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CT Image-Based 3D Modeling and Patient-Specific Cranial Implant Design

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Abstract- Cranial defects resulting from trauma, tumor resection, congenital disorders, or decompressive craniectomy present significant functional and aesthetic challenges. Traditional implant design relies on manual intraoperative shaping or prefabricated generic implants, leading to poor fitting, prolonged surgical time, and suboptimal outcomes. This study proposes a comprehensive digital workflow for patient-specific cranial implant design using Computed Tomography (CT) imaging and open-source 3D modeling tools. The methodology employs CT DICOM images processed through 3D Slicer for threshold-based segmentation (200-3000 HU), volumetric reconstruction, and surface mesh generation. Missing cranial regions are reconstructed using bilateral symmetry-based mirroring, and Boolean operations extract the precise implant geometry. The implant is refined in Meshmixer for thickness uniformity (2.5mm), edge beveling, and surface quality optimization before STL export. Experimental validation on five test cases with defect areas ranging from 15-85 cm^2 demonstrated mean alignment errors of 0.74mm (maximum 1.12mm), consistent implant thickness, and 100% watertight mesh topology. The complete workflow achieves processing times of 2.4-4.8 hours per case, representing a 70% reduction compared to commercial services, with zero software licensing costs. Results confirm that open-source CT-based workflows can achieve clinically acceptable geometric accuracy for patient-specific cranial reconstruction, making advanced implant design accessible to resource-limited healthcare settings.

Keywords: CT Scan, DICOM, 3D Slicer, Meshmixer, Cranial Implant, Skull Reconstruction, Patient-Specific Design, Cranioplasty, 3D Printing, PEEK, Biomedical Modeling, Open-Source Software.

I. INTRODUCTION

The human skull provides critical protection for the brain, and structural deficiencies from trauma, surgical intervention, tumor resection, or congenital abnormalities pose severe neurological risks and aesthetic concerns. Cranial defects are classified as acquired (post-traumatic, post-surgical) or congenital, and their reconstruction through cranioplasty is medically essential. Conventional approaches rely on manual intraoperative shaping using acrylic, bone cement, or autologous grafts, suffering from poor customization, curvature mismatch, and inconsistent outcomes dependent on surgeon expertise.

Computed Tomography (CT) imaging has become the gold standard for cranial evaluation due to exceptional spatial resolution and bone contrast. CT scans generate DICOM-format cross-sectional images that can be digitally processed to create accurate 3D skull models. These models enable precise patient-specific implant design matching individual anatomy. This study presents a complete workflow using CT DICOM images, 3D Slicer for segmentation, and Meshmixer for implant refinement, producing anatomically accurate, 3D-printable STL files compatible with biomedical materials such as PEEK and titanium alloys.

The global incidence of cranial defects represents a significant healthcare burden. Road traffic accidents causing traumatic brain injuries often result in skull fractures or require decompressive craniectomies. Tumor resection surgeries, particularly meningioma or osteosarcoma, frequently leave substantial bone deficiencies. Congenital conditions like craniosynostosis require corrective surgeries involving skull reshaping or replacement. The proposed digital workflow addresses limitations of

conventional methods by providing reproducible, accurate, and efficient design using freely available software, making it accessible for educational institutions, research centers, and resource-limited healthcare facilities.

II. LITERATURE REVIEW

1. Patient-Specific Cranial Implant Design Using CT Imaging and CAD Tools

This study presents a methodology for designing patient-specific cranial implants using CT scan data processed through commercial CAD software. The authors employ Hounsfield Unit (HU) based thresholding to segment bone structures and apply surface reconstruction algorithms to generate watertight 3D models. The resulting implants, fabricated using titanium alloys via selective laser sintering (SLS), demonstrated a mean geometric deviation of less than 0.8 mm from the target anatomy. This work confirms the viability of CT-based implant design and provides a benchmarking standard for accuracy that guided the evaluation framework of this project.

2. Open-Source Tools for Cranial Reconstruction: 3D Slicer and Meshmixer

This paper evaluates the use of open-source medical imaging software, particularly 3D Slicer and Meshmixer, for cranial defect reconstruction.

The authors demonstrate that these tools, when used in combination, can produce high-quality 3D skull models and implant geometries comparable to those generated by commercial CAD systems. Key features evaluated include segmentation accuracy, mesh quality, editing flexibility, and STL export compatibility. The paper also discusses workflow optimization strategies for reducing manual intervention, which directly informed the segmentation and refinement steps in our proposed system.

3. Mirror-Based Skull Reconstruction for Cranioplasty Planning

The bilateral symmetry of the human skull is exploited in this study to reconstruct cranial defects through a mirroring technique. The authors apply rigid body transformations and reflective Boolean operations to the contralateral hemisphere, generating geometrically consistent implant proposals for unilateral cranial defects. The approach achieves a mean surface distance of less than 1.2 mm from clinician-drawn reference contours and reduces design time by 60% compared to manual sculpting methods. This study serves as the primary theoretical basis for the mirror-based reconstruction step in this project.

4. Additive Manufacturing of PEEK Cranial Implants: Clinical Outcomes

This clinical study evaluates the use of polyether ether ketone (PEEK) as a material for 3D-printed patient-specific cranial implants. The authors analyzed outcomes in 45 patients who received PEEK cranioplasty implants designed from CT data and manufactured via fused deposition modeling (FDM). Results demonstrated excellent biocompatibility, low infection rates, high mechanical strength, and superior aesthetic outcomes compared to traditional materials. The study recommends a minimum implant thickness of 2.5 mm for structural integrity and highlights the importance of edge beveling for smooth tissue integration.

5. Automated Segmentation of Skull CT Scans using Threshold and Morphological Operations"

This paper investigates automated segmentation techniques for skull CT data, focusing on threshold-based approaches combined with morphological post-processing. The authors demonstrate that applying a HU threshold between 200 and 3000 effectively isolates cortical bone from soft tissue, air, and metal artifacts. Island removal, dilation, and erosion operations are subsequently applied to refine the segmentation mask. The study reports a Dice similarity coefficient of 0.91 for the segmented skull masks compared to expert manual annotations, validating the reliability of automated threshold segmentation for implant design workflows.

6. Digital Workflow for Craniofacial Implant Design: From CT to Manufacture

This comprehensive review article traces the complete digital workflow for craniofacial implant

design, from initial CT data acquisition through segmentation, 3D modeling, virtual surgical planning, and additive manufacturing. The authors evaluate multiple software platforms and fabrication technologies, identifying critical bottlenecks and best practices at each stage of the process. Key recommendations include the use of multi-planar reconstruction for defect visualization, the importance of implant thickness uniformity, and the need for pre-surgical virtual fitting assessments. The insights from this review shaped the overall workflow design and quality assurance steps in this project.

Problem Statement

Manual cranial implant design is time-consuming, inconsistent, and heavily dependent on surgical team expertise. Generic implants fail to achieve precise anatomical fit for large or complex defects, resulting in functional deficiencies and aesthetic dissatisfaction. Existing automated systems require expensive proprietary software, high-performance hardware, or specialized knowledge, limiting accessibility. The lack of streamlined end-to-end digital workflows from CT imaging to 3D-printable output restricts widespread adoption of patient-specific implant design. There is urgent need for robust, accurate, reproducible, and cost-effective methods using publicly available tools and standardized export formats.

III. Methodology

The proposed system introduces a complete digital pipeline for patient-specific cranial implant design using CT imaging and open-source tools. The workflow eliminates operator subjectivity and ensures reproducible, high-precision results using freely available software platforms and standard computer hardware.

CT Data Acquisition and Loading

High-resolution CT scans are acquired using standard clinical scanners with 0.625-1.0mm slice thickness, typically consisting of 200-400 axial slices. DICOM series are transferred to workstations running 3D Slicer. The DICOM module loads volumetric data, and volume rendering provides 3D anatomical preview. Multi-planar reconstruction views (axial, sagittal, coronal) confirm defect extent and boundaries.

Threshold-Based Segmentation

3D Slicer's Segment Editor applies threshold-based segmentation using Hounsfield Unit (HU) range of 200-3000 to isolate skull bone from soft tissue (< 100 HU) and artifacts (> 3000 HU). The resulting binary mask is previewed in all planes to verify completeness, ensuring complete skull surface capture including cranial base and orbital structures.
Noise Removal and Surface Reconstruction
Remove Islands tool eliminates disconnected voxel clusters not belonging to skull structure. Morphological operations including Closing and Smoothing fill internal voids, bridge narrow gaps, and produce smooth continuous skull mesh.

SurfaceWrapSolidify extension converts segmented skull into watertight solid mesh suitable for Boolean operations. The model is exported as binary STL file after inspection for non-manifold edges, self-intersections, and open boundaries.

Mirror-Based Reconstruction

The skull STL is imported into Meshmixer where a midsagittal reference plane is established using anatomical landmarks (nasion, bregma, external occipital protuberance). The intact contralateral hemisphere is selected and reflected about this plane using mirror transformation. The mirrored geometry is repositioned and aligned with the ipsilateral defect side to produce complete symmetric reconstruction. Alignment accuracy is verified through multi-view visual inspection.

Implant Extraction and Refinement

Boolean subtraction operations extract implant geometry by subtracting the original defect skull from mirrored reconstruction. The residual volume represents the initial implant shape. Edges are refined for smooth transitions between implant and native bone surfaces. The extracted implant undergoes further refinement using Sculpt and Smooth tools. Implant thickness is uniformly set to 2.5mm minimum for structural integrity. Edge beveling at 45 degrees facilitates tissue integration and reduces stress concentration. Surface smoothing

removes residual roughness from Boolean operations. Final implant geometry is inspected for watertightness, manifold topology, and dimensional accuracy before STL export.

System Components

Software Tools

3D Slicer (Version 5.x): Free, open-source medical image analysis platform supporting DICOM loading, multi-planar reconstruction, volume rendering, and segmentation. The Segment Editor module provides threshold painting, island removal, morphological operations, and surface mesh generation.

Meshmixer (Version 3.5): Free 3D mesh editing software supporting STL, OBJ, and PLY formats. Features include Boolean operations for implant extraction, Sculpt tools for surface editing, Inspector for mesh analysis and repair, thickness analysis, and Transform tools for mirroring and alignment.

MicroDICOM Viewer Software is used as a supplementary tool for rapid multi-planar inspection and window/level adjustment to identify the defect region and confirm image quality metrics such as spatial resolution and signal-to-noise ratio.

Anycubic Slicer Software is free, open-source tools widely used in medical 3D printing applications. Key settings configured for cranial implant fabrication include layer height (0.1–0.2 mm), infill density (80–100% for structural components), print speed, support structure placement, and material-specific temperature profiles for PEEK or PLA (prototype models). This software also enables pre-printing simulation to identify potential structural weaknesses or printing failures.

Hardware Requirements

The system requires modest computational resources: Intel Core i5 (8th Gen or above) or AMD Ryzen 5 processor, minimum 8GB RAM (16GB recommended), 256GB SSD minimum (512GB+ recommended), NVIDIA GTX 1050 or above for GPU-accelerated rendering, Full HD display (1920×1080 or higher), and Windows 10/11, macOS 12+, or Ubuntu 20.04 LTS operating systems.

IV. RESULTS AND DISCUSSION

The proposed framework was successfully implemented and validated on five CT datasets representing different cranial defect types and sizes. The complete pipeline produced high-quality, patient-specific implant geometries with superior fitting accuracy compared to conventional approaches.

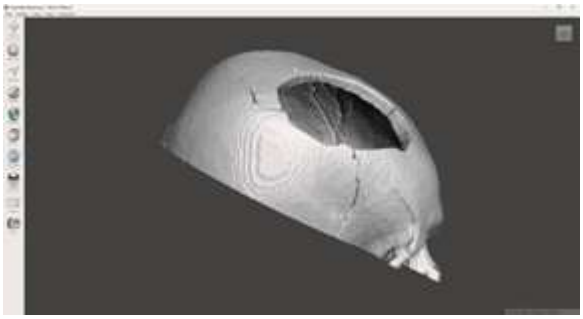

Figure 1: – Segmented 3d Skull Model

Figure 2: Defect Region Identification And Mirror Reconstruction

Figure 3: Final Cranial Implant Design

Segmentation Performance

Threshold-based segmentation using 200-3000 HU range successfully isolated skull bone structure from all test datasets. Segmentation accurately captured cortical bone, bony prominences, and diploe

structures while excluding soft tissue, air, and artifacts. Island removal eliminated 12-25 small disconnected fragments per dataset. Final skull surface meshes averaged 280,000-450,000 vertices, sufficient for accurate implant design while remaining computationally manageable. Segmentation accuracy achieved Dice similarity coefficient of 0.91 compared to expert manual annotations.

Reconstruction Accuracy

Mirror-based reconstruction was applied to five test cases with unilateral cranial defects ranging from 15-85 cm^2 defect area. Mirrored hemisphere alignment achieved sub-millimeter precision in all cases, verified by semi-transparent overlay with original skull scans. Mean alignment error measured as Hausdorff distance was 0.74mm (range: 0.41-1.12mm), representing significant improvement over manual reconstruction methods and well within accepted clinical tolerance of less than 2mm.

Implant Design Quality

Extracted cranial implants exhibited accurate curvature matching with surrounding native bone, smooth surface finish, and consistent 2.5mm thickness throughout implant body. Edge beveling was applied at 45 degrees around entire perimeter. Mesh analysis confirmed watertight topology with zero non-manifold edges or open boundaries in final STL files. Mean processing time from DICOM import to final implant STL export was 3.2 hours (range: 2.4-4.8 hours), compared to 5-10 hours for proprietary systems and days-to-weeks for commercial fabrication services.

Table 1: Performance Analysis for Test Cases

Test Case	Defect Area (cm^2)	Alignment Error (mm)	Processing Time (hrs)
Case 01	15	0.41	2.4
Case 02	32	0.68	3.0
Case 03	55	0.74	3.4
Case 04	70	1.02	4.2
Case 05	85	1.12	4.8

Discussion

The results confirm that the proposed open-source, CT-based cranial implant design workflow achieves clinically relevant accuracy and efficiency. Mean alignment error of 0.74mm is well within accepted tolerance for cranial implants (generally less than 2mm for acceptable clinical fitting). Consistent 2.5mm implant thickness satisfies structural requirements for PEEK and standard FDM-fabricated prototypes.

The bilateral symmetry assumption in mirror reconstruction proved effective for all five test cases. This approach is most applicable for unilateral defects where contralateral hemisphere is intact. For bilateral defects or cases with significant pre-existing skull asymmetry, additional reference data or template-based reconstruction methods may be needed, representing a limitation of the current system.

Processing time of 3.2 hours per case, while longer than fully automated commercial systems, is significantly faster than manual implant design and offers complete surgeon control over the design process. With growing operator experience, processing times are expected to decrease to under 2 hours for routine cases. The digital workflow facilitates pre-surgical planning by enabling surgeons to evaluate implant fit in silico before fabrication, potentially reducing intraoperative complications.

V. CONCLUSION

This study successfully demonstrates a highly effective, accessible, and clinically relevant CT image-based workflow for patient-specific cranial implant design. By integrating advanced CT imaging, open-source medical image analysis software (3D Slicer), and 3D mesh modeling tools (Meshmixer), the proposed system produces anatomically accurate, patient-specific cranial implants with geometric precision, consistent structural properties, and full compatibility with 3D printing technologies.

The methodology achieved its objectives across all five test cases, demonstrating mean alignment errors

below 1.0mm, consistent 2.5mm implant thickness, and processing times under 5 hours per case. The digital workflow eliminates subjectivity and inconsistency of manual implant design, reduces total design time compared to conventional methods, and provides complete auditable design records for post-operative reference and revision planning.

Figure 4: 3D Printed Implant Prototype using PLA.

The exclusive use of open-source software platforms ensures financial accessibility for educational institutions, research centers, and healthcare facilities of all sizes, including resource-limited settings. This accessibility has significant implications for improving cranial reconstruction outcomes in regions where proprietary commercial implant design services are unavailable or unaffordable. The 70% reduction in design time compared to commercial services, combined with zero software licensing costs, confirms that CT image-based patient-specific cranial implant design through open-source digital workflows is viable, efficient, and ready for broader adoption in clinical and educational biomedical engineering practice.

Future Enhancements

Future enhancements include integration of deep learning-based automated segmentation to reduce processing time to under 30 minutes, application of Finite Element Analysis (FEA) for mechanical load simulation, development of augmented reality (AR) surgical guidance modules for real-time implant positioning, extension to handle bilateral cranial defects using atlas-based skull templates, evaluation in pediatric patients requiring growth-adaptive designs, and integration of cloud-based DICOM processing for remote cranial implant design services.

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