Total Face, Double Jaw, and Tongue Transplant Simulation: A Cadaveric Study Using Computer-Assisted Techniques


Baltimore, Md.

**Background:** With the transplantation of more extensive facial vascularized composite allografts, fundamental craniofacial and aesthetic principles become increasingly important. In addition, computer-assisted planning and intraoperative navigation may improve precision and efficiency in these complex procedures.

**Methods:** Ten mock face transplants were performed in 20 cadavers. The vascularized composite allograft consisted of all facial skin, mimetic muscles, the tongue, the midface by means of a Le Fort III osteotomy, and the mandible by means of sagittal split osteotomies. Craniofacial computed tomographic scans were obtained before and after the mock transplants. Surgical planning software was used to virtually plan the osteotomies, and a surgical navigation system guided the osteotomies intraoperatively. Cephalometric analyses were compared between the virtually planned transplants and the actual postoperative results.

**Results:** The combination of preoperative computerized planning and intraoperative guidance consistently produced a vascularized composite allograft that could be easily fixated to the prepared recipient, with only minimal burring of osteotomy sites necessary. Satisfactory occlusion was maintained, and postoperative computed tomography confirmed accurate skeletal fixation. Insignificant differences with regard to cephalometric analyses were noted when predicted and actual postoperative data were compared.

**Conclusions:** The authors' experience treating severe craniofacial injury allowed consistent transfer of facial vascularized composite allografts, maintaining proper occlusion. Preoperative computer planning and intraoperative navigation ensured precise osteotomies and a good donor-recipient skeletal match, which greatly reduced the need for intraoperative adjustments and manipulation. This total facial vascularized composite allograft represents one of the most extensive described and is intended to represent a typical central facial demolition pattern. (Plast. Reconstr. Surg. 130: 815, 2012.)

The field of facial transplantation has experienced exponential growth since the first clinical case in 2005, with 23 transplants now reported worldwide. Increasing confidence in surgical techniques and anatomical knowledge has allowed rapid progression from transplantation of partial facial segments composed of soft tissue alone to transplantation of full faces including underlying bone. Surgeons have now successfully transplanted isolated maxillary and mandibular segments, and the two in combination. Despite overwhelmingly positive outcomes to date, there remains considerable room for improvement with regard to allograft appearance and function. As facial vascularized composite allografts become more complex, the need to adhere to fundamental aesthetic and craniofacial principles, especially the maintenance of dental occlusion, becomes increasingly important.

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A face transplant is composed of two distinct operations, requiring careful coordination between surgeons recovering the allograft and preparing the recipient. This is a long and intricate process, with reported operative times ranging from 14 to 36 hours. The procedure is especially complex when multiple bone segments are being transplanted into a recipient with challenging anatomy resulting from numerous prior attempts at reconstruction. To improve surgical precision and efficiency, surgeons have recently begun using computer-assisted planning and intraoperative navigation in craniofacial surgery. These technologies may also be well-suited for use in facial transplantation, leading to shorter operative times and more precise skeletal osteotomies and fixation.

Advances in facial transplantation have been aided by multiple cadaveric studies helping to define the soft-tissue, bony, and vascular anatomy relevant for procurement and inset of a facial allograft. In this cadaveric model, we approach full osteomyocutaneous facial transplantation with a perspective cultivated through years of experience with autologous reconstruction of complex facial injuries. Our novel protocol uses multiple computer-assisted techniques and is built on a foundation of aesthetic and craniofacial principles. We hope our findings will add to the established knowledge base and improve both the functional and aesthetic outcomes after facial transplantation.

**MATERIALS AND METHODS**

**Cadaveric Subjects**

Between May of 2011 and January of 2012, 10 mock face transplants were performed in 20 fresh cadavers by two teams of three surgeons. One team procured the donor allograft and the other team simultaneously prepared the recipient face.

**Computer-Assisted Planning and Intraoperative Guidance**

Before the dissection, five titanium intermaxillary fixation screws (Synthes, Inc., West Chester, Pa.) were placed in both the maxilla and mandible of the donor and recipient cadavers. The screws were located in the midline, lateral to the canines, and between the first and second molars. The cadaveric skulls were placed in intermaxillary fixation using elastic bands to establish stable occlusion and then imaged by means of computed tomography. Titanium screws and elastic bands were chosen instead of stainless steel screws and wires to reduce scatter artifact. Three-dimensional reconstruction images of the donor and recipient skulls were superimposed using surgical modeling software (ProPlan CMF (Synthes) and SurgiCase Connect (Materialise, Leuven, Belgium)) to allow preoperative transplant simulation. Based on these projections, the Le Fort III and mandibular sagittal split osteotomies were planned for both the donor and recipient cadavers (Fig. 1). Stereolithographic models were produced, representing the recipient skulls after undergoing the planned Le Fort III osteotomies. Cutting guides for the recipient Le Fort III osteotomies were also fabricated and used during the mock transplantation.

A computer navigation device was applied to the cadaveric skulls, and the Le Fort III osteotomies were performed with the guidance of computed tomography–based navigation (Fig. 2) (eNlite Navigation System; Stryker Navigation). Intraoperative navigation was again used after transfer of the facial allograft to ensure that the operative result was in accordance with the preoperative simulation. After the mock transplantation was complete, computed tomographic scans of the donor-recipient hybrid were obtained (Fig. 1). Cephalometric parameters (sella-nasion–point A, sella–nasion–point B, and occlusal plane angle) were also calculated and compared between the planned and actual postoperative hybrid skeletons by means of paired t tests.

**Donor Surgical Technique**

The incisions were marked, beginning with a bilateral apron incision at the level of the clavicles, extending cranially into bilateral preauricular incisions and ending in a coronal incision. Lower eyelid subciliary and upper eyelid supraciliary incisions were also marked.

Dissection began in the right neck, where a skin flap was raised in a subplatysmal plane, preserving the external jugular vein and ligating it caudally. The great auricular nerve was identified overlying the sternocleidomastoid muscle and incised, and a portion of the proximal trunk was saved for potential use as a nerve graft. The sternocleidomastoid muscle was then retracted to expose the great vessels. The internal jugular vein was dissected cranially, recognizing and preserving the thyrolinguofacial trunk. The external carotid artery was then dissected, and the facial and lingual arteries were identified and preserved. The superior thyroid and ascending
pharyngeal arteries were ligated, as was the internal maxillary artery to decrease blood loss during the planned Le Fort III osteotomies. The posterior belly of the digastric muscle was then identified with the common facial vein overlying it. Both bellies of the digastric, along with the stylohyoid, were excised to facilitate exposure of the facial artery. The facial vessels were dissected to the submandibular gland, which was included in the facial vascularized composite allograft. The bilateral lingual arteries were then dissected distally within the mylohyoid muscle to the tongue base. The thyro-linguofacial trunk was dissected cranially, identifying the anterior and posterior facial vein branches. The posterior facial vein was traced posteriorly to identify and protect the lower division of facial nerve. The same procedure was then repeated in the contralateral neck.

A preauricular incision was made and dissection carried anteriorly in a sub-superficial musculoaponeurotic system plane, leaving the parotidomasseteric fascia and parotid gland intact. The buccal nerve and Stensen duct were identified, and the duct was divided. The facial nerve branches were then dissected individually and transected. The masseter muscle was exposed, allowing incision of the pterygomaseteric sling and stripping of the muscular attachments off the mandible. The same procedure was then repeated in the contralateral face.

Right upper supracciliary and lower subciliary eyelid incisions were performed. The lower lid dissection was carried in a suborbicularis, preseptal plane down to the orbital rim. Dissection then proceeded medially anterior to the medial canthus, leaving the soft tissue attached to the lateral nasal bones. Laterally, the lateral canthus was transected, and dissection was carried superiorly, first identifying the supraorbital rim and then identifying and

Fig. 1. Preoperative computerized surgical planning of donor (above, left) and recipient (above, right) osteotomies, with simulated donor-recipient hybrid (below, left) and true postoperative result (below, right).
The coronal incision was made, and dissection was carried anteriorly in a subgaleal plane, transitioning to a subperiosteal plane 1 cm above the supraorbital rims. The supraorbital nerves were again identified bilaterally, dissected out of their foramina, and transected. The coronal and eyelid dissections were then connected, exposing the nasofrontal region and the lateral orbitozygomatic bones in preparation for the Le Fort III osteotomies.

Next, the tongue was incised to the floor of the mouth, protecting the lingual blood supply and transecting the lingual nerves. The intraoral incision was extended bilaterally into the lingual mucosa to expose the alveolar ridges of the mandible. A transverse incision was also made in the soft palate connecting to the floor-of-mouth incision laterally, and the palatal soft tissue was elevated partially off the hard palate to expose the pterygoid plates.

Bilateral sagittal split osteotomies of the mandible were performed using an intraoral and extraoral approach. The inferior alveolar nerve was identified and transected as proximally as possible. The preoperatively planned Le Fort III osteotomies were marked with the guidance of intraoperative navigation. The bone cuts were then made extending anterior to the zygomatic arches and posterior to the orbital rims, staying anterior to the lacrimal duct. Osteotomies of the pterygoid-maxillary junctions were performed, and the maxillomandibular complex was separated at the Le Fort III level exposing the nasal septum, which was transected leaving only the vascular pedicles in continuity. The maxillomandibular complex was placed in intermaxillary fixation using elastic bands.

With the vascular pedicles still attached, the donor facial allograft was fitted to the prefabricated stereolithographic model of the recipient skull (Fig. 3), and the donor bones were burred down as needed. Fixation plates were also adapted at this time.

**Recipient Surgical Technique**

The recipient cadaver was prepared in a manner similar to that used for the donor, except for the following key distinctions. To perform the Le Fort III osteotomies, prefabricated cutting guides were fixated to the zygomatic and nasofrontal areas, and intraoperative navigation was used to confirm their proper placement. The great auricular and lingual nerves were preserved in the recipient, as were the superior thyroid, ascending pharyngeal, and lingual arteries, and the thyroid and lingual venous branches. The frontalis and orbicularis muscles were preserved.

Fig. 2. To simulate a clinical vascularized composite allograft, preoperatively fabricated cutting guides were used only for the recipient Le Fort III osteotomies (above). For the donor, intraoperative navigation was used to accurately reproduce the planned osteotomies (center and below).

protecting the supraorbital neurovascular bundle. The supratrochlear neurovascular bundle was ligated. Next, the orbital floor was explored, identifying the infraorbital nerve and dissecting it out of the foramen and floor before transecting it at the posterior extent of the orbit. The same procedure was then repeated in the contralateral periorbital region.
by raising the coronal flap in a suprafrontalis plane and the eyelid flaps in a supraorbicularis plane. In addition, the Stensen duct was preserved.

To ensure adequate pedicle length, the facial nerve branches and inferior alveolar, supraorbital, and infraorbital nerves were transected more distally. Likewise, additional eyelid skin was maintained in the recipient by placing the lower eyelid incision at the lid-cheek junction and the upper eyelid incisions at the lid-brow junction. This excess eyelid skin could be trimmed accordingly during final inset. Lastly, lateral canthotomies were not necessary for exposure.

Transfer of the Facial Allograft

To separate the donor allograft, the internal jugular vein was ligated and transected cranially and caudally. The external carotid was ligated and transected at the carotid bifurcation. The recipient facial arteries and veins were ligated and transected, and the recipient facial tissue was removed. The donor allograft was fitted to the recipient, and the bones were fixated by means of 0.7-mm miniplates (MatrixMIDFACE Plating System; Synthes) placed at the nasofrontal and zygomatic interfaces. The mandibular segments were fixated using bicortical 1.85-mm positional lag screws (MatrixORTHOGNATHIC Plating System; Synthes). The overlapping skin was trimmed accordingly and inset.

RESULTS

Outcomes after Mock Facial Transplantation

The total time required for completion of the mock transplantations ranged from 8 to 10 hours, with an average time of 9 ± 0.84 hours. Our method for facial allograft recovery produced a vascularized composite allograft containing all the skin and mimetic musculature of the face, and the entire maxilla and anterior portion of the mandible (Fig. 4). By including the lingual arteries in the allograft, we were also able to transfer a variable tongue segment, ranging from the anterior half alone to the entire tongue. Using the recipient stereolithographic model, the Le Fort III fixation plates could easily be fitted to the donor facial segment and prevent before division of the vascular pedicles.

After transfer of the facial allograft, inspection revealed adequate pedicle lengths for all anticipated vascular anastomoses and neurorrhapies. The combination of preoperative computer-assisted planning and intraoperative navigation consistently produced a donor allograft that could be easily fixated to the prepared recipient, with no more than minimal burring of the Le Fort III osteotomy sites. Although the fixation plates had to be modified with minimal out-of-plane bending in all cases, they never had to be replaced or repositioned. Using intraoperative navigation software preprogrammed with the planned donor-recipient facial skeletal hybrid, accurate and symmetrical fixation of the donor and recipient bones was confirmed.

By placing the donor maxillomandibular segment in intermaxillary fixation before transfer (Fig. 5), proper occlusion was maintained after fixation of the donor allograft to the recipient skull. There was adequate soft tissue included in the allograft for coverage of the entire recipient defect (Fig. 6).
Cephalometric Analyses

There were no significant differences in sella-nasion-point A, sella-nasion-point B, or occlusal plane angles between the virtually planned hybrid skeletons and the actual postoperative results (Table 1 and Fig. 7).

DISCUSSION

This cadaveric model represents an evolution in the planning and technique for full osteomucocutaneous facial transplantation including the total face, double jaw, and tongue. Previous face transplants have included variable portions of the maxilla and mandible, but only one reported case has also included all of the facial soft tissues. In addition, restoration of dental occlusion has posed a consistent and formidable challenge in prior face transplants and has not been adequately addressed. We present a novel technique for transplantation of the maxilla and mandible based on considerable experience with craniofacial reconstruction using Le Fort III osteotomies for the maxilla and bilateral sagittal split osteotomies for the mandible. The goals of total osteomucocutaneous facial transplantation should extend beyond simple fixation of the donor and recipient skeletons to include flawless integration of the skeletal components and maintenance of dental occlusion. By pairing a Le Fort III approach with bilateral sagittal split osteotomies and placing the donor allograft in intermaxillary fixation, we seek to ensure that the recipient will have a superior functional and aesthetic outcome.

In a further effort to achieve the best possible cosmetic result, we aimed to disguise all of the skin suture lines at the "seams" of the aesthetic subunits by placing the incisions in areas that were not easily visible. Drawing on our experience with aesthetic facial reconstructive surgery, we combined a coronal incision hidden in the hair-bearing scalp with a preauricular face-lift incision and extended the neck incision low enough so that it would be mostly hidden by clothing. Likewise,
Fig. 6. Preoperative views of recipient (left) and donor (center), and postoperative view (right). In this case, a female donor allograft was transferred to a male recipient. Note the relatively masculine appearance postoperatively, despite inclusion of a significant portion of the underlying facial skeleton.

Table 1. Cephalometric Averages for All Mock Transplantations

<table>
<thead>
<tr>
<th>Cephalometric Parameter</th>
<th>Predicted (degrees)</th>
<th>Actual (degrees)</th>
<th>Absolute Difference (degrees)*</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNA</td>
<td>79.3 ± 2.3</td>
<td>80.2 ± 2.7</td>
<td>0.9 ± 1.0</td>
<td>0.48</td>
</tr>
<tr>
<td>SNB</td>
<td>75.2 ± 4.1</td>
<td>75.4 ± 4.2</td>
<td>0.2 ± 0.3</td>
<td>0.36</td>
</tr>
<tr>
<td>Occlusal plane</td>
<td>9.0 ± 4.5</td>
<td>11.2 ± 5.0</td>
<td>2.6 ± 1.7</td>
<td>0.08</td>
</tr>
</tbody>
</table>

SNA, sella-nasion–point A; SNB, sella-nasion–point B.

*The "Absolute Difference" column shows the mean difference between the paired predicted and actual angles for each cadaver (i.e., it is a mean of multiple data points). It does not represent the difference between the single average value for predicted angles and single average value for actual angles.

we attempted to place the eyelid incisions just superior and inferior to the upper and lower ciliary lines, respectively.

Computer assistance based on computed tomographic imaging was used at multiple stages of our mock transplants and proved essential in achieving ideal outcomes. By obtaining preoperative computed tomographic scans of both the donor and the recipient, we were able to take advantage of surgical modeling software to virtually superimpose the two facial skeletons before setting foot in the operating room. This allowed us to methodically simulate the planned osteotomies and refine our result. We were also able to create a stereolithographic model representing the recipient facial skeleton after undergoing the proposed Le Fort III osteotomies. Siemionow and Ozkurk reported using a stereolithographic model of the recipient during their face transplant, but this model did not include preoperatively planned osteotomies and was instead used to guide the extent of donor facial graft dissection. In contrast, our model allowed adaptation of the donor facial vascularized composite allograft to the recipient skull while the vascular pedicles were still attached, allowing the surgical team to make fine adjustments to the donor osteotomies and prebend fixation plates without incurring additional ischemia time.

In a clinical face transplant, generally less than 24 hours elapses between donor identification and the facial recovery procedure. Although computer-assisted planning is possible in this time frame, there is not adequate time to fabricate and deliver cutting guides for the donor osteotomies. For the recipient, however, cutting guides can be fabricated well in advance of the transplant operation. Once a donor is identified, donor osteotomies that are compatible with these prefabricated recipient cutting guides can then be planned and executed with the assistance of intraoperative navigation. This is why cutting guides were only produced for the recipient osteotomies in our mock transplant. The combination of recipient cutting guides and intraoperative computer-assisted guidance allowed us to make precise Le Fort III osteotomies, ensuring a match between the recipient and donor facial skeletons and reducing the time required for intraoperative adjustments. In addition, intraoperative navigation confirmed the accuracy of the osteotomies and guided fixation. Unlike
more obtrusive fixed surgical navigation systems, the mobile receiver unit used in this study has a small footprint and would not impede the ability of multiple surgical transplant teams to operate on a donor simultaneously.

Once the Le Fort III segment placement was established, the donor mandibular segment could readily be fixated to the recipient because the maxilla and mandible were maintained in an occlusal relationship with internmaxillary fixation. The use of bilateral sagittal split osteotomies ensured maximal osseous contact and permitted straightforward adjustment of the mandible to “fit” the maxilla, as would be done in a traditional orthognathic procedure. In contrast to the simple transverse mandibular osteotomies used in prior face transplants, bilateral sagittal split osteotomies obviated the need for significant additional osteotomies in the case of mandibular excess or creation of segmental defects in the case of mandibular deficiency.

The structures included in our mock facial vascularized composite allograft were based on a typical central face demolition pattern of high-energy injury that we have observed repeatedly in our high-volume trauma center. These patients generally have destruction of the lower facial and midfacial skeleton and associated soft tissues. In addition, their foreheads are often disfigured after flap harvests for attempted reconstruction of the midface soft tissue. Although the allograft we describe includes the full face, double jaw, and tongue, this basic template could easily be modified to address the specific defects in a number of patients we have treated. These injuries also mimic the types of isolated lower face and midface trauma encountered by our soldiers, given the fact that their helmets tend to reduce injury to the upper face and cranial vault. Therefore, a reliable method for transplantation of these facial tissues may also be of substantial benefit to our wounded warriors.
CONCLUSIONS

Facial transplantation becomes increasingly challenging as centers move forward with transplantation of more extensive facial segments including significant cutaneous and bony components. In this cadaveric model representing the reconstructive needs of a typical victim of high-energy facial trauma, mock transplants of a full face, double jaw, and tongue vascularized composite allograft were performed. Despite the complexity of this allograft, consistently acceptable outcomes were achieved by strict adherence to aesthetic and craniofacial principles. In addition, surgical accuracy and efficiency were improved through the seamless integration of multiple computer-assisted techniques, both preoperatively and intraoperatively. Moving forward, an application of the lessons learned in this model could optimize recipient outcomes in clinical facial transplantation.

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REFERENCES


