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AJNR Am J Neuroradiol 2013, 34 (10) 1873-1881
doi: https://doi.org/10.3174/ajnr.A3268
http://www.ajnr.org/content/34/10/1873

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ABSTRACT

SUMMARY: Facial allotransplantation replaces missing facial structures with anatomically identical tissues, providing desired functional, esthetic, and psychosocial benefits far superior to those of conventional methods. On the basis of very encouraging initial results, it is likely that more procedures will be performed in the near future. Typical candidates have extremely complex vascular anatomy due to severe injury and/or multiple prior reconstructive attempts; thus, each procedure is uniquely determined by the defects and vascular anatomy of the candidate. We detail CT angiography vascular mapping, noting the clinical relevance of the imaging, the angiosome concept and noninvasive delineation of the key vessels, and current controversies related to the vascular anastomoses.

Restoring complex facial components such as eyelid and/or lip function is nearly impossible (Figs 1*A* and 2*A*) with conventional reconstructive techniques.[1,2] Allotransplantation is accepted as the only option for the most complex craniofacial reconstruction (Fig 1*A*, -*B*). On the basis of the large population of patients with facial defects and encouraging initial results,[3] it is likely that face transplantation will become a more common procedure. This underscores the need for radiologists to recognize the need for vascular mapping in these patients and to learn key aspects of the surgery that are important for image acquisition and reporting.

There have been approximately 20 face transplantations performed to date; 4 of these patients, including 3 from the United States,[3] had "full" face transplantation,[4] defined as restoration of the forehead, eyelids, nose, lips, chin, and cheeks, with or without bone. Patients with smaller defects can undergo so-called "partial" transplantation (Fig 1). Although candidate screening includes patients with malignancy and congenital etiologies, most patients to date have had severe trauma. For our patients, suitable brain dead, sex-, and skin color–matched donors are identified from our regional organ bank.

The intricacy of facial transplantation includes vascular preparation of both the recipient site and donor allograft. Long (15–22 hours) operation times[5,6] and massive (up to 35 units) blood loss[7] have been reported. The vascular anastomoses are the most critical part of the operation. Although 1 arterial and venous anastomosis appears adequate for perfusion of facial tissues, additional vessels are typically connected to ensure adequate facial blood flow.[8,9]

Open dialogue between surgeons and radiologists is critical to assess potential anastomoses and 3D relationships between vessels and other structures (eg, shrapnel, bone fragments) and to minimize the risk of critical blood loss and ischemia time.

The radiologist is charged with preoperative identification of the best target arteries. The risk of vascular anastomotic complications can be reduced if vessels with unfavorable anatomy are excluded from anastomoses. Preoperative knowledge of vascular anatomy allows the surgeons to plan ahead and prepare backup options such as vein grafts. We have observed that the elimination of vascular "unknowns" has led to more timely operations.

Face transplantation surgery is highly variable, and surgical planning for each case is unique. For the allograft, the recipient's tissue deficits determine the design, ranging from partial to full facial transplantation. The allograft includes not only the skin but also the underlying soft tissues, cartilage, and bone, depending on the defect of the recipient. This article focuses on the importance of the blood vessels. High-quality noninvasive image acquisition and postprocessing are essential because there is variation in subject anatomies, common sources for arterial and venous anasto-

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Paper previously presented in part and awarded a Radiological Society of North America 2010 Certificate of Merit, a Radiological Society of North America 2011 Excellence in Design Award, and an Excellent Educational Poster Award at: 71st Annual Meeting of the Japan Radiological Society, April 12–15, 2012; Yokohama, Japan.

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http://dx.doi.org/10.3174/ajnr.A3268

FIG 1. A 59-year-old man who underwent partial face transplantation. *A*, Severe disfigurement of the midface caused by a high-voltage burn injury is demonstrated, despite multiple conventional reconstructive attempts. *B*, Two-year postoperative follow-up illustrates restoration of form and function.

moses are often depleted by previous reconstructive efforts or injury, and the surgical dissection can be very difficult due to scarring and fibrosis.

Literature supports CT vascular mapping for living hepatic and renal donors,[10,11] considering it fundamental for safety and surgical outcomes.[12,13] One distinction for facial transplantation imaging is that selection of donor vessels is affected by both allograft design and the recipient's vascular anatomy as a result of extensive defects or prior interventions. Moreover, head and neck vascular anatomy has higher patient-to-patient variability, particularly with respect to venous outflow, emphasizing the importance of preoperative mapping for reliable microvascular anastomoses and minimizing the risk of venous congestion and thrombosis in anastomotic vessels, the most common complications of microsurgery.

This article illustrates vascular CT for surgical planning. The angiosome concept is presented with respect to its influence on the donor vessel selection. Relevant controversies for vessel anastomoses are discussed, and current CT protocols are emphasized.

VASCULAR CONSIDERATIONS IN FACIAL TRANSPLANTATION

Donor Vessels and Angiosomes

The allograft design is determined by the recipient's defect (Figs 1*A*, 2*A*, and 3*A*). The vascular pedicles or donor vessels are chosen by using the angiosome (Fig 3*D*) concept,[14,15] to optimize adequate perfusion. Each angiosome has a source artery that supplies 3D composite blocks of skin and underlying tissues (muscles, nerves, and bones).[16] This concept suggests that multiple arteries are needed for perfusion of the facial skin and most of the facial skin is supplied by the superficial temporal, facial, and ophthalmic arteries.[16] However, several anastomotic networks allow perfusion of multiple adjacent territories[17-20] or across the midline.[8,9] Thus, a source artery can also perfuse neighboring angiosomes when connecting potential vessels, called "choke vessels," open, and subsequently develop into collateral vessels.[15] For example, the source artery for the ophthalmic angiosome of the central forehead is typically a branch of the internal carotid artery. However, this angiosome can be supplied by reversed flow from the adjacent superficial temporal and facial artery territories.[17]

Selection of Recipient Vessels

Although the head and neck have a rich and often redundant vascular network,[21] in our experience, it is common that the typical target vessels are depleted from either massive defects or multiple surgeries (Figs 2*B*, -*C* and 4). When it is available for surgery, CTA mapping of the course, caliber, contour, and 3D relationship to metal from the injury or prior surgeries is the most important preoperative step. CTA preoperatively identifies alternative recipient vessels when more suitable vessels are depleted. The usual strategy[22] is to identify adjacent small vessels by CTA.[23] When small neighboring vessels are not available, major neck vessels, such as the internal jugular system, can be used.[22]

Another critical element of surgical planning is the identification of anatomic variants (Table and Fig 5).[24] Both arteries and veins can have a common trunk, leading to larger caliber vessels compared with the smaller individual vessels. Larger caliber trunks are considered more favorable because the anastomosis is simpler and safer. Duplications are also common, and in general, these are considered advantageous because of increased options for anastomoses. Seventeen percent of individuals have dupli-

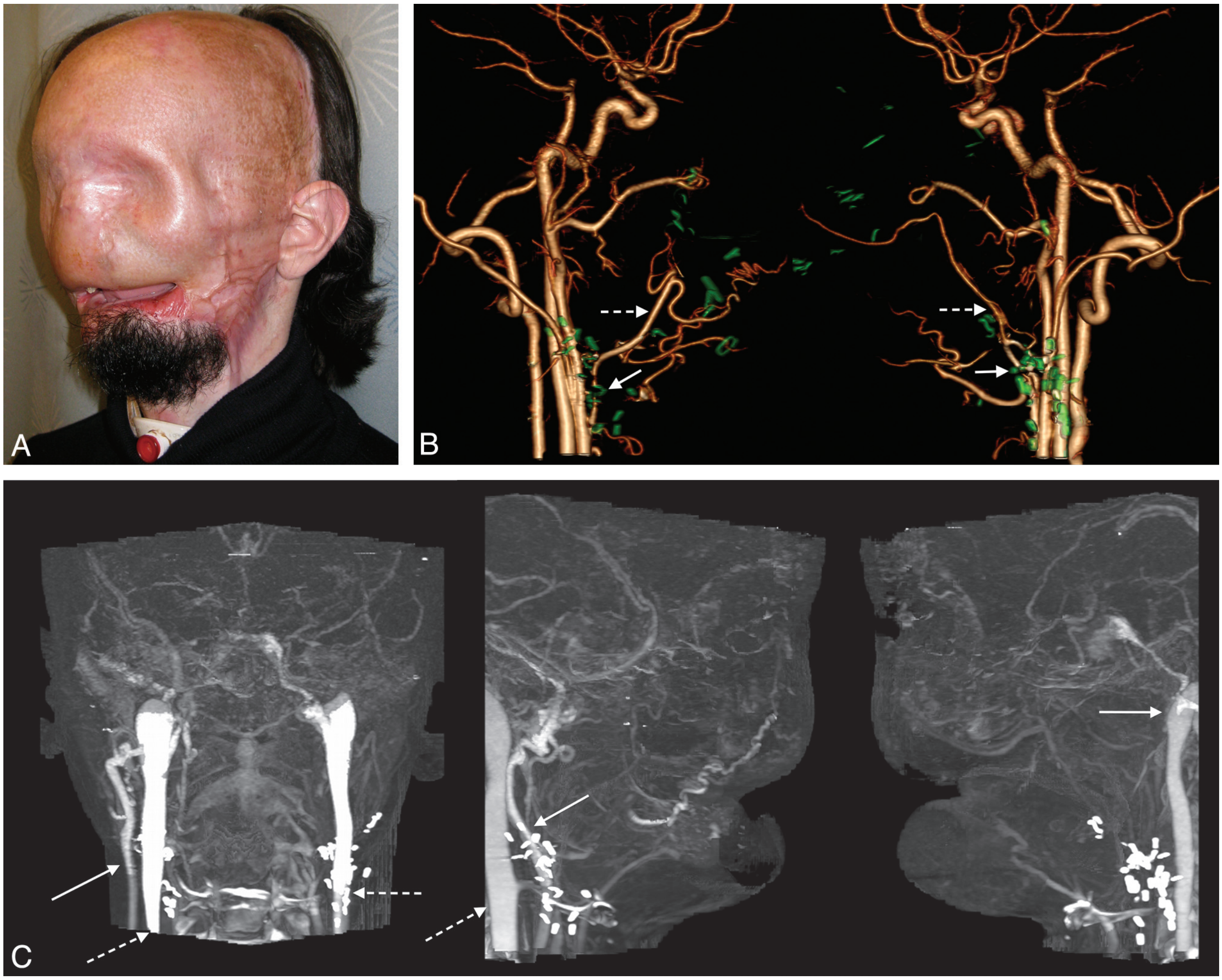

FIG 2. Candidate for full face transplantation. *A*, After catastrophic loss of facial tissues, muscle flaps and skin grafts placed during >20 surgeries rendered the patient's face featureless. *B*, Surgical-planning volume-rendered CT angiography depicts residual arteries after previous reconstructions using bilateral free latissimus muscle and serratus muscle flap arteries (*dashed arrows*), which are anastomosed end-to-end to the bilateral facial artery stumps (*arrows*). While not ideal, those facial and/or flap arteries are technically available and considered for microsurgical anastomoses. Prior surgical clips are rendered in green using the multiobject segmentation described in the text. *C*, Venous images from the same CT acquisition show occluded or absent bilateral anterior, posterior facial, and left external jugular veins. Patency of the right external jugular vein (*arrow*) and bilateral internal jugular veins (*dashed arrows*) is confirmed.

cated external jugular veins, and 30% of individuals have duplicated anterior jugular veins.[24]

As a general rule, 2 venous anastomoses are used to maintain sufficient outflow. Conventional thinking is that compared with the corresponding arteries, selection of drainage veins is considered less critical.[25] However, it is essential to maintain sufficient drainage because venous congestion and thrombosis are the most common cause of flap failure.[26,27] Additionally, there is a high incidence of venous thrombosis after neck dissection, up to 30% in the internal jugular vein.[28-30]

Planning Vascular Anastomoses

Once all vessels are identified, planning the vascular anastomoses considers the following: 1) optimal size match between donor and recipient vessels, 2) sufficient length between the allograft pedicle and donor vessel, and 3) surgical accessibility of the pedicle. Communication between the radiologist and surgeon by using the postprocessing methods described below is essential to portray the spatial relationships.

Surgical planning meticulously considers and matches the caliber and length of recipient and donor vessels. When these are highly compatible, it is possible to perform end-to-end anastomoses; the technique is simple and easily performed with less blood flow turbulence. However, other techniques are often required, usually from large-diameter discrepancies that increase the technical difficulty of the anastomoses and the reliability of the final conduit. Moreover, abrupt caliber changes are also undesirable because these induce turbulence and predispose to platelet aggregation.[31] In related interventions, artery size discrepancy[32] and/or intricate anastomoses[33] have been shown to have higher complication rates.

In our experience, 3-fold diameter discrepancies between donor and recipient vessels have been encountered and are accommodated for by end-to-side anastomoses. Other options would include sleeve and so-called "fishmouth" anastomoses for the management of size discrepancies in microvascular anastomosis.[31] Practically, an end-to-side anastomosis is often the only

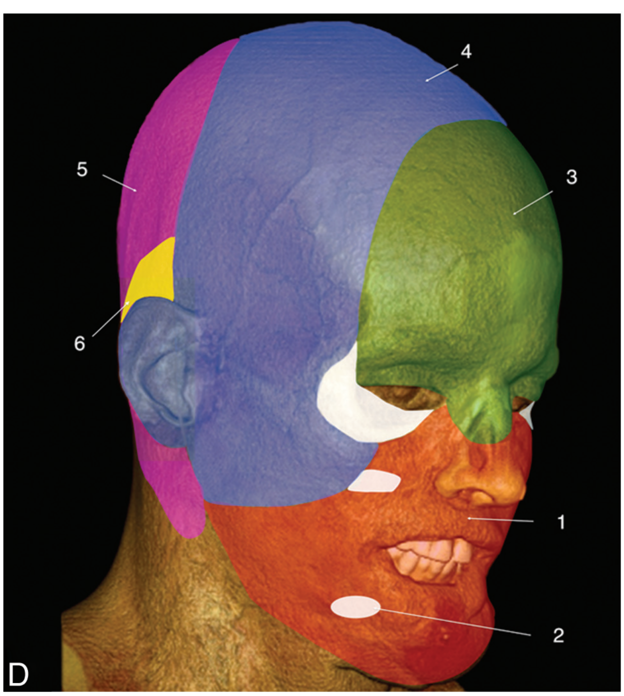

FIG 3. Candidate for full face transplantation. *A*, After a high-voltage injury, several flap and graft procedures resulted in persistent disfigurement. The patient wore a nasal prosthesis, removed for this photograph. *B*, Representative sagittal (left) and anteroposterior (right) projections from CT volume rendering. Volumes are viewed from an arbitrary angle to characterize branch and smaller vessels—for example, those from the external carotid artery that may be available for anastomoses. The nasal prosthesis was included in the CT acquisition. *C*, Sagittal cine CT images provide time resolution and enable separation of arteries and veins so that each dataset can be individually postprocessed. *D*, Angiosomes of the face overlaid on a volume-rendered CT image, including all soft-tissue components and numbered according to the source artery: 1) facial, 2) internal maxillary, 3) ophthalmic and internal carotid, 4) superficial temporal, 5) vertebral, and 6) posterior auricular. Lower and midface (orange) allografts can be perfused solely by facial arteries. Although the lower two-thirds of the face includes internal maxillary artery angiosomes, this territory can also be perfused by the facial artery via neighboring angiosome collateral vessels. For procedures in which the allograft includes the upper face and scalp (green and blue), the facial and superficial temporal arteries should be included, with the external carotid artery as the source vessel.

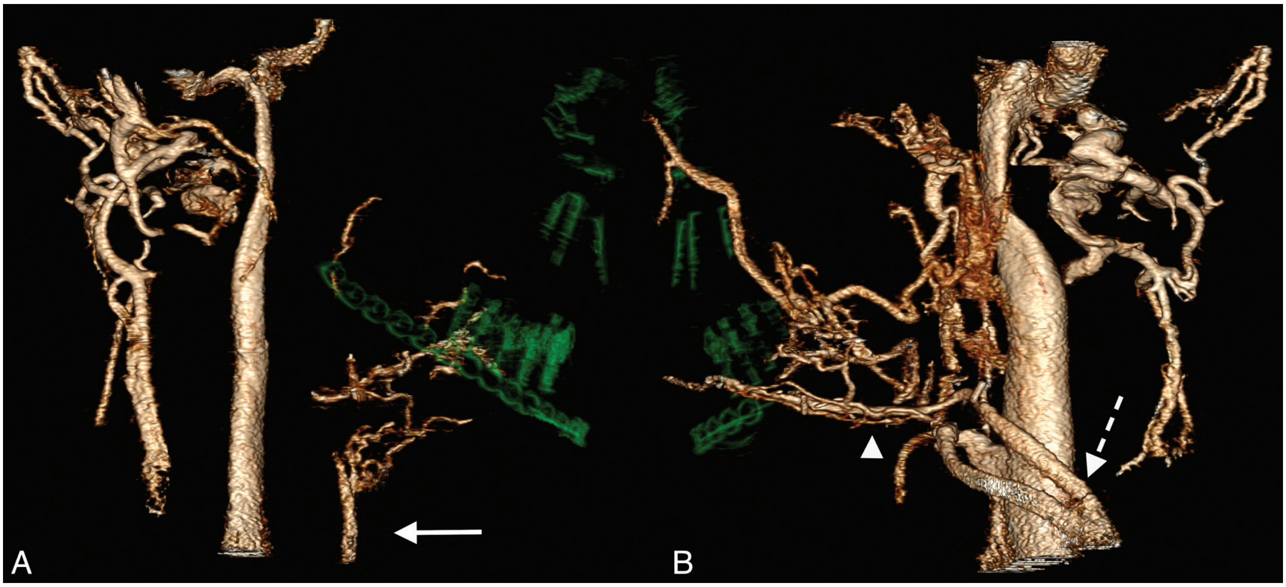

FIG 4. Volume-rendered venous-only reformatted images from a candidate who had a blast injury. *A*, Anterior and posterior facial veins and the external jugular vein are absent on the right, presumably from the injury. Imaging confirms the patency of the anterior jugular vein (*arrow*), a potential alternative for flap drainage. *B*, On the left, the external jugular vein (*dashed arrow*) and anterior facial vein (*arrowhead*) are available for flap drainage.

Major variations in branching patterns of the external carotid artery (3 types) and variations in the confluence of the facial, lingual, and superior thyroid veins with internal jugular vein (5 types)

Variant Type	Description
Arterial	
Noncommon trunk	Facial, lingual, and superior thyroid arteries arise separately from the ECA
Truncus linguofacialis	Facial and lingual arteries arise from the ECA in a common trunk
Truncus thyrolingualis	Superior thyroid and lingual arteries arise from the ECA in a common trunk
Venous	
Thyrolinguofacialis	Facial, lingual, and superior thyroid veins form a thyrolinguofacialis vein
Linguofacialis	Facial and lingual veins form a venous stem
Thyrofacialis	Facial and superior thyroid veins join together, and separate lingua l vein joins into the IJV
Nonfacial vein	Superior thyroid and lingual veins join together into the IJV
Separation	Lingual and superior thyroid veins fuse independently with the IJV

Note:—ECA indicates external carotid artery; IJV, internal jugular vein.

available option. Both rat microsurgery studies and human vascular surgery studies have shown no differences in patency rates between end-to-end and end-to-side anastomoses.[34-36] As the number of procedures and surgical approaches evolve, selection criteria will vary among surgeons, based on personal preferences and complex patient and donor presentations.

Surgical Controversies

There are 3 main controversies in face transplantation that influence preoperative CT acquisition and interpretation.

1) Is One Arterial Anastomosis Sufficient for Perfusion of a Full Face Allograft?

Increasing evidence suggests that 1 arterial anastomosis may be sufficient for tissue perfusion.[8,9,37] However, bilateral single arterial anastomoses are prudent to minimize the risk of flap ischemia due possible anastomotic complications (blood clot, stenosis, and vascular compression from head rotation). Thus, as noted in the image reformation section below, arterial maps should include all potential major branches from the external carotid system because of scar tissue and the potential for unexpected vascular findings at surgery.

2) Can the Facial Artery Alone Perfuse the Maxilla?

Cadaveric studies have suggested that the facial artery cannot adequately perfuse the maxilla.[9,17] However, there is accumulating evidence that the facial artery can adequately perfuse both the entire maxilla and the mandible anteriorly from the insertion of the masseter muscle.[37,38] A successful, defined by improved esthetic and functional outcome after surgery, facial transplantation suggests that the facial artery alone can perfuse a midfacial allograft that includes the maxilla.[8]

3) Should Bilateral External Carotid Artery Anastomoses Be Performed?

We are cautious regarding bilateral end-to-end anastomoses because there is a presumed increased risk of ischemia in certain external carotid territories such as the hypopharynx.[8] On the other hand, Meningaud et al[9] have reported bilateral end-to-end external carotid artery anastomoses,[7] suggesting that this is often the best option because of sufficient arterial length for cervical connections and the large diameter that is safer for anastomosis. Of note, these reports[7,9] did not specify the exact location of the anastomoses, and the relationship to the lingual artery (ie, proximal or distal) was not clear. Although experience to date with bilateral external carotid artery anastomoses is largely anecdotal, there is a recognized risk of catastrophic ocular ischemia from

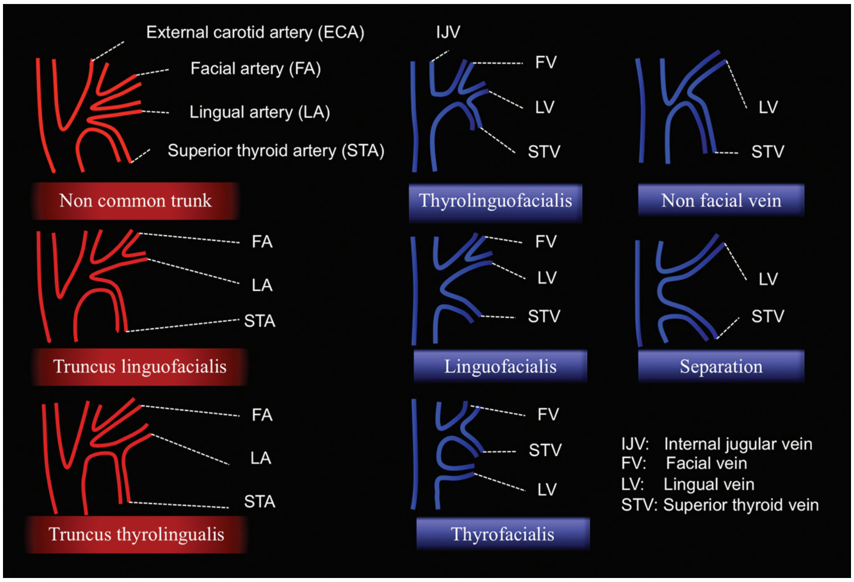

FIG 5. Major variations in branching patterns of the external carotid artery (3 types) and variations of the confluence of the facial, lingual, and superior thyroid veins with the internal jugular vein (5 types), described by Shima et al.[24] Descriptions of each variation are found in the Table.

anastomosis between the external carotid and the ophthalmic arteries.[39] Alizai et al[40] reported 2 cases of ocular ischemic syndrome due to bilateral external carotid artery occlusion.

IMAGING FOR PREOPERATIVE SURGICAL PLANNING

Rationale

We hypothesize that meticulous vascular mapping can reduce the procedure time, similar to results in breast reconstruction, by using abdominal perforator flaps[41] and anterolateral thigh flaps.[42] We also postulate that catastrophic iatrogenic vascular injury can be avoided with CTA and careful surgical planning. Of note, Liu et al[42] demonstrated that preoperative CTA for patients undergoing an anterolateral thigh flap was associated with a significant reduction in major surgical complications, as well as the length of surgery and the need for a secondary debulking procedure. A shortened operation time enhances patient safety. Finally, although details regarding imaging and surgery related to bone allografts or prostheses are beyond the scope of this review, 3D and 2D reformatted CT is the best technique[43] to provide accurate assessment of severe bone defects,[37,38] facilitating 3D understanding of skeletal stability, rotation, and displacement of bony fragments. Volumetric CT also enables 3D cephalometric measurements and creation of physical models of bones, which can be used for designing or improving bone allografts or prostheses.

CT Image Acquisition

Presurgical vascular mapping is challenging because the vessels are small, the FOV must be large enough to include the full extent of the external carotid artery and those branches that could be used for anastomoses, and there may be substantial metal artifacts (implants and shrapnel). In addition, patients are generally young, and thus cumulative radiation doses are a concern, particularly because both arterial and venous maps are needed.

At our institution, all surgical-planning CT images[23] are acquired axially with 320 × 0.5 mm detector row CT (Aquilion One; Toshiba Medical Systems, Tochigi-ken, Japan), which covers the entire FOV,[44] to enable multiple phases by using intermittent dynamic volumes with a 0.75-second gantry rotation. The protocol (Fig 6), initially developed[45] for brain perfusion, includes pure arterial and venous volumes for input to postprocessing software. For patients with at least partial vision, the gantry is angulated to limit radiation to the orbits; and regarding the inferior aspect of the FOV, care is taken to limit radiation to the thyroid,[46] usually by limiting the craniocaudal coverage to 14 cm (280 × 0.5 mm detector row acquisition).

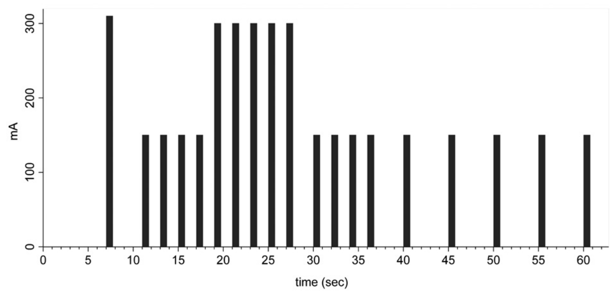

FIG 6. Timing diagram for a 320–detector row CT acquisition for face transplantation candidates. Each bar refers to 1 phase of the multiphasic axial acquisition; each volume includes the entire anatomy required for surgical planning.

The contrast injection is timed by using a 20-mL test bolus to time the dual (EmpowerCTA; ACIST Medical, New York, New York) main injection (60-mL iopamidol, 370 mg I/mL, Isovue-370; Bracco Diagnostics, Princeton, New Jersey), followed by 40-mL normal saline.

CT Image Postprocessing

Volume rendering illustrates the spatial relationships between skin, soft tissues, vessels, and bones (Fig 7). Vascular overlays show the presurgical orientation of different facial structures (Fig 8) that are important for planning the dissection.

There are several considerations related to the anastomoses.

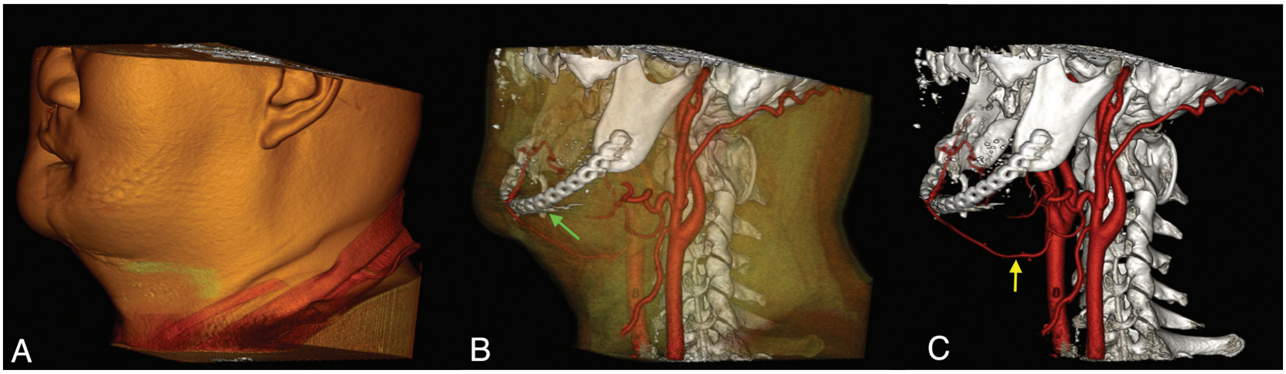

FIG 7. Candidate for full face transplantation. *A*, Volume-rendered image including full soft tissues. *B*, Skin and superficial soft tissues have been shadowed. This view depicts the relationship of the bones, postsurgical hardware (green arrow), and segmented arteries. *C*, Volume rendering that exclusively shows the bones, postsurgical hardware, and arteries. The superior thyroid artery (*yellow arrow*) is used for the anastomosis of free flap, and its surgically altered course is demonstrated.

FIG 8. Face transplantation candidate shown with fusion of the preoperative photograph and CT venography images. Meticulous CT segmentation and feature mapping are used to depict preoperative structures critical for rapid, precise, surgical dissection.

The course and branches of the external carotid artery should be documented. In our experience, it is important to map and annotate the facial, superior thyroid, lingual, and superficial temporal arteries (Fig 3*B*) because these are common targets for recipient vessels. Although there is often a close correlation between arteries and veins, venous drainage does not always parallel arterial territories.[16] While the use of the external jugular and facial veins has been reported, there is a rich venous network, and preoperative imaging should include venous enhancement to identify all veins, including the anterior jugular vein, internal jugular vein, and vein grafts from prior procedures. Imaging characterization includes patency, diameter, and variation. Vascular diameters are essential for surgical planning, and manual correction of vessel segmentation is required. Specifically, caliber changes and specific branching patterns must be meticulously illustrated to minimize the risk of complications and provide secondary and tertiary surgical options.

Regarding shrapnel, metal implants from prior reconstruction, and bone fragments from initial trauma, postprocessing considerations include the 3D spatial relationships of blood vessels and neighboring structures and the presence of artifacts. Multiplanar reformation, maximum intensity projections, and volume rendering define the 3D spatial relationships of blood vessels and neighboring structures. We routinely use multiobject segmentation (Vitrea fX 6.0; Vital Images, A Toshiba Medical Systems Group Company, Minnetonka, Minnesota) to portray the spatial relationships (Fig 9*B*). Metal artifacts can limit the assessment of blood vessels, though these artifacts are generally less severe than those in corresponding MR images.[47]

4D volumes (3 spatial planes plus time) enable cine (Fig 3*C*) assessment of small-caliber vessels similar to that described in the lower extremity.[48] The drawback of multiphase CT is increased radiation exposure in comparison with fewer phases that could, in theory, give the same static information. However, preoperative acquisition of multiple phases largely ensures that essential pure arterial and venous images are available for postprocessing and interpretation. As in other high-flow body parts,[48] the timing for separation of small arteries versus veins can be challenging, particularly if there are unexpected findings such as a postinjury or postoperative fistula or asymmetric blood flow from injury or previous reconstructive surgeries. Thus, we advocate multiphase imaging, keeping in mind that the risks associated with life-long immunosuppression and the operation itself are far greater than those from surgical planning vascular CTA.

Future Directions

For most vascular mapping applications before transplantation,[49,50] CT angiography has replaced invasive conventional angiography. The challenges for CT, namely small-caliber vessels, rapid transit time, and metal artifacts, also pose challenges for advanced MR imaging acquisitions. For face transplantation candidates, initial comparisons between time-resolved imaging[51,52]

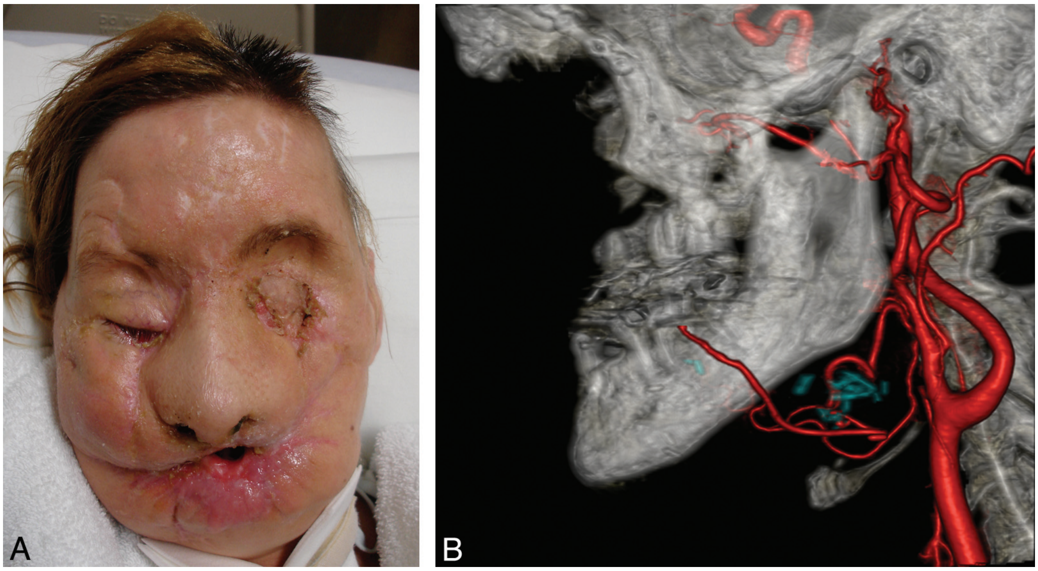

FIG 9. Candidate for full face transplantation who was attacked by a chimpanzee. *A*, Photograph of the victim after multiple conventional reconstructive surgeries for catastrophic facial injury, demonstrating the limitation of conventional surgical options. *B*, Volume-rendered reformations of CT images by using multiobject segmentation to rapidly communicate information to the surgical team. In red, the arteries, including the course of right facial artery, are clearly demonstrated. The facial artery was used for the anterolateral thigh flap immediately after the injury. The anastomosis can be identified via surgical clips rendered in green.

suggested the superiority of CT when compared to MR.[47] Moreover, axial wide-area-detector CT protocols provide datasets amenable for future studies of tissue perfusion after surgery and in the clinical setting of tissue rejection.

MR angiography is an attractive alternative for follow-up studies, particularly in patients with few metallic implants and thus relatively low susceptibility artifacts. For suspected complications, specialized imaging such as diffusion-weighted sequences for allograft function[53] and high-resolution vessel wall sequences[54,55] for rejection can be performed. These can be complementary to 3D high-spatial-resolution MR angiography and time-resolved sequences for arterial and venous separation.

CONCLUSIONS

Face transplantation is now accepted as the only option for the most complex craniofacial reconstruction. With initial technical successes, the number of patients will continue to increase, emphasizing the need for radiologists to understand the surgical relevance, preoperative arterial and venous mapping, and current controversies regarding vascular anastomoses. Face transplantation candidates require complex CT protocols to depict arterial and venous imaging of the external carotid arteries and veins, their branches, and changes from severe facial injuries and prior attempts at reconstruction. The complexity of this process is reflected in the technical challenges of image acquisition and interpretation in patients with unexpected anatomy from severe deformity and prior surgical reconstructions. Meticulous communication between radiologists and surgeons related to vascular anastomoses will facilitate preoperative planning and optimization of the surgical technique.

Disclosures: Ericka Bueno—*RELATED*: Department of Defense,* *Comments*: U.S. Department of Defense research contract with my institution (Contract W911QY-09-C-021). David Enterline—*UNRELATED*: *Consultancy*: Bayer Healthcare, DFine Inc, *Grants/Grants Pending*: Siemens Healthcare,* Guerbet Group,* *Payment for Lectures (including service on Speakers Bureaus)*: Bayer Healthcare, Bracco Diagnostics, *Stock/Stock Options*: Pioneer Surgical Technology, Medical Simulation Corp. Frank Rybicki—*RELATED*: *Grant*: United States Department of Defense,* Contract W911QY-09-C-021; grant support to the institution from Toshiba Medical Systems Corp. and Bracco Diagnostics. *Money paid to the institution.

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