

From medical imaging to 3D printed anatomical models: a low-cost, affordable 3D printing approach

De imágenes médicas a modelos anatómicos impresos en 3D: un enfoque de impresión 3D asequible y de bajo costo

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Abstract

Objective: To share our experience in creating precise anatomical models using available open-source software.

Methods: An affordable method is presented, where from a DICOM format of a computed tomography, a segmentation of the region of interest is achieved. The image is then processed for surface improvement and the DICOM format is converted to STL. Error correction is achieved and the model is optimized to be printed by stereolithography with a desktop 3D printer.

Results: Precise measurements of the dimensions of the DICOM file (CT), the STL file, and the printed model (3D) were carried out. For the C6 vertebra, the dimensions of the horizontal axis were 55.3 mm (CT), 55.337 mm (STL), and 55.3183 mm (3D). The dimensions of the vertebral body were 14.2 mm (CT), 14.551 mm (STL), and 14.8159 mm (3D). The length of the spinous process was 18.2 mm (CT), 18.283 mm (STL), and 18.2266 mm (3D), while its width was 8.5 mm (CT), 8.3644 mm (STL), and 8.3226 mm (3D). For the C7 vertebra, the dimensions of the horizontal axis were 58.6 mm (CT), 58.739 mm (STL), and 58.7144 mm (3D). The dimensions of the vertebral body were 14 mm (CT), 14.0255 mm (STL), and 14.2312 mm (3D). The length of the spinous process was 18.7 mm (CT), 18.79 mm (STL), and 18.6458 mm (3D), and its width was 8.9 mm (CT), 8.988 mm (STL), and 8.9760 mm (3D). **Conclusion:** The printing of a 3D model of bone tissue using this algorithm is a viable, useful option with high precision.

Keywords: 3D printing. Virtual planning. Surgical planning. Mandibular reconstruction. Stereolithography.

Resumen

Objetivo: Compartir nuestra experiencia para crear modelos anatómicos precisos utilizando software con licencia abierta disponibles. **Métodos:** Se presenta un método asequible, en donde a partir de un formato DICOM de una tomografía computarizada se logra una segmentación de la región de interés. Posteriormente se procesa la imagen para una mejora de superficie y se realiza la conversión de formato DICOM a STL. Se logra la corrección de errores y se optimiza el modelo para luego ser impreso por medio de estereolitografía con una impresora 3D de escritorio. **Resultados:** Se efectuaron mediciones precisas de las dimensiones del archivo DICOM (TC), del archivo STL y del modelo impreso (3D). Para la vértebra C6, las dimensiones del eje horizontal fueron 55.3 mm (TC), 55.337 mm (STL) y 55.3183 mm (3D). Las dimensiones del cuerpo

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vertebral fueron 14.2 mm (TC), 14.551 mm (STL) y 14.8159 mm (3D). La longitud de la apófisis espinosa fue de 18.2 mm (TC), 18.283 mm (STL) y 18.2266 mm (3D), mientras que su ancho fue de 8.5 mm (TC), 8.3644 mm (STL) y 8.3226 mm (3D). Para la vértebra C7, las dimensiones del eje horizontal fueron 58.6 mm (TC), 58.739 mm (STL) y 58.7144 mm (3D). Las dimensiones del cuerpo vertebral fueron 14 mm (TC), 14.0255 mm (STL) y 14.2312 mm (3D). La longitud de la apófisis espinosa fue de 18.7 mm (TC), 18.79 mm (STL) y 18.6458 mm (3D), y su ancho fue de 8.9 mm (TC), 8.988 mm (STL) y 8.9760 mm (3D). **Conclusión:** La impresión de un modelo en 3D de tejido óseo mediante este algoritmo resulta una opción viable, útil y con una alta precisión.

Palabras clave: Impresión 3D. Planificación virtual. Planificación quirúrgica. Reconstrucción mandibular. Estereolitografía.

Introduction

The application of 3D printing technology in the medical field is not new. As interest among surgical professionals and the availability of low-cost 3D printers have increased, biomedical advances and benefits in medicine through rapid prototyping have been achieved. 3D printing has expanded in the medical field for various applications, including prosthetics, implants, and customized models, as well as in medical education, among other areas. These applications have generated valuable benefits in terms of the customization of medical equipment and patient care¹. One could think that implementing this technology involves high costs and requires a high level of expertise and specialization, making it unfeasible in certain hospitals, and, therefore, outsourcing services is often a possible alternative. Various companies offer 3D printing services, but in many cases, the costs associated with these services are not affordable for patients^{2,3}. This article evaluates the feasibility of using free-licensed software, along with a desktop printer, for the design, fabrication, and application of patient-specific anatomical bone models, which provide extensive and detailed information for the preoperative planning of complex fractures, deformities, and bone tumors, among others. These models have potential uses in preoperative planning, enhancing patient understanding of their pathology and the procedure, improving doctor-patient communication, and supporting training personnel by facilitating knowledge acquisition through haptic feedback⁴.

Method

With the patient's prior consent, neck images were obtained from a 16-slice multidetector computed tomography scanner (Brilliance 16; Philips Medical), acquiring images of the cervical spine to create a model of 2 vertebral bodies (C6 and C7), which represent bone tissue with a complex surface, unlike a long bone,

to simulate a clinical situation where spinal surgery planning would be performed. Volumetric data were acquired (1 mm slice thickness, 140 kVp, 103 mA). The next step involves obtaining a format that allows for 3D printing, using a file with STL (stereolithography) extension so that the printer can execute the commands in millimeter coordinates on the x, y, and z axes.

To outline the boundaries of the tissues or organs of interest and generate a 3D reconstruction for further analysis, a segmentation process is performed. Image segmentation is a technique used in digital imaging to organize scanned volumes into connected, non-overlapping, discrete, homogeneous, and semantically meaningful regions. Each of these partitions consists of sets of pixels or voxels, and the differences between each voxel in intensity (densities) or texture represent an opportunity from which this partition is made. This process can be manual, adjusting the contours of the selected volume manually, which can be time-consuming and exhausting, or automatic through multiple tools with algorithms that divide into regions with similar intensity or texture characteristics. Due to their particular nature, these algorithms have no proper rule for validating the obtained segmentation results, nor do they guarantee a feasible model for 3D printing; therefore, a semi-automatic approach was adapted.

During our process, the radiology team supervised and supported the development of the segmentation. The Slicer program, in the segment editor module, has multiple tools for segmentation. We used thresholding, which allows manual adjustment of threshold ranges, to select the Hounsfield units that cover the region of interest with little or no mottling of other structures. The ranges were adjusted to ensure that the largest bone structure of interest was selected. To ensure accuracy in volume segmentation, each of the CT scans was reviewed to reinforce scrupulousness and precision. With the paint and draw options, details were refined by manually removing "undesired volume" and adding "missing volume." Next, structures within the selected threshold

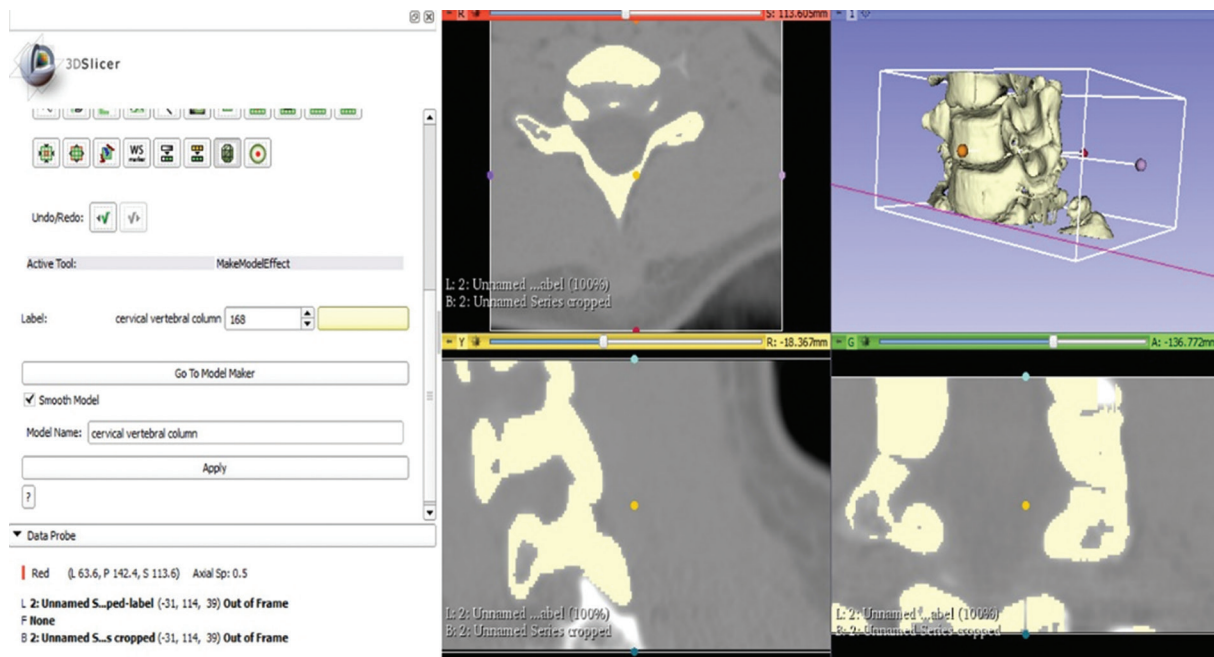


Figure 1. Model during processing in 3D Slicer. Segmentation and refinements are performed, non-interesting regions are removed, and "Create Surface" is selected to visualize our structure in a 3D reconstruction.

that were not part of the region of interest were removed; this was facilitated by cropping the workspace with the crop option, then selecting the structure of interest with the "keep selected island" option and using scissors to manually and meticulously surround the volume of interest, selecting "erase outside." Afterwards, the create surface option was selected to visualize our structure in a 3D reconstruction (Fig. 1).

The volume saved in STL format was loaded into Blender software to optimize the model and prepare it for printing. The mesh was created in the model using the Edit Mode option, which generates the mesh in the 3D model. Afterwards, one of the vertices of the exterior mesh was selected, and the linked option was used to select everything linked to that vertex, which is the entire exterior mesh of the vertebrae. Following this, the Inverse option was used to select all the internal meshes that had been generated within the model internal cavity, which are vertices and edges decoupled from the rest of the object. Having selected them, any geometry was deleted with the delete option to clean the model and improve the printing process; subsequently, gaps were filled, and the surface was smoothed (Figs. 2 and 3).

The file was re-exported in STL format and printed on a Formlabs Form 1 3D printer that uses SLA

(stereolithography) technology with UV light to solidify a photopolymer resin according to the STL format commands. Using this type of printer provides great precision and detail to the 3D model, as the layer thickness is 25 to 200 μm (Fig. 4).

Figure 5 illustrates the methodology used to create the printed model.

To assess the feasibility and accuracy of the printed model, measurements were taken on the tomography (Philips multi-modality DICOM Viewer R3.0 SP15, Philips Medical Systems), on the STL format model before printing (Blender), and on the printed model, which were performed on a Keyence IM-7020 measurement system (Keyence, Mexico).

Results

Table 1 illustrates the main characteristics of the printed model.

Measurements were taken of the dimensions of the DICOM file, as well as of the STL file, and subsequently measurements of the printed model. The radiology, engineering, and medical teams were involved in all measurements. The largest horizontal axis of the transverse apophysis to the transverse apophysis, the largest anteroposterior axis of the vertebral body, the largest anteroposterior axis of the spinous process,

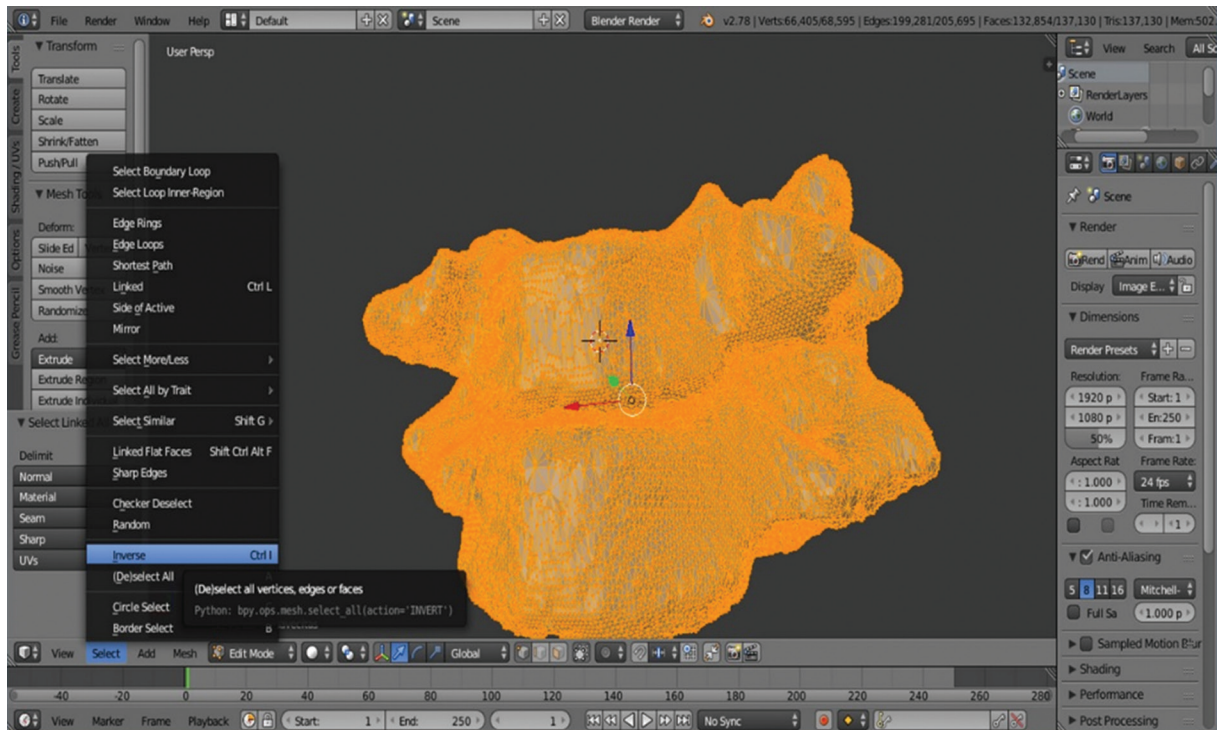


Figure 2. The volume saved in STL format is loaded into Blender software, where model cleaning and enhancement begin. A mesh is created, and disconnected vertices and edges are removed to improve the printing process.

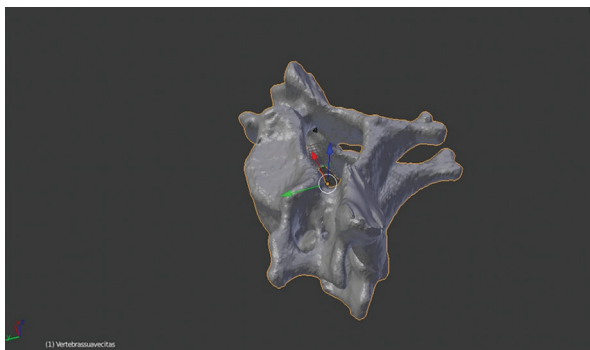


Figure 3. In Blender, once the model is optimized, gaps are filled, and the surface is smoothed.



Figure 4. 3D printed model.

and the largest laterolateral axis of the spinous process were measured (Fig. 6). Comparisons were made between the CT image and the STL file, as well as between the printed model and the CT image. Table 2 illustrates the results of the measurements obtained.

Discussion

The advancement of 3D printing technology has enabled the creation of representative physical 3D models using a printer. This has significantly benefited the

medical field with numerous applications in surgery, primarily in traumatology and orthopedics, maxillo-facial, plastic, vascular, and neurosurgery, among others, revolutionizing the dynamics of medicine and biomedical engineering in patient treatment in an increasingly focused on personalized medicine^{5,6}. The applications of 3D printing in health care are not limited to surgical planning; they extend from educating

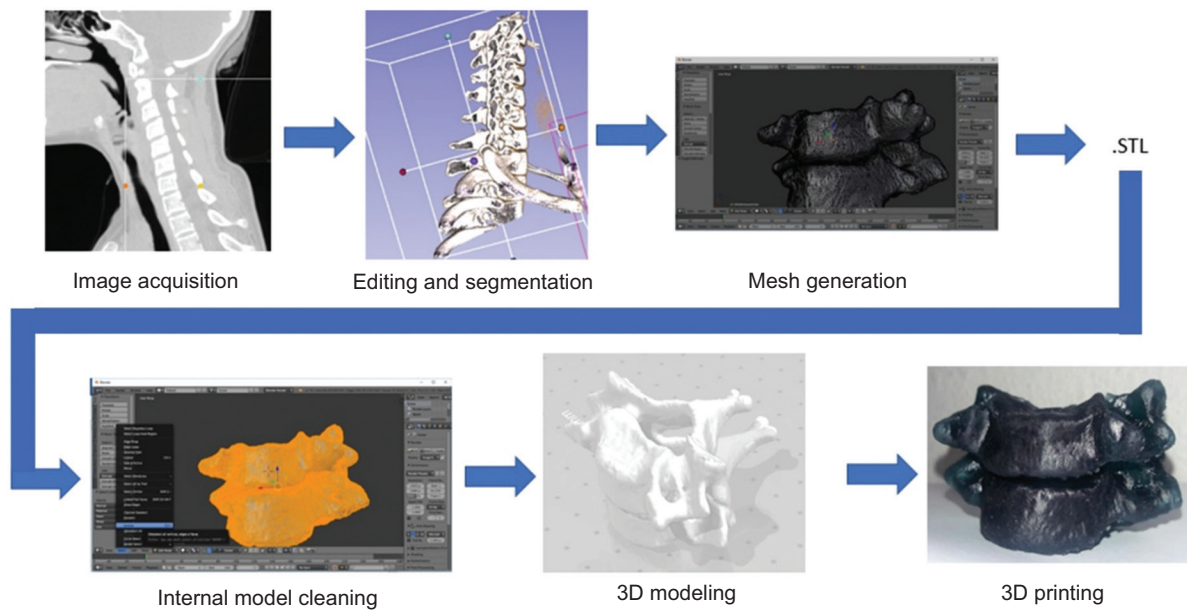


Figure 5. Summary of the workflow for creating a 3D printed model.

Table 1. Summary of the main characteristics of the printed model

Formlabs Form 1 (Formlabs, Boston, United States)	
Vertices	66.405
Faces	132.854
Printing and Resin Curing Time	10.5 hours
Printing Cost (UACJ Rapid Prototyping Lab)	231 mexican

patients and students to creating customized tools and prosthetics for each case^{1,7}.

There are various software options available to process medical images and generate 3D models for printing, some of which are free of charge, while others are paid. Free options include 3D Slicer and MeshLab, which offer a wide range of tools and functionalities for processing medical images and creating 3D models. However, these alternatives may have limitations in terms of technical support and updates, though they present a cost advantage for institutions with limited resources⁸.

Philips IntelliSpace Portal¹⁰ and Materialise Mimics are prominent options in the market but have the drawback of being paid software. To utilize these platforms and access their extensive advanced functionalities, analysis tools, and specialized technical

support, it is necessary to acquire the corresponding license^{9,10}.

Nevertheless, when using these software options, additional programs are also required for mesh editing, which are used to refine and adjust the 3D models generated by both free and paid software. These programs are particularly important when using free solutions like 3D Slicer, as the resulting 3D models may have imperfections and require minor adjustments. The functionalities of these editing programs include scaling, moving, and rotating the piece, removing undesired areas through imperfect segmentation, closing gaps, smoothing areas with deformities, modifying the geometry of specific areas, and cutting the piece to create different sections¹¹.

The vertebral anatomical model used in this review was characterized by its low cost, making it a financially viable alternative. This model was designed as an educational resource for both students and patients undergoing surgical procedures. It was developed using the free software 3D Slicer and refined through the program Blender, known for being an open-source, free 3D creation platform. This approach to model creation demonstrates an efficient strategy based on the accessibility of cutting-edge technologies. The printing was done using the Form 1 desktop SLA printer (FormLabs, United States) from the rapid prototyping lab at University Autónoma de Ciudad Juárez, which is available to the general public. A final

Table 2. Measurement results of the 3D printed model, STL formats, and CT scan

	C6 CT	C6 STL	C6 3D	C7 CT	C7 STL	C7 3D
Largest horizontal axis	55.3 mm	55.337 mm	55.3183 mm	58.6 mm	58.739 mm	58.7144 mm
Vertebral body	14.2 mm	14.551 mm	14.8159 mm	14.1 mm	14.025 mm	14.2312 mm
Spinous process length	18.2 mm	18.283 mm	18.2266 mm	18.7 mm	18.790 mm	18.6458 mm
Spinous process width	8.5 mm	8.364 mm	8.3226 mm	8.9 mm	8.988 mm	8.9760 mm

3D: 3D printed model; STL: Model in STL format in Slicer; CT: Model in computed tomography (CT) scan.

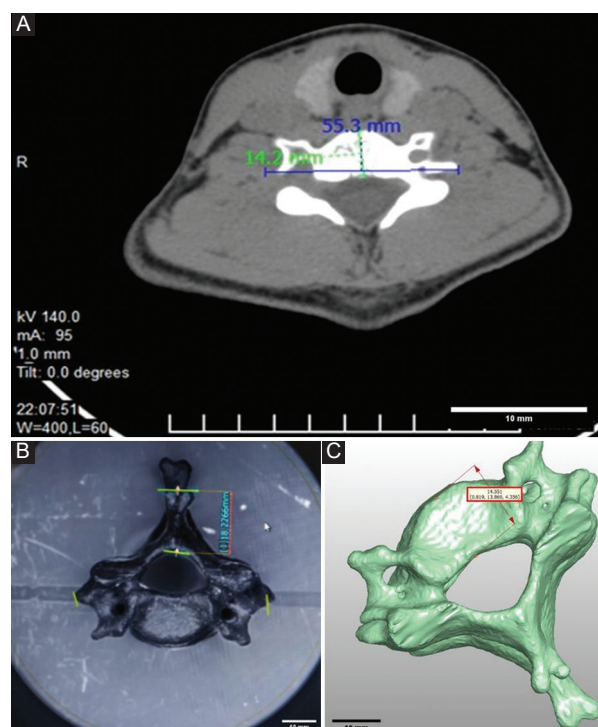


Figure 6. A: measurement of the anteroposterior axis of the vertebral body using 3D Slicer software. B: measurement of the anteroposterior axis of the spinous apophysis on the 3D printed model using the Keyence IM-7020 measurement system (Keyence, Mexico). C: measurement of the horizontal axis from transverse apophysis to transverse apophysis in CT scan images.

model of high precision and quality was obtained for approximately 200 Mexican pesos or 9 US dollars. The time taken to create this model, from obtaining the CT scan to the complete printing of the model, was approximately 15 hours.

The time needed to print a 3D medical model can vary depending on several factors, including the desired level of detail and the layer thickness used for printing. Thinner layers can capture finer details, but at the expense of longer printing times; for example, a sample piece printed with a layer thickness of

100 μm in standard resin takes approximately 2 hours to print. However, printing the same piece at 50 μm would take about twice as long, and printing it at 25 μm would require nearly 7 hours. The printing time can also affect production costs, as longer printing times may result in higher material costs and prolonged use of the printing equipment. Therefore, it is essential to consider the balance between printing time and the level of detail required when generating 3D medical models¹²⁻¹⁴.

The level of precision and fineness that can be achieved in 3D printing depends on several factors, including the printing technology used, the resolution of the printer, the quality of the materials, and the complexity of the model. In general, stereolithography (SLA) and fused deposition modeling (FDM) are popular 3D printing technologies that can achieve high precision and fineness in printed models. SLA uses a high-precision laser to solidify liquid resin layer by layer, allowing for extremely fine print resolutions, up to 25 microns or even less in some cases. FDM uses a thermoplastic filament to build the model layer by layer and print quality can vary depending on the printer resolution and quality of the filament used. Most modern 3D printers have a print accuracy ranging from 0.1 mm up to 0.3 mm, and some high-end printers can achieve an accuracy of up to 0.02 mm or even less¹²⁻¹⁵.

To implement this, the software and hardware requirements will largely depend on the goals of the 3D printing center; for example, the resolution and material requirements for creating a preoperative educational model for patients or medical students will be much lower than those for a preoperative model intended for a pediatric cardiothoracic surgeon to simulate the intraoperative environment of a complex congenital heart defect. 3D Slicer provides high resolution and an intuitive interface for free, primarily when there are significant Hounsfield unit differences between adjacent structures, such as bone and

contrast-enhanced structures like vascular structures in angiograms, to name a few. Werz et al.¹⁶ described in a study that the creation of maxillary models using a desktop 3D printer for maxillofacial surgery practice by students and residents was more cost-effective than obtaining maxillary models from third parties, and categorized these models as “good” for simulating and practicing certain surgical procedures^{16,17}.

The required model size will also help determine the necessary hardware; for example, a pediatric heart model is small enough to fit within the popular Form 1 or Form 2 desktop SLA printer (FormLabs, United States), but a full-size adult pelvis is not, and it would need to be printed in parts or use a larger capacity printer.

In the realm of 3D printing, various materials can be used depending on the printing technology used and the type of object to be printed. Common materials include polymers, such as polycarbonate (PC), polylactic acid (PLA), polyether ether ketone (PEEK), and polycarbonate urethane (PCU), which are also biocompatible^{18,19}. Resins, on the other hand, are used in stereolithography (SLA) and digital light processing (DLP) printing technologies, with polyethylene glycol (PEG), poly(D, L-lactide) (PDLLA), poly-ε-caprolactone (PCL), and poly(propylene fumarate) (PPF) being some of the most widely used, and they are also biocompatible^{18,20}. Additionally, 3D printing with metals, such as titanium, stainless steel, aluminum, copper, and gold has become popular, with titanium being the most used for 3D printing implants and customized prostheses²¹⁻²⁵. Bioinert ceramics, such as alumina and zirconia offer high chemical stability, providing promising advantages for their use as implants in patients²⁶.

It is crucial to note that not all materials used in the 3D printing process are safe; even if not used as implants, handling models that generate resin residues or powders can pose a health risk if the necessary precautions and safety measures are not taken during the handling of these materials²⁷.

Regarding the Formlabs Form 1 3D printer, it employs an exclusive liquid photopolymer resin known as Formlabs Standard Resin, specifically formulated for use with the stereolithography (SLA) technology used in the above-mentioned printer. Its curing process is performed using a high-precision laser, resulting in the creation of parts with superior quality and resolution. Formlabs Standard Resin offers a combination of strength, rigidity, and durability, and there are other specialized resin varieties available for the

Form 1 printer, such as flexible resins, transparent resins, and high-temperature resins^{28,29}. In addition to its application in printing 3D models for educational purposes³⁰ and improving communication with patients, the use of 3D prints is experiencing significant growth in its use as tools for preoperative planning and the fabrication of prostheses, particularly in the fields of orthopedic and maxillofacial surgery. The utility of 3D printing has been demonstrated in total knee arthroplasty; current literature suggests that satisfactory clinical and radiological outcomes could be achieved with the help of 3D printing, even demonstrating greater precision in implanting an articular prosthesis³¹⁻³³. In total hip arthroplasty, 3D printing technology has been shown to improve surgical efficiency, shorten surgical times, and reduce radiation exposure. This technology also offers new potential for the treatment of complex hip joint diseases, indicating that 3D printing has enormous potential in this area^{3,34-38}. In hand surgery, its utility has been demonstrated in constructing patient-specific models for preoperative planning, designing patient-specific orthopedic and prosthetic devices, generating patient-specific hardware and prostheses, and applications in resident and student education³⁹. In spinal surgery, it has shown practical value and has become popular as a reference for clinical education and diagnostic aid, as well as for improving communication between physician and patient and in the planning of surgical approaches, in addition to its utility as a reference for complex surgeries⁴⁰⁻⁴⁵. In maxillofacial surgery, it allows for better planning and preoperative training for procedures and pre-molding of plates^{46,47}. Additionally, the use of 3D printing methods in orthognathic surgery offers the benefit of optimal functional and aesthetic outcomes, patient satisfaction, and precise translation of the treatment plan to the patient⁴⁸.

The use of 3D-printed models in plastic surgery is a new field, experiencing significant growth, particularly in the area of reconstructive surgery, with promising results in precise anatomic biomodels, surgical cutting guides for reconstruction, and the fabrication of patient-specific implants, which have a potentially immense future impact on the reconstruction of traumatic injuries, the development of facial and limb prostheses, as well as advancements in biological and synthetic implants⁴⁹⁻⁵⁵.

In a review conducted by Tack et al., it was reported that most branches of reported studies are in orthopedic surgery, accounting for 45.1%, with knee surgery representing 30.7%, hip surgery 8.3%, shoulder

surgery 2.1%, and hand surgery 1.7%. Maxillofacial surgery accounts for a significant proportion, at 24.1%, followed by cranial surgery and spinal surgery, representing 12.7% and 7.4%, respectively⁴.

When approaching a surgical patient, the surgeon is faced daily with the challenge of interpreting and working with two-dimensional images, from which they must diagnose, plan, and make surgical decisions, often requiring considerable skill and experience, especially with unique or complex diseases. Although the objective is usually achieved, communication within the surgical team can be inefficient, as this skill is not always shared by all members, particularly the less experienced ones. Three-dimensionally-printed anatomical models are a useful tool for studying complex cases and planning preoperative strategies, such as tool selection and surgical approach organization. Additionally, they can serve as surgical guides and for preoperative training of residents, as well as for preoperative education of the patient and their family. The visual feedback provided by these models can also improve effective communication with patients and their families, which is especially important when personalized prostheses are required to repair anatomical defects with the greatest precision possible^{30,56}.

In the plastic and reconstructive surgery service, as well as in the maxillofacial surgery service, we have used this algorithm over the past few years for the planning and execution of reconstructive surgeries, particularly in head and neck reconstruction (Fig. 7), where the implementation of a 3D-printed model of the patient's bone structure for pre- and intraoperative planning of a free fibula flap has reduced risks and costs in our center. Another illustrative example of a model prepared for subsequent 3D printing is shown in figure 8. Through the use of multiple tools available in Blender, it is possible not only to segment and isolate specific bone structures but also to select a preferred bone segment for subsequent three-dimensional printing. This approach allows for greater customization and adaptability in the generation of anatomical models, thereby optimizing the surgical planning process and the production of personalized prostheses.

Given the growing popularity of 3D printing in the medical field, question arises as to whether this technology truly provides added value, or superior benefits vs conventional imaging or computer simulation during the surgical process. In a review⁴, considering all applications of 3D printing, it was found that it reduced surgical time in 46% of studies. In 76% of reports, it

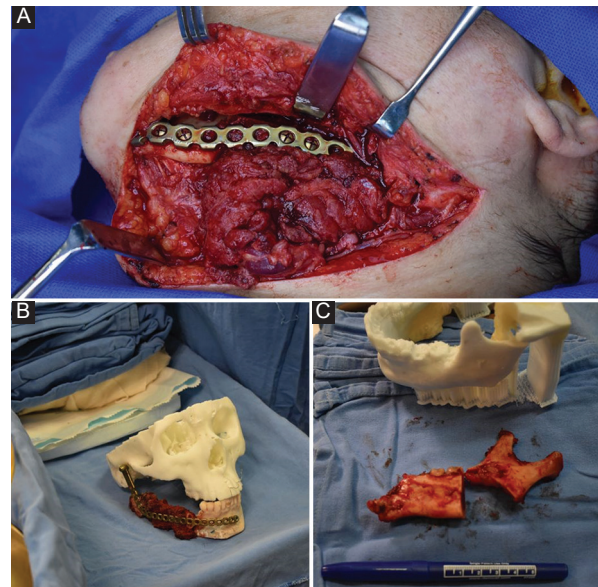


Figure 7. A: 3D printed model of the facial skeleton for pre- and intraoperative planning during patient reconstruction using a free fibula flap and a reconstruction plate. B: free fibula flap with reconstruction plate after placement and fixation in the patient's mandibular defect. C: 3D printed model used for planning the partial resection of the mandible, as well as for pre-contouring the reconstruction plate. The model high precision is evident vs the resected piece.

is mentioned that printing had good accuracy, and 72% reported improvement in outcomes. Studies demonstrate a reduction in surgical time when 3D prints are used for implant modeling, preoperative planning, creation of personalized implants, and as surgical guides. Additionally, shorter fluoroscopy times have been reported in thoracic spine surgery, and reduced use of contrast media and fluoroscopy in abdominal aortic aneurysm repair and cardiovascular surgery in cohorts where 3D-printed anatomical models were used as preoperative preparation^{56–58}. However, the use of this technology in medicine involves high costs: 33% of the articles report that this technology is more expensive⁴. Depending on the existing infrastructure, creating an in-house center can be very costly and requires expertise that is difficult to find, often making it an unviable initial option for small medical centers.

Except for image acquisition, outsourcing is an option for the remaining steps of the 3D printing workflow. Currently, there is no software available that can integrate all the necessary processes for creating 3D models from medical images. Although various specialized tools exist for each stage of the process, their integration has been limited by the lack of a comprehensive solution. Nonetheless, some companies

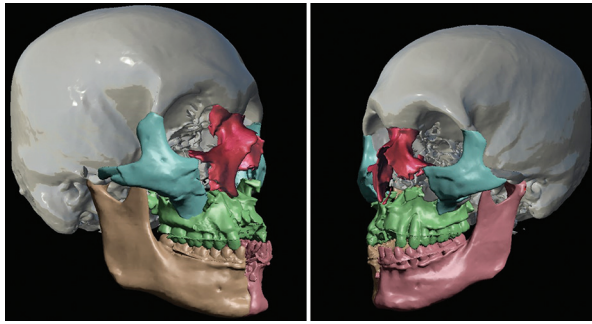


Figure 8. Anatomical model specifically prepared for 3D printing, representing a patient with panfacial fractures. This model has been generated for use in the surgical planning of these fractures. It will facilitate spatial visualization and understanding of anatomical complexity, which is crucial for precise surgical intervention planning.

offer services that allow for all processes, from obtaining medical images to printing the final model, to be performed. Examples include 3D Systems (United States) and Materialise (Belgium), which offer these services at a medical grade, including DICOM conversion, segmentation, and printing all in one, though their cost often reaches several thousand dollars^{3,12,13}. Moreover, outsourcing services adds complexity to project management. The transfer of data and sensitive medical information can also pose challenges related to patient safety and privacy.

Despite this, the use of 3D models in certain surgical scenarios reduces surgery times and could imply a financial benefit that justifies the investment in a printing center, for which prospective studies are needed to estimate these figures more clearly⁵⁸.

Conclusion

The proposed method allows for the fabrication of 1:1 scale models of bone structures with high precision and detail. Using a computed tomography scan and the patient's anatomy, we designed and manufactured a 3D-printed model. The methodology is low-cost and very easy to perform. This study is valuable on multiple levels, as it not only documents feasibility and accuracy but also inspires other researchers in terms of study design and technique by establishing tangible workflows.

Based on the parameters obtained in the results analysis, the design of a 3D-printed model from anatomical images of bone tissue using available web software represents a viable option for preoperative use, especially in selected cases such as complex, rare,

and high-risk surgeries, in which the cost-benefit of adding 3D printing is truly feasible and cost-effective. Technological advancements have driven exponential development in the field and a significant reduction in costs. Applications in medicine have been largely described in case reports; although more complex studies continue to emerge, further research focusing on clinical benefits is needed to design guidelines.

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Conflicts of interest

None declared.

Ethical disclosures

Protection of human and animal subjects. The authors declare that no experiments were performed on humans or animals for this study.

Confidentiality of data. The authors declare that they have followed the protocols of their work center on the publication of patient data.

Right to privacy and informed consent. The authors have obtained the written informed consent of the patients or subjects mentioned in the article. The corresponding author is in possession of this document.

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