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Unilateral cranial defect bone reconstruction utilising 3D design and manufacturing

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Abstract: A cranial contour defect can occur when bone is removed following direct trauma, removal of a tumor or for surgical access to the brain. These defects impair function (protection) and aesthetic contour and require a design strategy for reconstructing the defect. In principle, if the defect is unilateral (one side) then designing a form to restore the contour could be assisted by attaining a mirror image of the undamaged side of the skull. As an alternative to mirroring the undamaged skull an interpolated surface could also be generated for repairing this cranial defect. A case with a unilateral left temporal bone defect was considered for this study. A cranioplasty reconstruction was to be performed to restore the bone contour. The patient's Computed Tomography (CT) scan (1 mm slice thickness) was saved in the raw file format Digital Imaging and Communication in Medicine (DICOM). The DICOM data was converted to a standard tessellation file (stl.) using MIMICS software (Materialise V24. Belgium). The stl. file of the skull was used to generate a 3D design of the implant using Computer-aided Design/ Computer-aided Manufacturing (CAD/CAM) software. The design was used to 3D print a base template, which could finally be used to fabricate the physical implant to restore the defect. This case explored the two techniques of mirroring and interpolation for repairing a cranial defect. A comparison of the two techniques was performed. Feedback from the surgeon suggested that interpolation provided a digitally accurate implant surface comparable to a mirrored implant.

I. Introduction

Trauma, infections, tumors, and compression caused by brain edema are some of the reasons for the removal of segments of the cranial bone [1]. The treatment of such cases requires the insertion of a cranial implant at the site of the defect to protect the brain tissue and correct the external deformity. The most used method previously was intraoperative bone grafting which involved increased operating time. In addition, the process led to poor outcomes when defects were large. To overcome the shortcomings of this process, many techniques have been introduced for the fabrication of custom cranial implants using a combination of medical imaging and Three-Dimensional (3D) CAD/CAM technology [2,3,4].

Such techniques allow for greater precision in terms of the implant shape and allow surgeons to better visualize the defect. Implants can be custom-made for individual patients, allowing for better fitting, simpler surgeries, lower chances of infection, and better recovery.

The most used technique in this field is the generation of an implant by a digital subtraction after performing a mirror-imaging process on the normal side of the cranium [5,6,7]. Other techniques include shape-based interpolation for creating implants customized to the defect [8]. A CAD tool that relies on interpolation properties of the Radial Basis Function to design a custom implant for large cranial defects (>100 cm2) was developed by Marreiros et al [9]. In this paper we propose an Edge Gap Factor (EGF) and present recommendations based upon the EGF for the selection of cranial defect bone reconstruction technique using 3D designing and manufacturing.

II. Material and methods

II.I. Creation of 3D models from DICOM files

Anonymized CT scans in the form of DICOM images of a subject with unilateral left cranial defect of the skull were obtained from Nottingham University Hospitals Trust (Nottingham, UK). The subject was recommended for cranioplasty reconstruction and to correct the skull defect, a 3D design approach was followed.

The DICOM data must be converted to a format that can be utilized by CAD CAM software. MIMICS (V24. Materialise, Belgium) allows the operator to select from the CT an area of interest, in this case bone, at a selected threshold value or Hounsfield unit (HU) of measurement (radio density). The HU range value (upper and lower limit) can then be grown from a few select points so only the structure required is selected. Bone is easy to select as it has relatively high density to soft tissue and muscles surrounding it. A routine CT (120-140kV) of the skull bone would be approximately +1000(HU)[10]. The threshold value limits may require manual adjustment in its HU range on a case-by-case basis. Once the threshold range was set, further refinement was completed using editing tools to crop and erase parts that are not required. The final file is usually smoothed (tool in MIMICS) to generate an improved surface to manufacture against. After the skull volume is rendered, it can be saved as a Standard Tessellation Language (STL) file as shown in figure 1. The STL file produced by 3D modeling systems as shown in figure 1 contained triangular facet representations of surfaces. This format was considered a standard data input for rapid prototyping and manufacturing systems [11].

II.II. Design of cranial implant using Mirroring

Once an STL file was obtained, a mirror image of the undamaged right side of the skull was obtained for generating the implant image for reconstructing the cranial defect.

A mirroring tool (Freeform V19, 3D Systems, USA) was used to create a mirrored counterpart of the skull. This counterpart is then registered to the original skull such that the defect in the original skull perfectly overlaps the corresponding healthy portion of the mirrored skull. Both sides of the skull are different so registration and alignment can take a few attempts. Assuming perfect symmetry of the skull, the regions should overlap as closely as possible. After manual alignment, the Align tool in Meshmixer (V3.5.474, Autodesk) was used to get a closer overlap. Then through Boolean subtraction, an implant was obtained. The implant was then manually sculpted to fit the defect perfectly. Any protrusions or gaps that remained were corrected manually using the sculpting tools in Meshmixer. The final mirrored image produced is shown in figure 2.

II.III. Design of cranial implant using Interpolation

For creating an interpolated implant DICOM files were imported into 3D Slicer (v5.0.2, The Slicer community) software's volume rendering module. The DICOM files were used to create a 3D model of the defected skull in this module. This model was used to study the defect in three-dimensional space to properly understand the problem. Then the 3 views of the DICOM files i.e., Axial, Sagittal, and Coronal, were used to analyze the best geometry in which the whole cranial defect could be analyzed.

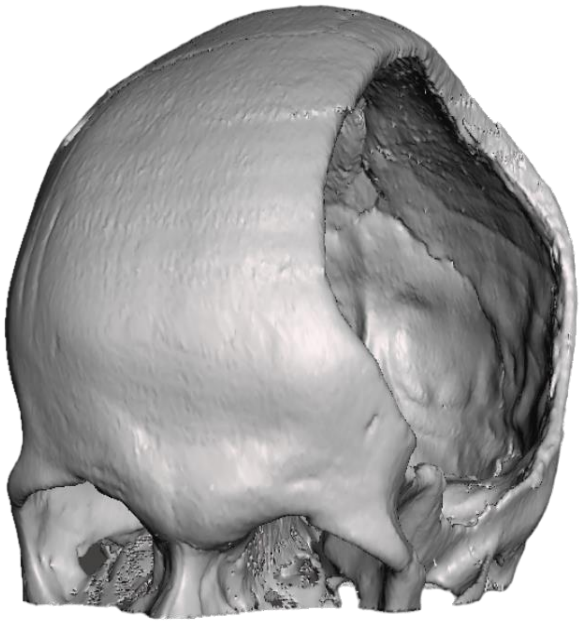

Figure 1: STL file generated from CT for unilateral cranial defect on the left side.

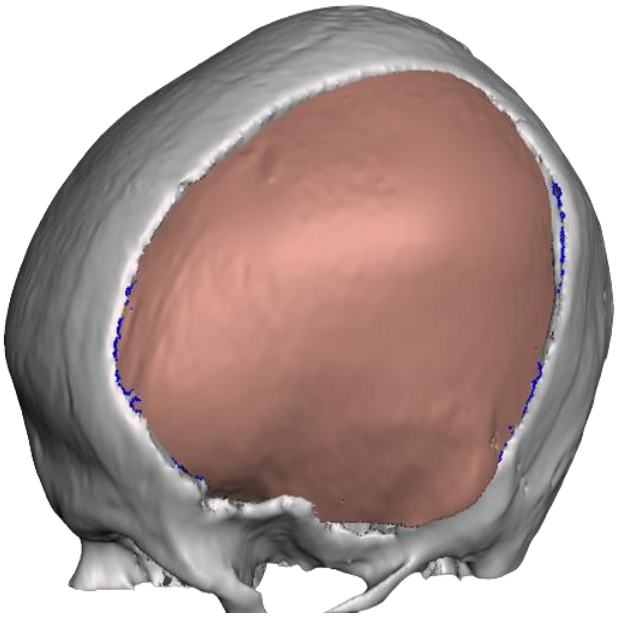

Figure 2: Implant for a large unilateral defect using mirroring.

Once the defect was properly identified in one of the three views, a new segment was created using the Segment Editor module in 3D Slicer. This newly created segment was then edited to reconstruct the defected skull in the selected view. Every iteration of each view (Axial, Sagittal, Coronal) is called a slice. Using the Paint tool of the Segment Editor module the contour of the missing skull was created on every fifth slice. The brush diameter is set to 2% to blend the created contour with the existing bone thickness. The final interpolated image produced are as shown in figure 3.

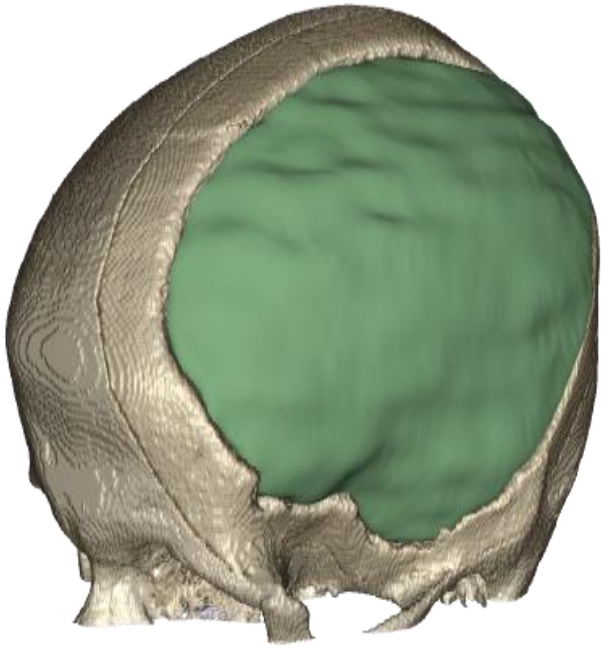

Figure 3: Implant for a large unilateral defect using Interpolation.

III. Results and discussion

Once the implant was generated using both mirror and interpolation techniques as shown in Figure 1, a quantitative comparison between the two methodologies was planned using open-source CloudCompare software (version 2.10.1; GPL software) [12]. CloudCompare facilitated the first alignment of the implant over the defect. For this, initially a manual alignment was performed after which fine alignment was done using the Iterative Closest Point (ICP) algorithm on CloudCompare software [13]. Gap size was measured between the implant and skull interface of the two implants reproduced, the one which indicated the least gap size was considered as the best fit solution. Then the distance between the two entities was computed to see how well the implant fits the defect.

Therefore, first the defected skull was selected as a reference and the distance from the implant was calculated. The signed distance was returned upon computation as shown in Figure 4.

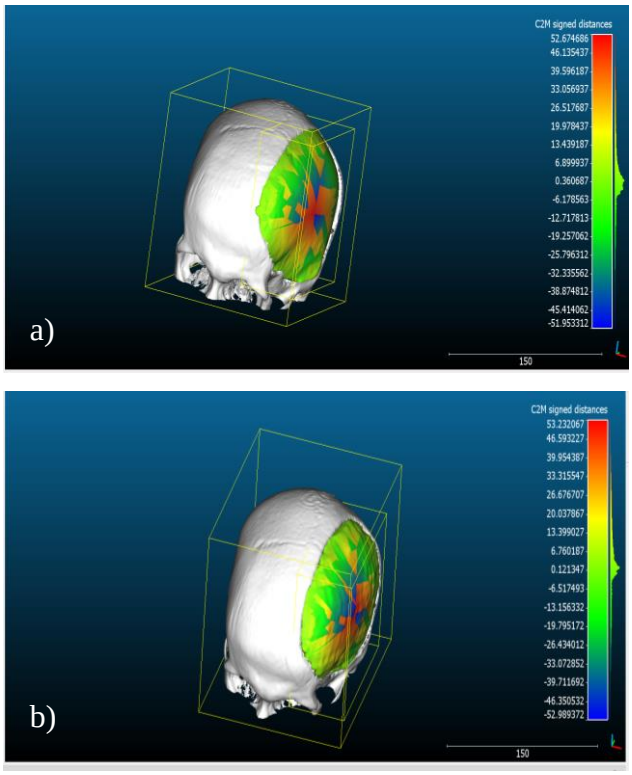

Figure 4: Distance measured between the edges of a large lateral defect and the implant created through a). Mirroring b). interpolation for fitting

For a comparison between the two methodologies, we have introduced an Edge Gap Factor (EGF). We defined this factor as the ratio of the mode edge deviation of the interpolated implant to that of the mirrored implant. If the EGF > 1, then the gap performance of mirrored implant is lesser than the interpolated one, while mirroring is better than interpolation because this implies that the mode edge deviation of interpolation is greater than that of mirroring. The less the edge deviation the better the fit of the implant.

Table 1: Gap size and EGF for the implant and defect.

Type of defect	Mode edge distance for interpolated implant	Mode edge distance for mirrored implant	Edge Gap factor (EGF)
Unilateral large	0.121	0.360	0.336

For an EGF < 1, then interpolation outperforms mirroring as the mode edge deviation for interpolation is less than that of mirroring in such a case.

For EGF = 1 then both implants provide the same gap size with skull interface techniques. Hence both implants have equal performance and may be considered interchangeable.

For the present case study, the value of EGF is 0.336 as computed in Table 1 and therefore interpolation had a higher performance being the EGF value less than 1.

The interpolation technique originates the near-original geometry of the defected skull using the morphological contour interpolation method. Interpolation is undertaken by first determining correspondence between shapes on adjacent segmented slices by detecting overlaps, then aligning the corresponding shapes, generating a transition sequence of one-pixel dilations, and taking the median as result. Recursion is employed if the original segmented slices are separated by more than one empty slice. This class is n-dimensional and supports inputs of 3 or more dimensions. `Slices' are n-1-dimensional and can be both automatically detected and manually set [14]. This method provides better reproducibility. In this paper, we present interpolation for every 5th slice to provide a well-fitted implant without a high computational load.

IV. Conclusions

Mirroring technique duplicates the corresponding healthy section from the opposite side of the skull, as a model for the mold. However, much of this assumes that the skull has ideal bilateral symmetry. Hence in case of a defect that crosses the sagittal plane it is not possible to create and implant through mirroring alone. An additional critique of this method is that most human skulls do not have ideal bilateral symmetry. Therefore, mirrored implants may not have the same curvature as the original skull at the site of the defect. For this, manual adjustment is required post mirroring which makes this process heavily user-dependent, thus reducing the reproducibility of the process.

For cases or defects, wherein mirroring relies on several assumptions, it is important to follow interpolation techniques for generating an accurate skull surface. Interpolation is inherently limited by the extent of dependence on computation resources for calculations and time duration. Therefore, the decision to follow either of the two approaches depends upon the collective experience of the surgeon and the design team, complexity of the case, availability of resources and time duration for delivery.

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Author's statement

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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