Craniofacial transplantation: seeing the whole picture

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Facial transplantation represents a paradigm shift in reconstructive plastic surgery. Tagliacozzi wrote of plastic surgeons that, “We restore, rebuild, and make whole those parts which nature hath given, but which fortune has taken away. Not so much that it may delight the eye, but that it might buoy up the spirit, and help the mind of the afflicted” [1]. At the time, reconstructive efforts could only make use of ‘spare parts’ found within the patient’s body in the form of flaps and grafts. The advent of facial transplantation eliminates donor-site limitations and introduces the prospect of restoring injured anatomy by replacing it with an ideal part from a donor. As these procedures are being performed with increasing frequency, dramatically more complex defects are being addressed. Just as facial transplantation evolved as a culmination of multiple pre-existing principles of plastic surgery and other disciplines, adequate imaging for these procedures, arguably some of the most complex of all surgical undertakings, demands that we look at visual data from a new perspective. We must take the best existing imaging techniques and synthesize them into a novel way of looking at patients. Here, we explore some of the imaging modalities presently most promising in this context, and offer a glimpse of what is to come as we learn to look at the face in an entirely new way.

The face is best thought of as a soft-tissue envelope resting on its rigid foundation, the craniofacial skeleton. Regardless of whether or not skeletal elements are being transplanted, the craniofacial skeleton must be precisely understood in any face transplant procedure as its contours and irregularities will ultimately define the appearance and function of the soft tissues to whom it gives shape. While 3D CT has come to offer a now indispensable view of a patient’s bony anatomy, the data is generally postprocessed by a radiologist or technician such that a series of 2D images of the 3D anatomy are played in sequence to produce a ‘flip-book’ of the anatomy rotating in 3D. The surgeon’s interaction with this model is limited to paging through 2D images; the surgeon cannot directly interact with the model. 3D CT can also offer a virtual view of a patient’s skin by setting windows for soft-tissue density display instead of bone density display. These contour maps, however, are grayscale and generally limited to the same lack of interactivity in their present formulation as their bony counterparts.

Fortunately, topographically accurate models of facial skin envelopes, complete with photorealistic texture mapping, can now be consistently obtained with commercially available hardware and software [2]. One of the most popular methodologies is stereophotogrammetry. The polygonal meshes generated from these scans are compatible with end user (surgeon) interaction.

The face is, of course, much more than skin and bones, and donor and recipient anatomy must be understood as such for the successful completion of a face transplant. Myriad imaging technologies are evolving to facilitate the visualization of the other structures critical to facial transplantation. 3D CT angiography (3D CTA) has been validated in accurately predicting perforator location in scenarios demanding precise anatomical foresight, as in designing chimeric flaps for complex facial reconstruction [3]. This technology is also increasingly utilized in planning perforator-based breast reconstructions, significantly reducing harvest time [4]. Vetted in these more traditional settings, 3D CTA offers a degree of anatomical precision especially important in planning microvascular anastomoses in...
the context of the "significant postoperative scarring and recipient vessel depletion" present in many potential face transplant recipients [5]. While 3D CTA delivers outstanding visualization of arteries and veins for anastomotic planning [6], like 3D CT, standard 3D CTA data is not routinely compatible with surgeon interaction.

The nerves that provide sensory and motor supply to the facial tissues must also be accounted for in designing the optimal face transplant. Toward this end, reconstructive surgeons can turn to tractography, a nascent technology initially designed to image neural pathways in the brain. Early studies indicate that these protocols can be translated to human peripheral nerve imaging [7,8]. Not only does this modality illustrate neural anatomy, but it is selective for viable neural tissue, making it ideal for tracking nerve regeneration after transplantation [9]. Moreover, the data generated with this modality correlates well with histological and even functional findings in a rodent model [10].

Looking at presently available imaging modalities, then, it is clear that we can image the majority of the tissues essential to successful facial transplantation with a great degree of consistency and detail. To unleash the true power of these technologies, two critical advances must occur. First, the data produced must be translated into a form that is compatible with real-time end-user interaction and modification. The utility of this development is well illustrated by the application of 3D printing to craniofacial surgery. Physical models of 3D CT data are printed by serial deposition of a modeling compound (i.e., stereolithography), and mock operations can be performed on the resulting models.

3D printing has been quite useful in planning complex movements of craniofacial bones. In orthognathic surgery, for example, the technique demonstrates where skeletal gaps will be present and allows for the creation of bone grafting templates that can be brought into the operating room when the procedure is performed [11]. 3D printing has also found applications in the design of osseous free flaps, where bone cutting guides are prefabricated to direct intraoperative osteotomies [12]. In other complex craniofacial procedures, such as facial bipartition for the correction of hypertelorism, model surgery simulates how movement of one part of the craniofacial skeleton (inferior orbital rims) affects another region (occlusal plane) [13].

3D printing has reduced operative times and improved outcomes [14,15]. Specifically, virtual planning decreases traumatic graft modification, decreases ischemia time, and ultimately improves bony contact and minimizes non-union [16]. Rose put it well when he wrote, "In complex facial puzzles ... the availability of a precise model at the time of surgery is invaluable in exact carving of the difficult spatial geometry of the bone grafts. That degree of precision saves us substantial amounts of time in 'nibbling, nip-picking, and fussin' around' to achieve the right size and shape of the bone graft" [17]. Consider the convenience of performing model surgery in virtual reality, free from the constraints of physical models. Early iterations of systems providing this functionality are promising, but missing an essential component.

This essential component is the second of the two 'critical advances' noted above: the vast amounts of imaging data available to the reconstructive surgeon must be integrated into a single 3D representation of recipient and donor anatomy. Individually, each imaging modality produces a valuable, but fundamentally incomplete, picture of the patient. No procedure has ever demanded such a complete representation of patient anatomy as facial transplantation.

It is in this context that we recently introduced a workflow, Visual Data Integration, which integrates data from multiple imaging sources into a single 3D representation of anatomy that supports real-time user interaction and modification [10]. This work draws from previous research in which Hollywood industry-standard computer graphics software (Autodesk® Maya®, Autodesk, Inc., CA, USA) was used to generate photorealistic polygonal meshes of craniofacial anatomy that could be freely manipulated in 3D space to illustrate important anatomical concepts and surgical principles [18–20]. In these studies a combination of cadaveric cross-sections, CT data, anatomical dissection, and literature review was used to construct an idealized model of craniofacial anatomy designed to clearly portray structural relationships. The resulting 3D models served as accurate anatomical references and were compatible with real-time user modification, but did not portray any one individual's anatomy.

Visual Data Integration, alternatively, is designed to incorporate a single patient's imaging data from disparate platforms into a single 3D photorealistic representation of all relevant aspects of that patient's anatomy. Data from each imaging modality (e.g., CT/CT angiography for bone, muscle and vasculature; tractography for nerve; stereo photogrammetry for skin) is
individual’s identity. Facial transplantation is a profound procedure with the potential to reverse once-irreparable facial damage. It is incumbent upon the reconstructive surgeon to intimately know his patient’s face from every perspective before he embarks upon its restoration. The methods described here may serve as a first step in this direction.

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■ Website