Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(8), 114–125
https://doi.org/10.12913/22998624/204756
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.03.19
Accepted: 2025.06.15
Published: 2025.07.01

Partial maxillofacial reconstruction: Design and additive manufacturing of individualized pre- and mid-surgery supplies

Emilia Smolarek[1*], Filip Górski[1], Magdalena Żukowska[1],
Łukasz Słowik[2], Maciej Okła[2]

[1] Faculty of Mechanical Engineering, Poznan University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland
[2] Poznan University of Medical Sciences, Collegium Maius, ul. Fredry 10, 61-701 Poznań, Poland
* Corresponding author e-mail: emilia.smolarek@student.put.poznan.pl

ABSTRACT

This paper presents a case study of pre- and mid- surgery supplies in the field of maxillofacial surgery. The operation involved the process of resection within the mandible and the implantation of a joint endoprosthesis. The methodology is based on medical data in DICOM format and a maxillofacial model in STL format obtained through structural scanning. The stages of work included processing medical data involving medical imaging segmentation, structural scanning, model design and their production using 3D printing. SLA technology and various materials for each model were used in the process. The entire process underwent clinical validation during the mandibular reconstruction surgery and analysis of the obtained results. Satisfactory maxillofacial models were obtained, allowing for precise positioning of the endoprosthesis and planning of the surgical procedure, while the individually tailored guides and templates were used during the surgery. The models significantly improved the quality of the surgery, shortened its duration, and accelerated the patient's recovery.

Keywords: 3D printing, surgery supplies, maxillofacial reconstruction, imaging-based design.

INTRODUCTION

In recent decades, interdisciplinary cooperation has driven innovation in the medical field, leading to advancements in diagnostic devices and treatments. By combining expertise from engineering, biotechnology, medicine, biology, and materials science, each discipline contributes to a comprehensive approach to problem-solving. Engineers focus on design, while doctors provide medical expertise, making their collaboration highly effective [1–4]. These collaborations have led to developments in tissue engineering, biocompatible materials, prosthetics, bionics, biomechanics, biomedical imaging, and nanotechnology [1, 2, 5]. Additive manufacturing (AM) has revolutionized the medical sector, offering vast opportunities for creating patient-specific biomedical products [4, 6]. One of the most promising applications of additive manufacturing in the medical field is the creation of customized implants covering different areas of the body [1–3]. Another application is the production of prostheses and orthopedic devices [4–7].

Thanks to AM the process of creating customized prostheses becomes not only efficient, but also economical [8–10]. In addition, additive manufacturing finds application in the production of surgical instruments and medical devices that can be customized to meet the requirements of a specific procedure or surgery [11, 12]. In the area of tissue engineering, 3D printing is being used to produce organs and living cells and tissues. The method also has an impact on surgical planning, enabling the creation of anatomical models of patients on which surgeons can hone their skills by simulating surgical procedures[11–13]. Such models can be divided into pre-operative, intra-operative and post-operative models. Each of these has different functions (Figure 1).

Pre-operative models are mainly used to simulate and plan surgical procedures before they are performed, and can also be used for communication between doctor and patient [14]. Intraoperative models have the most practical application, as they are used during actual surgery. They help with navigation during procedures, while increasing surgeon confidence and improving visualization of the patient's anatomical structures. Postoperative models are most often used to visualize the patient's structures after procedures, to verify the correctness of the procedure performed or the patient's recovery [15]. Depending on the function of the models, different additive manufacturing techniques and materials are also used. When the model is taken to the operating room and used during procedures then it must be made of biocompatible and sterilizable materials. This is an extremely important requirement for such models [16]. On the other hand, when the model is to provide only visual functions then there is no need to use compatible materials, and you can opt for those with the highest accuracy.

Additive manufacturing involves creating pre-designed 3D objects using a printer and CAD software. The process involves applying material layer by layer, creating a shape that conforms to a digital model. AM techniques are widely used in medicine, especially in dentistry, prosthetics, implantology and surgery. In the future, printing organs and tissues could help extend the lives of patients struggling with various diseases [17]. There are a number of AM techniques, which are classified according to workspace, machine dimensions or materials used - the most common criterion for division. The main technologies applied in biomedical engineering include FDM (fused deposition modeling) [18–20], SLA (stereolithography) [21–24], PolyJet [25–27] and SLS (selective laser sintering) [28–30], among others [25, 31]. AM technology is transforming maxillofacial surgery by enabling precise, personalized models and implants through affordable 3D printing. This innovation enhances treatment for complex anatomical defects, improving surgical precision and outcomes. Many medical facilities now use AM labs to streamline the production of surgical models and optimize treatment planning [32–35].

A key application of AM technology is the creation of personalized surgical plates for mandibular and maxillary reconstruction, particularly after oncological procedures. It allows for the production of custom plates and cutting templates, ensuring precise bone segment shaping in fibula or scapula-based reconstructions. This improves accuracy, reducing deviations in bone positioning by over 30% and minimizing manual plate adjustments, leading to shorter, more predictable surgeries [36–40].

AM also facilitates custom titanium implants for complex jawbone defects. SLM-produced implants integrate well with bone, supporting healing, vascularization, and structural stability, while restoring facial function and aesthetics, including chewing and symmetry [41–43]. AM technology is revolutionizing orbital reconstruction by enabling precise surgical planning and the creation of custom implants. Using CT scans and 3D modeling, surgeons can design implants that perfectly match the patient's fracture by mirroring the healthy side of the orbit. This approach improves implant alignment, reduces deformities, and restores orbital symmetry, effectively minimizing complications like double vision and enophthalmia [44–47].

During the literature review, the authors observed that one of the less commonly used approaches in preoperative planning in maxillofacial

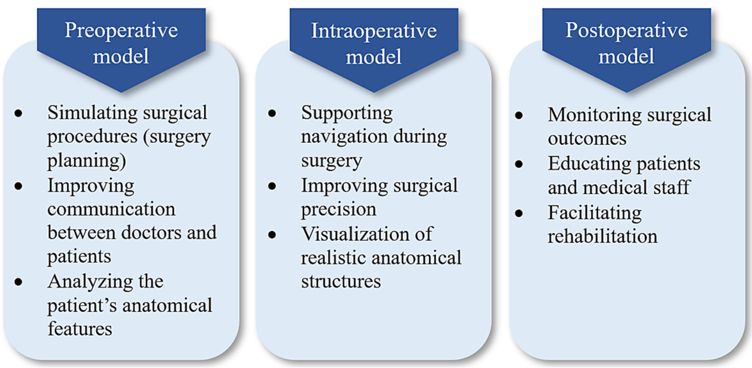

Figure 1. Division and functions of operative models (based on [14])

surgery is the application of dual printing of operative models. Standard practice typically involves printing either a preoperative model or an intraoperative model, whereas utilizing both simultaneously can offer significant diagnostic and surgical benefits with only a slightly increased workload. Furthermore, the analysis indicates that bone models dominate in maxillofacial surgery, while the reconstruction of soft tissues, nerves, and blood vessels remains a relatively uncommon practice. The literature includes cases where soft tissues are considered mainly in numerical analyses, such as the finite element method (FEM), however, their physical implementation in the form of 3D-printed models is still not widespread.

MATERIALS AND METHODS

Concept and plan of work

The aim of the study was to design and create personalized preoperative and intraoperative tools, including anatomical craniofacial models, as well as custom surgical guides and templates. Their application was intended to facilitate the planning and execution of a complex surgical procedure in a patient for whom standard methods would be insufficient. The task also included the development of a detailed methodology for their manufacturing to ensure that the tools are precisely tailored to the patient's individual anatomical features. A key goal of the project was to develop models to facilitate the planning and preparation of implants prior to surgery, as well as to streamline the reconstruction procedure in the craniofacial region and reduce surgical time. The work was divided into several key stages (Figure 2). It began with a preliminary consultation and the collection of medical data, during which the maxillofacial surgery team determined the requirements for the anatomical models and their functionality. Computed tomography (CT) scan data of the patient was gathered and used to prepare the craniofacial models.

Next, the collected CT data was processed through segmentation to extract key anatomical structures of the craniofacial region. The models were then printed using DLP technology and underwent finishing procedures, including UV cleaning and curing. Based on the printed models, physicians identified the precise resection areas and tested the reconstruction plate to ensure a precise fit according to surgical requirements.

Subsequently, individualized templates and guides were designed and printed using a scanned model with the reconstruction plate. These guides underwent finishing processing in preparation for use during surgery. In the final stage, clinical validation of the fabricated models and instruments was conducted to ensure their accuracy and functionality. Each step contributed to the main goal of the work - to provide effective support for surgeons and optimize the surgical process through the use of personalized, additively manufactured surgical aids.

The study conducted is distinguished by an innovative and comprehensive approach to the process of designing and manufacturing models to support maxillofacial surgery. The innovation of the methodology consists in a multi-step and at the same time highly efficient process, which includes both the use of 3D printing technology and reverse engineering elements. A key point in the process is doubled 3D printing process

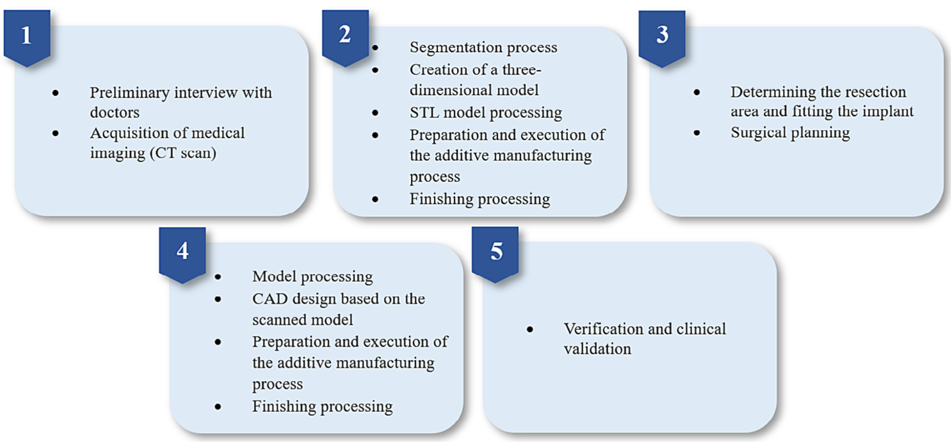

Figure 2. Diagram illustrating the stages of work

– anatomical structures printed firstly are then preoperatively used for the development of models that are later used as intraoperative guides. These models are closely linked – intraoperative models are created on the basis of preoperative ones after simulated surgery (its results are incorporated by 3D scanning of "operated" model), ensuring consistency and accuracy in the planning and execution of procedures.

While routine cases are widely discussed in the literature, there is a lack of approaches dedicated to very complex and rare cases. This study attempts to address that gap by developing a new methodology specifically aimed at treating such challenging conditions. The proposed approach enables comprehensive support in the treatment of highly intricate cases, and its impact on the effectiveness of surgery and patient recovery opens up new possibilities in modern surgery.

Case study

The conducted study was based on patient data obtained from medical imaging performed at the University Clinical Hospital in Poznań. The subject was a 54-year-old oncology patient treated for a maxillary tumor, who had undergone extensive surgical procedures, including a left maxillectomy, eye enucleation, and radio- and chemotherapy. In 2020, the patient underwent surgery for temporomandibular joint ankylosis, but imaging in 2023 revealed progressive osteolysis of the left mandibular head and thickening of joint structures (Figure 3). Due to the advanced destruction of bone tissue, a decision was made to resect a segment of the mandible and implant a joint endoprosthesis. The planning process required the use of personalized craniofacial models and surgical guides, which enabled precise reconstruction of anatomical structures, improved implant fit, and facilitated the surgical procedure.

Segmentation and additive manufacturing of anatomical models

The segmentation process was carried out using the free version of InVesalius 3.1.1 software, which allows for the processing of medical images in DICOM format. Once imported, the data was displayed in three standard orientations—axial, sagittal, and coronal—facilitating thorough analysis and the selection of appropriate segmentation parameters.

By default, the software suggests threshold values for bone tissue ranging from 226 to 3071. To achieve a more detailed representation of bone structures and include a slight tissue margin, the lower threshold was adjusted to 160. This modification caused the segmentation to encompass not only bone tissue but also fragments of the CT scanner apparatus. Based on the modified parameters, a three-dimensional surface was generated. During the analysis of this 3D surface, artifacts were identified, particularly in the form of mesh gaps near the orbital regions. All artifacts and mesh errors were corrected in subsequent steps to ensure maximum model accuracy. Figure 4 shows a section of the program window, displaying the medical imaging data and the generated three-dimensional model. Once a satisfactory three-dimensional geometry was obtained, the final model was exported as a point cloud in STL format.

To prepare the model for additive manufacturing and achieve the desired result, the GOM Inspect 2017 software was utilized. The model processing involved removing artifacts and

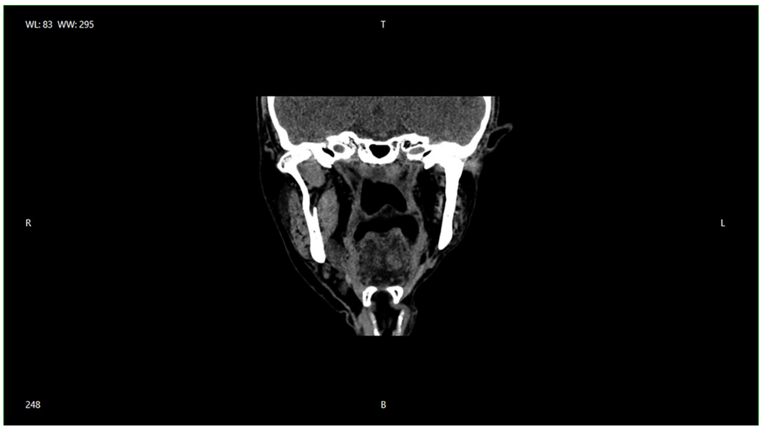

Figure 3. Coronal slice view with visible adhesion on the left side

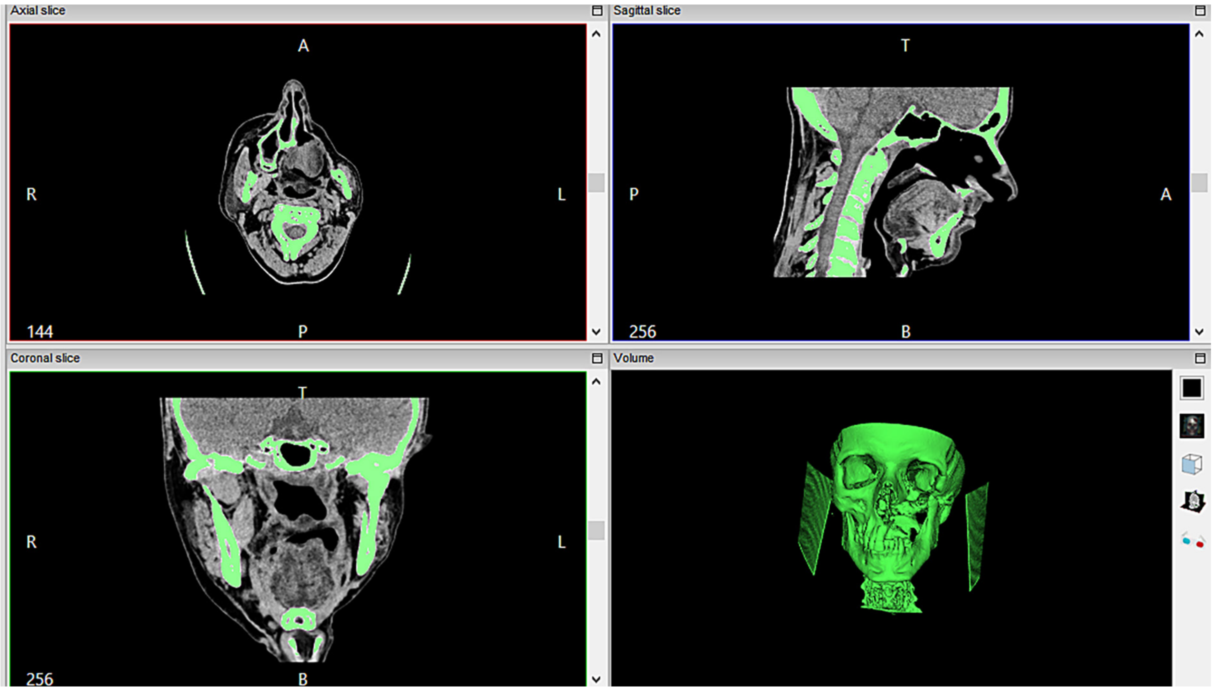

Figure 4. Medical imaging data and a segmented 3D model

reducing its volume. The results of this process are presented in Figure 5.

In the next stage of preparing the model for surgery, a detailed procedure was conducted to separate the mandible from the maxilla and other cranial elements. This operation required particular precision, especially in the area of the temporomandibular joint, where the connection line was carefully divided to minimize interference with the patient's anatomy. Additionally, the separation of the maxilla and mandible had to be performed near the teeth, as the tomographic images revealed overlapping of the upper and lower dentition due to facial muscle contractions and the lack of mandibular mobility in the patient. Executing the separation in this area enabled the correct division of the two dentitions. The final model in STL format served as the foundation for additive manufacturing, with its completed form shown in Figure 6.

The process of preparing for additive manufacturing began with configuring the appropriate printing parameters using Chitubox versions 1.9.5 and 1.8.0, depending on the specific requirements of the printer (Table 1). A key step in preparing the model was to add supports to prevent deformation, stabilize the structure and strengthen protruding parts. In addition, key parameters such as layer thickness and exposure time were carefully adjusted to ensure the best print quality. Once the model was prepared, it was exported in CTB format and saved to a USB drive, which was inserted into the printer.

The printer manufacturer's resin, which did not require sterilization, was used to print preoperative models, including craniofacial, mandibular

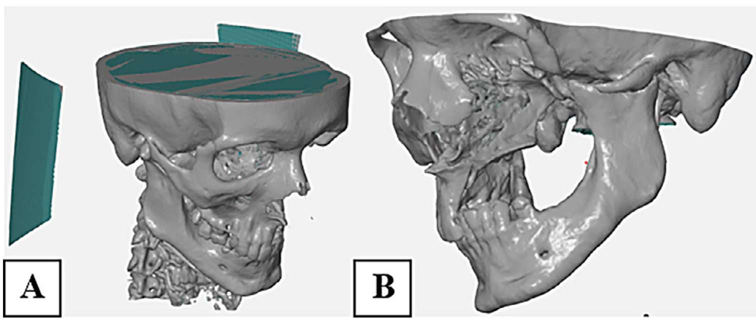

Figure 5. (a) The model after segmentation (b) model after processing

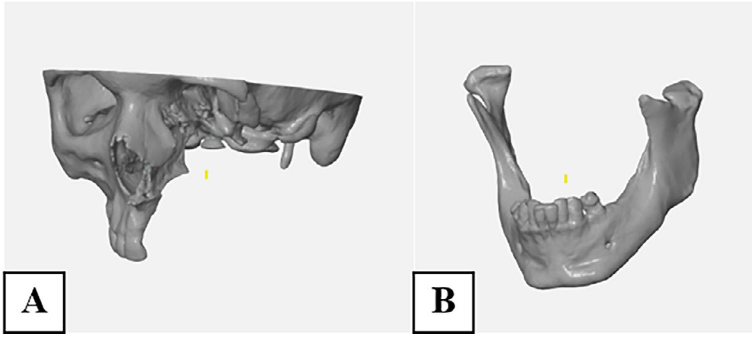

Figure 6. Final models (a) Maxilla with cranial fragment (b) Mandible

Table 1. Information on additive manufacturing of anatomical models

Model	Face - Skull	Mandible	Maxilla
Material	Anycubic basic resin skin	Phrozen aqua resin grey 8K	Anycubic basic resin light beige
Printer	Phrozen sonic mighty 8K	Phrozen sonic mighty 4K	Phrozen sonic mighty 8K
Layer thickness [mm]	0.05	0.05	0.05
Estimated printing time	13 hrs 37 mins.	7 hrs 31 mins	13 hrs 46 mins.

and maxillofacial models. After printing, the models were thoroughly cleaned with isopropyl alcohol, and all supports were removed. The final step was to cure the prints with ultraviolet light using Anycubic Wash and Cure Plus to increase their strength. Table 1 summarizes the highlights of the prints.

Custom surgical planning

The printed models were handed over to the doctors, who performed the fitting of the endoprosthesis. Using modeling wax, craniofacial symmetry was achieved, and the endoprosthesis was then precisely positioned and aligned at the correct angle. After the fitting process, the entire assembly – the plate with the endoprosthesis – was secured to the mandibular model.

To prepare precise surgical templates, it was necessary to scan the model with the pre-fitted implants in order to obtain an accurate representation of the patient's anatomical details. The EinScan Pro spatial scanner (manufactured by Shining 3D) and its dedicated software, ExScan Pro, were used for this purpose. The model, placed on a rotary table, rotated during the scanning process, capturing all relevant details and creating an accurate three-dimensional geometry. This 3D representation was essential for the subsequent design of customized surgical templates. The design of the surgical guides and templates began with aligning the scanned model to the mandibular model using GOM Inspect software to ensure a precise fit of the endoprosthesis. Horizontal and vertical cut lines were marked, and small sections were removed from the base model of the mandible. Guide rails were designed to facilitate cutting in the mandible, measuring 29.5 mm for the vertical line and 27.5 mm for the horizontal line. The rails were created in Autodesk Inventor 2023 with a thickness of 3 mm and saved in STL format. Template bases were designed with 0.2 mm offsets to account for manufacturing accuracy. Holes with a diameter of 2 mm were also added. Both cutting templates were created, aligned, and finalized in Meshmixer 3.5, with smoothing applied.

The final design step involved creating a template for positioning the reconstruction plate on the mandible during surgery. This was done in the same manner as the cutting guides, with additional holes of 3 mm radius for screw insertion to fix the plate onto the mandible. The models were then refined to remove artifacts and ensure smooth surfaces. All components were designed to enhance surgical precision and improve outcomes.

For the intraoperative models (cutting guides and plate template), the preparation process for additive manufacturing was identical to that for the anatomical models, except that the surgical guides and template were printed from a biocompatible disinfection-resistant material to meet medical standards. Table 2 summarizes the highlights of

Table 2. Information on additive manufacturing of surgical guides

Model	Surgical guides	Template for plate
Material	NextDent surgical guide	NextDent surgical guide
Printer	Phrozen sonic mighty 4K	Phrozen sonic mighty 8K
Layer thickness [mm]	0.05	0.05
Estimated printing time	48 min	3 h 31 min

these prints. The produced models served as both preoperative and intraoperative aids. The model covering the entire face and skull primarily acted as a visual aid. It allowed the doctors to assess facial asymmetry and closely examine the area where the fusion occurred. Separate models of the mandible and maxilla were used to align facial symmetry, define the area for mandibular resection, and precisely adjust the implant in the form of a reconstructive plate with a joint endoprosthesis. They also enabled the pre-planning of surgical procedures. The guide models and template model were then taken to the operating room.

RESULTS

Manufacturing results

All models were printed in the additive manufacturing laboratory at the University Clinical Hospital in Poznań, and each one successfully met the required accuracy and functionality.

Table 3 presents a summary of the key information regarding the produced models, including the design and additive manufacturing times. It also includes the mass of the products and concludes with an economic analysis. The economic analysis of the produced items involved non-commercial cost estimation, considering manufacturing expenses, as well as the time spent on design, scanning, and post-processing. The time required to obtain each product was mainly dependent on the additive manufacturing time.

The entire process is relatively straightforward, and a person with engineering expertise should have no problem managing this approach to design and product manufacturing. The most challenging task was developing the design methodology to ensure that the models closely represented the patient's anatomical structures. Once this was achieved, the design, additive manufacturing, and post-processing became much easier. However, during the finishing process, patience and careful handling were required, particularly when removing support structures, to avoid damaging or breaking printed model fragments. The final models are shown in Figure 7.

Pre-operative planning and design results

The anatomical models proved to be very helpful in preoperative planning and significantly facilitated the design of cutting guides and the plate template. They allowed doctors to visually align the patient's facial symmetry and adjust the reconstructive plate along with the endoprosthesis. The results of this process are shown in Figures 8a and 8b. The doctors were very satisfied with the proposed methodology, which included, among other things, dual printing. This allowed them to plan and simulate the course of the surgery, and it also made the actual operation easier to perform. To confirm and evaluate the results, a survey was developed and distributed to the doctors.

During scanning, not all elements of the model could be captured, but the most important part – the plate and its placement on the mandible – was properly recorded. Figure 8c shows the scanning result and the isolated plate segment, which was processed to achieve the best surface quality. The results of the design of the cutting guides and the plate template are shown in Figures 8d, 8e, and 8f.

Table 3. Summary of key information on the produced models

Model	Face - skull	Mandible	Maxilla	Surgical guides	Template for plate
Mass [g]	283	105	220	5	5
Design time	6 h	2 h	2 h	2 h 30 min	2 h
Printing time	15 h 01 min	8 h 01 min	15 h 22 min	50 min	3 h 48 min
Cost [USD]	127.88	45.22	46.68	51.92	42.23

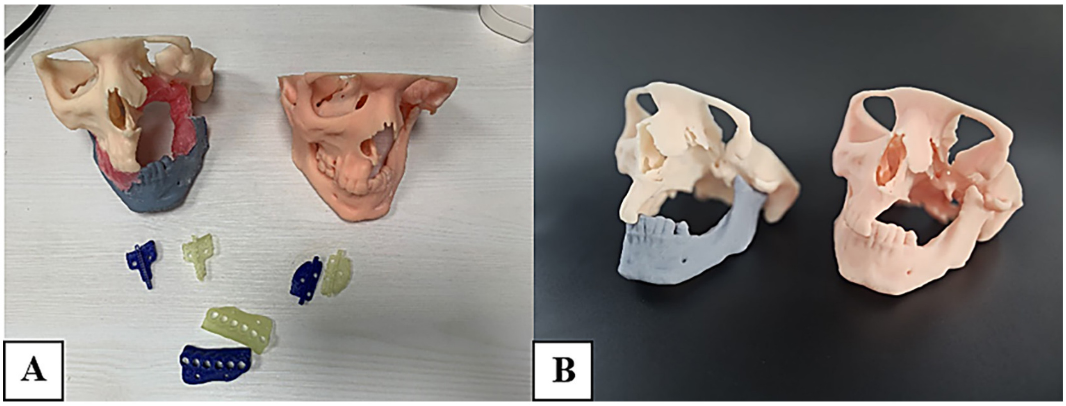

Figure 7. Final printed models: (a) anatomical models with cutting guides and the template for the reconstruction plate, (b) anatomical models

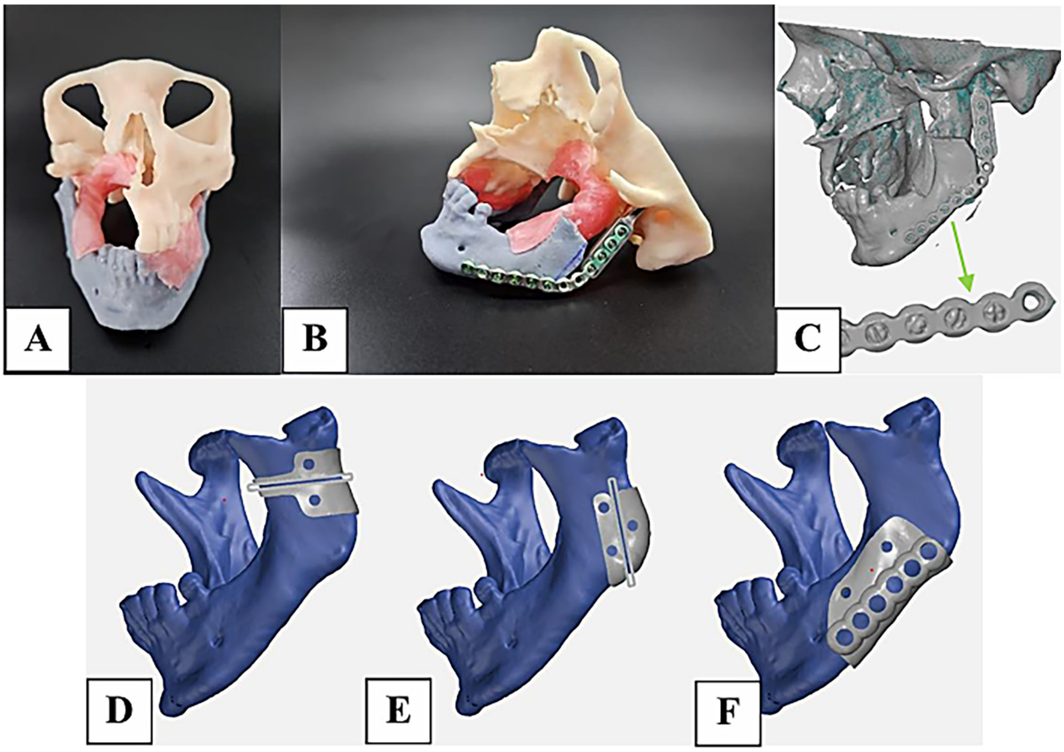

Figure 8. (a) Model after symmetry adjustment; (b) model after fitting and attaching the reconstructive plate with endoprosthesis; (c) obtained mesh after scanning (top) and processed fragment of the reconstructive plate (bottom); (d) final model of the horizontal cutting guide; (e) final model of the vertical cutting guide; (f) final model of the template for the reconstructive plate

Clinical validation results

The manufactured models served as preoperative and intraoperative aids. The complete craniofacial model acted as a visual guide, enabling physicians to assess facial asymmetry and analyze the fusion area. Separate mandibular and maxillary models were used to establish symmetry, determine the resection area, and fit the implant with the reconstruction plate. These models also facilitated preliminary surgical planning. Before surgery, the guides and templates were sterilized at 134 °C. The templates were used in the following order: the horizontal cutting template, the vertical cutting template, and finally, the plate template. Each was secured to the bone with screws to prevent any movement of the templates.

Their effectiveness and functionality were evaluated using a survey with 11 questions on a 5-point Likert scale. To summarize the results obtained:

- Highly positive feedback from physicians regarding the anatomical accuracy of the craniofacial structures.
- Models significantly improved visualization and planning of the procedure.
- High compatibility of the guides and templates with the patient's anatomy, validating the method's efficacy.
- Lower rating for the horizontal guide due to the absence of a clear reference point, complicating precise placement.
- Reduced surgery time thanks to preoperative preparation with the models.
- Positive influence of customized models on the outcome of the reconstruction, tailored to the patient's unique anatomy.
- Lower rating for guide surface quality due to residual support marks; however, the template was highly rated for smoothness and durability.

The patient quickly regained mandibular mobility and was able to eat independently the following day – a remarkable achievement fulfilling their long-standing aspiration.

The results of the additive manufacturing and preoperative planning were overall successful, with the produced models serving as invaluable tools for the medical team during the surgical process. The anatomical models accurately represented the patient's craniofacial structures, providing crucial visual aids that helped doctors assess facial symmetry and plan the procedure with greater precision. The dual printing method, which involved both the full craniofacial model and specific models for the mandible and maxilla, facilitated a deeper understanding of the patient's anatomy, which translated into more effective planning and execution of the surgery.

The time required for designing and printing the models, while varied, was largely influenced by the complexity of the anatomical features and the time required for additive manufacturing. The preoperative planning results were validated by the surgeons, who reported high satisfaction with the models' accuracy and the way they helped to visualize the procedure. This methodology significantly reduced surgery time and allowed for a more streamlined operation, which was also confirmed by the positive feedback from the medical professionals who completed the survey. In terms of clinical validation, the models proved to be highly effective both as preoperative aids and intraoperative guides. The surgical guides and the implant template were carefully tested during the surgery and showed excellent compatibility with the patient's anatomy. The guides fit securely into place, while the template for the reconstruction plate proved highly effective in positioning the implant accurately on the mandible. The sterilization of the guides and templates further enhanced their practicality in a surgical setting, ensuring they met the necessary medical standards for use in operating rooms.

While some challenges were faced, such as surface deformations on the surgical guides due to the support structures, the results were still deemed highly satisfactory by the medical team. These challenges were addressed by refining the design and printing processes, with future recommendations suggesting improvements in support structure optimization and guide base thickness. Additionally, the fine details of the model produced by the Phrozen Sonic Mighty 8K printer were crucial for capturing small anatomical features, which improved the surgical precision.

Combination of engineering expertise with medical knowledge has shown the great potential of 3D printed models in improving surgical outcomes, particularly in the field of maxillofacial surgery. The results highlight the significant role of modern medical imaging and additive manufacturing in facilitating more efficient surgeries and improving patient recovery. Despite some minor setbacks related to surface quality and support structure issues, the methodology used proved to be highly effective, with excellent feedback from the physicians. This demonstrates that 3D printed models are becoming an indispensable tool in preoperative planning and intraoperative procedures, ultimately enhancing the quality of care provided to patients.

CONCLUSIONS

In conclusion, the produced anatomical models and surgical guides significantly improved preoperative planning and intraoperative procedures in maxillofacial surgery. These models provided high anatomical accuracy, allowing for the simulation of the procedure, which contributed to better preparation for the surgeons and a deeper understanding of the patient's anatomy. Despite minor challenges related to surface quality and support structures, the overall methodology proved to be effective, with positive feedback from the medical team. The use of dual printing and reverse engineering techniques proved to be innovative and positively impacted the management of complex patient cases in maxillofacial surgery. This process could be permanently implemented in hospitals to facilitate the execution of such procedures in the future. The application of additive manufacturing in medical settings demonstrated its potential for reducing surgery time, improving outcomes, and supporting personalized patient treatment, highlighting the growing importance of these technologies in modern surgical practices.

Acknowledgements

The study was partially financed by Polish Ministry of Science and Higher Education, within a research subsidy.

REFERENCES

1. Singh HN, Agrawal S, Kuthe AM. Design of customized implants and 3D printing of symmetric and asymmetric cranial cavities. *J Mech Behav Biomed Mater* 2023; 146: 106061. https://doi.org/10.1016/j.jmbbm.2023.106061
2. Moiduddin K, Al-Ahmari A, Kindi M Al, et al. Customized porous implants by additive manufacturing for zygomatic reconstruction. *Biocybern Biomed Eng* 2016; 36: 719–730. https://doi.org/10.1016/j.bbe.2016.07.005
3. Safali S, Berk T, Makelov B, et al. The Possibilities of Personalized 3D Printed Implants—A Case Series Study. *Medicina (B Aires)* 2023; 59: 249. https://doi.org/10.3390/medicina59020249
4. Maroti P, Schlegl AT, Nagy B, et al. Additive manufacturing in limb prosthetics and orthotics: the past, present and future of 3D printing orthopedic assistive devices. Medical Additive Manufacturing: Concepts and Fundamentals 2024; 179–207. http://dx.doi.org/10.1016/B978-0-323-95383-2.00028-7
5. Boolos M, Corbin S, Herrmann A, et al. 3D printed orthotic leg brace with movement assist. Annals of 3D Printed Medicine 2022; 7: 100062. https://doi.org/10.1016/j.stlm.2022.100062
6. Leite M, Soares B, Lopes V, et al. Design for personalized medicine in orthotics and prosthetics. *Procedia CIRP* 2019; 84: 457–461. https://doi.org/10.1016/j.procir.2019.04.254
7. Thomas A, Muñecas T. A rehabilitation protocol for the use of a 3D-printed prosthetic hand in pediatrics: A case report. Journal of Hand Therapy 2023; 36: 967–973. https://doi.org/10.1016/j.jht.2022.10.010
8. Tavangarian F, Proano C. Additive Manufacturing for the Fabrication of Pylon in Lower Limb Prosthesis. Contributed Papers from MS&T17. MS&T18, 2018, pp. 852–859. https://doi.org/10.7449/2018/MST2018852859
9. Seiti M, Ginestra P. Additive Manufacturing for orthopedic applications: Case study on market impact. Procedia Comput Sci 2022; 217: 737–745. http://dx.doi.org/10.1016/j.procs.2022.12.270
10. Mobarak MH, Islam MA, Hossain N, et al. Recent advances of additive manufacturing in implant fabrication – A review. Applied Surface Science Advances 2023; 18: 100462. https://doi.org/10.1016/j.apsadv.2023.100462
11. Sheoran AJ, Kumar H, Arora PK, et al. Bio-Medical applications of Additive Manufacturing: A Review. Procedia Manuf 2020; 51: 663–670. http://dx.doi.org/10.1016/j.promfg.2020.10.093
12. Kumar R, Kumar M, Chohan JS. The role of additive manufacturing for biomedical applications: A critical review. J Manuf Process 2021; 64: 828–850. https://doi.org/10.1016/j.jmapro.2021.02.022
13. Lai J, Wang C, Wang M. 3D printing in biomedical engineering: Processes, materials, and applications. Appl Phys Rev; 8. Epub ahead of print 1 June 2021. http://dx.doi.org/10.1063/5.0024177
14. Żukowska M, Rad MA, Górski F. Additive Manufacturing of 3D Anatomical Models—Review of Processes, Materials and Applications. Materials 2023; 16: 880. https://doi.org/10.3390/ma16020880
15. Cohen A, Laviv A, Berman P, et al. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology 2009; 108: 661–666. https://doi.org/10.1016/j.tripleo.2009.05.023
16. Sharma N, Cao S, Msallem B, et al. Effects of Steam Sterilization on 3D Printed Biocompatible Resin Materials for Surgical Guides—An Accuracy Assessment Study. Journal of Clinical Medicine 2020; 9: 1506. https://doi.org/10.3390/jcm9051506
17. Bozkurt Y, Karayel E. 3D printing technology; methods, biomedical applications, future opportunities and trends. Journal of Materials Research and Technology 2021; 14: 1430–1450. https://doi.org/10.1016/j.jmrt.2021.07.050
18. Xu X, Wang H, Shen L, et al. Application and evaluation of fused deposition modeling technique in customized medical products. Int J Pharm 2023; 640: 122999. https://doi.org/10.1016/j.ijpharm.2023.122999
19. Rahim TNAT, Abdullah AM, Akil HM, et al. The improvement of mechanical and thermal

properties of polyamide 12 3D printed parts by fused deposition modelling. Express Polym Lett 2017; 11: 963–982. http://dx.doi.org/10.3144/expresspolymlett.2017.92
20. Awad A, Gaisford S, Basit AW. Fused deposition modelling: Advances in engineering and medicine. AAPS Advances in the Pharmaceutical Sciences Series. Springer Verlag, 2018; 107–132. http://dx.doi.org/10.1007/978-3-319-90755-0_6
21. Unkovskiy A, Schmidt F, Beuer F, et al. Stereolithography vs. Direct Light Processing for Rapid Manufacturing of Complete Denture Bases: An In Vitro Accuracy Analysis. J Clin Med 2021; 10: 1070. https://doi.org/10.3390/jcm10051070
22. Bajaj P, Chan V, Jeong JH, et al. 3-D biofabrication using stereolithography for biology and medicine. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS 2012; 6805–6808. https://doi.org/10.1109/embc.2012.6347557
23. Raman R, Bashir R. Stereolithographic 3D bioprinting for biomedical applications. In: Essentials of 3D Biofabrication and Translation. Elsevier Inc., 2015; 89–121. https://doi.org/10.1016/B978-0-12-800972-7.00006-2
24. Kushwaha AK, Rahman MH, Hart D, et al. Fundamentals of stereolithography: techniques, properties, and applications. In: Tribology of Additively Manufactured Materials: Fundamentals, Modeling, and Applications. Elsevier, 2022; 87–106. http://dx.doi.org/10.1016/B978-0-12-821328-5.00003-2
25. Abdulhameed O, Al-Ahmari A, Ameen W, et al. Additive manufacturing: Challenges, trends, and applications. Advances in Mechanical Engineering 2019; 11: 1-27. http://dx.doi.org/10.1177/1687814018822880
26. Ghilan A, Chiriac AP, Nita LE, et al. Trends in 3D Printing Processes for Biomedical Field: Opportunities and Challenges. J Polym Environ 2020; 28: 1345–1367. https://doi.org/10.1007/s10924-020-01722-x
27. Schneider KH, Oberoi G, Unger E, et al. Medical 3D printing with polyjet technology: effect of material type and printing orientation on printability, surface structure and cytotoxicity. 3D Print Med 2023; 9: 27. https://doi.org/10.1186/s41205-023-00190-y
28. Pan T, Zhu W, Yan C, et al. Selective laser sintering 3D printing of biomedical polymer materials. Gaofenzi Cailiao Kexue Yu Gongcheng/Polymeric Materials Science and Engineering 2016; 32: 178–183. http://dx.doi.org/10.16865/j.cnki.1000-7555.2016.03.033
29. Saffarzadeh M, Gillispie GJ, Brown P. Selective Laser Sintering (SLS) rapid protytping technology: A review of medical applications. Proceedings of the 53rd Annual Rocky Mountain Bioengineering Symposium, RMBS 2016 and 53rd International ISA Biomedical Sciences Instrumentation Symposium 2016; 142–149.
30. Riza SH, Masood SH, Rashid RAR, et al. Selective laser sintering in biomedical manufacturing. In: Metallic Biomaterials Processing and Medical Device Manufacturing. Elsevier, 2020, pp. 193–233. http://dx.doi.org/10.1016/B978-0-08-102965-7.00006-0
31. Gebhardt A, Hötter J-S. Additive Manufacturing. München, Germany: Carl Hanser Verlag GmbH & Co. KG, 2016. Epub ahead of print 2016. DOI: 10.1007/978-1-56990-583-8. http://dx.doi.org/10.1007/978-1-56990-583-8
32. Zoabi A, Redenski I, Oren D, et al. 3D Printing and Virtual Surgical Planning in Oral and Maxillofacial Surgery. Journal of Clinical Medicine 2022; 11: 2385. https://doi.org/10.3390/jcm11092385
33. Ostaș D, Almășan O, Ileșan RR, et al. Point-of-Care Virtual Surgical Planning and 3D Printing in Oral and Cranio-Maxillofacial Surgery: A Narrative Review. *J Clin Med* 2022; 11: 6625. https://doi.org/10.3390/jcm11226625
34. Louvrier A, Marty P, Barrabé A, et al. How useful is 3D printing in maxillofacial surgery? J Stomatol Oral Maxillofac Surg 2017; 118: 206–212. https://doi.org/10.1016/j.jormas.2017.07.002
35. Assari A. Usability Of Three-dimensional Printing in Maxillofacial Surgery: A Narrative Review. Open Dent J; 17. Epub ahead of print 2023. https://doi.org/10.2174/18742106-v17-e230508-2023-37
36. Yang W, Choi WS, Wong MC-M, et al. Three-Dimensionally Printed Patient-Specific Surgical Plates Increase Accuracy of Oncologic Head and Neck Reconstruction Versus Conventional Surgical Plates: A Comparative Study. Ann Surg Oncol 2021; 28: 363–375. https://doi.org/10.1245/s10434-020-08732-y
37. Yang W, Choi WS, Leung YY, et al. Three-dimensional printing of patient-specific surgical plates in head and neck reconstruction: A prospective pilot study. Oral Oncol 2018; 78: 31–36. https://doi.org/10.1016/j.oraloncology.2018.01.005
38. Abo Sharkh H, Makhoul N. In-House Surgeon-Led Virtual Surgical Planning for Maxillofacial Reconstruction. Journal of Oral and Maxillofacial Surgery 2020; 78: 651–660. https://doi.org/10.1016/j.joms.2019.11.013
39. Nyirjesy SC, Heller M, von Windheim N, et al. The role of computer aided design/computer assisted manufacturing (CAD/CAM) and 3- dimensional printing in head and neck oncologic surgery: A review and future directions. Oral Oncol 2022; 132: 105976. https://doi.org/10.1016/j.oraloncology.2022.105976
40. Hadad H, Boos Lima FB, Shirinbak I, et al. The Impact of 3D Printing on Oral and Maxillofacial Surgery. J 3D Print Med; 7. Epub ahead of print 30 June 2023. http://dx.doi.org/10.2217/3dp-2022-0025

41. Li Y, Liu H, Wang C, et al. 3D printing titanium grid scaffold facilitates osteogenesis in mandibular segmental defects. *npj* Regenerative Medicine 2023; 8: 1–11. https://doi.org/10.1038/s41536-023-00308-0
42. Zhong C, Zhao Y, Xing H, et al. Assembly of 3D-printed Ti scaffold and free vascularized fibula using a customized Ti plate for the reconstruction of mandibular defects. Biodes Manuf 2022; 5: 424–429. http://dx.doi.org/10.1007/s42242-021-00181-0
43. Lim HK, Choi YJ, Choi WC, et al. Reconstruction of maxillofacial bone defects using patient-specific long-lasting titanium implants. Scientific Reports 2022; 12: 1–12. https://doi.org/10.1038/s41598-022-11200-0
44. Fan B, Chen H, Sun YJ, et al. Clinical effects of 3-D printing-assisted personalized reconstructive surgery for blowout orbital fractures. Graefe's Archive for Clinical and Experimental Ophthalmology 2017; 255: 2051–2057. https://doi.org/10.1007/s00417-017-3766-y
45. Murray-Douglass A, Snoswell C, Winter C, et al. Three-dimensional (3D) printing for post-traumatic orbital reconstruction, a systematic review and meta-analysis. British Journal of Oral and Maxillofacial Surgery 2022; 60: 1176–1183. https://doi.org/10.1016/j.bjoms.2022.07.001
46. Weadock WJ, Heisel CJ, Kahana A, et al. Use of 3D Printed Models to Create Molds for Shaping Implants for Surgical Repair of Orbital Fractures. Acad Radiol 2020; 27: 536–542. https://doi.org/10.1016/j.acra.2019.06.023
47. Kang S, Kwon J, Ahn CJ, et al. Generation of customized orbital implant templates using 3-dimensional printing for orbital wall reconstruction. Eye 2018; 32: 1864–1870. https://doi.org/10.1038/s41433-018-0193-1