Virtual Transplantation in Designing a Facial Prosthesis for Extensive Maxillofacial Defects that Cross the Facial Midline Using Computer-Assisted Technology

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Purpose: The aim of this article was to demonstrate a novel approach to designing facial prostheses using the transplantation concept and computer-assisted technology for extensive, large, maxillofacial defects that cross the facial midline. ***Materials and Methods:*** The three-dimensional (3D) facial surface images of a patient and his relative were reconstructed using data obtained through optical scanning. Based on these images, the corresponding portion of the relative's face was transplanted to the patient's where the defect was located, which could not be rehabilitated using mirror projection, to design the virtual facial prosthesis without the eye. A 3D model of an artificial eye that mimicked the patient's remaining one was developed, transplanted, and fit onto the virtual prosthesis. A personalized retention structure for the artificial eye was designed on the virtual facial prosthesis. The wax prosthesis was manufactured through rapid prototyping, and the definitive silicone prosthesis was completed. ***Results:*** The size, shape, and cosmetic appearance of the prosthesis were satisfactory and matched the defect area well. The patient's facial appearance was recovered perfectly with the prosthesis, as determined through clinical evaluation. ***Conclusion:*** The optical 3D imaging and computer-aided design/computer-assisted manufacturing system used in this study can design and fabricate facial prostheses more precisely than conventional manual sculpturing techniques. The discomfort generally associated with such conventional methods was decreased greatly. The virtual transplantation used to design the facial prosthesis for the maxillofacial defect, which crossed the facial midline, and the development of the retention structure for the eye were both feasible. *Int J Prosthodont 2010;23:513–520.*

Maxillofacial defects secondary to the treatment of neoplasms, congenital malformations, and trauma can result in multiple physiologic and psychologic obstructions and require restoration in all patients.[1] Prosthetic rehabilitation and surgical reconstruction are the two main methods used to treat these defects.[2–7] In some patients, especially those with extensive maxillofacial defects including the maxilla, nose, upper lip, cheek, and orbital content, surgical reconstruction may be an extreme challenge, and the administration of immunodepressants following an allograft operation can result in complications. Therefore, a highly realistic prosthetic rehabilitation, an alternative to surgery, may be the best option to elevate quality of life.

In recent years, as a result of the development of computer technology, many studies have focused on the design and manufacturing of facial prostheses using computer-aided design (CAD) and rapid prototyping (RP) technologies. In such studies, a three-dimensional (3D) image of the surface of a patient's face was reconstructed. The normal portion of interest was mirrored on the defective side, and the design of the facial prosthesis was completed using the mirrored image.[8,9] Then, the wax pattern of the facial prosthesis was processed through RP technology.[8–13] With these methods, the precision and efficacy in processing facial prostheses have been greatly improved.

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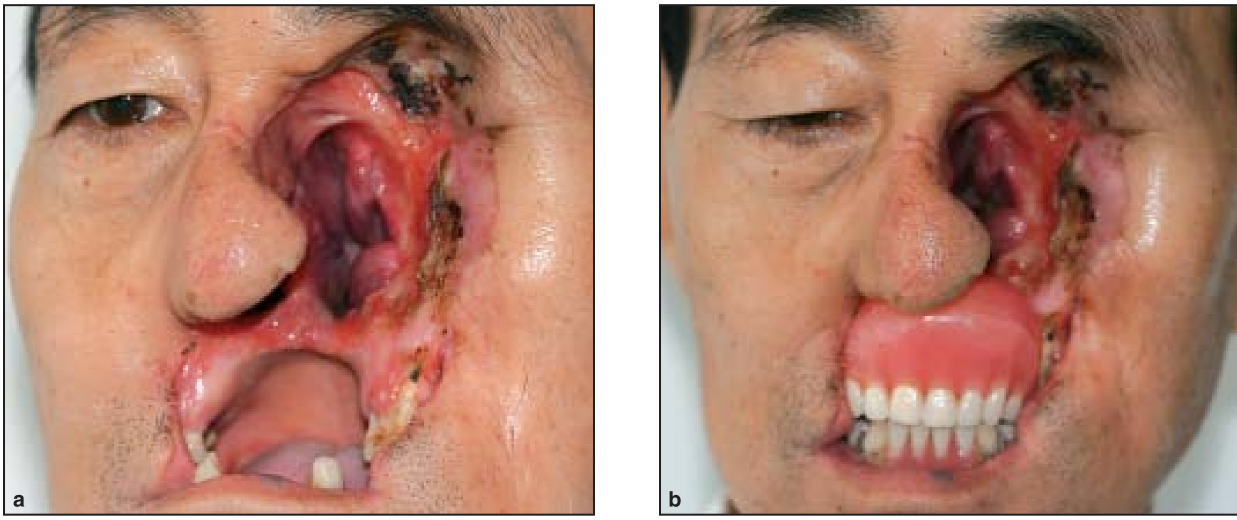


Fig 1 A middle-aged man with an extensive combined maxillofacial defect after excision of a neurofibrosarcoma involving the left orbital content, part of the nose and left cheek, the entire upper lip, and anterior maxilla. **(a)** Before and **(b)** after restoration with a removable obturator for the anterior maxillary defect.

Unfortunately, some maxillofacial defects are extensive and cross the facial midline. In such instances, after mirror projection of the healthy side using the method mentioned previously, the portion crossing the facial midline cannot be rehabilitated. Meanwhile, when the eye and orbital tissue are involved, the mirrored portion does not include an eye that can be used to design a facial prosthesis. To resolve these problems, an alternative approach to designing a facial prosthesis to restore an extensive maxillofacial defect crossing the facial midline was investigated. In addition, an eye retention structure that fit the facial prosthesis was designed using CAD technology, aided by the conception of an allograft and artificial material transplantation.

Materials and Methods

All procedures were in accordance with the ethical standards of the Committee on Human Experimentation of the Fourth Military Medical University, and the research involving the scanning of the patient's face using a 3D sensing system was approved by the ethics committee.

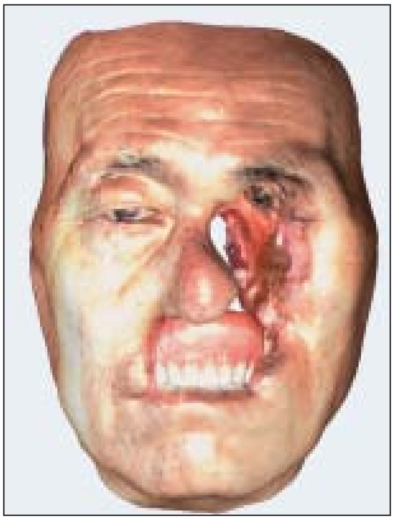
The patient in this study suffered from extensive maxillofacial defects resulting from tumor excision. The defects involved the left eye and orbital tissue, a portion of the nose and left cheek, the majority of the upper lip (except for the portion close to the angle of the mouth), and the anterior maxilla, which crossed the facial midline. Before designing the facial prosthesis, the missing maxilla and teeth were restored with a removable obturator (Fig 1). There was no interaction between the obturator and the facial prosthesis to protect the remaining maxillary teeth.

Reconstruction of the Patient's Facial Surface

The acquisition of data corresponding to the patient's facial surface was performed in a point cloud format with a 3D sensing system II (3DSS, Shanghai Digital Manufacturing). Before scanning, the patient was asked to sit up straight and maintain a natural facial expression, keeping the remaining eye open naturally and the presence of orthophoria when the patient looked straight ahead. The measuring system was initialized and calibrated according to the manufacturer's recommendation. To avoid invisible areas created by the scanning perspective, anterior left and right 45-degree measurements were performed. The 3D point cloud data of the facial surface were transmitted to a personal computer and saved in ASCII format. The original 3D facial image of the patient was generated by merging the two perspective data sets and saved in .STL format using the Geomagic Studio 10.0 software (Geomagic Software) (Fig 2).

Designing the Facial Prosthesis

In existing methods for designing facial prostheses with computer-aided technology, the original 3D facial image is mirrored, or the selected area of interest



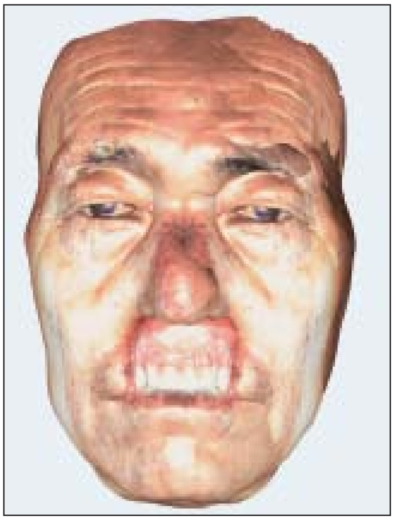
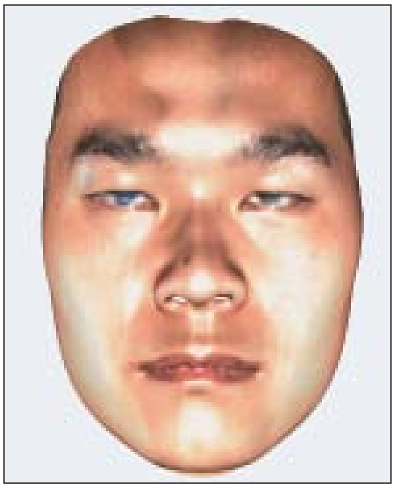


Fig 2 *(left)* The original 3D facial image of the patient generated by merging 3D point cloud data.

Fig 3 *(right)* Overlapped original facial image and mirrored image. The defect involving the left orbital area and cheek and part of the nose could be rehabilitated using the mirrored image, but the defect area crossing the midline (upper lip) still remained defective, as well as the missing eye.



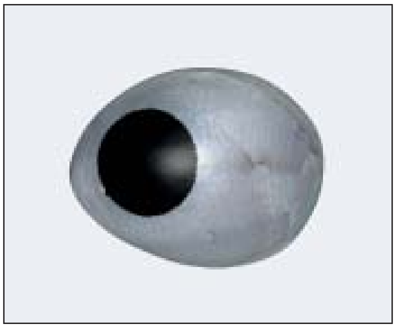


Fig 4 *(left)* Three-dimensional facial image of the patient's son, whose facial appearance was similar.

Fig 5 *(right)* Three-dimensional model of a personalized artificial eye that mimicked the remaining eye of the patient.

on the contralateral healthy side is mirrored to the defect side using the facial midline as the axis of symmetry. The defect area can then be rehabilitated through modifying the mirrored image. However, in this patient, after mirroring the image, the upper lip defect, which crossed the midline, remained defective, and none of the normal area of the patient's own facial image could be used for rehabilitation. Meanwhile, the missing eye could not be obtained through mirroring the remaining one. This was because only the surface between the upper and lower eyelids of the remaining eye could be scanned by projecting visible structured light onto the patient's face, and thus, this could not be used to fabricate an artificial eye to help design the facial prosthesis (Fig 3). To resolve these problems, an allograft and artificial material transplantation were used.

The 3D facial image of the patient's son (the donor) was generated using the same method. A prefabricated artificial eye was selected and scanned, and the point cloud data of every surface were obtained and transmitted into the Geomagic Studio software to generate the 3D model (Figs 4 and 5).

The patient's original facial image was mirrored using the facial midline as the axis of symmetry. Then, the original and mirrored images were overlapped to obtain a compound double-image. The donor's facial image was overlapped with the compound double-image to generate a compound trebling image. Using the compound trebling image, the donor's facial image was made transparent, and the desired graft area was selected and separated according to the remaining defective portion (Fig 6).

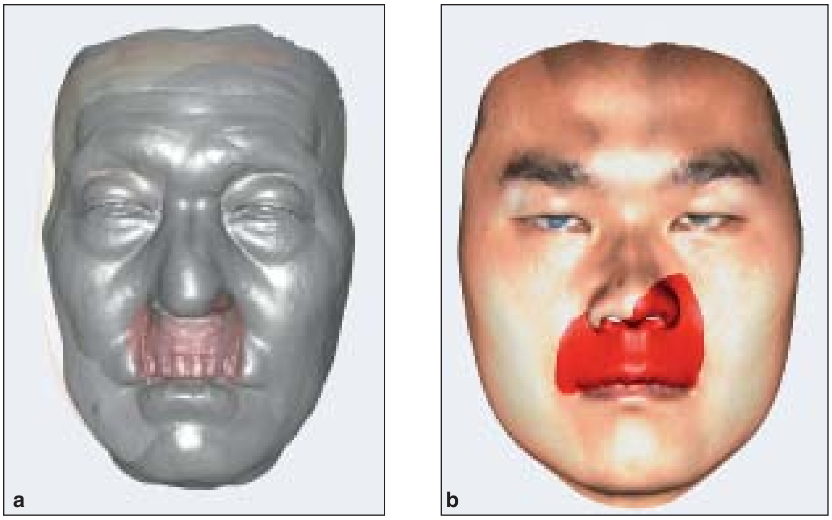


Fig 6 **(a)** The overlapped images (original and mirrored facial images of the patient and facial image of the donor) in which the donor's facial image was transparent. **(b)** The graft to be used for the defect area of the upper lip was determined on the transparent donor's facial image *(red).*

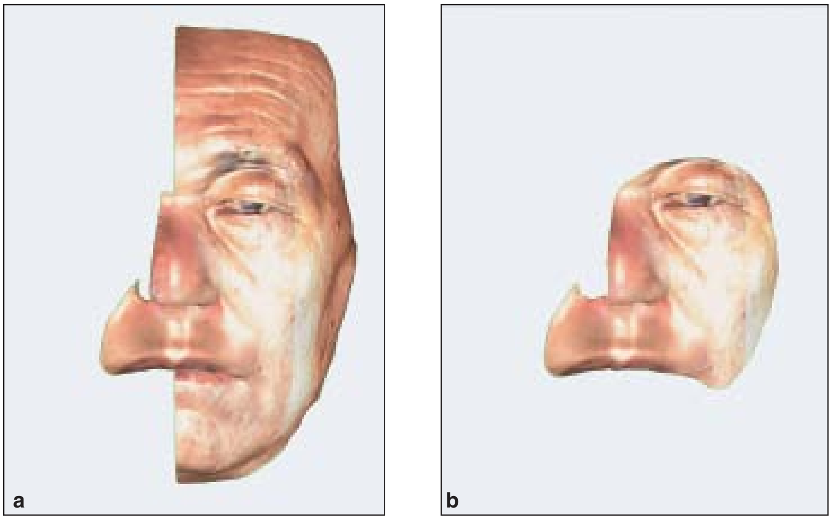


Fig 7 The merged image of the grafted portion and the patient's mirrored image without the eye **(a)** before and **(b)** after the unwanted portion was removed.

The separated graft portion was transferred onto the overlapped compound double-image composed of the original and mirrored patient facial images. The position, size, and shape of the grafted portion were modified as needed. The patient was also allowed input via suggestions or expectations for the prosthesis as the operator designed it using the computer. After modification, the grafted portion was merged together with the mirrored image. The two merged portions were repositioned on the original image, and after removing the unwanted area, the preliminary virtual facial prosthesis, without the eye, was obtained (Fig 7).

The 3D model of the selected artificial eye was fit within the provisional virtual prosthesis, and the resulting combination was reset to the original facial image. The left-right, superoinferior, or anteroposterior views of the 3D model of the selected artificial eye were revised according to those of the remaining eye (Fig 8). The patient also added his own suggestions.

The anterior surface of the 3D model of the selected eye was extracted as a curved surface, which was enlarged to 0.1 mm externally. The enlarged curved surface was shelled to a 2-mm thickness on the outside to obtain a body model that matched the eye completely so that it could be positioned as a retention structure. The virtual retention structure and provisional facial prosthesis were merged to obtain the definitive virtual facial prosthesis (Fig 9).

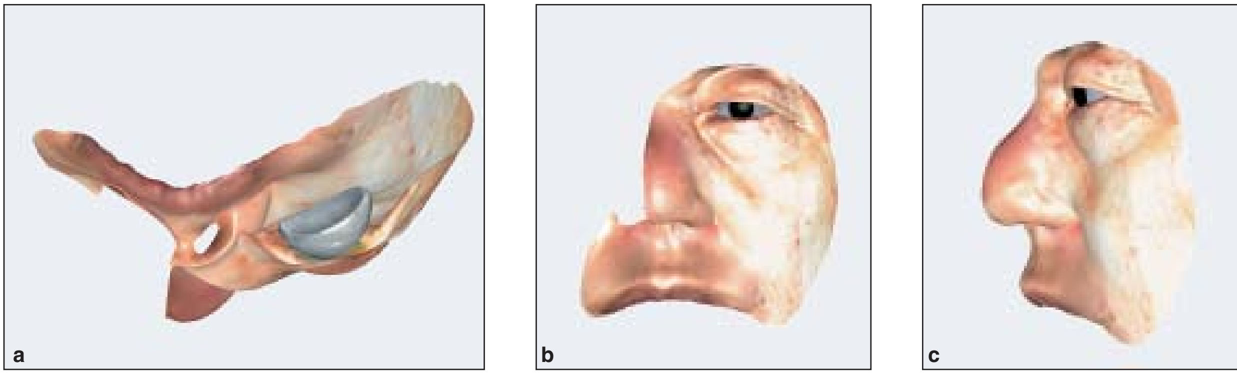


Fig 8 **(a)** Superoinferior, **(b)** anterior, and **(c)** left-right views of the artificial eye fit onto the preliminary facial prosthesis.

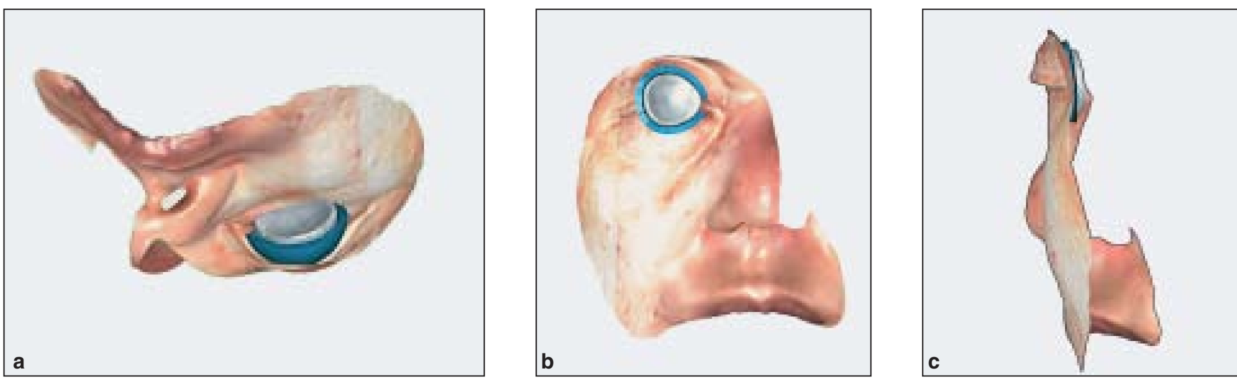


Fig 9 **(a)** Superoinferior, **(b)** anterior, and **(c)** left-right views of the retention structure *(blue)* for the eye, which matched the eye completely and held it in position.

Manufacturing the Definitive Facial Prosthesis

The definitive virtual facial prosthesis was transmitted into the host computer of an AFS-360 laser rapid prototyping machine (Beijing Longyuan Automated Fabrication System). The physical prosthesis, based on the reduced image, was processed using PSB resin oatmeal (Beijing Longyuan Automated Fabrication System), replacing the stone master cast obtained using the conventional impression technique. The definitive virtual facial prosthesis was processed into a wax pattern with WAX-100 composite wax powder (Beijing Longyuan Automated Fabrication System).

The selected artificial eye was positioned and attached to its retention structure using base plate wax (Shanghai Medical Instruments), and the position of eye was again revised according to the condition of the patient. After the patient tried the wax prosthesis, it was sealed onto the reduced facial physical cast (Fig 10). It is possible for some special characteristics, such as texture, wart, or nevus, to be finished manually in the wax prosthesis. The definitive silicone prosthesis was achieved using routine procedures and MDX4-4210 silicone (Factor II) and then applied to the patient (Fig 11). Sufficient retention was obtained using a prosthetic adhesive (Daro Adhesive Extra Strength, Factor II).

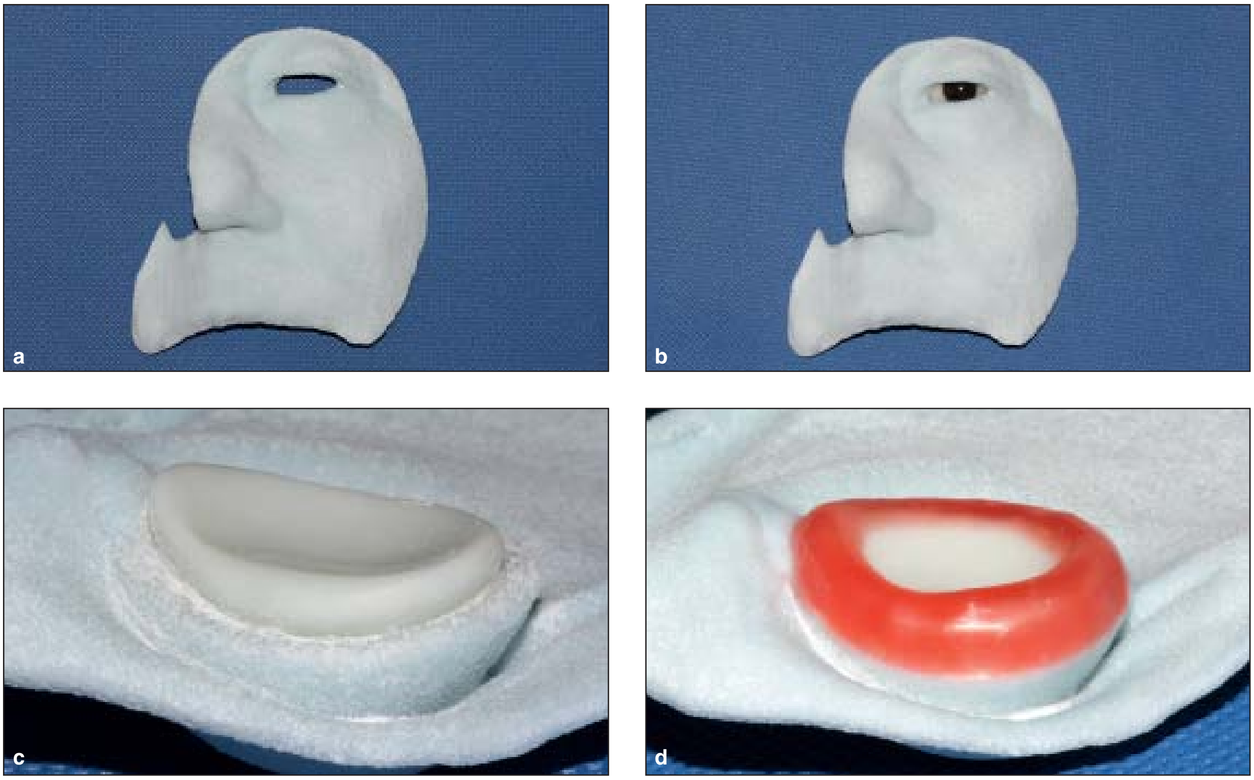


Fig 10 Wax facial prosthesis **(a)** before and **(b)** after placement of the selected artificial eye, manufactured using RP technology. **(c)** Posterior view of the wax prosthesis showing the retention structure and the selected eye. **(d)** The eye was easily sealed into the retention structure using base plate wax.

Fig 11 Definitive silicone facial prosthesis applied to the patient. The size, visual impression, and cosmetic appearance of the prosthesis were satisfactory both to the patient and clinicians. The patent almost fully regained his original appearance.

Results

The defect area crossed facial midline, which could not be rehabilitated through only the mirrored image and was restored using the virtual transplantation technique. The grafted portion was modified easily according to the patient's original facial characteristics and was merged with the mirrored image to finish the design of the prosthesis. The position of the artificial eye was revised objectively in the virtual situation. The retention structure allowed for simple and precise attachment of the eye to the wax prosthesis. The prosthesis matched the defect area well, and the size, visual impression, and cosmetic appearance of the prosthesis were satisfactory for both the patient and clinicians. The patent's appearance was almost fully recovered and his quality of life was greatly improved. Because of the remaining upper lip close to the angle of the mouth, salivary leakage was successfully avoided.

Discussion

For some patients, there is great apprehension toward any surgery after tumor resection. Radiotherapy results in a compromised condition of the local tissue, and surgical reconstruction of maxillofacial defects is improper. Surgical reconstruction of the eye has not yet been developed. Therefore, if the eye is involved, such as in this patient, the rehabilitation of the eye needs to occur in the form of a prosthesis. With regard to ethics, change in facial appearance after autologous or allogenic tissue reconstruction could affect the patient's quality of life psychologically. Long-term administration of immunodepressants after allogenic tissue transplantation can cause complications. Therefore, a highly realistic prosthetic rehabilitation, an alternative to surgery, may be the best option to elevate the quality of life of a patient who suffers from extensive combined maxillofacial defects.

The conventional method to generate a facial prosthesis (applying alginate or silicone material to the patient's face) is mostly dependant on the technician's artistic ability to produce the wax pattern, which is complicated and time-consuming. Also, the conventional impression technique may deform the soft tissue because of the pressure resulting from these materials and can ultimately cause patient suffering.[14–17]

Optical scanning using the 3DSS system as described is a noncontact and nonlaser method and does not expose the patient to the radiation that computed tomography and magnetic resonance imaging do. Optical scanning with 3DSS also does not cause discomfort or distortion of the facial soft tissue compared to the conventional impression technique, which has been used widely to obtain 3D data of the facial surface of patients with maxillofacial defects. The 3D image generated from surface data can be used to design the desired orbital, auricular, nasal, or other facial prosthesis using the Geomagic Studio software. It is designed to handle the most demanding reverse engineering, product design, and RP challenges. Geomagic Studio transforms 3D scanned data and polygon meshes into accurate 3D digital models, which are a perfect complement to the CAD tools and outputs of industry standard formats, including STL, IGES, STEP, and native CAD files.

However, up until recently, studies have designed facial prostheses using the mirror projection technique for facial defects not crossing the facial midline, and the prosthesis can be obtained through modifying the mirrored image. No reports have described a method to design prostheses for patients with extensive combined maxillofacial defects crossing the facial midline, especially the design of an artificial eye using computer-assisted technology.

In the current patient, the defect crossed the facial midline, and the missing eye could not be rehabilitated through the mirrored image. The virtual transplantation method used in this study resolved this problem perfectly. In view of ethical principles and to avoid psychologic rejection, a relative whose facial appearance mimicked the patient was recruited as the donor. The donor's facial image was made transparent on the compilation of the three overlapped images (original and mirrored facial images of the patient and the facial image of the donor). The donor site could then be selected precisely based on the range of the defect. The grafted portion was revised, cut, and merged repeatedly and optionally in a virtual environment, in accordance with the patient's need for designing a satisfactory prosthesis.

When processing a facial prosthesis using the conventional technique, the location of the artificial eye in the prosthesis is dependant mostly on subjective judgment and the experience of the technician. Even if some distances, such as that from the pupil to the facial midline and from the pupil to the upper eyelid, have been measured to assist in locating the eye, results obtained through direct measurements are not always precise. For this patient, the distance from the pupil to the facial midline could not be measured by penetrating the nasal dorsum, so it was simply an estimated value. Furthermore, any slight movement of the patient or technician during measurement would result in inaccuracies. Therefore, the 3D model of the selected personalized artificial eye was transplanted onto the prosthesis in the virtual environment, and the distances mentioned previously were used to locate the eye so that it could be measured objectively and precisely using the "Measure 3D Distance" function of the Geomagic software. Moreover, obtaining the revised position of the eye in the virtual environment was concise and simpler than that of the conventional method. To achieve the foregoing precise measurements, it was important that the patient maintained a natural facial expression and the presence of orthophoria when looking straight ahead, without opening or closing the eye when scanning.

Because there are only two matched surfaces between the wax prosthesis and the eye, the eye can move easily along the corresponding surface of the prosthesis. Accordingly, it is important to determine how to transmit the precise virtual location onto the RP wax prosthesis. In this study, the external surface of the eye was extracted, enlarged to 0.1 mm outward, and was shelled to a 2-mm thickness to be converted into a stereolithographic model, which was used as the retention structure. Because the extracted external surface was the same size as the eye, it was enlarged outward or the eye would not have been located in the retention structure. After RP manufacturing, the retention structure was converted into a solid unit together with the prosthesis, and the selected eye was placed using base plate wax.

Conclusion

Virtual transplantation is an easy method to design prostheses for maxillofacial defects crossing the facial midline. However, the management of point cloud data to generate the facial image, the merging of several images, and the development of the thin edge of the prosthesis still proposed some difficulties to the clinician. For some aspects, such as the processing of double eyelids and the dermal ridge, the technician's help was essential. In the future, a database composed of 3D facial images could be created, which could provide a reference if needed. A deformed appearance resulting from trauma or excision of neoplasms could then be returned as closely as possible to the original appearance to improve the quality of life.

Acknowledgments

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