to remove tumours [27].

Clinical Background - Reconstructions

Reconstruction of the cranium is primarily undertaken to restore its protective and cosmetic functions [28]. Further benefits involve the relief of neurological symptoms – potentially caused by atmospheric pressure acting upon the dura and brain via the skin flap [27]. To minimise infection risk, cranioplasty should be undertaken at least six months after craniectomy [29] with up to fourteen months reported by Cabraja et al. [20]. The defect shape can change over time as the bone remodels – which can be problematic for pre-fabricated implants based on older scans from the time of the original surgery [5]. Soft tissues can also change during this time and have been shown to obstruct the successful insertion of implants fabricated in materials which are difficult to modify in-theatre [4].

Generally, cranioplasty implant geometry is based on mirroring contralateral healthy anatomy – unless the defect crosses the midline, in which cases contours were assessed for aesthetic continuity with surrounding tissues [30]. Edwards [31] highlighted the importance of keeping cranioplasty implant extents as small as possible – to reduce the size of the raised skin flap. Raising the skin flap is the most time-consuming stage of the surgical procedure [32]. After inserting the implant, suturing

without tension of the skin is essential to prevent implant exposure [33]. This can be achieved by using skin expanders [33] or by depressing the otherwise optimal cosmetic contours of an implant design before fabrication [18].

Conventional Reconstructions – Autologous Material

Reconstructing with the patient's own bone flap (after storing it cryogenically, or in the patient's abdomen post-craniectomy) is still considered the 'gold standard' [34-36]. This is surprising – given the high frequency of major bone resorption which required revision surgery (30.4% of patients, in one study) [37]. Patients with PEEK or titanium cranioplasty implants experienced lower complication rates and shorter hospital stays than for patients with re-implanted bone flaps [13], but primary treatment costs were reported as being higher. Lethaus et al. [13] also noted the relatively short follow-up history for alloplastic materials – which may indicate the reason for the enduring 'gold standard' label resting with bone flaps.

However, when successful, the autologous approach resulted in complete biological integration [36]. Furthermore, Lauerman and Stein [2] recommended recreating the original cranial vault volume to avoid potential complications – if the swelling is low enough. Logically, replacing the full-thickness of original cranium – by using the original portion of cranium itself – was identified as one method of achieving this.

Conventional Reconstructions – Alloplastic Materials

There is a significant body of published literature focusing on the review and evaluation of alloplastic cranioplasty implant materials; and it is clearly still the major area of controversy. The use of acrylic (PMMA) was commonly described thanks to its low cost, and its ability to be easily shaped [23]. PMMA implants were fabricated intraoperatively by mixing a liquid polymer and powdered monomer, then forming the flowing material manually, and (where necessary) making adjustments using burrs after the mix has hardened [38]. Alternatively, the implants were pre-formed via a moulding technique [23] which can save time in-theatre. However, Vahtsevanos et al. [39] listed several major disadvantages to PMMA including: incomplete biological inertia; tendency to fracture; high local temperatures (during intraoperative polymerisation); and inflammatory scarring. Other reported intraoperatively-shaped materials included titanium mesh and hydroxyapatite. The latter could exhibit bioactive behaviour and avoided many of the listed problems with PMMA, but it did require a dry anatomical defect site and took longer to set [38].

Making an assessment of the nature of a craniectomy defect, during pre-operative alloplastic implant planning, historically involved taking an impression manually through the patient's skin-flap [32]. In the 1990's however, techniques were developed for representing defects using stacked cross-sections derived from individual patient Computed Tomography (CT) scan-data slices [21], and using milled polyurethane foam models [19]. Now, the conventional approach in the NHS is shown to rely on AM medical models [4, 31, 40]. It is these models on which the hospital-laboratory design and fabrication processes for common pressed-titanium implants are based. This process results in implants which: can achieve aesthetically pleasing results in a material which is strong and dimensionally stable [40]; are inexpensive relative to current digitally designed and additively manufactured plates [4]; which can be adjusted in-theatre by trimming or bending [4]; and which have excellent biocompatibility [38]. The combined, highly-skilled design and fabrication process was undertaken by maxillofacial prosthetists or laboratory technologists in the published literature, not by the operating surgeon as previously referenced in autologous reconstruction and acrylic examples. However, surgeon-consultation was recommended by Edwards [31]. Similar

implants were produced by pre-shaping titanium mesh [41] or in a non-NHS laboratory setting, by hydroforming titanium sheet [15].

Digital Reconstructions – Alloplastic Materials

General benefits from using CAD to design patient-specific devices are well established in the literature: improved accuracy of fit, reduced theatre time, and a reduced likelihood of surgical revisions [42]. With AM titanium parts specifically, the ability to incorporate porous areas, coatings, and varied internal structures can result in tailored mechanical properties [43], and improved osseointegration [44]. As highlighted previously, despite some clear potential benefits this approach has not been shown to be widely undertaken on a routine basis, particularly for simpler implant geometries such as cranioplasty, because of high costs relative to conventional and semi-digital workflows [4]. Furthermore, access to specialised planning and design services, or similar in-house skills, is limited. Where the hospital capability does exist, it varies in extent and is inconsistently integrated - across prosthetics laboratories [45], individual units [46], and photographic departments [47].

Digitally designed cranioplasty implants have been fabricated from: titanium using AM [35, 48, 49], titanium using Computer Numerically Controlled (CNC) machining [20, 25, 50], and from PolyEther Ether Ketone (PEEK) also using CNC [8, 13, 41, 51, 52]. Lethaus et al. [13] emphasised key benefits of PEEK in relation to AM titanium; it is closer in strength, stiffness, and elasticity to the original bone, which reduces stress shielding. Likewise it has a lower thermal conductivity, lower density, and lighter weight than titanium, contributing to improved patient comfort, especially in particularly hot or cold environments [53]. PEEK implants have been modified in-theatre using burrs [36] and are radiolucent for improved clarity in post-operative imaging [54]. Although AM Ti6Al4V Extra Low Interstitials (ELI) implants were difficult or impossible to modify intra-operatively, this limitation was mitigated with a robust design process to build-in positional flexibility, via the curation of high-fidelity specifications [4, 8]. PEEK does not have bioactive potential like titanium [13], and high upfront expense was often raised as a significant negative factor [41, 52, 53].

Literature – Implications

Reviewing the literature has demonstrated a clear gap in published knowledge about the accuracy of implant production – involving the fluid and iterative combination of design and fabrication activities in the hospital laboratory, as well as the fidelity of conventional and digital fabrication processes themselves. As described, accuracy is an important consideration in cranioplasty implant design because of the aesthetic and morphological impacts of the procedure, and the success of the post-operative skin-flap coverage. With material-selection still a significant topic of controversy, the benefits of alloplastic pre-formed reconstructions have substantial backing. AM titanium and CNC PEEK, with CAD design as their prerequisite, are represented as promising routes to producing implants using fully digital methods; each with relative merits. AM titanium alone will be explored in this study, to exclude any accuracy effects from material choice.

Methods

Research partners included a metal AM equipment manufacturer, a maxillofacial unit, and a specialist surgical and prosthetic design and research institute. Study activities were divided according to partner expertise. Generally this amounted to

division according to which stakeholder would usually undertake each role for a real clinical case. This meant that tasks were assigned to production engineers and a reconstructive scientist at the metal AM equipment manufacturer, two reconstructive scientists and one surgeon at the maxillofacial unit, and three design engineers at the design and research institute. A summary is provided in Table 1.

TAKE IN FIGURE 2

Figure 2 – Original Cranium Geometry from Scan Data

CT scan-data of a healthy cranium was segmented for bone by a design engineer at the institute using Mimics Version 18 (Materialise, Leuven, Belgium). After exporting the geometry (Figure 2) in the STereoLithography (STL) format, the cranium was imported into FreeForm Modelling Plus V2015 (3D Systems, Rock Hill, SC, USA). This is general engineering and design CAD modelling software with a bundled proprietary haptic 'PHANTOM' interface. On a duplicate of this initial model, a defect was added on the patient's right in the form of a hole of a moderate cranioplasty size (as judged by the reconstructive scientists). The defect did not cross the midline, which ensured mirroring was a consistent basis for implant design across all workflows. A suitable extents-crop (see the removal of material inferiorly between Figures 2 and 3) was agreed with the reconstructive scientists, to realistically minimise model costs while still providing enough material to assess new contours against the contralateral (intact) side. These cropped models with artificial craniectomies (Figure 4) will be referred to as "defect models" in the remainder of the text. The virtual, ideal (i.e. unmodified) contour model (Figure 2) will be referred to as the "ideal reconstruction" in the remainder of the text.

TAKE IN TABLE 1

Table 1 – Overview of Task Allocation

Across four different implant design and fabrication workflows, a total of eight implants were fabricated, fixed to defect models, scanned, compared against the ideal reconstruction, assessed for accuracy, and for clinical suitability. One each, of the conventional and semi-digital implants were fabricated, because of their reliance on time-poor clinical human resources. Three each of the digital and semi-automated digital implants were fabricated, on account of their design and fabrication by non-clinical staff. Each of the four workflows is described in detail below.

TAKE IN FIGURE 3

Figure 3 – Cranium Geometry with Artificially Modelled Defect

TAKE IN FIGURE 4

Figure 4 – SLA Defect Model

Conventionally Designed and Fabricated Cranioplasty Implant

Process A, undertaken by reconstructive scientists, was described by Peel and Eggbeer [4] as: manual re-contouring of an AM defect model using clay; creation of a dental-stone press tool; swaging 0.5mm thick commercially pure titanium sheet; and then refining the implant through further pressing, drilling, polishing, de-burring, and engraving. StereoLithography Apparatus (SLA) was used to produce the defect model, following the institute's established protocols. Design specification points were derived from the standard processes for the maxillofacial unit and reconstructive scientists undertaking this implant design and fabrication. This resulted in an overlay approach, and the implant overlapping the defect edge by a 5mm (with slight variations because of the manual trimming). 2.0mm diameter fixation screw-holes were drilled into the periphery of the implant. Fluid transfer holes of 4.0mm diameter were arbitrarily spaced across the plate surface. The surface was polished using pumice and a rotating brush. Finally, the implant was screwed-onto a defect model.

Semi-Conventionally Designed and Fabricated Cranioplasty Implant

Process B was undertaken in the same way as the conventional process described above, with one key exception. The defect was reconstructed prior to fabrication of the medical model by a design engineer at the institute, and the reconstruction verified by a reconstructive scientist. This eliminated manual carving. Instead, virtual sculpting tools were used in FreeForm, having initially mirrored the healthy contralateral anatomy as a starting point. The reconstruction was initially judged visually, and verified using digital measurements from the anatomy midline to key landmarks. Supplying the reconstructive scientist with this type of model reduces the cost of this key component [4] and removes the time-consuming manual carving stage at the maxillofacial unit.

Digitally Designed and Fabricated Cranioplasty (Manual, Non-Specialised Software)

In Process C, two institute design engineers, and one reconstructive scientist at the AM equipment manufacturer, extrapolated the semi-conventional approach to achieve an implant design. A 0.5mm layer was added on top of the reconstructed virtual model in FreeForm. A similarly onlay approach was taken to permit comparisons with the other approaches, and to reflect the maxillofacial unit's requests in a real clinical case. Holes of the same diameter as for the conventional and semi-digital implants were added for fixation and fluid transfer. Screw countersinks were designed-in – with a compensatory amount of material built-up around the screw-heads to facilitate this without compromising the minimum thickness of the implant. Upon completion of the design, the implant components were exported in the STL file format for fabrication. Production engineers supported the implants for fabrication using QuantAM file preparation software (Renishaw PLC, UK). The implants were fabricated by Laser Melting (LM) (AM250, Renishaw, Miskin, UK) using Ti6Al4V ELI (grade 23). The production engineers then followed a standard medical implant post processing procedure including a vacuum heat-treatment cycle, support removal, and (in this case) tumble polishing to a satin finish.

Digital Cranioplasty (Semi-Automated, Specialised Software)

In Process D, one reconstructive scientist and two design engineers operated a new specialist cranioplasty implant software prototype (ADEPT, Renishaw PLC, UK) to create implants which adhered to the same previously-stated design specifications. The software automatically generated a mirrored form, and prompted the users to assess the result and amend it where necessary. Users were then guided through detailing stages by a wizard feature, to add the fixation and fluid transfer holes. Upon completion and approval of the three designs, the implants were fabricated and post-processed in the same way as the manual digital workflow.

Clinical Placement and Evaluation

The eight implants were each completed and then fixed to their respective defect models for evaluation and testing, and assessed for clinical suitability by the same consultant maxillofacial surgeon. The surgeon was subjectively verifying the design and fabrication of the devices against what they would be happy to use in theatre to repair the artificial model defect if it were real bone in a real patient.

Laser Scan Analyses

The final implant-model assemblies were scanned using the FARO Edge ScanArm (FARO, USA) via PolyWorks software (InnovMetric Software Inc., QC, Canada). The resulting scans were analysed using IMInspect (InnovMetric Software Inc., QC, Canada). Scans were aligned with the STL of the ideal contours, and the aligned scan data then cleaned to within a 5mm border of the STL. The differential between the ideal reconstruction and the scanned implant-cranium assemblies was illustrated by colour maps. The scans provided mean deviation values at user-selected points. Those points were selected post-hoc, on the basis of proximity to extreme deviations and typical deviations as shown by the colour mapping.

This scanning equipment and software setup was chosen for three key reasons: it could provide quantitative measures of the implants and immediately adjacent cranium models relatively quickly compared to contact methods; it could facilitate registration with the ideal geometry and display overlay images; and it was available to the researchers as part of the collaborative project.

Results

‘Positive deviation’, shown towards the orange-red end of the scale, will refer to implant deviations which were superficial to the ideal contours. ‘Negative deviation’, shown towards the blue-pink end of the scale, will refer to implant deviations which were deeper than the ideal contours. Results are presented in Table 2 below. Values for maximum positive and negative deviations exclude the screw heads used for fixation.

TAKE IN TABLE 2

Table 2 – Design and Fabrication Process Outcomes and Scanning Results

Discussion

Research Relevance

These results must be considered in the context of the study limitations, prior to evaluating their relevance. This was a laboratory study, unable to assess true clinical impacts of the implants on soft tissues laid over the finished implant contours. There were only one each, of the Process A and B implants, and only three each of the Process C and D implant sub-groups. Statistical significance could therefore not be established. Additionally, only one craniectomy defect was tested, which did not extend beyond the midline. At the implantation (i.e. fixation-to-a-model) stage, subjective variability was introduced on account of the surgeon (deliberately, as standard practice) pressing gently on the conventional and semi-conventional plates prior to securing the screws. Clearly, this subjective aspect contributed to the deviation-measures in a way that was absent from the stiffer, fixed shape AM implants. This was unavoidable.

Finally, the discrete impacts of distinct design and fabrication activities were not explicitly and independently assessed. Indeed, the line between design and fabrication was especially blurred in Processes A and B which relied on designing-through-making, without necessarily establishing clear design intent up-front [4]. Responsibility for the results was easier to assign for the AM produced implants using Processes C and D; on account of their being built in a tightly-controlled, BS EN ISO 13485-compliant [55] system. The form of the devices in those instances was determined by the design process alone, not by potential flaws in, or variations from the manufacturing process. Furthermore, as opposed to designing-through-doing, the very necessity of creating a finished design before fabrication with AM, ensures more thorough consideration towards the front-end of the process. The specific nature of individual details is more likely to be driven by the designer, rather than serendipity when, for example, a crease in the plate after swaging leads to removal of material from that area.

With the limitations acknowledged, the results can be said to apply to the implants measured in this research, while indicating, but requiring future work to confirm, wider validity. The four cranioplasty production methods tested in this research are all used, to varying degrees, in current practice. Therefore, this study is valid for comparing current clinical techniques. This work focused on the accuracy and efficacy of the aesthetic reconstruction and with that, implant fit. Lethaus et al. [35] addressed the relative mechanical efficacies of titanium and PEEK for cranioplasty; with regard to the protective function for the brain.

Relative Accuracies

There were no *clear and obvious* trends when comparing the implants, other than confirmation that the emerging techniques for digitally designed implants (of both sub-group C and D) produced implants that were as accurate, or more accurate than those produced by established Processes A and B. This finding in and of itself represents a key indicator for the continued development of digital design and AM cranioplasty applications. Some minor insights were evident, though they should be verified in future work. Insofar as can be inferred from this data, the digital techniques (Process D in particular) produced implants with the largest cumulative areas of negative deviation from the ideal contours. This, alongside the smaller maximum values for that negative deviation, and smaller maximum values for positive deviation, suggested that digitally designed and AM implants provided the better and more consistent balance between contour accuracy and theoretical skin flap tension.

Clinical Relevance

All of the implants produced for this study were subjectively verified by one consultant surgeon as acceptable for use in real surgery. However, they could not be assessed in terms of post-surgery clinical outcomes either quantitatively or qualitatively, as they were not implanted. Previous reports have largely relied on subjective qualitative assessments of the cosmetic result, whereas this work has introduced a degree of quantitative rigour, at least to the pre-surgery stage. This is important for contributing evidence towards supporting the continued adoption of digitally designed and AM devices.

Negative deviations on the scale shown by the results in this research are effectively 'perfect' reconstructions in that they directly negate the implant thickness. Even at the most extreme positive deviations in these results, the aesthetic significance of the inaccuracies is questionable; especially when the layers of overlaying soft tissues are considered. Palpability and visibility have though, been demonstrated to be more significant concerns where this layer is thinner, such as in temporo-orbital-frontal reconstructions [8].

For the sake of comparability, implants from Processes C and D in this study were constrained to replicating the on-lay approach of implants from Processes A and B. Cranioplasty plates that fit entirely within the defect, via an inlay approach making them level with the surrounding anatomy, were not investigated. Such implants can offer aesthetic and comfort advantages by alleviating palpability through the skin. In light of work by Carloni et al. [33] on skin flap tension, a total elimination of positive deviation from the ideal result would also have been preferable. However, this would have created an unfair comparison with conventional devices which did not have this potential. While this was unavoidable, it is important to acknowledge the additional design freedoms offered by CAD and AM (or CNC).

In addition to the direct impact of aesthetics, other tangential benefits of digitally designed and AM implants are brought into focus, including consistency, repeatability, and accessibility. In-hospital laboratory provision is less-common outside of the UK NHS. Therefore, digitally designed, AM produced implants offer a proven method of routine, effective, and safe production; especially where cost is a less significant factor, such as in insurance-based healthcare systems. As the trend for reductions in AM costs [56] continues, it is reasonable to anticipate the use of sub-optimal cranioplasty methods and materials (highlighted as such by the literature review) will be phased out; as digital design and AM fabrication become accessible by the majority of countries.

Infrastructure and Regulatory Considerations

Unlike those from hospital laboratories, commercially produced patient specific implants must conform to strict quality management [55] and regulatory standards [57]. Furthermore, there are no agreed standard procedures or specifications for conventionally produced cranioplasty implants, with a high degree of variability across practitioners more likely as a result. They require highly skilled staff, significant experience, laboratory facilities, and specialised knowledge; but they are time consuming – sometimes competing with patient-facing clinical work, and can lack clear design intent [4]. In-hospital skillsets are evolving. Polymer printers are increasingly common on-site [47, 58], but the economic argument cannot generally be made for metal printers thanks to high capital and infrastructure costs, and a need for specialist operators [5].

When new drugs, techniques, or technologies are seeking to enter the UK NHS market, the major gatekeeper is value. Clinical outcomes, and their value judgement counterparts, are assessed for efficacy, efficiency, and quality-of-life by the National Institute for health and Care Excellence (NICE) [59]. Currently, NICE offers limited advice to clinicians about digitally designed implants specifically; focusing on customised implants as a whole [60, 61]. This situation in the UK mirrors more urgent concerns from clinicians and researchers in the USA [62] and Australia [63, 64] with regulatory and health-insurance billing vacuums, respectively.

With increasing discussion, development, and emphasis on quality management and regulatory compliance, it is possible to envisage a medium term future in which commercially produced patient-specific implants become the norm. In such a scenario, design services may be distributed across hospitals and external organisations, because of more cost-effective infrastructure and regulatory compliance relative to manufacturing. When based in-hospital, Process D enables a shift in users; away from expert designers, towards non-designers, non-engineers, and other non-CAD specialists like reconstructive scientists or surgeons. The full implications of such a switch should be explored fully in future work. It would be likely to alleviate some of the collaboration barriers to routine use of CAD and AM for simpler implants [4]. Complex implant projects or brand new applications, which have been shown to rely on multi-disciplinary teams with a broad range of design, engineering, and clinical expertise [7], are unlikely to be automated to any significant degree in the short term.

Conclusions and Future Work

In conclusion, semi-automated digitally designed, non-automated digitally-designed, and additively manufactured cranioplasty implants were as accurate as conventionally produced and semi-conventionally produced titanium implants in this study. When additional factors like skin flap tension and implant thickness were considered, a potential improvement could be inferred relative to laboratory made devices. This aspect requires verification across a larger sample size and a wider range of cranioplasty defect locations in future studies. With the digitally designed implants being no worse than the existing UK standard plates, the potential non-accuracy related benefits like accessibility, consistency, and regulatory compliance were considered as being of increased importance. By partially automating the design of simple, routine implants, and additively manufacturing them under validated systems, routine adoption of AM devices may be possible in the short to medium term.

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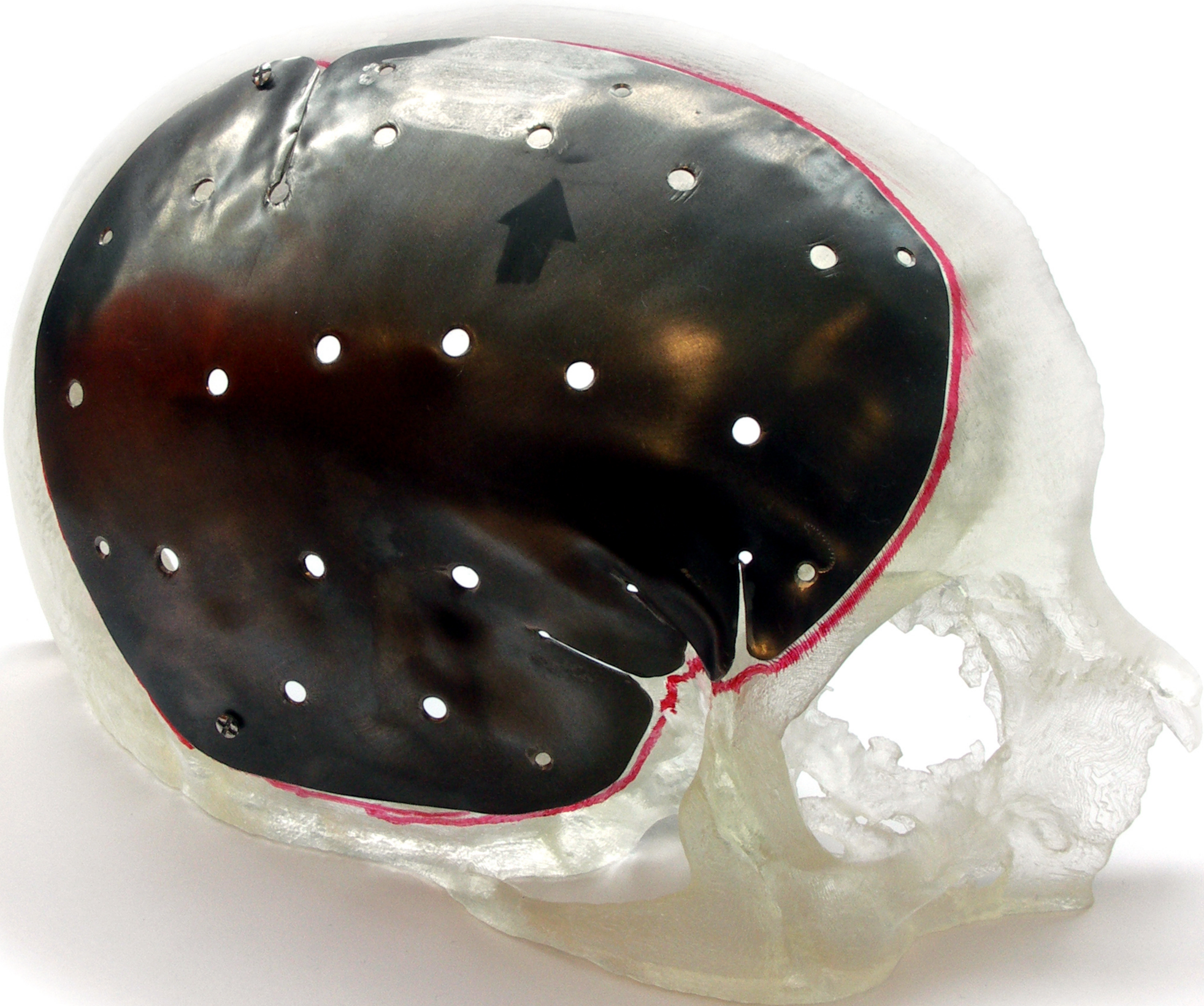
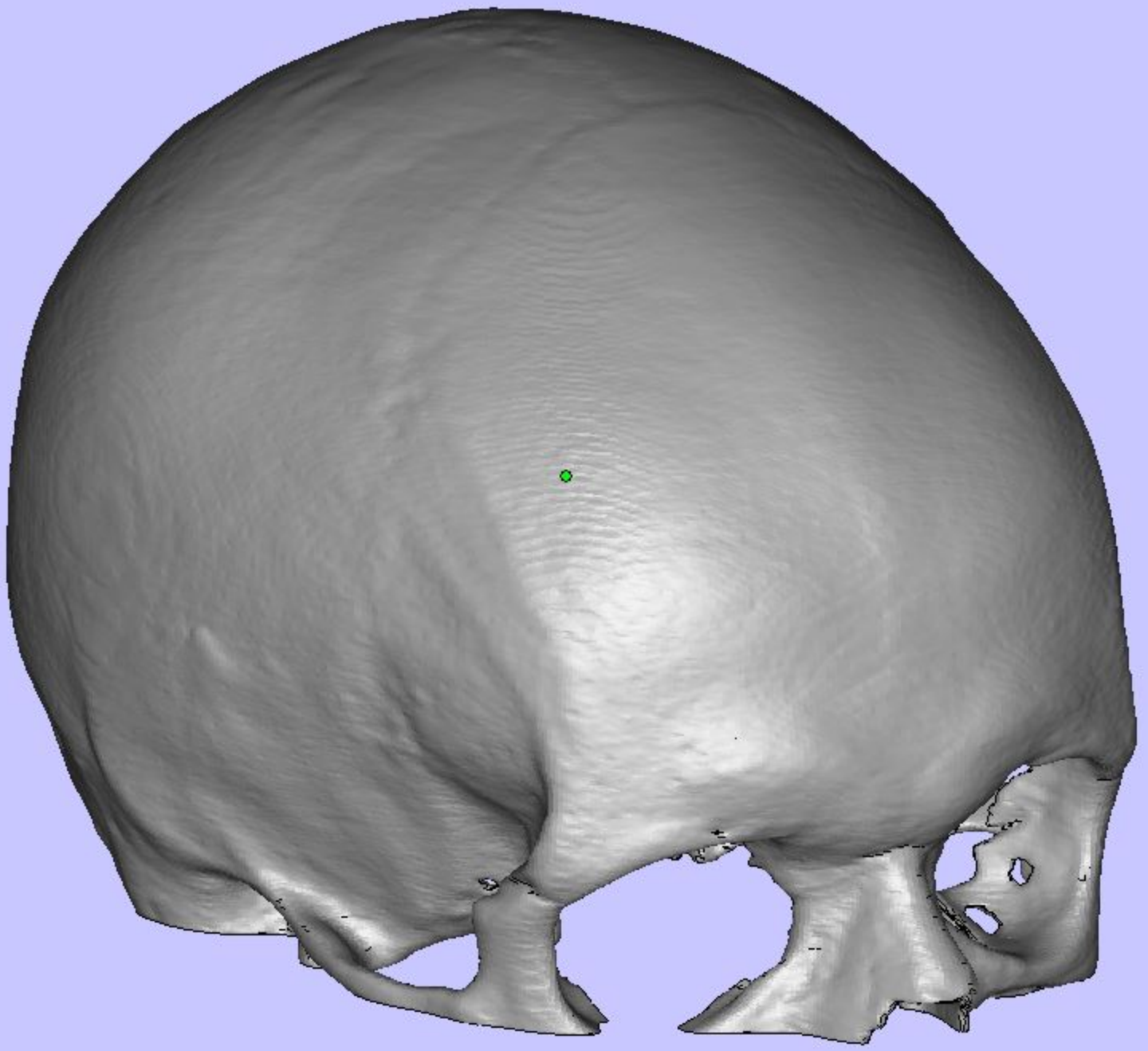
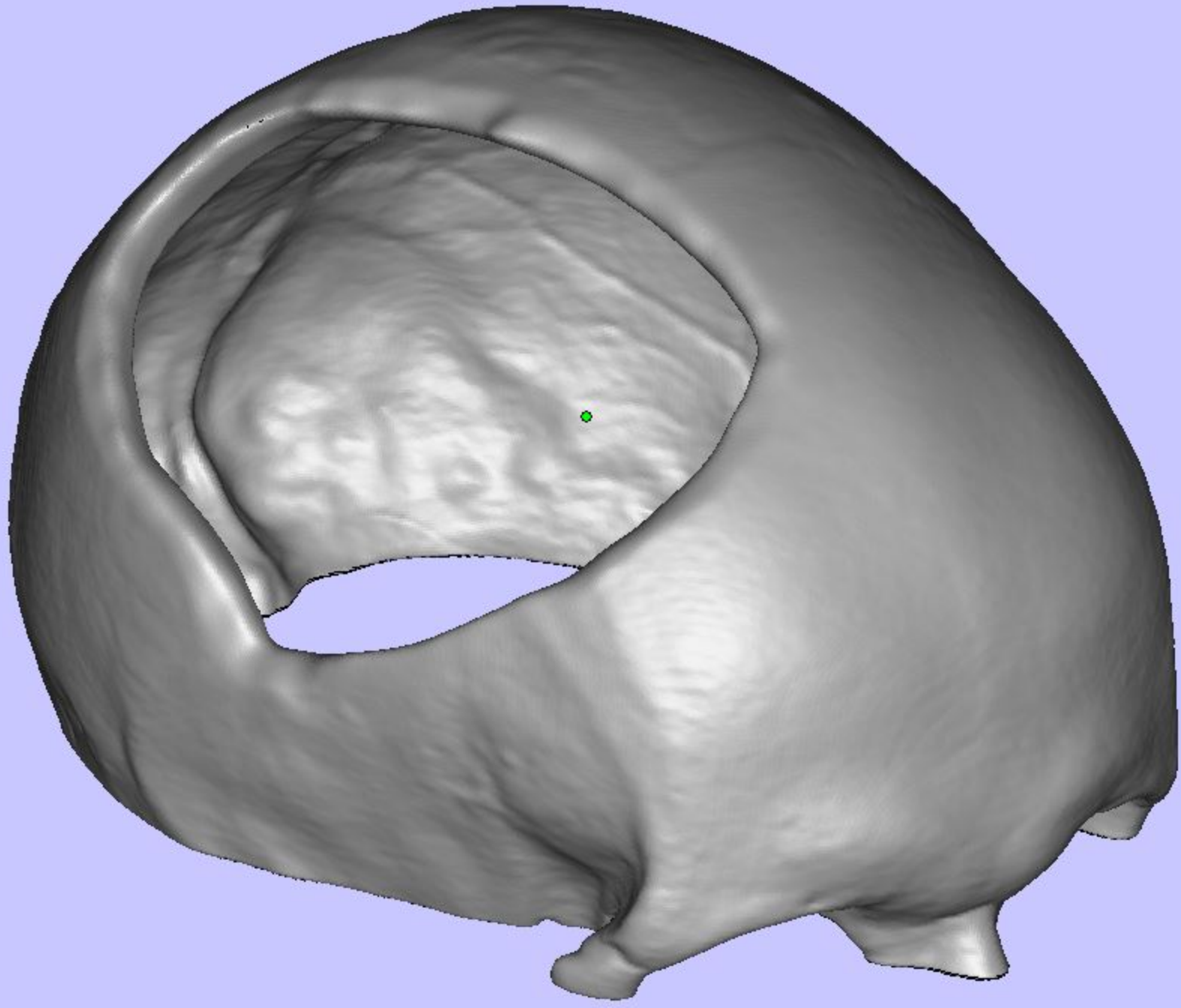
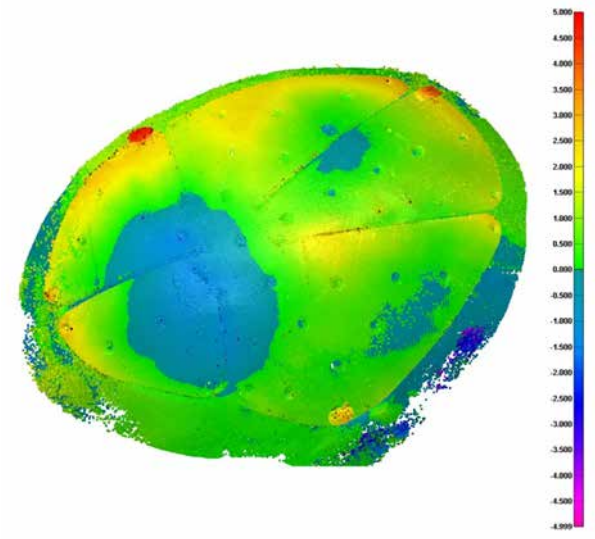
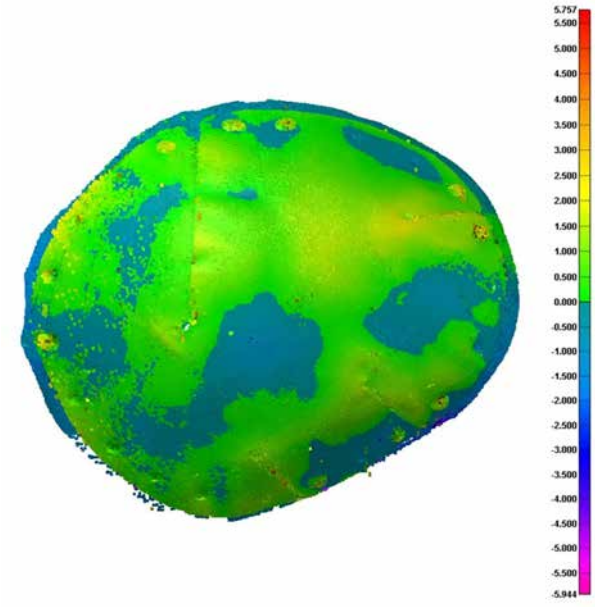
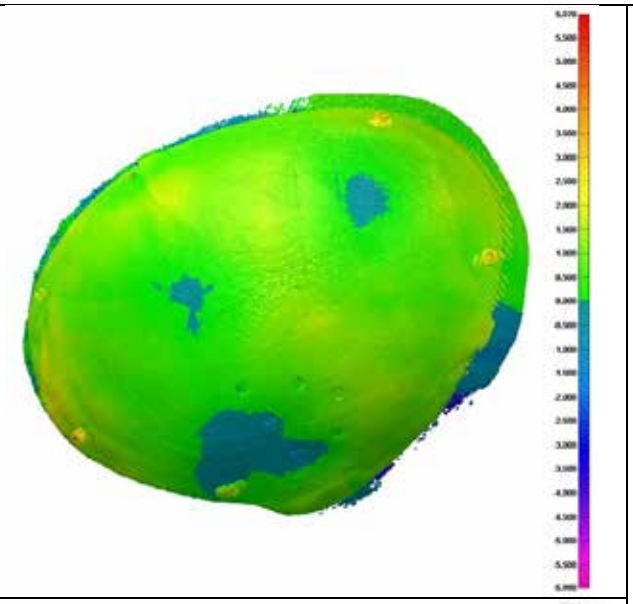
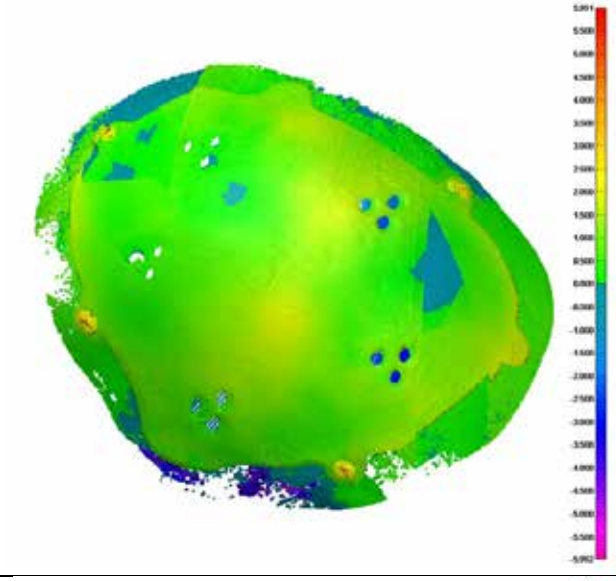
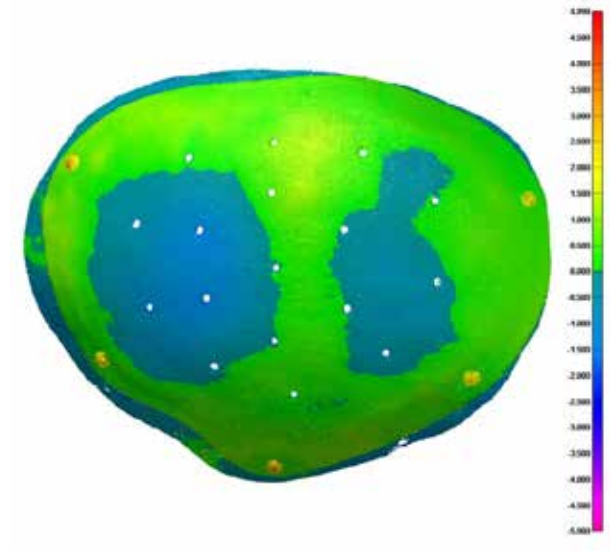


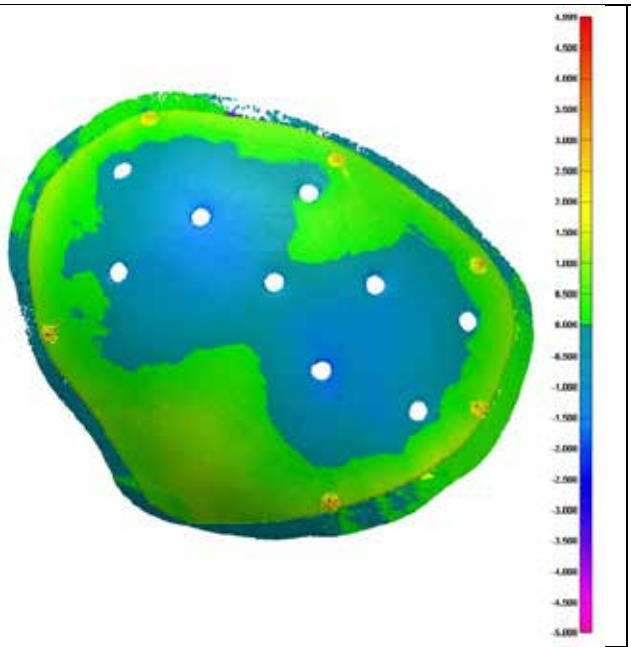
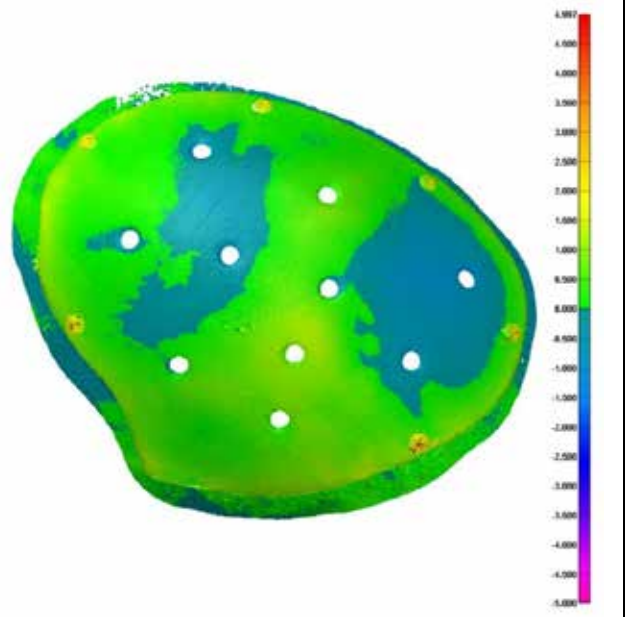




Role	From	Research Task(s)
Design Engineer (1)	Research institute.	Study conception. Manuscript authoring and preparation.
Design Engineer (2)		Study conception. Design of 1x implant using Process C. Design of 1x implant using Process D. Manuscript editing.
Researcher		Laser scanning of finished implants. Manuscript editing.
Design Engineer (3)		Design of 1x reconstructed anatomical model for Process B. Design of 1x implant using Process C. Design of 1x implant using Process D. Fabrication of all SLA cranium models. Laser scanning of finished implants.
Reconstructive Scientist (1)	Maxillofacial unit.	Design and fabrication of implant using Process A.
Reconstructive Scientist 2		Design and fabrication of implant using Process B.
Consultant Cranio-maxillofacial Surgeon		Subjective judgment as to clinical suitability of all implants (design verification).
Production engineers.	Metal AM equipment manufacturer.	Fabrication of all implants for Processes C and D.
Reconstructive scientist 3.		Design of 1x implant using Process C. Design of 1x implant using Process D.

Implant	Differential Map between Scan of Digital Implant-Model Assembly and Ideal Reconstruction	Max. Pos. Dev.	Max. Neg. Dev.	Comments	Clinically Verified?
Process A 		3.5mm	0.5mm-1.0mm	The majority of the implant deviated 0.5-1.0mm positively from the ideal reconstruction; reflecting the implant thickness of 0.5mm. The negative deviation occurred mostly around the area of maximum curvature at the apex of the plate. The positive deviation occurred most severely at the implant edge.	Y
Process B 		Around 2.0mm	0.5-1.0mm	Again, the majority of the implant deviated 0.5-1.0mm positively from the ideal reconstruction; reflecting the implant thickness of 0.5mm. There was no discernible pattern to the areas of positive and negative deviation.	Y

Process C – Implant 1 		2.0-2.5mm	0.5-1.0mm	The majority of the implants contours deviated 0.5-1.0mm positively from the ideal reconstruction; reflecting the implant thicknesses of 0.5mm. Between the three implants in this category, there were no discernible patterns to the areas of positive and negative deviation.	Y
Process C – Implant 2 					
Process C – Implant 3 					

Process D – Implant 1 		2.0-2.5mm	0.5-1.0mm	The maximum deviations occurred in fewer locations than for the majority of the other implants, and had smaller extents in those locations. The majority of the implants contours deviated 0.5-1.0mm positively from the ideal reconstruction; reflecting the implant thicknesses of 0.5mm. Between the three implants in this category, there were no discernible patterns to the areas of positive and negative deviation. The first implant in this category demonstrated the largest extent of negative deviation, relative to all of the implants in this study.	Y
Process D – Implant 2 					
Process D – Implant 3