Video Article

Designing CAD/CAM Surgical Guides for Maxillary Reconstruction Using an In-house Approach

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Abstract

Computer-aided design/computer-assisted manufacturing (CAD/CAM) is now being evaluated as a preparative technique for maxillofacial surgery. Because this technique is expensive and available in only limited areas of the world, we developed a novel CAD/CAM surgical guide using an in-house approach. By using the CAD software, the maxillary resection area and cutting planes and the fibular cutting planes and angles are determined. Once the resection area is decided, the necessary faces are extracted using a Boolean modifier. These superficial faces are united to fit the surface of the bones and thickened to stabilize the solids. Not only the cutting guides for the fibula and maxilla but also the location arrangement of the transferred bone segments is defined by thickening the superficial faces. The CAD design is recorded as .stl files and three-dimensionally (3-D) printed as actual surgical guides. To check the accuracy of the guides, model surgery using 3-D-printed facial and fibular models is performed. These methods may be used to assist surgeons where commercial guides are not available.

Video Link

The video component of this article can be found at https://www.jove.com/video/58015/

Introduction

The use of CAD/CAM techniques has recently increased in dental and denture work. Following this evolution of CAD/CAM, osteocutaneous flap transfers using CAD/CAM are now used in the field of mandibular reconstruction after an oncologic wide resection of malignant tumors[1,2,3]. Several companies in Western countries have begun to supply and sell a CAD/CAM cutting guide for the mandible region. A CAD/CAM reconstruction of the mandible is considered to have an advantage in terms of accuracy[4,5,6,7,8,9,10,11]. However, a disadvantage is that this technique is available in limited areas worldwide and it is very expensive[12]. Thus, CAD/CAM reconstruction for maxillary lesions has not yet become popular. The number of the cases of maxillary reconstruction is lower than that for the mandible, and commercial guides are not common.

Because commercial maxillary CAD/CAM guides are not sold in Japan, we have developed CAD/CAM surgical guides using an in-house approach. The clinical effectiveness of the CAD/CAM guides has already been reported[13,14,15,16,17,18,19], but there is no report of how to design them. The purpose of the present report is to show the CAD/CAM design method using a low-cost in-house approach.

Protocol

This study was approved by the authors' institutional review board, and written consent forms were completed by all patients.

1. Preparation of Materials

1. Use a personal computer, computed tomographic (CT) data of facial bone and fibula, conversion software such as InVesalius[20], and three-dimensional (3-D) CAD software (*e.g.*, Blender[21]).
   NOTE: A maximum thickness of 1 mm slices of CT data is recommended for an accurate design. For the actual surgical simulation, use the patient's CT data. For research, use free human 3-D data[22].
2. Use a 3-D printer[23], screws, metal plates, and a small saw, to check not only the designs but also real objects and results.
   NOTE: The present study is experimental. Metal plates, screws, and a small saw can be used for the model surgery. Instead of metal plates, plastic-fixation plates can be also printed by the 3-D printer, together with the surgical guides.

3. Transfer the imaging data of both facial bone and fibula into 3-D data (.stl format) using InVesalius[20].
NOTE: CT data is essentially recorded in the form of two-dimensional (2-D) pictures. Thus, before using the 3-D data, it is necessary to convert the data into 3-D data. Free software is sufficient for this purpose. This report does not explain how to transfer the data into a 3-D file; instructional videos and guides are available elsewhere.
4. Import each .stl file into Blender[21].
NOTE: CAD software usually accepts a .stl-style 3-D format. At first, maxillary and fibular .stl files should be opened in the specific CAD software by importing them.

2. Design

1. **Deciding on the area of bone removal and solidifying a bone defect**
    1. Decide on the area to be excised.
    NOTE: In this experimental simulation surgery, any part of the maxilla can be set as an excised area. Because reconstruction after total maxillectomy is difficult, only a small part of the maxilla will be a choice for beginners. In a clinical setting, otorhinolaryngologists will decide the area according to the cancerous region.
    2. Make a large plane and place it on the border of the area for removal in the object mode (**Figures 1a** and **1b**). Follow that by placing a second plane (**Figures 1b**-**1d**) and continue to do so until the planes surround the whole area for removal. Unite these planes in the object mode.
    3. Select the vertices of all these planes and connect them to each other by making edges and faces (**Figure 1e**) in the edit mode to surround the areas for removal.
    NOTE: The excision planes should be copied and maintained because these original planes are used and discarded when solidifying the excision. In the present study, copying every plane and solid on every occasion is recommended in order to make it possible to reuse them.
    4. Subtract the resectable solid from the facial bone using a Boolean modifier in the edit mode. This results in a shaved facial bone (**Figure 1f**), which is the maxillary defect model.

2. **Placing a fibula bone**
    1. Place a fibula into the maxillary defect area (**Figure 2a**). Place small cubes at two points (8 cm distal from the fibular head and 5 cm proximal from the lateral malleolus) in the fibula as markers (purple small cubes are shown in **Figure 2**).
    NOTE: In clinical situations, a fibula can be used between 8 cm distal from the fibular head and 5 cm proximal from the lateral malleolus. By this marking, we can easily understand the areas that can be used.
    2. Link small cubes to the fibula as a parent setting in the object mode.
    3. Place small cubes as markers in several points in the maxillary lesion where reconstruction is necessary. With this marking, the visibility of the necessary reproduction points is increased.
    4. Fit the fibula to the front margin of the alveolar bone in the object mode, if the fibula is placed from the midline.
    5. Use the previous plane of the midline maxillary osteotomy as a first fibular osteotomy plane (**Figure 2b**).
    6. Place a new osteotomy plane where appropriate in the object mode (**Figure 2c**). Link this new plane to the fibula as a parent setting.
    NOTE: By setting the parent to the fibula, the relative orientation between this new osteotomy plane and the fibula is always maintained even if the fibula is moved into different places. The area of the fibula that is surrounded by these two cutting planes becomes the first fibular block.
    7. Copy the fibula and two planes of osteotomy as a parent setting in the object mode. Move this copied fibula, which has the first block area with two cutting planes on both ends, to the second area where reconstruction is necessary (**Figure 2e**) to plan the second fibula block.
    8. Place the second cutting plane by adding a new plane in the object mode.
    NOTE: The first and second cutting plane will become the ends of the second fibula block. If a third block is necessary, similar procedures are added. The appropriate length of the gaps between the adjacent fibular blocks should be maintained.
    NOTE: The gap between the first and second block is considered to be key to having a comfortable osteotomy. If this gap is wide, the osteotomy will be easy because of the wide working space, but the vascular length is somewhat wasted. By contrast, if the gap is narrow, osteotomy becomes troublesome, but the second or third block can be designed by eliminating the waste of the unused bone.

3. **Designing the fibular cutting guides**
    1. Visualize only the fibula and cutting planes for designing the fibula cutting guide in the object mode (**Figure 3a**).
    2. Make each cutting plane smaller to occupy only half the area of the fibula cutting section by sliding vertexes along the edges (**Figures 3b**-**3d**) in the edit mode.
    NOTE: The fitting side of the cutting guide is the lateral aspect of the fibula. Because the feeding vessels are located in the medial aspect, the guide is not designed in the medial aspect.
    3. Unite two planes of the ends to build a solid in the object mode (**Figures 4a**-**4e**). Select the vertexes of all these planes and connect them to each other by making edges and faces in the edit mode to form a rectangular solid.
    4. Subtract the fibula from this rectangular solid by using a Boolean modifier (**Figures 5a**-**5c**).
    NOTE: The surface of this subtraction completely fits the fibular lateral aspect. The same procedures are repeated in every necessary fibular block.
    5. Unite each subtracted solid in the object mode.
    6. Place a cube near the subtracted solids (**Figure 5d**). Extrude faces to make pillars (**Figures 5e**-**5g**). Unite these pillars to the subtracted solids. This is the fibular cutting guide (**Figures 5h**-**5j**).

4. **Osteotomy cutting guide for the maxilla**
NOTE: To cut the maxilla, it is not necessary to design the guide for every cutting surface, because only limited areas are to be reconstructed using the fibula. Usually, two cutting guides, which cover the medial alveolar and lateral zygomatic areas, are designed.

1. Prepare the maxillary and zygomatic planes that were the original remaining surface after the maxillary removal. A margin of 1 cm in width is sufficient (**Figure 6a**).
2. Extrude the faces prepared in step 2.4.1 to thicken the plane and to solidify them in the edit mode using the solidify modifier (**Figure 6b**).
3. Delete the thickened solid over the resection planes, which were decided in step 2.1, on both ends; this is how the maxillary cutting guides are designed.
NOTE: If the fitting surface is jagged, a smaller fitting area is sufficient. If the fitting surface is apt to be flat, a large area is needed to avoid any slippage of the guide.

5. **Fixation guide for the fibular segments**
NOTE: Fibular segments that are to be transferred to the maxilla are considered to be accurate in size and length, but the location of the transfer can deviate freely if the fixation guide is not used. The fibula and each cutting plane (as made in step 2.2) are used again in this segment.
    1. Construct each fibular block in the Boolean modifier by taking out the intersection area between the fibula and the solid with cutting planes on both ends (**Figures 7a** and **7b**) in the edit mode.
    2. Extract half of the superficial surface of each fibular block.
    3. Unite all of these surfaces in the object mode (**Figure 7c**).
    4. Delete small faces in the edit mode by using a knife cut (**Figure 8a**) to secure the spaces for fitting the metal plates.
    5. Thicken the surface by using a solidifying modifier in the edit mode (**Figures 8b**-**8e**).
    NOTE: A minimum 2–3 mm of thickness is necessary to stabilize the fixation guide and avoid warping. If the wing is designed on both ends, it will help the guide to the maxilla without using any metal plates.

3. 3-D Printing for Model Surgery and Real Guides

NOTE: The main purpose of this report is to show the method of designing surgical guides; the procedure described below is not necessary if 3-D printing is not needed.

1. Export the designs of the guides in .stl format, which can be 3-D printed.
2. Print all guides and bones.
NOTE: In printing, rafts are considered to disturb smooth surface printing and lead to a jagged surface and poor fit to the bone, so the plane that needs to be smooth must be pointed upward.
3. **Perform the model surgery as follows:**
    1. Similar to actual surgery, fit the maxillary cutting guide to the facial bone model first (**Figure 9a**). Then, cut the facial bone along with the cutting plane using a saw.
    2. Attach the fibular cutting guide to the fibular bone model and cut it into pieces (**Figure 9b**). Attach the fibular blocks to the fixation guide (**Figures 9c** and **9d**).
    3. Fix this fixation guide complex to the maxillary defect using screws and plates (**Figure 9e**). After fixing the fibular segments to the maxilla in the area where the fixation guide does not attach by using screws and plates, remove the fixation guide. This completes the reconstruction (**Figure 9f**).

4. Scan the 3-D-reconstructed image and record it in .stl format using a 3-D scanner[24].
5. Compare the post-model surgery .stl file and the CAD reconstructed design (**Figure 10**) using comparison software[25].
NOTE: By comparing the virtual reconstruction design and the guided reconstruction model, actual accuracy is calculated. Because CAD/CAM accuracy is obtained within a 2.5 mm deviation in the mandibular reconstruction[10], a similar precision should be required in this method. If the required accuracy cannot be obtained, redo the virtual design.

Representative Results

Using the procedure presented here, the resection area was determined first. Using CAD software, the resection area was completely circumscribed by the faces. This area was subtracted from the facial bone by a Boolean operation. The fibula image was placed on the defect, and fibular cutting faces were placed in the appropriate reconstructed points. All fibular cutting faces were linked to the fibula in a parent setting. These faces were made smaller and were united to make solids. The fibula was subtracted from these solids and then became the fibular cutting guides. The remaining surfaces of the facial bone were also thickened; these became the maxillary cutting guides. The superficial sides of the fibular segments are united and extracted to become a fixation guide. Finally, the fibular cutting guide, the maxillary cutting guide, and the fibular fixation guide were designed in Blender. These designs of the guides were exported in .stl format. They became real plastic objects by 3-D printing (**Figures 9a** and **9b**).

Model surgery was performed (**Figures 9c**-**9f**). A maxillary cutting guide and fibular cutting guide were completely fitted to the facial bone and fibular bone models. Cutting the models with a saw and fixing the results with titanium plates and screws were also done. After the fixation, a 3-D-reconstructed image was determined by the 3-D scanner[24]. The post-model surgery .stl file and the CAD reconstructed design were compared in terms of accuracy of the guides and procedures using comparison software[25]. The data from the model surgery are shown in **Figure 10**; the reconstruction can be performed approximately within a 2 mm deviation.

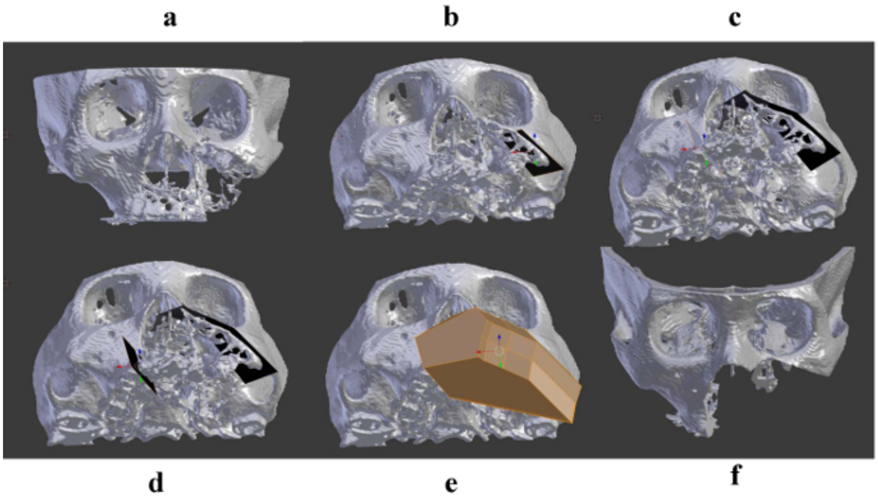

Figure 1: Deciding on the area of maxillary resection. (**a**) The original facial bone .stl file is imported to Blender. (**b**) The first cutting plane is inserted in the zygomatic lesion. (**c**) The next cutting plane is placed. (**d**) The cutting plane of the alveolar area is also set. (**e**) The cutting planes must be united and surround the excision area completely. (**f**) By using a Boolean modifier, the maxillectomy area is subtracted from the facial bone. Please click here to view a larger version of this figure.

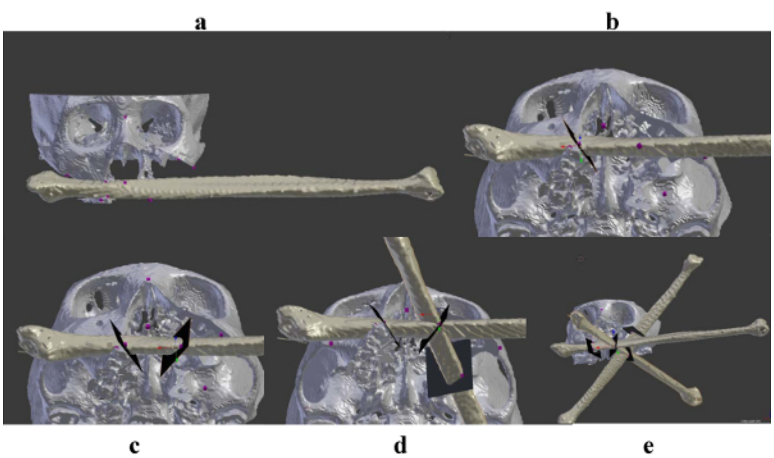

Figure 2: Planning the location of the fibular segments. (**a**) The fibular .stl file is imported to Blender. The distal portion of the fibula is placed in the alveolar area first. (**b**) The cutting plane is copied and linked to the fibula as a parent setting. (**c**) According to the preference of the planning surgeon, the next cutting plane is placed on the fibula. The fibular area that is sandwiched between these two planes becomes the first necessary fibular segment. (**d**) To determine the location of the next fibular segment, the copied fibula is placed. The next cutting planes are also placed according to the judgment of the surgeon. (**e**) Finally, three fibular blocks are designed, as in this example. Please click here to view a larger version of this figure.

Figure 3: Sliding the vertex along the edge. (**a**) Three pairs of the cutting planes are linked to the fibula as a parent setting. (**b**-**d**) To obtain an appropriate guide design, the vertex of the plane is moved along the edge in the edit mode. Please click here to view a larger version of this figure.

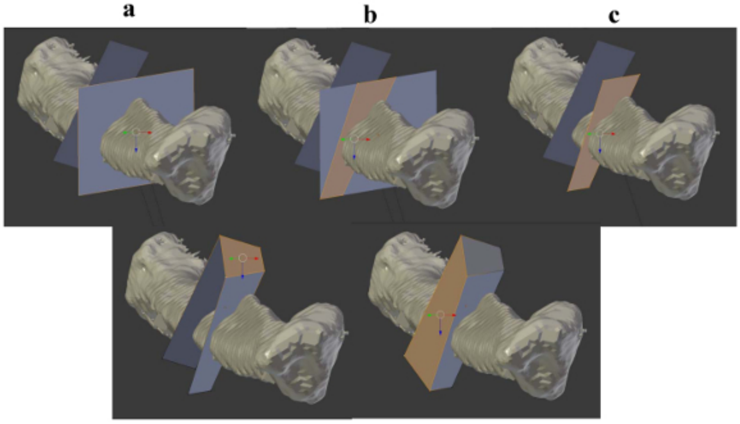

Figure 4: Designing the box for preparation to make the fibular cutting guide. (**a**) This cutting plane is going to be reduced in size to become an appropriate cutting guide size. (**b**) The final size of the cutting plane is highlighted. (**c**) The cutting plane is determined by sliding the vertex along the edge, similarly to **Figure 3**. (**d**) Both cutting planes are united by adding the new plane in the object mode. (**e**) Finally, the planes are added to surround the whole surface in the edit mode. Please click here to view a larger version of this figure.

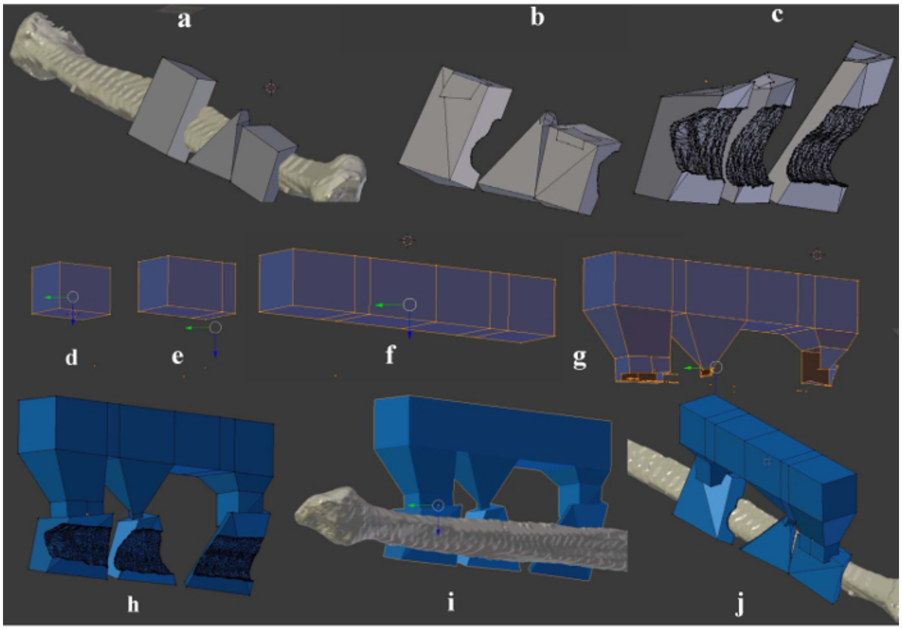

Figure 5: Making the fibular cutting guide. (**a**) Using the procedures shown in **Figure 4**, three boxes are designed. (**b**) Each box is shared by the fibula using the subtraction of a Boolean modifier. (**c**) The opposite surface of each box is completely the same as the fibular surface. (**d**) To make pillars, a cube is placed near the subtracted solids. (**e**) A face of this cube is extruded. (**f**) By repeating this extrude, the main pillar is made. (**g**) By adding other pillars, attachments to the subtracted solids are made. (**h**) The pillar and the subtracted solids are united. (**i** and **j**) This cutting guide completely fits to the surface of the fibula. Each edge becomes the cutting plane, which guides the cutting saw. Please click here to view a larger version of this figure.

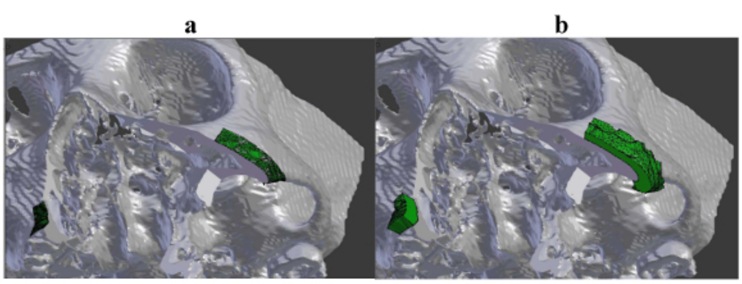

Figure 6: Designing the maxillary cutting guide. (**a**) The remaining surfaces of the maxilla and the zygoma are prepared just adjacent to the cutting area. (**b**) These planes are thickened to construct the solid to fit to the zygomatic and maxillary bones, using a solidifying modifier in the edit mode. The edge of this solid becomes the bone saw cutting plane. Please click here to view a larger version of this figure.

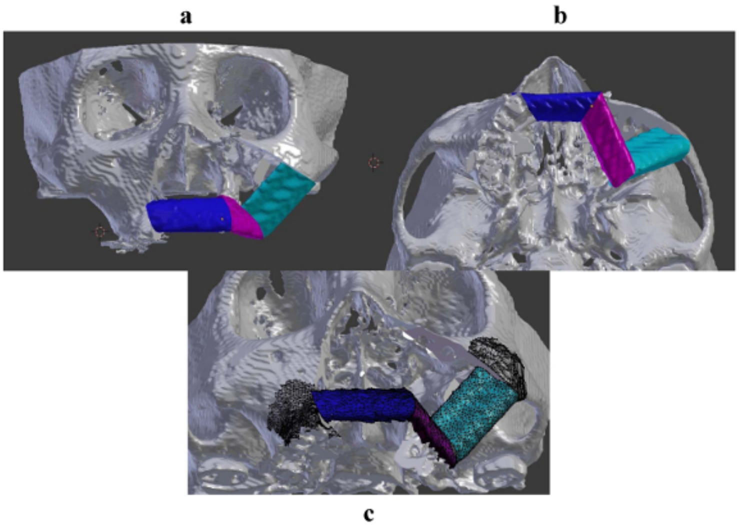

Figure 7: Taking out the transfer plane. (**a**) Each fibular segment is separated using the intersection of a Boolean modifier. (**b**) In this case, alveolar reconstruction is given priority over the zygomatic prominence. (**c**) Every superficial face is collected and united to prepare for the construction of the fixation guide. Please click here to view a larger version of this figure.

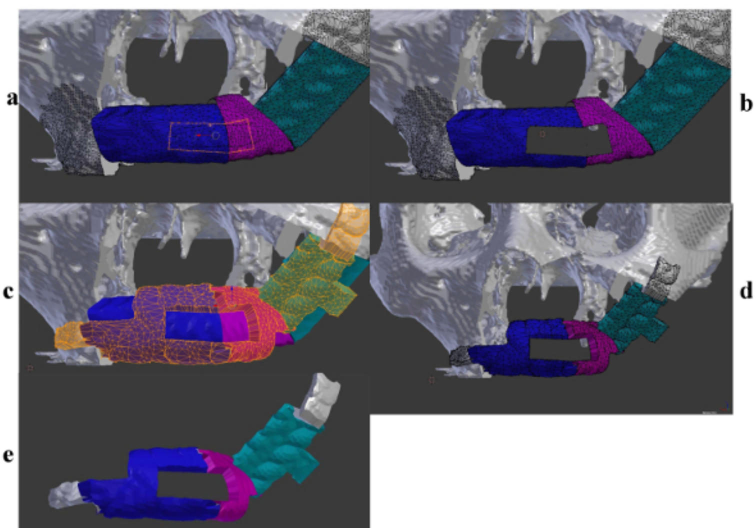

Figure 8: Designing the fixation guide of the fibular segments. (**a**) Using a knife tool, the lines are designed to the superficial surface. (**b**) A small window is made by deleting the vertices and faces. This window is used for the titanium plate fixation. (**c**) After making several windows, the superficial surface is thickened using a solidifying modifier. (**d** and **e**) Only the fixation guide is visualized. On both ends, the wings are added to fix this guide to the remaining facial bone. Please click here to view a larger version of this figure.

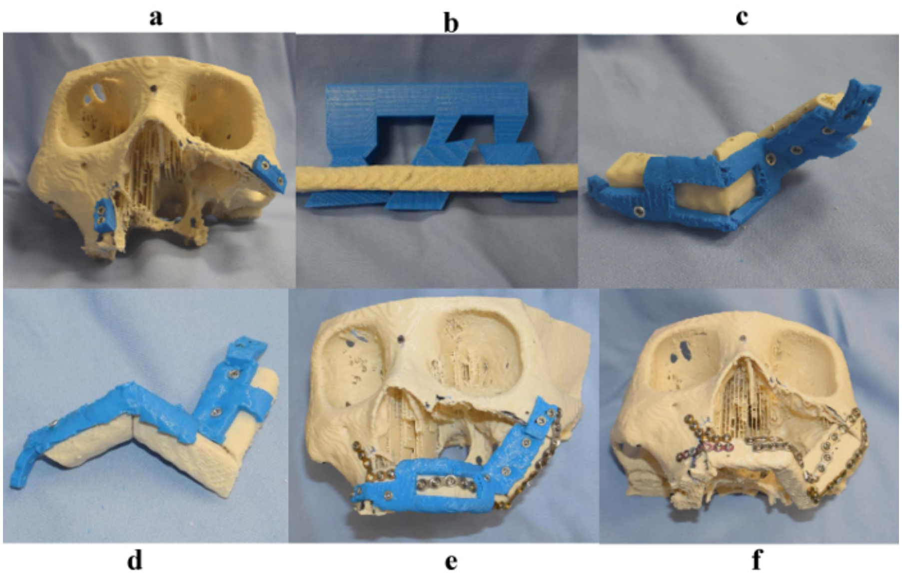

Figure 9: Model surgery. (**a**) Using a 3-D printer, the facial bone, fibular bone, and surgical guides can be realized. (**b**) The cutting guide is examined to fit to the fibula completely. (**c** and **d**) The fibular segments that were cut by using the cutting guide are set to the fixation guide. The fixation guide can completely fit to the cut segments. (**e** and **f**) Using the titanium plates and screws, fibular segments are transferred to the maxilla. After removing the fixation guide, additional plates and screws are added for a stronger fixation. Please click here to view a larger version of this figure.

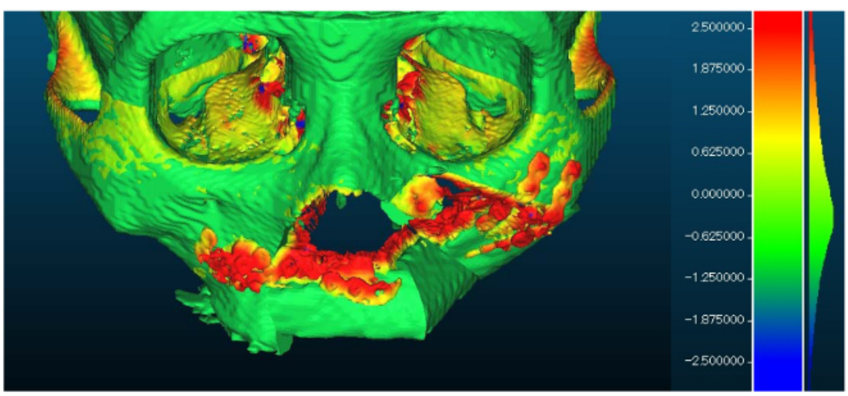

Figure 10: Comparing the model to the plan. The post-surgery model is 3-D scanned and compared to the virtual plan. The scale (millimeter) shows the deviation distance from the virtual plan. The transferred bones mostly have a low deviation (green), while the metal fixation plates have a higher deviation (red). However, the deviation is largely below 2 mm. This image is different from the sample shown in **Figure 9**. Please click here to view a larger version of this figure.

Discussion

CAD/CAM reconstruction is considered to contribute to the attainment of an accurate osteotomy length, width, and angle in cutting bones while using cutting guides[4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19]. The transferred arrangements of the bones are also considered to be accurate using a fixation guide[11]. Because the order, process, cutting plane, and arrangement plan are already decided upon before the actual surgery, time-saving is another advantage[2,12,13,14].

Moreover, in addition to these theoretical advantages, a strength of the CAD/CAM technique is that because of the surgical guides, any surgeon can cut in the same place in the same way, thus standardizing the technique. If the guides are very accurate, it is possible that every surgeon can obtain accurate reconstruction results rather than using a free-hand approach where results are rather dependent on expertise. Because this CAD/CAM technique has emerged quite recently, reports similar to this are few. Commercial guides are available in Western countries; however, design methods are not open to the public. As this design method is new, we expect it to be developed and spread widely in the future.

This in-house CAD/CAM approach does not always demonstrate superiority. One clinical problem is that this technique becomes useless when the CT exam data is not made of thin and fine slices or is obtained just before the surgery, and the surgeon either does not decide on the resection area quickly or suddenly changes the resection area intra-operatively.

A design-making problem is that, if the designer does not have sufficient experience to see and learn the surgical procedure, an appropriate surgical guide design cannot be obtained. After all, in that situation, the designer does not know what exact space the actual surgeon would make in order to be free of objects in every surgical situation.

As a cost problem, a 3-D printer is necessary for a beginner designer to create trial-and-error designs to materialize the actual guides. After becoming a well-experienced designer, the materialization of the design is no longer indispensable. Luckily, computers and 3-D printers are becoming cheaper, which means we can design and manufacture surgical guides independently without having to rely on the services of expensive companies. A disadvantage is that we cannot yet 3-D print the metal plates used for the fixation. Plastic is the main material we can use for 3-D printing. Thus, we must pre-bend the metal plates before the surgery. As inexpensive 3-D printers that can handle metals are expected to come into use in the future, fixation plates may also be designed then, and all procedures will be less dependent on free-hand techniques.

Fused deposition modeling (FDM) is one of the most used 3-D printing technologies. 3-D objects are built by extruding thermoplastic polymers through a nozzle. When the thermoplastic materials get cold, internal stresses may generate deformations (warping)[26]. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the predominant plastics used for thermoplastic filaments. Petropolis *et al.*[7] mentioned that, because ABS mandible models are particularly prone to warping, ABS plastics are less ideal for surgical models when compared with PLA. Both ABS and PLA plastics are gas sterilizable and sufficiently rigid to serve as a template[27]. Compared with ABS, PLA is less flexible with a lower melting temperature. Thus, we used PLA and a low-temperature plasma sterilization method under 45 °C in a clinical situation. Because the glass temperature of the PLA we used is 60 °C, we did not use either autoclave sterilization (approximately 121 °C) or ethylene gas oxide sterilization (approximately 60 °C).

Warping deformation remains a possibility. However, previous reports validated the accuracy of FDM-printed models in the field of maxillofacial surgery[28]. Several articles used a comparative study of the dry human mandible and FDM-printed replica using scanned CT data. These studies showed that consumer-grade FDM-printed models have an acceptable accuracy, similar to the results of industrial selective laser sintering (SLS) printers[27,29,30]. Nizam *et al.*[1] argued that the quality of the CT scan is also one of the main determinants of dimensional errors, alongside the rapid prototype machine.

Even if the precise guides are designed virtually, the printed guides sometimes do not fit the pre-operative surgical bone models. We considered there to be two reasons for this.

1. The superficial bony shape of the area where the guide is designed to be attached is too flat to be hooked (especially maxilla). If these surfaces are smooth and not uneven, the guide surface is prone to become slippery and has a possibility of mis-fitting to the wrong bony area. To avoid this situation, the attached area should be designed wider and broader to catch the exact bony area. At the same time, if the attached area becomes larger, the undermined area becomes larger, which results in a wider scar.

2. On the other hand, the plastic surgical guide is also difficult to fit if the shape of this surface is too uneven and complicated. Because a rough surface with many small processes of the CAD/CAM guides induces friction resistance when attached to the bone, overly winded and complicated guide surfaces are also prone to mis-fit to the wrong place. To avoid these situations, trial-and-error printing and model surgery prior to the actual surgery are necessary. As a result, outsourcing the 3-D printing is not recommended.

Finally, even if the guide was able to fit in the model surgery, when it does not fit in clinical situations, it should be considered to be a kind of reference guide. This is similar to when commercial guides do not fit. Final decisions in real surgery should be made based upon the recognition of occlusion and facial aesthetics by the surgeon, not by the guide.

Although the apparent cost seems to be cheaper using the in-house CAD/CAM approach than commercial approaches, the real cost, which includes the surgeon's voluntary work and the time for designing and printing, is always underestimated or neglected. However, even if commercial guides become cheaper, this in-house approach still has a unique advantage, which is that surgeons can directly and easily perform trial-and-error reconstructions in a virtual simulation and realize the location relationship between the facial bone and the fibular segments.

The design of guides is limited to hard tissue such as the bone in this report. However, surgical guides can be designed for soft tissue cutting and fixing such as fat or muscle tissues. Guides are considered to be applicable in surgeries for the purpose of performing 3-D structural reconstruction using soft tissues. Fixation guides will soon be designed for breast reconstructions after cancer ablative surgery in a best-fit reshaping of the transferred adipose tissue from the abdomen to the breast.

In conclusion, by using an in-house approach, CAD/CAM surgical guides can be designed and printed at a hospital. In addition to using an accurate reconstruction by CAD/CAM, these techniques can also be used by surgeons who live outside regions where commercial guides are available. This technique is an option for maxillary reconstructions.

Disclosures

The authors have nothing to declare.

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