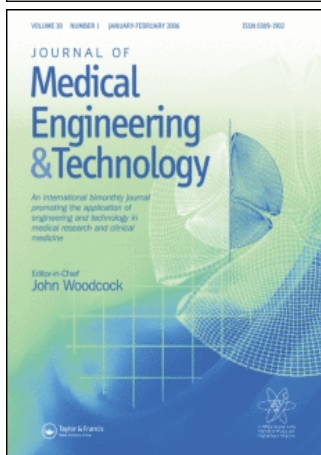


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Reverse engineering techniques for cranioplasty: a case study

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This paper presents rapid prototyping and reverse engineering techniques applied to create an implant for the surgical reconstruction of a large cranial defect. A series of computed tomography (CT) images was obtained and purpose built software was used to extract the cranial geometry in a point cloud. The point cloud produced was used for: (a) the creation of a stereolithographic (STL) physical model for direct assessment of the cranial defect; and (b) the creation of a 3D mould model for the fabrication of the patient-specific implant.

Keywords: Cranioplasty; Implant modelling; Rapid prototyping; Reverse engineering

1. Introduction

Rapid prototyping techniques have been used in medical applications for the production of dimensionally accurate physical models from three-dimensional (3D) diagnostic images. The advent of 3D imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) has enabled the *in vivo* non-invasive extraction of high-resolution patient-specific anatomic information. A combination of 3D imaging and rapid prototyping techniques has been used in maxillofacial surgery for the production of customized prostheses for cranioplasty and for preoperative planning.

Preoperative planning is of prime importance in maxillofacial surgery. The construction of dimensionally accurate 3D physical models using rapid prototyping (RP) technology has enabled surgeons to simulate complex interventions and thus reduce the duration of operation and the risk of intraoperative and postoperative complications [1,2].

Cranioplasty is a technique applied to the design of customized implants that are used to restore the cranial

integrity and facial aesthetics of patients with cranial defects. The first xenograft was recorded by Meekeren in 1668, who successfully used a canine bone to repair a cranial defect in a Russian man [3]. During the same century Falopius performed a cranioplasty using a gold plate. The next advance in cranioplasty was the experimental ground-work in bone grafting, performed in the late 19th and early 20th centuries, when many soldiers suffered from cranial defects from war-related injuries [4]. Advances during the last two decades include the use of new materials such as carbon-based polymers, calcium-based alloplasts, metallic implants and biological grafts in order to cover large cranial defects. The increasing number of patients who survive the accidents causing their bone defects has led to an increase in the number of cranioplasties performed [5,6,7]. Current cranioplasty research focuses on two basic areas: (a) development of optimal osteo-integration materials; and (b) development of novel procedures and techniques for customizing implant model generation [8,9,10].

Methyl methacrylate is a widely used material in cranioplasties. However, its use in reconstructing large

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cranial defects can lead to poor aesthetic outcome due to its high intraoperative plasticity. Furthermore, its intraoperative moulding by exothermic reaction has been associated with complications due to localized tissue damage [11]. The production of physical stereolithographic models for maxillofacial surgery avoids complications associated with intraoperative moulding and also offers (a) improved preoperative planning that is critical in complex operations; (b) graft fabrication with improved dimensional accuracy and shape; and (c) advanced learning tools for surgical training.

In cranioplasty applications, since the physical model is available, building medical models essentially involves reverse engineering. Novel image processing algorithms integrated in modern software tools combined with reverse engineering techniques can dramatically improve the surgical efficiency in reconstructive cranioplasty [12]. This paper reports in detail a case where RP and reverse engineering techniques are applied to produce an implant for the surgical reconstruction of a large cranial defect.

2. The problem

Figure 1 presents the case of a 19-year-old female with a large post trauma defect in the left-frontal bone. The cranial section missing extended to an area of approximately $9.5 \times 5.2 \text{ cm}^2$. The patient initially presented with cerebrospinal fluid leak and the presence of encephalic tissue in the nasal cavity because of a severe nasoethmoidal and frontal bone fracture. There was also fracture of zygomatic bone. The extensive frontal bone defect was the result of complicating osteomyelitis. Following the initial management of the patient and the healing process, reconstruction of the cranial defect was required to restore the structural integrity of the skull and the patient's facial aesthetics.

Conventional cranioplasty is based on the open cold cure moulding technique and reconstruction of the implant on a

freehand basis. Taking impressions of the defect directly through the patient's scalp is a major problem. Intraoperative moulding extends the duration of the operation and has been associated with complications due to localized tissue damage from the exothermic reaction during the material curing process.

Furthermore, the limited intraoperative overview of larger osseous areas impedes judgment of symmetry [13]. Several reviewed cases of titanium cranioplasty found that most were ill-fitting, or aesthetically poor [14,15,16]. Conventional cranioplasty techniques are primarily based on the manual skills and experience of the surgeon. Only an accurately fabricated prosthesis fits into the defect properly and reduces the probability of subsequent movement, dislodgement and extrusion [17].

The presented approach aims at creating a perfect model for the implant in order to:

- reduce the risk of localized tissue damage from the exothermic curing reaction;
- reduce the intraoperative time; and
- avoid asymmetrical reconstruction using reverse engineering techniques.

The approach used in the case presented here includes two parallel phases (figure 2): (1) the creation of the medical rapid prototyping (MRP) model; and (2) the implementation of reverse engineering techniques for the design and creation of the exact implant required.

3. Phase 1: Creation of the MRP model

3.1. Acquisition of high quality 3D image data

Successful integration of imaging and RP technologies depends on the ability to provide special purpose computer graphics software tools for efficient handling and modification of 2D and 3D data. Initially a series of CT images

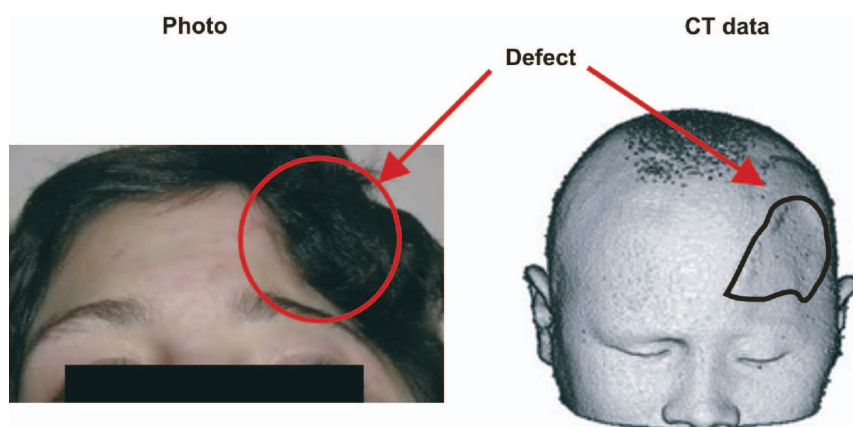


Figure 1. Photograph of patient before surgery and initial CT point cloud data.

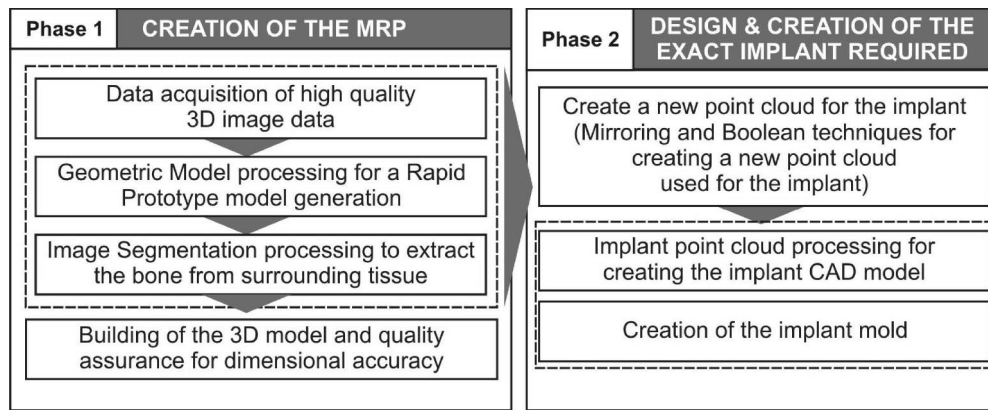


Figure 2. Reverse engineering phases for cranioplasty.

through the whole head spaced at intervals of 1 mm was used to model the skull.

3.2. CT image segmentation

To produce the skull model segmentation of the CT images obtained from the patient's head was applied to extract bone from the surrounding tissue. This was achieved using the purpose-built software 'Anatomos' [18]. In order to segment bone the appropriate 'window' was chosen based on the greyscale intensity histogram of voxels. The high intensity values of bone permitted an easy segmentation from neighbouring structures in each slice. The correct 'bone window' was verified with 3D shaded surface reconstructions of the skull. After scaling, our 3D software exported the point cloud in ASCII format appropriate for further processing.

3.3. Rapid prototype cranial model creation

MRP can be defined as the manufacturing of dimensionally accurate physical models of human anatomy derived from medical images using rapid prototyping technologies [19,20].

In order to produce a high quality MRP model, special processing focused on creating a flawless closed surface sterolithographic model (STL) is required [21]. Common problems in this process include noise input, triangle intersections and surface inconsistencies. Rapid prototyping requires a polygon object with triangles connected on all edges (manifold object) enclosing a volume.

The commercial software package Raindrop Geomagic Studio 7 was used for the development of the STL model. The procedure applied consisted of two phases: point processing and polygon processing (figure 3).

The point processing phase included the following steps:

- Disconnected point removal. Point clusters that were disconnected from the point cloud of the main head bone were removed.

- Removal of outliers. Points that were not part of the main head bone point cloud, caused by unintentional capture from the CT, were selected and removed.
- Noise reduction.
- Selected head bone removal. Small internal head bones, which were not in the region of interest, were manually removed from the point cloud. Furthermore, the back of the head bone was also removed, in order to obtain better access to the cranial defect.
- Conversion into a polygon object (wrapping). Wrapping is equivalent to stretching a plastic sheet around a point cloud object and pulling it tight to reveal a polygonal surface. There are many extra refinements that can be applied to a polygon object that cannot be applied to a point object, such as curvature based smoothing and noise reduction, spike removal and hole filling.

The polygon processing phase included the following steps:

- Polygon cleaning. This process produces a polygonal surface that conforms to the head bone shape defined by the underlying point set.
- Spike removal. This process smoothes the head bone surface by removing single-point spikes.
- Noise reduction. This process compensates for CT errors by moving points to statistically correct locations. Noise can cause sharp edges to become dull or smooth curves to become rough.
- Hole filling. This process filled the gaps in the head bone polygon object that were caused by sparse underlying point data. All holes must be closed in order to produce the required closed surface model for RP. This is very important as incorrect hole filling can very easily lead to self intersecting triangles and distortion of the actual model.
- Intersection fixing. Self-intersecting triangles are sometimes generated during wrapping, converting a CAD

model to polygons, or editing a polygon model with certain operations and can lead to important flaws to the final RP model. In this process these triangles were repaired by manually deleting and reconstructing the gaps.

- Closed surface RP-ready model creation.

3.4. Model reconstruction and quality assurance for dimensional accuracy

A number of potential sources of error are associated with various phases of the 3D model reconstruction. Some of these errors can be avoided, while others cannot. The influence of model accuracy on surgical planning is a key factor in the application of RP technology [22]. The closed surface RP-ready model was compared with initial CT point cloud data. The dimensional accuracy of the RP-produced cranial implant is primarily determined by spatial resolution of the 3D imaging technique applied to extract anatomic data from the patient. Therefore, errors introduced during image manipulation and physical model production phases should be constrained to the in-plane resolution of the CT acquisition. Error analysis in the present case showed that the error, defined as the deviation of the 3D model surface from the initial CT point cloud, has a distribution with a mean of 0.07 mm and a standard deviation of 0.1 mm (figure 4). This error was well below the spatial resolution of the CT scan (1 mm), indicating a very accurate modelling result.

Two different RP machines were used to create the MRP model: a Z-cooperation 510 and a Stratasys

Dimension SST 3D printer. The Dimension 3D printer and the Z-cooperation printer provided MRP models with maximum layer thicknesses of 0.245 mm and 0.08 mm, respectively. The two maximum layer thicknesses from the two machines ensure the dimensional accuracy of the RP models (figure 5).

The creation of the physical RP model of the skull in addition to the implant is not absolutely necessary for surgical reconstruction of the cranial defect. However, it

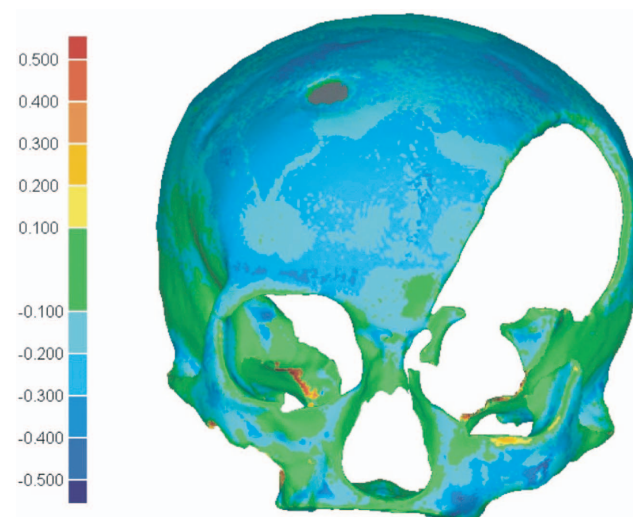


Figure 4. Distance map resulting from the comparison of the closed surface RP-ready model with the initial CT point cloud data.

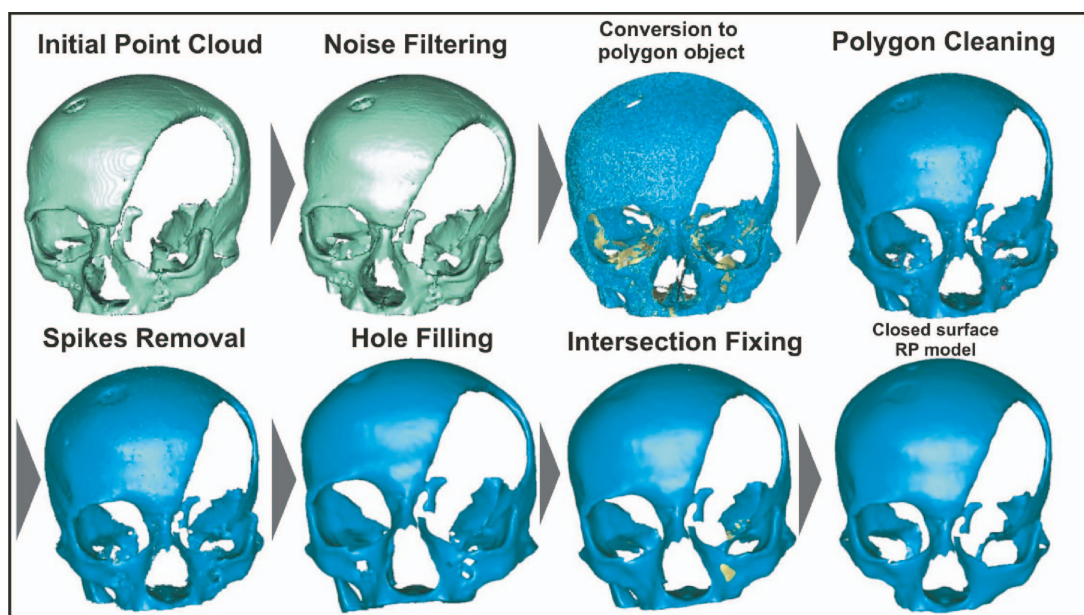


Figure 3. Different processes for producing the final RP model.

offers additional benefits to the surgeon, such surgery simulation and improved preoperative planning, and is a valuable tool for surgical training.



Figure 5. The RP head model.

4. Phase 2: Design and creation of the exact implant required

4.1. Creation of the implant point cloud

In order to create a perfect model for the implant, points from the symmetric left solid part of the head bone were used. In this way, the challenge was to extract the exact points to be used for the implant from the left part. For this, a datum plane exactly in the middle of the head bone was created. Three key points in the nose were selected for the datum plane definition. Next, an area of points from the left part that could cover the missing part from the right was selected (red part of figure 6). These points were mirrored according to the created datum plane. Boolean operations were then applied to isolate the set of points required to reconstruct the cranial defect surface and produce the implant model (figure 6).

4.2. Point cloud processing for the creation of the implant CAD model and mould

The new generated point cloud that defines the implant 3D geometry was then processed as in phase 1.3. But this time the goal was not only to create an STL model for rapid prototyping, but also to develop a CAD surface model that could be used for creation of the implant mould. For this,

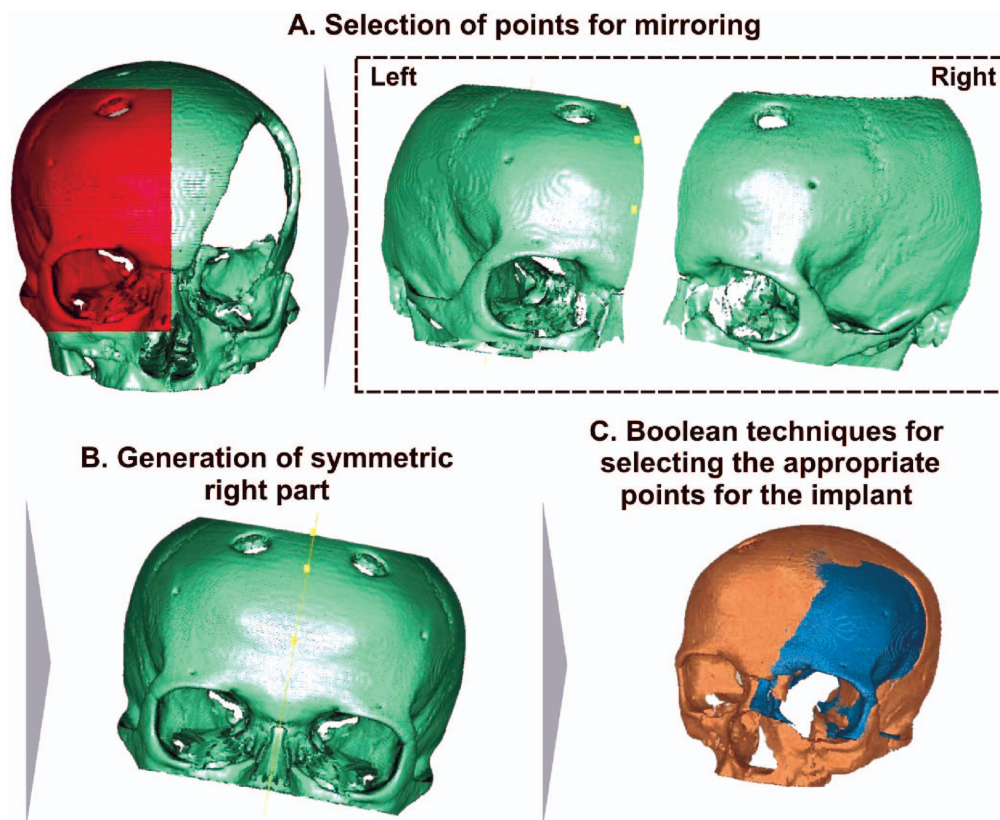


Figure 6: Reverse engineering techniques for implant point cloud creation.

further processing included construction, editing and repairing surface patches in order to create a CAD model appropriate for mould design and manufacture (figure 7). The commercial software Pro/engineer wildfire Mould Design was used for development of the implant mould model.

The prosthesis could be made directly from the computer model without the creation of a physical model of the skull. However, as mentioned above, construction of the physical model of the skull offers additional benefits to the surgeon which may improve the outcome of the intervention.

5. Results and conclusions

The prosthesis created using the RP-based cranial reconstruction approach was an exact fit to the patient's cranial

defect and produced a very symmetric skull outline (figure 8). The implant rested passively on the body margin all around the defect. Titanium screws were used for implant fixation, and were placed under the hair-bearing area of the temporal muscle, making them neither palpable nor visible. The approach presented here resulted in a 30% decrease of the total operation time due to the precise fit of the RP-produced implant, which minimized intraoperative manipulations to achieve implant fixation. The time of fixation of the implant, from the exposure of the body margins to the placement of the final screw, was 16 minutes. Achieving a good implant fit is important not only to restore the symmetry of the skull but also to prevent the implant from damaging skin or brain tissue. This method thus leads to a more promising long-term prognosis for the patient.

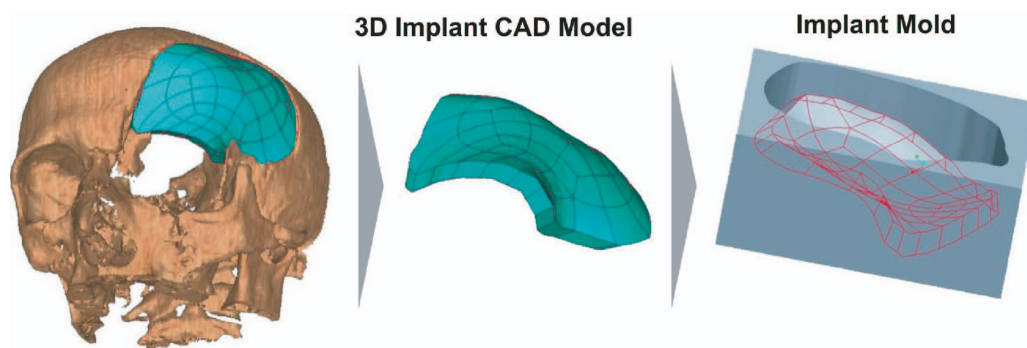


Figure 7. Creation of 3D implant model and mould.

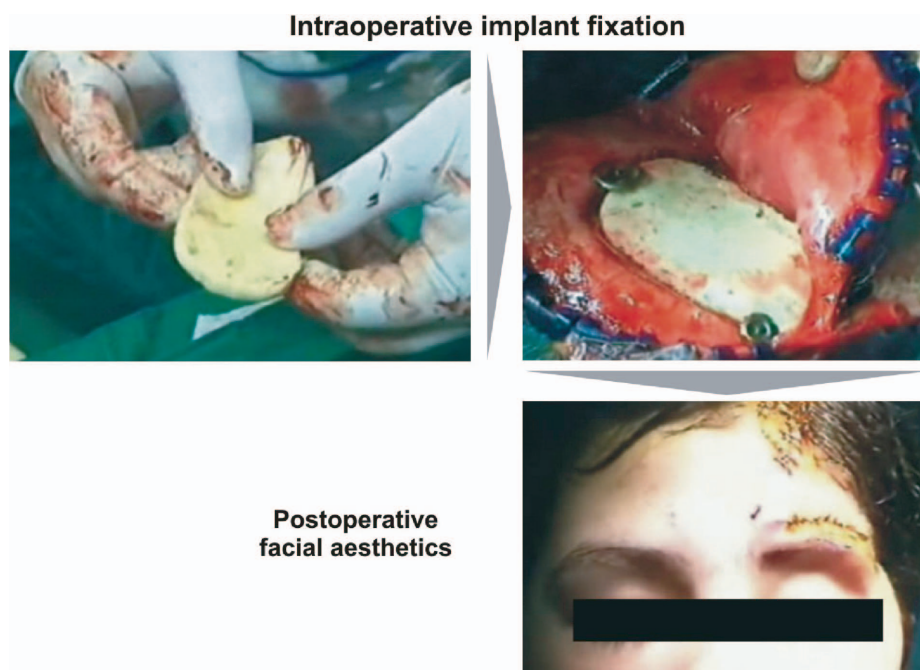


Figure 8. Implant fixation and surgical outcome.

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