Best Face Forward: Virtual Modeling and Custom Device Fabrication to Optimize Craniofacial Vascularized Composite Allotransplantation

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Summary: Craniofacial vascularized composite allotransplantation is especially challenging when bony components are required. Matching the complex three-dimensional anatomy of the donor and recipient craniofacial skeletons to optimize bony contact and dental occlusion is a time-consuming step in the operating room. Currently, few tools exist to facilitate this process. The authors describe the development of a virtual planning protocol and patient-specific device design to efficiently match the donor and recipient skeletal elements in craniofacial vascularized composite allotransplantation. The protocol was validated in a cadaveric transplant. This innovative planning method allows a "snap-fit" reconstruction using custom surgical guides while maintaining facial height and width and functional occlusion. Postoperative overlay technology in the virtual environment provides an objective outcome analysis. (*Plast. Reconstr. Surg.* 131: 64, 2013.)

With increasing numbers of craniofacial vascularized composite allotransplantation procedures performed, the scientific focus has shifted from the clinical feasibility to optimizing technical points and functional outcomes.[1] Traditional two-dimensional templates and stereolithographic models of the recipient defect have been used for preoperative planning. The donor harvest routinely includes more bone than is needed in the recipient. This approach requires significant intraoperative adjustments and "eyeballing" to achieve a satisfactory fit between the donor and recipient skeletal segments and occlusal components. To increase predictability in the planning and execution of craniofacial vascularized composite allotransplantation, we have developed a virtual surgical planning protocol that uses custom fabricated surgical tools to precisely match the recipient defect with the donor skeleton. This innovative method optimizes bony contact and occlusal relationships, resulting in a "snap-fit" reconstruction. Furthermore, postoperative overlay technology in the virtual environment provides an objective means for outcome analysis.

Table 1. Intermolar and Facial Width Measurements for the Donor and Recipients in Both the Virtual and Cadaver Models

	Virtual Donor (mm)	Virtual Recipient (mm)	Cadaver Donor (mm)	Cadaver Recipient (mm)
Intermolar (mesiobuccal cusp), mm	52.8	48.4	53.5	50.9
Interzygomatic, mm	81.5	82.8	94.0	97.9

MATERIALS AND METHODS

After institutional review board approval, a "donor" and "recipient" were selected with similar

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(<5-mm difference) intermolar and interzygomatic widths (Table 1). Craniofacial computed tomographic data were rendered in three dimensions within the simulated surgical environment where they could be manipulated freely during the virtual transplant procedure. A multidisciplinary team of craniofacial surgeons, microsurgeons, orthodontists, and computer engineers (Medical Modeling, Inc., Golden, Colo.) collaborated during the Web-based conference, with the

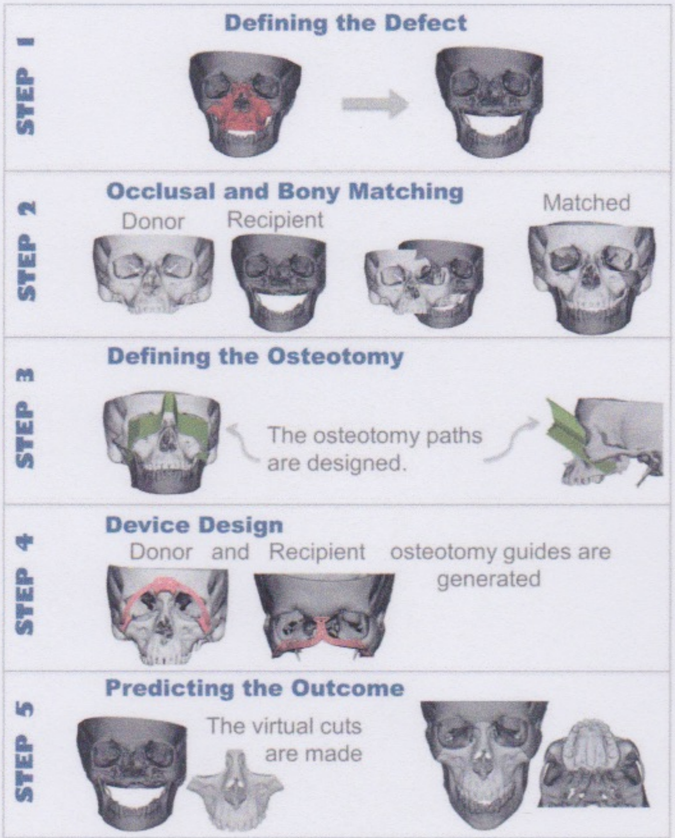


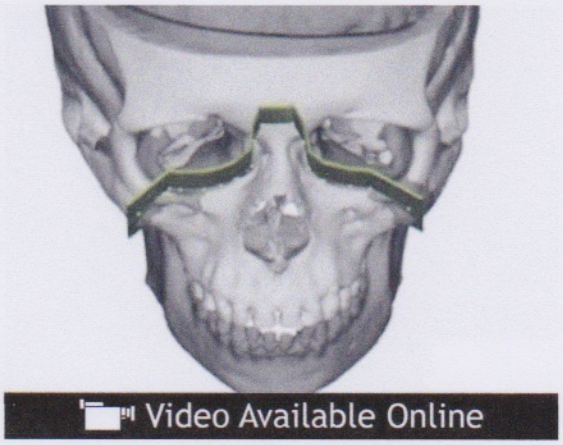
Fig. 1. (*Above*) In step 1, craniofacial computed tomographic data were rendered in three dimensions within the simulated surgical environment and a facial defect was defined. (*Second row*) In step 2, the craniofacial skeletons of the "donor" and "recipient" patients were superimposed in the virtual environment. The donor maxillary arch and recipient mandibular arch were positioned to create a centric occlusion with maximum intercuspation at the premolar and molar regions. Minor positional and rotational adjustments were then made to correct any discrepancies in the dental midlines and occlusal cant. The final position of the facial skeletons was then locked into place based on this occlusion. (*Third row*) In step 3, the overlay of the donor and recipient skeletons in the virtual environment identified the osteotomy sites, which will result in optimal bony fit and alignment. (*Fourth row*) In step 4, the virtual cutting guides were designed based on the planned osteotomies. (*Below*) In step 5, the osteotomies were made and the transplant was completed in the virtual environment. The resultant hybrid image demonstrated precise bony fit and alignment. (These steps are illustrated in detail in **Videos, Supplemental Digital Content 1 through 3, *http://links.lww.com/PRS/A627*, *http://links.lww.com/PRS/A628***, and ***http://links.lww.com/PRS/A629***, respectively.)

main goals being determination of the amount of recipient débridement, paths of osteotomies, skeletal alignment, dental occlusion, and feasibility of device design. Two sessions lasting between 1 and 2 hours each were required to finalize the virtual plan. Patient-specific dental splints, débridement guides, and osteotomy guides were fabricated using rapid prototyping technology based on an additive cross-sectional manufacturing to render the virtual models in polymethyl methacrylate. The virtual transplant was then validated in fresh cadaver specimens. Final outcomes of bone position, skeletal contact, restoration of the craniofacial buttresses, and dental occlusion were evaluated quantitatively by performing a volumetric overlay analysis of the postoperative cadaver computed tomographic scan and the preoperative virtual plan.

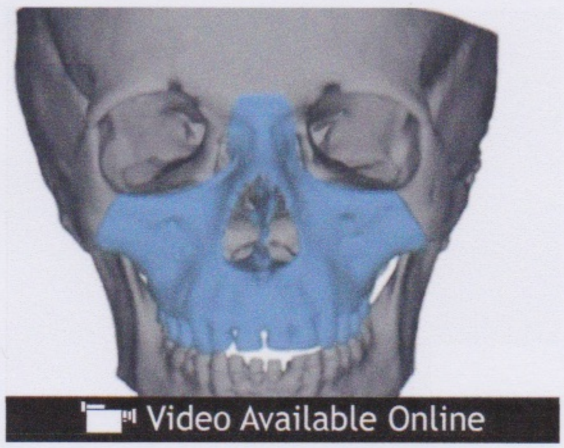
RESULTS

We expanded our current use of virtual surgical planning technology from oncologic and posttraumatic reconstruction to craniofacial vascularized composite allotransplantation by performing a simulated facial transplant on virtual patients (Fig. 1).[2–6] "Recipient" craniofacial computed tomographic data were rendered in three dimensions within the simulated surgical environment and a facial defect was defined (Fig. 1, *above*, step 1). The craniofacial skeletons of donors and recipients were superimposed in the virtual environment (Fig. 1, *second row*, step 2). (**See Video, Supplemental Digital Content 1,** which shows the craniofacial skeletons of donor and recipient superimposed, ***http://links.lww.com/PRS/A627***. The final position of the superimposed three-dimensional reconstructions is determined by creating a functional occlusion.) The final position of the superimposed skeletons was determined by creating a centric occlusion with maximum intercuspation of the premolars and molars, which was registered using a virtual dental splint. The osteotomy paths were then designed in areas of skeletal overlap to optimize bony alignment and contact (Fig. 1, *third row*, step 3). (**See Video, Supplemental Digital Content 2,** which shows the osteotomy paths, designed to optimize bony alignment and contact, ***http://links.lww.com/PRS/A628***.) Virtual cutting guides were generated based on the planned osteotomies (Fig. 1, *fourth row*, step 4). The virtual osteotomies were

Video 1. Supplemental Digital Content 1 shows the craniofacial skeletons of donor and recipient superimposed, ***http://links.lww.com/PRS/A627***. The final position of the superimposed three-dimensional reconstructions is determined by creating a functional occlusion.



Video 2. Supplemental Digital Content 2 shows the osteotomy paths, designed to optimize bony alignment and contact, ***http://links.lww.com/PRS/A628***.



Video 3. Supplemental Digital Content 3 hich shows the resultant hybrid craniofacial skeleton, with excellent bony alignment and contact, ***http://links.lww.com/PRS/A629***.

made and the transplant was completed in the computer environment. The resultant hybrid craniofacial skeleton demonstrated precise bony alignment and contact (Fig. 1, *below*, step 5). (**See Video, Supplemental Digital Content 3,** which shows the resultant hybrid craniofacial skeleton, with excellent bony alignment and contact, ***http://links.lww.com/PRS/A629.***)

Based on this experience, we developed a transplant protocol and virtually designed custom surgical osteotomy guides in anticipation of a cadaver transplant. Using rapid prototyping technology, we rendered the virtual osteotomy guides in polymethyl methacrylate to validate the protocol in a set of fresh cadaver specimens (Fig. 2). The débridement guide produced an optimally shaped defect to fit with the planned donor graft, and the procurement guide produced a complementary composite tissue allograft to fit into the recipient facial defect (Fig. 3, *above*). Precise fit of the donor and recipient tissues was achieved based on the establishment of a centric occlusion using a dental

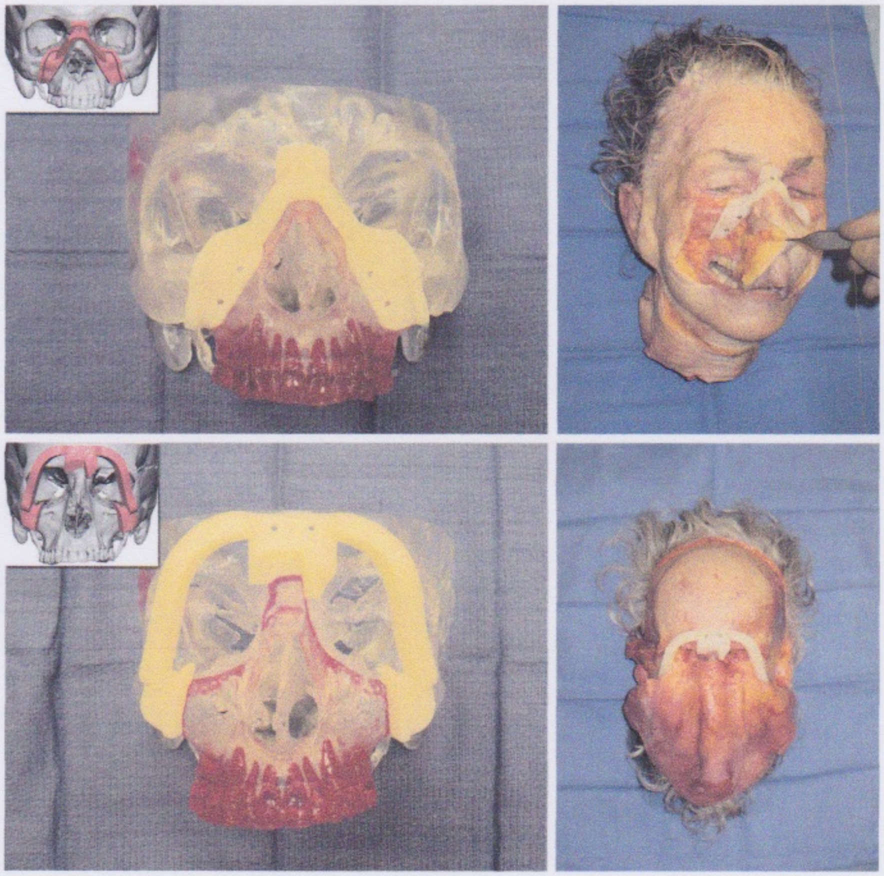


Fig. 2. (*Left*) Matching virtual surgical osteotomy guides were developed in anticipation of a cadaver transplant to precisely débride and define the facial defect in the recipient patient (*above*) and to facilitate precise facial allograft procurement from the donor (*below*). Using rapid prototyping technology, we rendered these virtual surgical osteotomy guides in polymethyl methacrylate to validate the experiment in a set of fresh cadaver specimens. (*Right*) The face transplant is performed in the cadaver model. In this example, the recipient defect is created using lateral cheek and subciliary incisions for exposure. The débridement guide (*above*) is placed inside the facial defect to define its limits. The donor harvest is exposed by means of a coronal incision extending preauricularly on the face and into a visor incision across the neck. Neurovascular bundles are identified and isolated. Subperiosteal dissection is performed from lateral to medial up to the point of the planned osteotomies. The procurement guide (*below*) is placed around the facial flap to include the essential components.

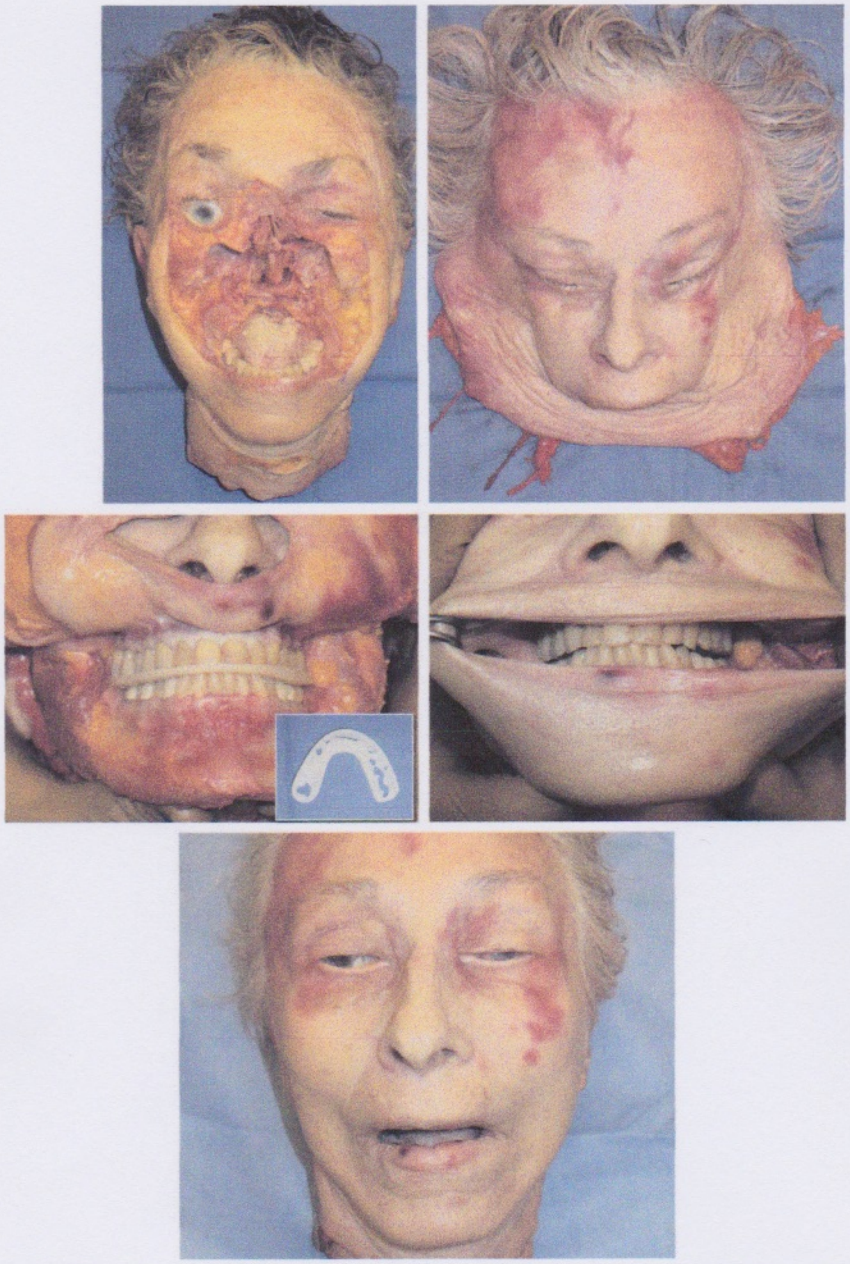
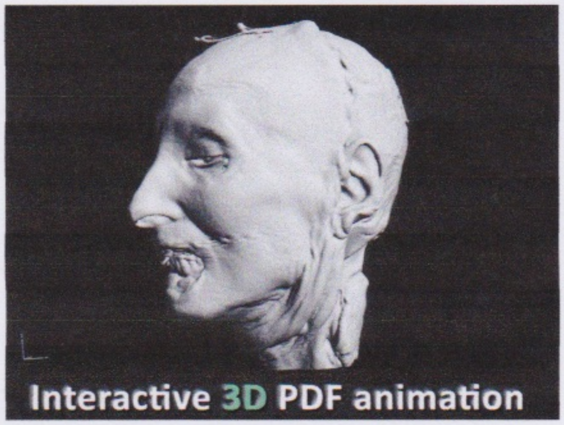


Fig. 3. (*Above*) The débridement guide produced an optimally shaped recipient defect (*left*) to fit with the planned donor graft, and the procurement guide produced a composite tissue allograft (*right*) optimally shaped to fit into the recipient patient's facial defect. (*Center*) Precise fit of the donor and recipient tissues was established based on occlusion using a dental splint produced by rapid prototyping as based on the virtual plan (*left*). A centric dental occlusion is present following the transplant (*right*). (*Below*) The resulting hybrid physiognomy combined characteristics of the donor and recipient.

splint produced by rapid prototyping (Fig. 3, *center*). The donor and recipient craniofacial skeletons were fixated using titanium plates and screws along the craniofacial buttresses. After the cadaveric face transplant, the resulting physiognomy combined characteristics of the donor and recipient and produced a centric dental occlusion (Fig. 3, *below*). High-resolution computed tomographic scanning of the hybrid cadaver confirmed precise bone apposition at the osteotomy sites (Fig. 4, *left*). Overlay analysis demonstrated that the virtual plan and computed tomographic scan of the hybrid cadaver were within 5mm of each other (Fig. 4, *right*). The final reconstruction can be manipulated and analyzed in the three-dimensional surgical environment to assess the surgical outcome. (**See Three-Dimensional Model, Supplemental Digital Content 4,** which shows a three-dimensional interactive model used to manipulate and analyze the surgical outcome in the simulated surgical environment, ***http://links.lww.com/PRS/A630.*** This format is portable, can be broadly distributed, and features the basic controls of the three-dimensional surgical environment.) Comparison between the preoperative, virtual plan, and postoperative images showed maintained position of the condylar head in the temporomandibular joint. (**See Figure, Supplemental Digital Content 5,** which shows a comparison between the preoperative (*left*), virtual planned procedure (*center*), and postoperative (*right*) images, showing maintained condylar position in the temporomandibular joint, ***http://links.lww.com/PRS/A637.***)



Three-Dimensional Model. Supplemental Digital Content 4 shows a three-dimensional interactive model used to manipulate and analyze the surgical outcome in the simulated surgical environment, ***http://links.lww.com/PRS/A630***. This format is portable, can be broadly distributed, and features the basic controls of the three-dimensional surgical environment.

DISCUSSION

Three-dimensional virtual surgical planning has become a paradigm shift in craniofacial reconstruction. It has been pioneered and already widely used at our institution for the treatment of oncologic defects and complex facial trauma, and in the planning of orthognathic surgery.[2–6] Anticipating a new era of craniofacial reconstruction in the form of vascularized composite allotransplantation, we have implemented this technology at an early stage of this surgical specialty development.

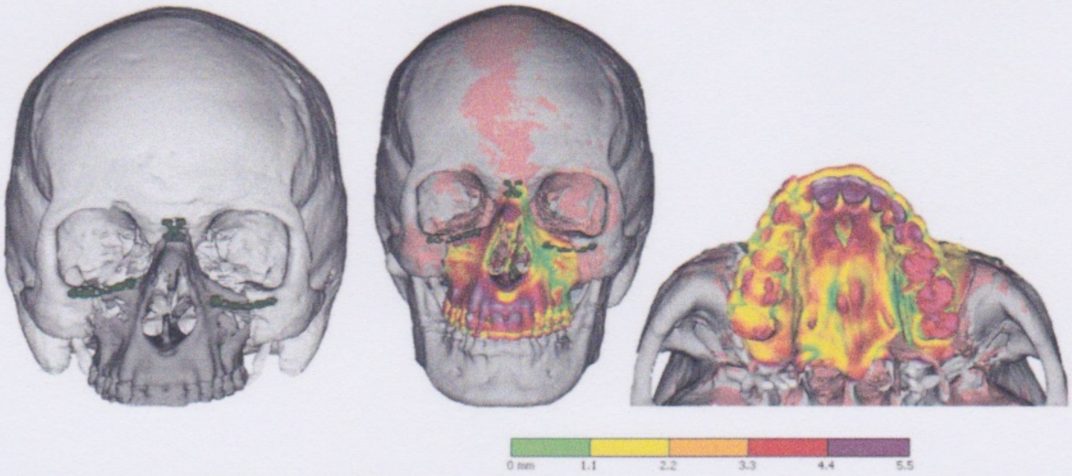


Fig. 4. (*Left*) A high-resolution postoperative computed tomographic scan of the hybrid cadaver confirms precise bone apposition at the osteotomy sites. (*Right*) An overlay analysis of the virtual plan and the postoperative computed tomographic scan of the hybrid cadaver confirms a match within 5 mm. The color bar illustrates variation from perfect fit.

Face transplantation is arguably the most complex three-dimensional craniofacial reconstruction described to date. Part of the challenge is that the donor and recipient tissues must be precisely matched in size and configuration. In the limited clinical experience to date, the work of fitting donor and recipient tissues has been performed intraoperatively, which is inefficient and prolongs the operation. In addition, the importance of establishing a functional dental occlusion cannot be overlooked. Our protocol starts with proper alignment of the maxillary and mandibular arches and then works backward to determine the osteotomy paths. This approach requires careful donor selection based on preoperative measurement of the intermolar distances of the recipient and potential donor. By using virtual surgical planning, we eliminate the time-consuming and imprecise guesswork from the operating room. Finally, an overlay analysis can be developed as a quantitative method of evaluating the accuracy of virtually planned craniofacial reconstructions, with the ability to assess long-term changes.

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