Application of Open-Source 3D Planning Software in Virtual Reconstruction of Complex Maxillofacial Defects

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ABSTRACT

Objective: To present our in-house 3D planning protocol utilizing open-source computer-aided design software and discuss specific applications in reconstruction of various craniomaxillofacial defects, demonstrating a free, accessible, efficient, accurate, and easily learnable alternative to expensive counterparts.

Methods:

Design: Case Series
Setting: Tertiary Private Training Hospital
Participants: Ten (10) patients who underwent CAD assisted reconstructive surgeries from February 2017 – May 2018.

Results: A total of 10 patients were included; 7 mandibular reconstructions were surgically reconstructed using our 3D planning protocol and achieved symmetric mandibular contour, with good functional occlusion after surgery; 1 cranioplasty and 1 orbital trauma case also achieved good symmetry and adequate correction of enophthalmos respectively. However, inadequate soft tissue correction was seen in 1 case of maxillary reconstruction despite achieving symmetric bony contour.

Conclusion: Our 3D planning protocol using open-source CAD applications is a viable alternative to expensive professional counterparts. Additional prospective studies may better demonstrate benefits in terms of accuracy and decreasing intraoperative time in craniomaxillofacial and head and neck reconstruction.

Keywords: *3D planning, computer-aided design; craniomaxillofacial reconstruction*

Functionality and aesthetics are two important aspects that remain a challenge in reconstruction of craniomaxillofacial (CMF) defects.[1,2] Over a decade, advancements in 3D

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planning aimed to address these challenges by improving efficiency and precision.[3] The 3D planning technique enables the operator to virtually inspect and manipulate a 3D object and transform it into a physical object through 3D printing. This is accomplished using computer-aided design (CAD) applications.

Proprietary or paid software dedicated for biomedical 3D designs are offered by professional companies for a fee. Such a service has demonstrated benefits in CMF reconstruction in other countries, while it remains underutilized in our country. This is due to unavailability of such a service locally, entailing additional costs and delays in surgery. On the other hand, free, open-source software are readily available for download in the internet with functions that are adapted to aid surgical reconstruction.

We present our in-house 3D planning protocol utilizing open-source CAD programs and discuss their utility in reconstruction of various craniomaxillofacial defects, thereby providing a free, accessible, efficient, accurate, and easily learnable alternative to expensive counterparts.

METHODS

With Institutional Review Board approval, this case series retrospectively reviewed patients in whom 3D planning was done using open-source CAD software, prior to surgical reconstruction of CMF defects between February 2017 and May 2018 at the University of Santo Tomas Hospital.

Patients with defects caused by neoplastic conditions (benign or malignant), trauma, and secondary defects caused by previous surgery who were candidates for surgery and CAD-assisted surgical reconstruction were all included. Patients with bilateral defects were not included since mirroring of the unaffected side (as a basis for reconstruction) could not be carried out. Data of these patients including age, gender, surgical indications, location of defect, operative time, preoperative and post-operative photo documentation, and actual 3D planning data were gathered and collated from medical records.

3D Planning Protocol using Open-Source Software

The 3D planning protocol included the 3D design of the anatomical model that would serve as guide for pre-bending of titanium implants that would be used for reconstruction. Basically, it starts from the acquisition and analysis of 3D data in the computer, up to virtual reconstruction of surgical or trauma defects. The following protocol was followed in every patient whom 3D planning was applied:

1. Data Acquisition from Digital Imaging and Communications in Medicine (DICOM) Files

For this protocol, Computed Tomography (CT) scans without contrast were used as an imaging modality in all patients since it better delineates the bony outline of involved structures. Slice thickness was not standardized among patients, however thin cuts (1-2 mm) are preferable as it translates to higher quality of the 3D reconstructed model. The CT DICOM data (used to store, exchange, and transmit medical images) was loaded in **3D slicer** *(http://www.slicer.org)*, an open-source software designed for analysis and visualization of medical images.[4] Once loaded, the images were cropped and limited to the area of interest (e.g. upper face, midface, mandible). This was followed by segmentation of the images by changing the threshold settings. Segmentation enables the user to delineate structures (e.g. bone or soft tissue) based on the parameters set. *(Figure 1)* For this protocol, only the bony structures were delineated which were then converted into a 3D object and saved as an STL file – a type of file recognized by CAD and 3D printing applications. The 2D images seen in the CT scans were now reconstructed into a 3D object which could be visualized, analyzed, and manipulated in three dimensions in a computer. These were all accomplished using 3D slicer.

2. Virtual Surgery

Virtual surgery involves the visualization, analysis of defect, resection of the involved segment (for tumors), mirroring, and virtual reconstruction. These steps were primarily done using **Meshmixer®** version 3.5 (Autodesk Inc., San Rafael, CA, USA), a free software that enables the user to redesign a 3D object or 3D mesh. The first step was to further isolate the area of interest. This step further decreased the cost of 3D printing by eliminating much of the uninvolved areas of the craniofacial skeleton. The next steps differed for each case depending on the affected craniofacial segment.

Mandible

For tumors involving the mandible, the next step was to identify the lines of resection and virtually perform a segmental mandibulectomy of the involved side. *(Figure 2)* The affected segment was highlighted and deleted. This mimics the segmental mandibulectomy during actual surgery. The next challenge was to bridge the gap caused by virtual resection. This was done by selecting the same area on the unaffected side based on bony landmarks. The selected segment was mirrored and dragged to the side of defect to bridge the gap. *(Figure 3)* These 2 parts were combined and saved as an STL file. The saved file was loaded to 3D printing software and printing was initialized.

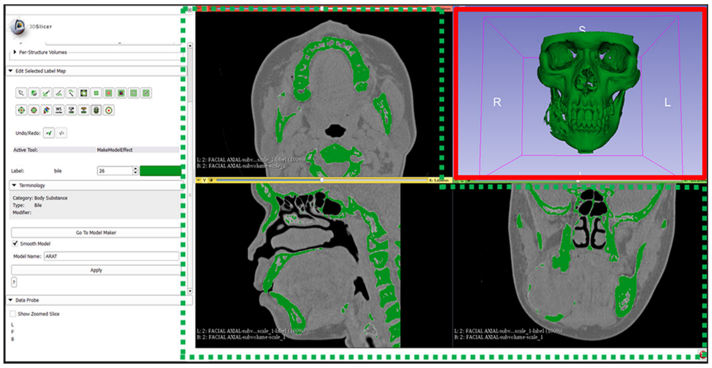

Figure 1. Segmentation (dotted outline) and conversion of axial, sagittal, and coronal 2D images into 3D model (solid outline) using a 3D slicer.

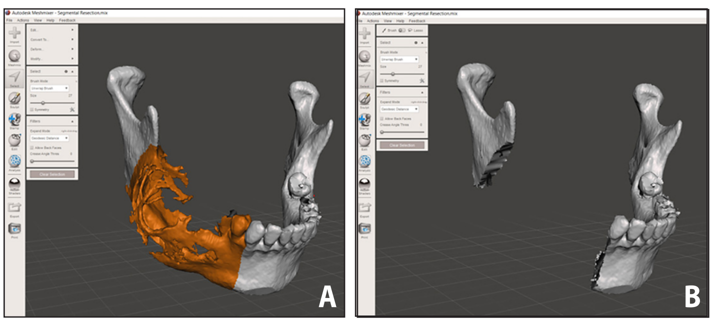

Figure 2. Virtual segmental resection of the involved side of the mandible **A.** tumor and margins; and **B.** virtual segmental resection

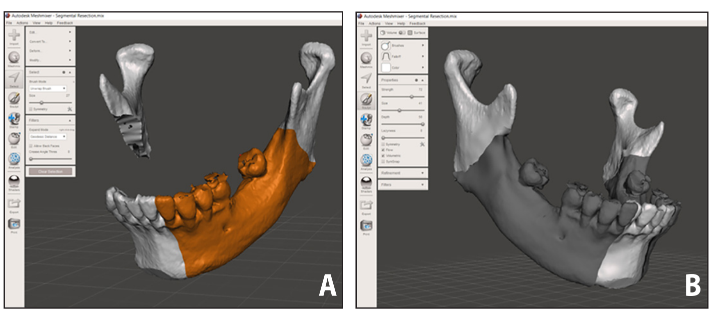

Figure 3. A. Virtual segmental mirroring of the uninvolved side **B.** to fill in the defect gap in the involved side.

Midface and Orbit

The steps for virtual reconstruction of these segments were the same as those for the mandible except for the mirroring technique. Mirroring of the midface and orbit was done by cutting the 3D model midline in its sagittal plane followed by duplicating and mirroring of the unaffected side. We noticed that this technique was not applicable to the mandible since this method disrupts its normal curvature especially when the lesion or resection extends to the anterior portion of the mandible. Segments of the midface and orbit could then be combined and loaded into the printing software.

Cranial Vault

Our protocol was used in one patient who underwent cranioplasty due to a unilateral temporoparietal defect. For this case, the initial steps were also similar to those of the other segments except that no mirroring was done. After converting into STL file, the 3D model of the cranial vault was printed as is (unreconstructed).

3. 3D Printing

Once reconstruction of the 3D object was completed, it was loaded in the 3D printing software to prepare for printing. We used the Ultimaker Cura Version 3.6 (Ultimaker B.V., Utrecht, Netherlands), a free and open-source application as our 3D printing software. The 3D printer was a Creality Ender 3 (Creality 3D Technology Co., Shenzhen, China), a fused deposition modelling (FDM) 3D printer which prints an object by adding layer by layer of melted polylactic acid (PLA) filament. Each layer has a minimum height of 0.4 mm which causes poor printing quality for bony structures less than 0.4 mm thick (e.g. medial orbital wall, orbital floor). Pre-contouring of titanium implants were made once 3D prints were available. Actual surgeries were performed using the pre-contoured implants.

RESULTS

A total of 10 patients who underwent CMF reconstruction using our in-house 3D planning protocol during the study period were included in this series. There were three males and seven females, with ages ranging from 14-62 years old (mean age, 33 years old; median age 30 years old).

The most common clinical indication for reconstruction was neoplasm resection. A total of seven patients had neoplastic conditions, of which six were benign tumors with one malignant tumor. One patient suffered orbital trauma. Other conditions included one post-surgical defect secondary to decompressive craniectomy, and one maxillary mucocele.

A total of seven patients underwent mandibulectomy; four segmental resections and three marginal resections. All four segmental resections were reconstructed using fibular osteocutaneous free flaps with titanium reconstruction plates. Mandibular defects after segmental resection were all classified as class L defects (lateral defect not crossing the contralateral central segment of the mandible) based on the classification used by Boyd.[5]

In all seven patients who underwent mandibulectomy, virtual resection and reconstruction was followed by mirroring of the uninvolved side to re-establish the normal contour of the mandible. Pre-bending of titanium reconstruction plate was done using the 3D printed anatomic model as a guide for the plate contour. The average time needed for pre-bending of titanium plates was 70 minutes.

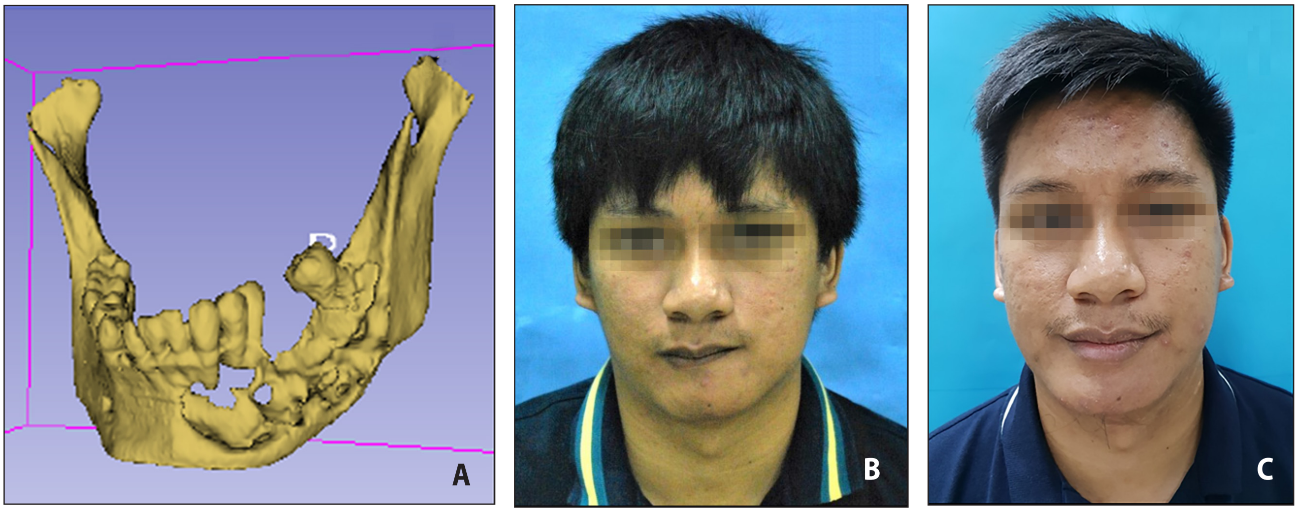

Figure 4. Representative case of a left segmental mandibulectomy reconstructed by fibular free flap with reconstruction plate **A.** shows the actual 3D planning, while **B.** and **C.** demonstrate the preoperative and 1 year post-operative photos of the patient, respectively.

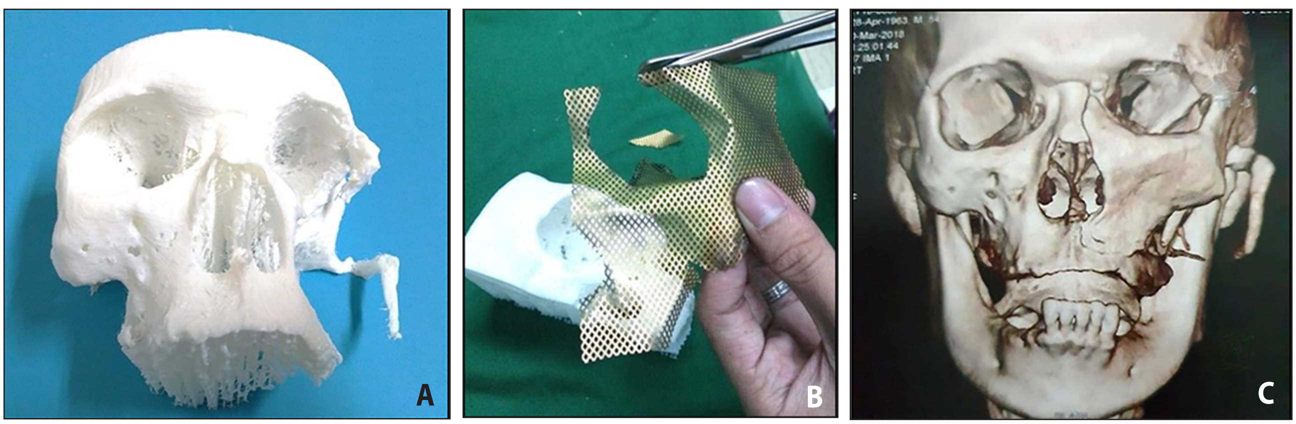

Figure 5. Case of maxillary mucocele reconstructed by titanium mesh with bone cement **A.** shows the 3D printed model demonstrating large maxillary defect, **B.** shows the preoperative shaping of titanium mesh, and **C.** shows the post-operative CT scan imaging of patient.

Intraoperatively, adjustments in reconstruction plate contour were made for the first two cases due to poor adaptation to the mandible, while only minor adjustments were needed in the succeeding cases. Among the four patients receiving a fibular free flap, operative time was decreased from 15 hours to seven hours as we also improved our technique in 3D planning. Reconstructions were all performed by a single microvascular reconstruction consultant. All patients who received mandibular reconstruction aided by 3D planning achieved symmetric mandibular contour with correct post-operative dental occlusion. No complications were observed. *Figure 4* shows a representative example of one patient who underwent segmental mandibulectomy with reconstruction using fibular free flap and pre-bent titanium reconstruction plate.

The one patient who had orbital floor and medial wall fractures secondary to a motor vehicular accident had enophthalmos of her right eye. Our 3D planning protocol was also applied resulting in adequate correction of enophthalmos. The aesthetic outcome was likewise satisfactory. For the secondary reconstruction of cranial defect secondary to decompressive craniectomy, a pre-shaped titanium mesh was used. Intraoperatively, the mesh accurately fit the defect with no additional bending required. Post-operative symmetry of the cranium was re-established.

Last was an interesting case of complex maxillary defect reconstruction. Preoperative planning showed a defect involving the entire anterior maxillary wall, including the malar prominence, leaving only a deformed zygomatic arch. The defect was caused by the compressive forces from a huge mucocele causing excessive bone loss of the midfacial area. The mirror image of the uninvolved side served as a guide for contouring the titanium mesh which was used in this case as a scaffold for the denser bone cement applied over it. Post-operative

CT scan showed adequate reconstruction of the bony structure and contour. However, we failed to consider the soft tissue contracture that was persisted post-operatively. *Figure 5* illustrates the planning and outcome of this case.

DISCUSSION

Our initial experience demonstrates the viability of our in-house 3D planning protocol utilizing open-source CAD programs and illustrates their utility in reconstruction of various craniomaxillofacial defects. They provide a free, accessible, efficient, accurate, and easily learnable alternative to expensive counterparts.

Mandibular reconstruction was the most common indication for our 3D planning protocol which was consistent with the literature review of Louvrier *et al.*[6] Other structures reconstructed include the cranium, orbit and maxilla. All achieved satisfactory functional and aesthetic outcomes except for one whose skin and soft tissue contracture remained a problem post-operatively.

Surgeries involving craniomaxillofacial structures are always a challenge because it is difficult to achieve facial symmetry especially when dealing with complex defects.[1,2] Precision is often the key to achieve symmetry but entails long and tedious surgeries. With the aid of 3D planning in surgery, surgeons are able to simultaneously achieve precision and efficiency.[6,7]

Previous studies showed that 3D planning in craniomaxillofacial surgery reduced operative time which indirectly decreased actual OR costs, duration of hospital stay, and improved patient's quality of life.[3,8] Other specific advantages include improved adaptation of reconstruction plates, decreased bone plate gap, decreased metal fatigue by reducing trial and error, aids in patient education, and serves as a teaching tool.[9] Such 3D planning has been used as a means to create 1) surgical guides, 2) patient-specific implants, 3) contour models, 4) occlusal splints, and 5) facial prosthesis.[6,10] Currently, the most advanced function of 3D planning and manufacturing is the creation of patient-specific implants.[8] An implant that is designed in the computer, with dimensions specific to the patient's defect, is printed directly using biocompatible materials.[6,8,13] However, this technology is not yet available in our local setting.

In our experience, 3D planning along with 3D printing has offered the advantages of preoperative planning of osteotomy, visualization of defect after virtual resection, and pre-contouring of reconstruction plates prior to actual surgery. It has also facilitated patient education and understanding through the use of patient-specific 3D printed anatomic models. We were able to accomplish these steps using open-source 3D applications that are widely available for download in the internet. The advantage of free applications is that many users will be able to test their functions, share their experiences, and demonstrate their own way of doing 3D design. Our team started creating virtual models by learning from video tutorials uploaded by other users, and eventually coming up with our own 3D planning protocol. Although proprietary software used by professional manufacturers may be ideal, the cost of whole 3D planning and manufacturing by such companies usually ranges from P180,000 to 300,000.[11] This is very costly for our local setting, offsetting any possible advantages. Using our own protocol, the cost may range from P500-1000 (depending on model size) when printing 3D designed models using our office-based, non-medical grade 3D printer. This offers a solution to both cost and logistic challenges that come with this technology.

Our 3D planning protocol has been applied in various craniomaxillofacial and head and neck reconstructions, most commonly in the reconstruction of mandibular defects. Reconstructing the original contour of the mandible is important and at the same time challenging since it may result in poor aesthetic and functional outcomes when inadequately corrected. In this case series, all seven mandibular reconstructions achieved satisfactory aesthetic results based on mandibular symmetry as well as good functional outcomes demonstrated by correct post-operative dental occlusion.

The average time of 70 minutes spent for pre-bending of titanium implants may be considered as the minimum time saved during surgery since the shaping of implants were already done preoperatively. However, plate contour adjustments were still made during our first two mandibular reconstructions due to poor adaptation of the pre-shaped implants to the mandible. We noticed that mirroring the whole unaffected side alters the contour and location of the condyle, hence the adjustments made during surgery. This problem was also noticed in the study of Khalifa *et al*.[12] Accuracy of the implants were improved when we changed our technique to segmental mirroring in which only the length and segment of the defect was selected and mirrored from the unaffected side causing only minor plate adjustments during surgery. Furthermore, the decreasing trend in intraoperative time seen over four consecutive cases of fibular free flap reconstruction aided by our protocol may reflect an improvement in the accurate shaping of the implants. The aforementioned problem was not experienced in other reconstructed craniofacial segments such as the orbit, maxilla and cranium.

The time spent for the entire planning including printing using our protocol was approximately 10 hours for one mandibular model. This may vary depending on the size of the 3D model being printed. In comparison, professional planning and manufacturing of these models may require four sessions of 45-minute web meetings with a biomedical engineer who does the designing, and one to two weeks production time and delivery to the USA and Europe which may take longer for our country.[7] Unlike engineers, surgeons are well-versed with the anatomy and surgical plans for the patient which may be considered advantageous when surgeons do the 3D planning themselves. This also makes web meetings unnecessary.

Despite the known advantages of an in-house 3D planning protocol, some challenges are still encountered in its use. The learning curve for 3D designing may vary depending on the computing skills of the operator who are surgeons themselves. A six-month duration and 10 cases were required to adequately learn the in-house approach for 3D planning, consistent with the experience of Numajiri *et al.*[13]

Moreover, intraoperative changes were sometimes noted that could affect the adherence of surgeons to the initial plan. Problems included sclerosis of surrounding tissues and local tissue contracture due to prior surgery, and shrinkage of tumor due to effects of preoperative chemotherapy or radiation.[13] In our experience, the actual intraoperative defect became larger compared to the preoperative 3D planning due to increase in tumor size caused by delays in surgery. This required additional, but minimal bending of the reconstruction plate.

Our protocol is currently limited to the creation of anatomic models. Functions of our currently used free software may not permit the creation of more advanced 3D models such as cutting guides or patient-specific implants. Rapid advancements in technology may soon allow users to design these models using free, and more advanced open-source CAD software.

In summary, our 3D planning protocol has been used in reconstruction of various craniomaxillofacial defects and has resulted in good surgical outcomes. The utilization of open-source CAD applications is an affordable, widely accessible, and viable alternative to expensive professional counterparts. Additional prospective studies using more objective assessments of surgical outcomes may better demonstrate these benefits.

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