Cost-Effective Solutions and Tools for Medical Image Processing and Design of Personalised Cranioplasty Implants

B.M. Pham, C.H. Le, N.T. Do, D.L. Vo, T. Le, R. Lee, M.S. Packianather, and S. Mengistu

Abstract

Cranial defects which are caused by bone tumors or traffic accidents are treated by cranioplasty techniques. Cranioplasty implants are required to protect the underlying brain, correct major aesthetic deformities, or both. With the rapid development of computer graphics, medical image processing (MIP) and manufacturing technologies in recent decades, nowadays, personalised cranioplasty implants can be designed and made to improve the quality of cranial defect treatments. However, software tools for MIP and 3D modelling of implants are expensive; and they normally require high technical skills. Especially, the process of design and development of personalised cranioplasty implants normally requires a multidisciplinary team, including experts in MIP, 3D design and modelling, and Biomedical Engineering; this leads to challenges and difficulties for technology transfers and implementations in hospitals. This research is aimed at developing, in particular, cost-effective solutions and tools for design and modeling of personalised cranioplasty implants, and to simplify the design and modelling of implants, as well as to reduce the design and modeling time. In this way, surgeons and engineers can conveniently and easily design personalised cranioplasty implants, without the need of using complex MIP and CAD tools; and as a result the cost of implants will be minimised.

B.M. Pham (✉) · N.T. Do
Vietnamese Academy of Science and Technology, Hoang Quoc Viet, Hanoi, Vietnam
e-mail: maypb@ioit.ac.vn

C.H. Le · S. Mengistu
Faculty of Engineering and Science, University of Greenwich, Kent, UK

D.L. Vo
Ho Chi Minh City Medicine and Pharmacy University, Ho Chi Minh, Vietnam

T. Le
International University-Vietnam National University, Ho Chi Minh, Vietnam

R. Lee
School of Applied Sciences, London South Bank University, London, UK

M.S. Packianather
School of Engineering, Cardiff University, Cardiff, UK

1 Introduction

Cranial defects which are caused by bone tumors or traffic accidents are treated by cranioplasty techniques. Cranioplasty implants are required to protect the underlying brain, correct major aesthetic deformities, or both. With the rapid development of computer graphics, Medical Image Processing (MIP) and manufacturing technologies in recent decades, especially the advancements of (Computer Aided Design/Computer Aided Manufacturing/Computer Numerical Control (CAD/CAM/CNC), Reverse Engineering (RE), and Rapid Prototyping and Manufacturing (RP&M), nowadays, personalised cranioplasty implants can be designed and made to improve the quality of cranial defect treatments

[1–5]. Although benefits of using personalised cranioplasty implants are well recognised, the number of clinical cases at hospitals is still limited, and this state-of-the-art treatment technology has not been widely applied due to difficulties of technology transfer to hospitals, high requirements of technical skills, and a high cost of personalised implants. The main reasons that lead to these difficulties include [1]: (1) Complexity of the implant design, (2) Challenges about multi-disciplinary collaboration & communication, and (3) High cost of technology. For the countries with low income, the cost-effective solutions for diagnosis and treatments are very important, and the cost of implants is one of the key criteria in the decision making process. The cost range of the personalised cranioplasty implants with the size of 150 × 165 mm is approximately from 300 to 4000 USD [5], depending on the biomaterials of implants (Bone cements, PMMA, Titanium alloys) and the complexity of cranial defects. In addition, advanced technologies for design and development of medical personalised products are expensive and not always available in the developing countries.

This research is aimed at developing, in particular, cost-effective solutions and tools for design and modeling of personalised cranioplasty implants, with the focus on the following objectives which address the above presented challenges: (1) Ease of use and high effectiveness, and (2) Cost-effective solutions. The design software tools and technological solutions should be convenient and simple to use. There is basically no need to use complex MIP and CAD as well as RE tools. Medical doctors or engineers should both be able to work on the implant design independently or with a fewer requirements about close collaborations and communications during the implant design and product development (DPD) process. The MIP and 3D CAD modeling software tools could be in-house developed for the specific types of applications. In this way, the cost of implants will be minimised.

2 Methods

The workflow and methods for design and modelling of personalised cranioplasty are presented in Fig. 1. The input data for development of cranioplasty implants is CT/MRI images in the form of DICOM data format. CT images are commonly used for bone reconstructions. First of all, a defective skull is reconstructed. Then, a boundary of a cranial defect is determined. The boundary of a cranial defect and an intact area of a skull are used as the input and guide to create an implant template which is an approximate shape (draft design) of an implant. Finally, the implant template is controlled and modified in details to obtain the optimal
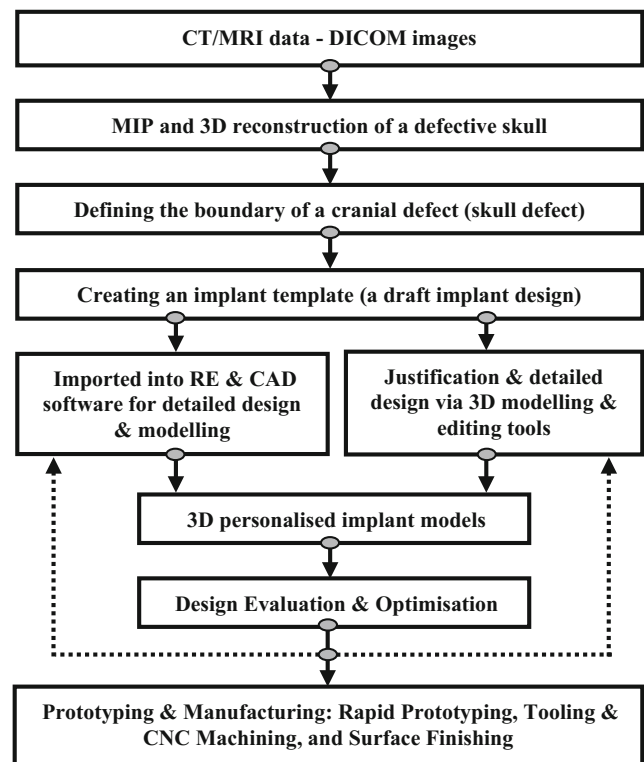

Fig. 1 Methods for development of personalised cranioplasty implants

shape of an implant. The following are the details of the algorithms and techniques used for modelling cranioplasty implants as shown in Fig. 1.

2.1 Step 1: Medical Image Processing—3D Reconstructions of a Defective Skull

Marching Cube (MC) is an efficient method for extracting isosurfaces from 3D scalar field [6]. The MC algorithm is used in this study to reconstruct 3D models of a defective skull. The following are the key points of the applied marching cubes algorithm. (a) *Inputs*: CT images in the form of DICOM format. Each CT slice image has (M×N) pixels, and the gray level of images. (b) *Outputs*: 3D models of bone structure (skulls). (c) *Algorithm*: A DICOM format does specify a lot of Transfer Syntaxes. For the compressed Transfer Syntaxes, the Meta data information is encoded using Explicit VR and Little Endian. The biggest challenge in the DICOM image processing is how to analyze and segment the data Area of Interest (AoI) such as bone, soft tissue, water, etc. In order to do this, the data conversion is required, based on the following two steps. (1) **Step 1**: *The pixel data values are converted into Hounsfield values (HU)*: For CT Images, the relationship between the Stored Values (SV) and the Hounsfield values is defined by the following

formula: $HU = SV * RescaleSlope + RescaleIntercept$. *RescaleSlope* and *RescaleIntercept* are retrieved from the *meta data section* of the DICOM file. (2) **Step 2**: *The Hounsfield values are converted into the grayscale values:* The stored values (SV) are converted into Hounsfield values (HU), the Hounsfield values are then converted further into **meaningful grayscale values** (Fig. 2a). The Hounsfield values range from −500 (e.g., lung) to +800 (e.g., bone).

After conducting the image analysis and segmentation based on the grayscale values, 3D models of AoI are reconstructed from the serial CT images, based on the Marching Cubes algorithm [6, 7]. The algorithm is implemented as follows. (a) *Inputs*: Serial CT images (x images—each image has mn pixels), threshold grayscale value (Iso-Value). (b) *Outputs*: 3D models of AoI (M). (c) *Algorithm*: The main content of the algorithm is as follows:

1. *M = Null.*
2. *For each Voxel of the CT Slice*
   2.1. *An own GridCell (GC) is created, GC is a cube.*
   2.2. *If all the vertex value of GC > IsoValue or < IsoValue, then GC is not selected.*
   2.3. *If there exist the vertex value of GC > IsoValue and also exist the value < IsoValue, then all the vertex value of GC is selected. $M = M \cap T$, where T is the vertices value of GC.*
3. *Optimize M.*

C# was used in combination with the ISG graphics library which was developed in-house based on the OpenGL graphics library. A series of tests were done to verify the algorithm and accuracies of the 3D reconstructed models. Figure 2b presents a typical example of 3D models of a head and skulls reconstructed form CT data which consists of 196 images; and each image has a size of 512 × 512 pixels.
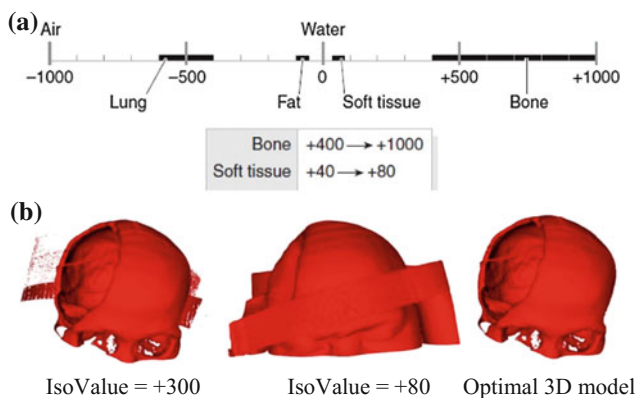

Fig. 2 **a** Grayscale for image segmentations. **b** 3D models of a skull and head reconstructed from DICOM images with different gray scales (IsoValue)

2.2 Step 2: Defining the Boundary of a Cranial Defect and Construction of an Implant Template

Determining an accurate cranial defect window plays an important role in design of an optimal implant. We developed a tool for defining a boundary of a defective window. A defect boundary is manually defined by a mouse. Each click of a mouse is a computational process between the *direction vector* V_i which is generated by the vector direction of the camera in conjunction with the coordinates of the cursor, in collision (intersection) with the surface of a 3D skull model. The result is a point (P_i) as shown in Fig. 3a.

Related methods for modeling cranioplasty implants are well documented in [3–5]. The construction of an implant template (the 1st version or a draft implant model) for the MIP and 3D modeling tools in this study is based on mirrored surfaces of a symmetrical intact area of a defective skull. For each point on the defective boundary (Fig. 3a, RED dots), a "symmetrical" point in the intact area (Fig. 3b, BLUE dots) could be found. Since a skull geometry normally is not 100% symmetrical; the created symmetrical points may not lie on a skull surface. This problem could be solved via the 2 following steps. (1) **Step 1**: Create a 'Blue point (P'i) which is a symmetrical point of a RED point (Pi) through a symmetrical axis Y. P'i is calculated via Pi'. x = −Pi.x. The point P'i is not always on a skull surface. (2) **Step 2**: Recalculate P'_i by using a vector V'_i which is a symmetrical vector of a vector V_i. The intersection between V'_i and the intact skull surface is the point P'i that is of interest. Finally, the symmetrical area of a cranial defect could be defined as shown in Fig. 3c in which the red points are the recalculated ones. Hence, an implant template could be obtained as shown in Fig. 3d. This implant template can be conveniently modified and edited in RE or CAD software to obtain the optimal one with a better accuracy and design features. In case, there is no RE or CAD tools available, an optimal design could be obtained using an additional 3D editing tool described in **Step 3**.

2.3 Step 3: Justification and Detailed Design via 3D Modelling Tools

In this step, an implant template is further adjusted and controlled to obtain the required form and shape of an implant. The adjustment is done by manipulating the surfaces for an optimal shape and a better contact between an implant and a skull via the following 2 steps: (1) Definitions of control points shown in Fig. 4a, b, and (2) Detailed adjusts, edit and controls of an implant model. Control points of an implant are created by a separate editing tool based on CT images as shown in Fig. 4c–f.

Fig. 3 **a** Definitions of a
boundary of a defective window.
b, **c** Identification of a
symmetrical intact area.
d Optimal symmetrical intact
area. **e** An implant template
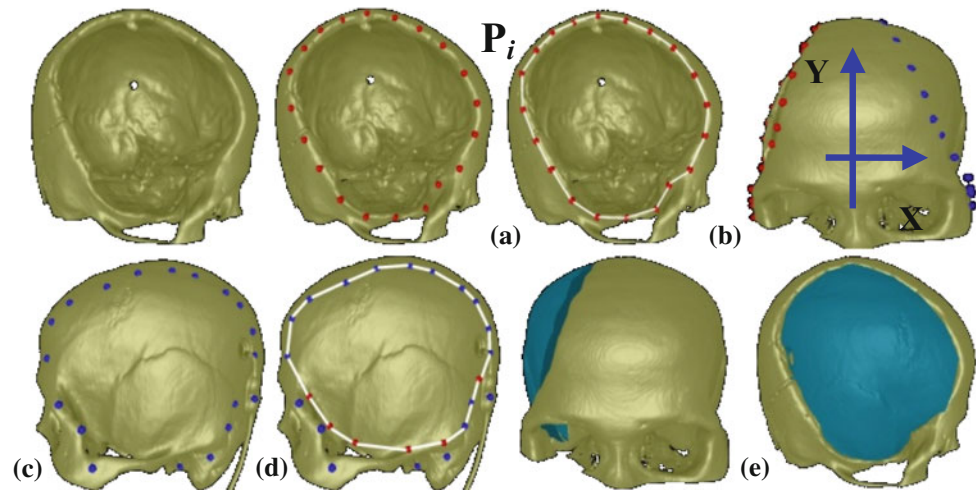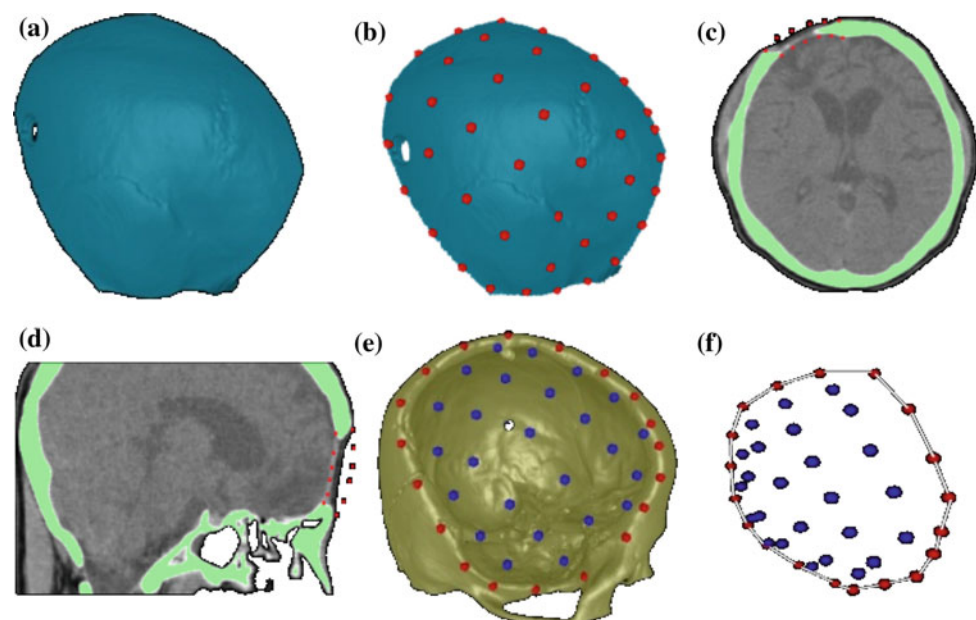created based on a symmetrical
intact area

Fig. 4 **a**,**b** Control points of an
implant **c**, **d** Defining control
points on CT images. Inputs for
the RBFs algorithm: Outer and
inner surfaces of an implant
template (**a**), Control points of an
implant template (**b**), and Control
points of a target implant (**e**, **f**)

A 3D modeling and editing tool is developed for *adjusting* and *controlling* an implant template to obtain an optimal form and shape based on the Radial Basis Function (RBF) [8] which is used for creating a smooth interpolation between the values known only at a discrete set of positions. The inputs for the RBFs algorithm are shown in Fig. 4b, f. It is assumed that the *deformation of an implant* when adjusted and controlled is known for n 3D positions x_i and this information is represented by a vector describing a 3D displacement u_i of the geometry that is positioned at x_i in the *original and undeformed state*. The x_i positions are considered as the control points that have been moved to positions $x_i + u_i$. Specifically, there are two steps of adjusting and controlling the implant template to be the optimal shape (target implant). The first step is to determine the transform function F, is a mapping from the control points shown in

Fig. 4b to the control points shown in Fig. 4e, f. The second step is to apply the function F with all the data on the implant template model shown in Fig. 4a. The RBF interpolation method is now used to transform these points to the new positions in order to obtain a target implant with the optimal shape as expected.

2.4 Step 4: Design Evaluation and Optimisation

An optimal model of an implant constructed in Step 3 is finally checked and evaluated so that it meets well both technical and clinical requirements. Figure 5h presents the evaluation of an implant thickness and a contact between an implant and a skull. Surgeons (medical doctors) are normally involved in this step. Design optimisation via the use of

Fig. 5 **a** External and internal surface of an implant. **b** A first design of an implant. **c** A final implant model. **e**, **f**, **g** A defective skulls and designed implant. **h** Design verification and evaluation: Checking the contact between an implant (*Red*) and a defective skull (*Blue*)
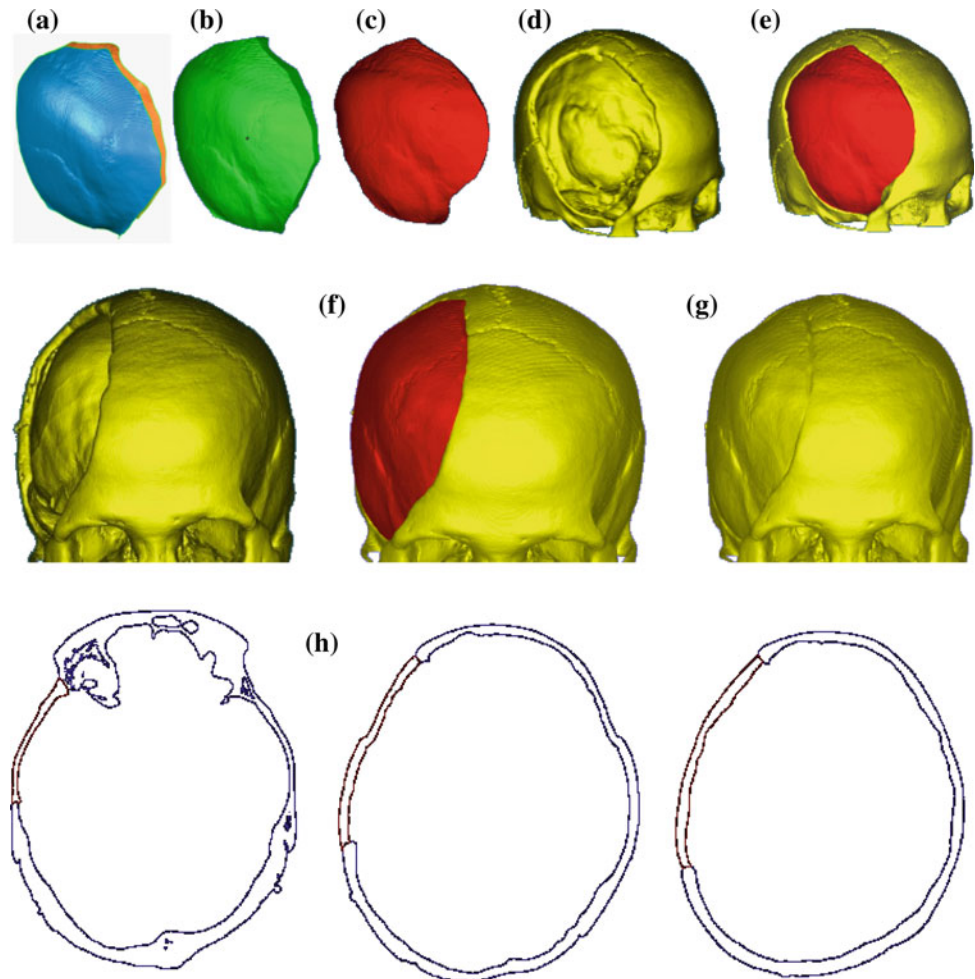
3 Results and Conclusions

A typical result of designing personalised cranioplasty implants based on the developed MIP and 3D modeling software tools and methods mentioned in Sect. 2 is presented in Fig. 5. In this case study, the defective skull does not have a good symmetry. However, the developed MIP and modeling tools are still effectively used for modelling an implant which meets well the technical and clinical requirement.

Basically, it takes about 2–4 h to complete design of a cranioplasty implant, from MIP to 3D design and modeling of an implant. Based on the draft model of an implant which is directly generated by the developed modeling tools (Fig. 5a, b), it takes about an additional 10–15 min to obtain an optimal implant model with the quality that is similar to the one that is designed based on the currently available MIP and RE packages in the market (Fig. 5c–g).

With the in-house developed MIP and modeling software packages, there is basically no need for additional RE and CAD software packages when working on the design and development of cranioplasty implants. The use of these MIP and modeling tools is not complex; surgeons and medical doctors with no strong background in CAD and 3D modeling are able to design cranioplasty implants. In this way, the cost of implants is minimised; and the technology transfer to hospitals is made more convenient. The next versions of this MIP and 3D modelling software will focus on solving the issues and challenges related to design and modelling of personalised implants for the cases in which the reference data or the symmetrical features are not available for the design. The future work will consider the workflow for optimizing the process of designing personalised cranioplasty implants in order to reduce the costs further. These software tools are to be integrated into the national open-architecture MIP and CAD system which is used for

Computer Aided Engineering (CAE) is done when necessary to assess the mechanical strength, design for manufacturing issues, as well as the use of different biomaterials for fabrication.

design and development of *patient* and *population-specific* medical products and services.

References

1. Hieu LC et al (2010) Integrated approaches for personalised cranio-maxillofacial implant design and manufacturing. IFMBE Proc 27(2010):119–122
2. Hieu LC et al (2005) Medical rapid prototyping applications and methods. Assembly Automation 25(4):284–292
3. Hieu LC et al (2004) A cheap technical solution for cranioplasty treatments. Technol Health Care 12(3):281–292
4. Hieu LC et al (2003) Design for medical rapid prototyping of cranioplasty implants. Rapid Prototyping Journal 9(3):175–186
5. Hieu LC et al (2002) Design and manufacturing of cranioplasty implant by 3-axis CNC milling. Technol Health Care 10(5):413–423
6. Dyken C et al (2008) High-speed marching cubes using histogram pyramids. Comput Graph Forum 27(8):2028–2039
7. Lorensen William E, Cline Harvey E (1987) Marching Cubes: a high resolution 3D surface construction algorithm. Comput Graph 21(4):163–169
8. Powell MJD (1992) The theory of radial basis function approximation. In: Light Will (ed) Advances in numerical analysis: wavelets, subdivision algorithms and radial functions, vol 2. Oxford University Press. Oxford, UK, pp 105–210