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Restoration of the Donor Face After Facial Allotransplantation: Digital Manufacturing Techniques

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Abstract

Introduction—Current protocols for facial transplantation include the mandatory fabrication of an alloplastic “mask” to restore the congruency of the donor site in the setting of “open casket” burial. However, there is currently a paucity of literature describing the current state-of-the-art and available options.

Methods—During this study, we identified that most of donor masks are fabricated using conventional methods of impression, molds, silicone, and/or acrylic application by an experienced anaplastologist or maxillofacial prosthetics technician. However, with the recent introduction of several enhanced computer-assisted technologies, our facial transplant team hypothesized that there were areas for improvement with respect to cost and preparation time.

Results—The use of digital imaging for virtual surgical manipulation, computer-assisted planning, and prefabricated surgical cutting guides—in the setting of facial transplantation—provided us a novel opportunity for digital design and fabrication of a donor mask. The results shown here demonstrate an acceptable appearance for “open-casket” burial while maintaining donor identity after facial organ recovery.

Conclusions—Several newer techniques for fabrication of facial transplant donor masks exist currently and are described within the article. These encompass digital impression, digital design, and additive manufacturing technology.

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Keywords

3-dimensional printing; scanning; computer design; AMT; additive manufacturing; craniofacial; binder jetting; materials jetting; mask; donor mask

Current autologous reconstructive options for devastating midfacial defects, especially those resulting from high-energy trauma, are limited.¹⁻³ These limitations have led surgeons to adopt alternative methods involving vascularized composite tissue allotransplantation and Le Fort-based, osteocutaneous facial transplantation to achieve better functional and aesthetic outcomes.⁴⁻⁶ These techniques, although very promising, are still nascent, and considered experimental procedures.

Critical to the advancement of the field, however, is the willingness of potential organ donors, and their families, to agree to donate this complex organ. Facial transplantation, as opposed to internal organ donation, necessarily requires aesthetic destruction of the donor to harvest the facial organ, making an already hard decision increasingly difficult. A recent systematic literature review published by Walker et al found that factors leading families to decide against donation of organs included underlying fears and concerns of violation, desecration, and the donor family member's perceptions of mutilation.^{7,8} Additionally, concerns regarding aesthetic destruction and/or disfigurement of the deceased person's body were weighted even more heavily in cases where the potential donor's body seemed unscathed.⁹ Given these factors, restoration of the donor's facial appearance after transplantation has become an ethical issue, and in certain countries, a legal requirement, making it an integral component of the facial alloflap harvest procedure.

Various methods of donor facial restoration have been described in the literature; most of which have incorporated various materials and traditional molding techniques to produce donor masks as a means to restore, as closely as possible, the donor's preoperative appearance. Mask materials used in previous facial alloflap donor restorations consisted of acrylic resins and silicone masks.^{10,11}

Although detailed descriptions of donor mask production have been mostly absent from the literature discussing donor alloflap harvest, a recent study by Quilichini et al¹¹ described in detail the process their team used in restoration of the donor's faces after 7 allograft procurements. In their recent paper, they describe the use of alginate to create a mold and impression in negative of the donor's face; a process requiring approximately 30 minutes to complete. This period seems to correlate with what Siemionow and Ozturk¹⁰ and Dorafshar et al¹² have described, and importantly, was not shown to cause any significant delays to the surgical team.

According to Quilichini et al, after the alginate impression is obtained, mask production continues in a separate room, with colored acrylic resins subsequently being poured into the mold. The mask is then refined by makeup application performed by a maxillofacial prosthetics technician or anaplastologist using a photograph of the donor.¹¹ At the end of the facial alloflap harvest, the mask is positioned on the donor under the surgeon's supervision.¹⁰ Average time of mask production in this series of 7 donor face restoration

procedures was approximately 4 hours, and the cost of materials estimated at US \$50 per mask.¹⁰ The use of silicone has also been described recently as well for this purpose. Its reported advantages over acrylic resin are lifelike morphologic results and texture; however, this technique will increase the production time¹¹ (Fig. 1).

Additive Manufacturing Technologies

Although donor mask fabrication by a maxillofacial prosthetic technician or an anaplastologist produces good aesthetic outcomes, some drawbacks do exist with regard to the logistics required to produce the mask, essentially adding a procedure to the surgical day at the donor location before transport. Digital imaging and design software, in conjunction with additive manufacturing (AM) however, provides an avenue to produce a donor mask remote from the site of alloflap harvest. The only prerequisite for this technique is that 3-dimensional surface data must be obtained. These data can be acquired in a multitude of fashions including reconstructions from a medical scan such as computed tomo-graphic (CT) scan, 3-dimensional photography, and/or 3-dimensional scanning.^{13–16} The digital representation of the donor's soft tissue can then be modified into a mask and fabricated/manufactured before the graft procedure.

Unlike the conventional impression techniques of using an impression medium such as alginate, plaster, or an elastomeric material, the fabrication of an AM mask is based on imaging of the donor. Digital topography files (.obj, .stl, .vrm1) can be obtained from 3-dimensional scanners, 3-dimensional photogrammetry systems, or computational reconstructions from medical imaging system's Digital Imaging and Communications in Medicine files, such as CT or magnetic resonance imaging. These types of files can be digitally modified to develop the final mask/mold file for any AM technology. The detail available in the finished product is related to the resolution of the image and choice of manufacturing process.

The use of medical data to fabricate silicone prosthesis with digital design and AM are already prevalent in the literature for fabricating facial prosthetic devices.^{16,17} These same techniques can be applied to donor mask fabrication. To accomplish this, the donor will have medical imaging performed as part of the protocol, so new images may not be necessary for fabrication of a mask. However, a color picture of the patient will be needed to color the mask. The use of a surface scanner is preferred because the quality of the surface texture is independent of slice reconstruction algorithms in medical imaging, and results border on those of a contact impression. Once the digital design of the mask has been established, the next step is to prepare it for the AM device you have selected, based on the application (Figs. 2 and 3).

Direct Binder Jetting

Direct binder jetting is AM technology in which the printer creates the model one layer at a time by spreading a layer of powder (plaster) and printing with a liquid binder in the cross section of the part using an inkjet-like process. Each subsequent layer bonds with the previous and the process is repeated until every layer has been printed, and a full color mask is produced. If this technique is chosen then a color "texture" or mask may need to be added

to the digital mask design. Some 3-dimensional scanners and 3-dimensional photogrammetry systems automatically map a picture or multiple picture files to the 3-dimensional surface file if exported as a .vrmf or .obj file. If the photograph(s) are not premapped or are not available (ie, CT scan), a digital picture with the face in a similar position can essentially be “wrapped” on the surface of the digital mask (Fig. 4).

The process involves designing, printing, and sealing the mask. This technique requires a minimum amount of “man hours” in that it can be designed and ready for printing in about an hour, the average print time is approximately 4 to 6 hours with approximately 30 minutes of finish time. However, the mask is fabricated from a bound gypsum product that is sealed producing a hard mask that needs to fit directly and securely over the remains of the donor which may be difficult due to skeletal undercuts from the dissected donor area (Fig. 5). In addition, there can be an element of “pixilation” or “stair-stepping” of the surface due to the resolution of the scan, design, or selected printer upon close examination, but color modifications can be made easily with acrylic paints. This method would be appropriate for the fabrication of a full face mask, if the goal of the mask is to preserve the donor’s dignity during transportation within the facility, and very limited (distant) viewing is expected.

Indirect Binder Jetting

This is a modification of the previous AM technology; however, instead of printing the mask directly, a mold of the mask is printed, and silicone with custom coloring is “processed” in the mold with a more conventional fabrication method by a qualified maxillofacial prosthetics technician or anaplastologist. This method takes advantage of the digital image to produce a mold, remote from the donor, and before the graft donation. Photographs of the donor are helpful for silicone intrinsic coloring, extrinsic painting, and customizing the mask. Among the advantages of this method are that the mask can be produced in silicone, allowing for control of the thickness. Because silicone is flexible and can be tinted, it is more easily modified for fit and color at the time of application. Also, cosmetic features such as eyelashes and hairs can be added to this type of mask. When properly colorized, such a mask can provide a more “lifelike” appearance; therefore, this technique is more appropriate if there is going to be an open-casket viewing. Production time for this method includes the original 6 to 8 hours to print the mold and another 3 to 4 hours for processing and coloring of the silicone; however, the actual “hands on” fabrication is approximately 4 to 5 hours (Fig. 6). The disadvantages of this method are that much of the detailed surface texture on the mask may need to be recreated due to limited printer resolution. This is done either by overpainting or modifications during the development of the mold, depending upon the resolution of the image capture technique used. However, in the absence of being able to make an onsite impression of the donor, this method represents an alternative method for producing a flexible silicone mask remotely.

Materials Jetting

This is an AM technology similar to binder jetting; however, instead of jetting drops of ink onto a powder; layers of a photopolymer are jetted onto a build tray and cured with UV light. The process continues as the layers are built upon themselves until the mask is

complete. The advantage of this system is that you have the availability to produce the mask with multiple materials if desired, both hard and soft which can be manipulated in the build file. This will allow the design of a mask that has the rigidity for support of some structures, but allow for the overall soft “silicone-like” quality. Due to the limited color selections, once the mask has been fabricated, the material is stained to a base shade, and coloring is applied using air brushes and conventional painting methods as needed to highlight features. This can all be performed before any surgical intervention. Design and full production of this polymer mask is approximately 8 to 10 hours and another 1 to 3 hours to colorize the prosthesis. Although some translucency can be maintained by staining the material, the surface texture and translucency of the mask may not match that of the donor due to limited printer resolution and subsequent over painting; therefore, a full mask is recommended.

Sheet Lamination

Sheet lamination is a process in which sheets of a material are bonded to form an object. Recent advances in this technology have resulted in the ability to fabricate a colored object from paper and glue. These printers boast the ability to print in over a million different colors. The product of this technology is similar to that of binder jetting in fabrication time and production of a rigid mask, however, due to the method used to cut the sheets, the surface is generally smooth and does not exhibit the “pixilation” or “stair stepping” appearance, unless it is part of the design from a poor resolution scan. In addition, the models colors are easily modified with acrylic paints and can be sealed using cyanoacrylate, resin, or wax. This type of donor mask would have the same issues with skeletal undercuts as other hard material fabrication methods. This is probably one of the most economic methods for fabrication; the raw material is print paper and glue (Fig. 7).

DISCUSSION

Custom fabrication of a donor mask should be a standard procedure detailed within all facial transplant protocols worldwide. Recent advances in virtual surgical planning with digital images have been incorporated in many of these protocols to describe cutting planes and design of surgical cutting guides that are prepared before the procedure. Of note, our team’s novel computer-assisted planning and execution system was developed in conjunction with our novel preclinical, swine maxillofacial transplant model.^{18–20} The same digital information that is used for these processes can be used to prepare the donor masks as well, streamlining many of the procedures needed on the day of the facial organ recovery. Presently, it seems that the conventional techniques of contact impression, mold fabrication, and direct silicone coloring provide the level of detail required to most closely replicate the donor site and, digital fabrication methods are best indicated for full mask fabrication with limited aesthetics. However, advances in digital capture, digital manufacturing devices, and materials show great promise in that they provides a method to remotely fabricate the mask from captured images and improve print resolutions.

The manner of donor restoration should be based on the wishes of the family, and optimized according to the desired method of posthumous ceremony. As such, the application of digital design and fabrication can be selected to meet that need. For example, if the family would

still wish some type of “open-casket” viewing, then custom fabrication in silicone or digital fabrication in silicone would be appropriate. However, if the mask is to preserve the dignity and identification of the donor during transfer within the hospital facility, a printed color mask using direct binder jetting or sheet lamination may be more appropriate and cost effective. Whichever technique is chosen, the technician should ensure that the color, highlights, and details of the mask reflect a more appropriate color palate and opacity more appropriate for a cadaver.

CONCLUSIONS

By optimizing the technique of donor facial restoration, we hoped to address some of the primary concerns families encounter when having to make a decision to offer their loved-one’s face as a donation. Presently, custom conventional fabrication of donor masks by an experienced maxillofacial laboratory technician or anaplastologist has some advantages over AM techniques. However, it is important to know that AM technology has been shown to produce an aesthetically acceptable prosthetic result, as presented here. Digital capture of the donor and design of the masks should account for many of the more detailed features and provide for secure application of the mask, as well as restore the congruency of the donor site. The present state of technology, to develop the impression and manufacture a mask using digital tools, is still in its developing stages and offers variety in the approach to be used. As AM technologies improve in their ability to model better resolutions, improve the ability to add color directly to the materials, and obtain 3-dimensional capture capabilities, the present gap between custom and digital fabrication techniques may be indistinguishable. Irrespective of the fabrication technique chosen, the prosthetic restoration of a donor’s face is integral to the facial transplantation procedure to ensure that greatest respect is paid to the deceased.

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FIGURE 1.
Donor mask fabricated from conventional fabrication techniques, note the detail.

FIGURE 2.
Surface geometry is developed from a CT scan.

FIGURE 3. Digital surface impression from CT scan and applied color mask. Note lamination/pixilation lines from a low-resolution CT scan.

FIGURE 4.
Direct binder jetted fabricate mask.

FIGURE 5.
Design and printed mold from binder jetting AMT.

FIGURE 6.
Indirect silicone masks from printed mold.

FIGURE 7. Sheet lamination fabricated mask. As with the binder jetted mask, note the lamination lines from the low resolution scan.