OPEN

PRS GLOBAL OPEN

ORIGINAL ARTICLE

Reconstructive

Computerized Approach to Facial Transplantation: Evolution and Application in 3 Consecutive Face Transplants

Elie P. Ramly, MD
Rami S. Kantar, MD
J. Rodrigo Diaz-Siso, MD
Allyson R. Alfonso, BS, BA
Eduardo D. Rodriguez, MD, DDS

Background: Face transplant (FT) candidates present with unique anatomic and functional defects unsuitable for autologous reconstruction, making the accurate design and transplantation of patient-specific allografts particularly challenging. In this case series, we present our computerized surgical planning (CSP) protocol for FT.

Methods: CSP, computer-aided design and manufacturing, intraoperative navigation, and intraoperative computerized tomography have been successfully incorporated into a comprehensive protocol. Three consecutive FTs were performed. CSP and postoperative results were compared using computerized tomography–derived cephalometric measurements, and the literature was reviewed.

Results: Two full and 1 partial FT were successfully performed using the CSP protocol. CSP facilitated the execution of FT with minor angular and translational cephalometric variations on immediate postoperative imaging. Our evolving experience was accompanied by a decreased reliance on cadaveric simulation, from 10 mock transplants and a research procurement before the senior author's first clinical FT (2012) to 6 mock transplants and no research procurement before the third FT (2018). Operative time was significantly reduced from 36 to 25 hours, as was the need for major orthognathic surgical revision. This reflects the learning curve and variable case complexity, but it is also representative of improved planning and execution, complemented by the systematic incorporation of CSP into FT.

Conclusions: A CSP protocol allows for refinement of operative flow, technique, and outcomes in partial and full FT. Standards for functional and esthetic outcomes are bound to evolve with the field's growth, and computerized planning and execution offer a reproducible approach to FT through objective quality assurance. *(Plast Reconstr Surg Glob Open 2019;7:e2379; doi: 10.1097/GOX.0000000000002379; Published online 19 August 2019.)*

INTRODUCTION

Face transplantation (FT) has evolved from the combination of craniofacial, microsurgical, and esthetic principles to deliver a comprehensive reconstructive solution for extensive composite facial defects not amenable to autologous reconstruction.[1] The 3-dimensional (3D) anatomy of the craniofacial skeleton and delicate soft tissue structures are in intimate functional relationship with the eyes, upper respiratory tract, and oral cavity, with important implications on facial esthetics and animation, speech, oral competence, and mastication. FT candidates present with unique defects that make accurate allograft design and transplantation particularly challenging.[2–8]

A standard systematic approach to FT has been developed by our team through cadaveric simulation and research allograft procurements with the successful completion of 3 clinical transplants.[5,6,9–13] The integration of surgical technology into both simulation and clinical FTs has played a pivotal role in achieving reliable results through efficient and accurate planning and execution.[14]

From the Hansjörg Wyss Department of Plastic Surgery, NYU Langone Health, New York, N.Y.

Received for publication May 17, 2019; accepted June 14, 2019.

DOI: 10.1097/GOX.0000000000002379

Disclosure: *Dr. Rodriguez has received speaker honoraria for unrelated activities from DePuy Synthes CMF and KLS Martin. None of the other authors has any financial disclosures. This work was supported by the Office of Naval Research (Grant N00014-10-1-0868), the US Department of Defense – Congressionally Directed Medical Research Programs (under Reconstructive Transplant Research Award W81XWH15-2-0036), and New York University Langone Health.*

Computerized surgical planning (CSP), computer-aided design and manufacturing (CAD/CAM), intraoperative navigation, intraoperative computerized tomography (CT), and formal and fluorescence angiography have been successfully incorporated into a comprehensive surgical approach to FT. Our longitudinal experience and lessons learned from the field have allowed us to leverage those technologies to customize our FT approach to a variety of complex scenarios while upholding patient safety.

This article describes our team's CSP protocol for FT through 3 consecutive clinical cases, with all 3 patients demonstrating satisfactory esthetic and functional outcomes at latest follow-up. The relevant literature is reviewed to provide context and insight.

METHODS

Patients and Procedures

Our FT program and quality improvement processes have been previously described in detail.[5,6,9–12,14–16] All research activities and clinical transplants were performed under Institutional Review Board approval, and this article conforms to the principles of the Declaration of Helsinki.[5,6,13] Patient authorizations for release of images and protected health information were obtained.

Three consecutive face transplants were performed by the senior author (E.D.R) (Table 1). Our CSP protocol for FT is presented in Figure 1. CSP and CAD/CAM, with or without intraoperative navigation and intraoperative CT, were incorporated in the preparatory cadaveric simulation and subsequent clinical transplant procedures to fit specific reconstructive needs in each scenario. Three-dimensional craniofacial CT data are first uploaded to a modeling software. This allows for the planning of donor and/or recipient osteotomies and the virtual superimposition of the donor allograft onto the recipient cranium for optimal skeletal alignment. Customized skeletal cutting guides are then designed, 3D-printed, and sterilized for timely delivery to the operating room. The CSP is then executed using the patient-specific cutting guides, with or without intraoperative navigation. Where appropriate, stereolithographic models are used to assist with modification of the skeletal interface and prebending of fixation plates before inducing ischemia. Allograft inset and rigid skeletal fixation are achieved in accordance with the CSP and confirmed using intraoperative or postoperative CT imaging. Before division of the donor vascular pedicles and after donor-to-recipient anastomoses, indocyanine green fluorescence angiography is used to confirm allograft perfusion and venous outflow (LifeCell SPY Elite Imaging System; LifeCell Corp., Branchburg, N.J.). A high fidelity mask is 3D-printed (LaGuardia Studio, New York City, N.Y.) from donor preoperative facial 3D images and fixed over the donor defect after allograft procurement. Alternatively, a silicone mask can be generated from preoperative facial impressions.[5,6]

Cephalometric Analysis

CT-derived cephalometric measurements were obtained including sella-nasion–A point angle, sella-nasion–B point angle, and Frankfort–occlusal plane angle from

Table 1. Characteristics of 3 Face Transplants

	Patient 1	Patient 2	Patient 3
Age, y (R/D)	37/21	41/26	25/23
Sex (R/D)	M/M	M/M	M/M
Initial injury, y	Self-inflicted GSW to the face, 1997	Full facial and total scalp burn injury while in the line of duty (firefighter), 2001	Self-inflicted GSW to the face, 2016
Extent of facial defect (R)	Forehead, eyelids, nose, cheek, lips, zygoma, maxilla, mandible	Scalp, forehead, eyelids, nose, cheeks, lower face, ears, lips, neck	Eyelids, nose, cheek, lips, maxilla, mandible, zygoma, right orbital floor
No. previous reconstructive procedures (R)	>20	>70	>10
Cadaveric simulation	10 cadaveric pairs	7 cadaveric pairs	6 cadaveric pairs
Cadaveric research procurements	1	1	0
Face transplant, y	Full, 2012	Full, 2015	Partial, 2018
Bones included in the allograft	Maxilla, zygoma, mandible	Nasal, genial, and orbitozygomatic skeletal segments	Maxilla, zygoma, mandible
D preoperative imaging	3D craniofacial CT	3D craniofacial CT, formal angiography	3D craniofacial CT, formal angiography
R preoperative imaging	3D craniofacial CT, formal angiography	3D craniofacial CT, formal angiography	3D craniofacial CT, formal angiography
Computerized surgical planning	Osteotomy planning Customized cutting guide design (R) Stereolithographic model (R specific)	Osteotomy planning Customized cutting guide design (D and R)	Osteotomy planning Customized cutting guide design (D and R) Stereolithographic model (R specific)
Intraoperative surgical navigation	Yes	No	Yes
Fluorescence angiography	Yes	Yes	Yes
Ischemia time	4h 26 min	3h 15 min	4h 35 min
Total operative time	36 h	25h 41 min	25 h

D, donor; GSW, gunshot wound; M, male; R, recipient.

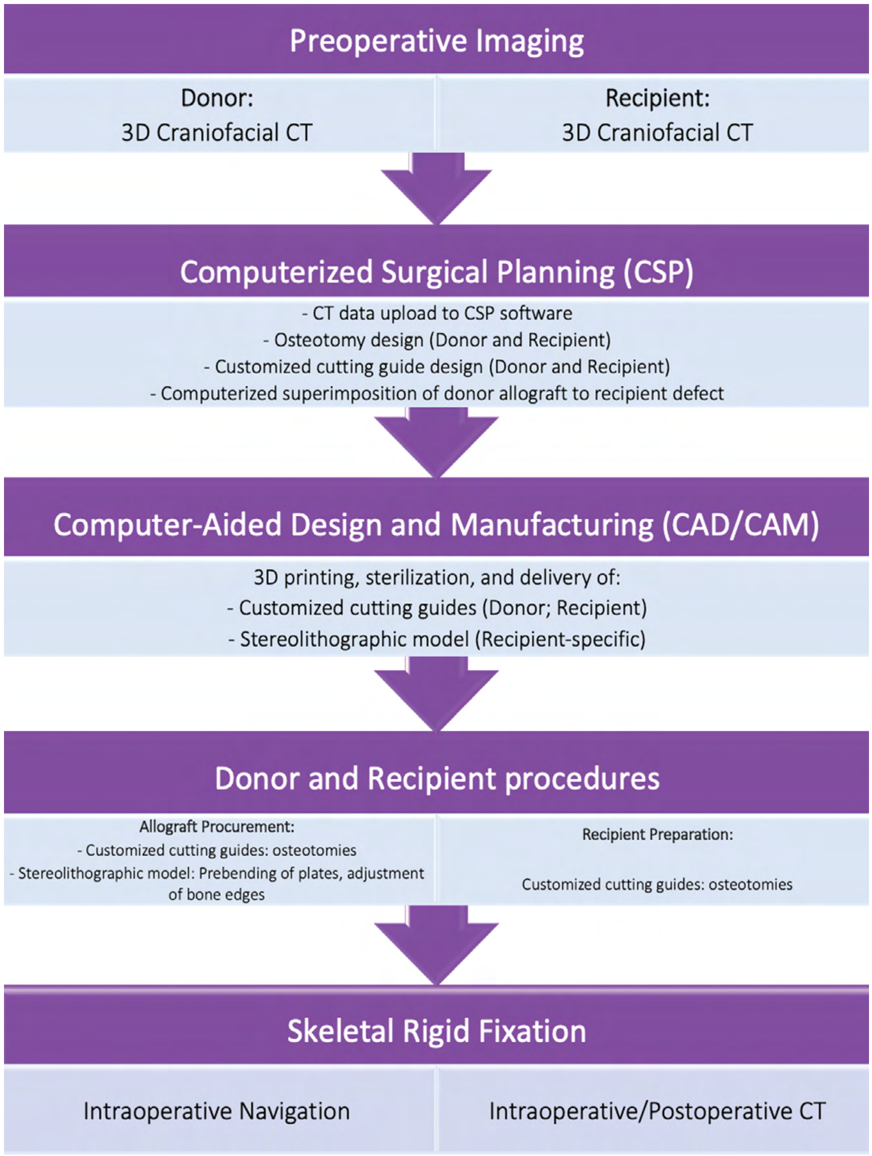

Fig. 1. CSP protocol for face transplantation. Certain elements of the protocol may be modified based on the specific clinical scenario. Printed with permission and copyrights retained by E.D.R.

preoperative CSP and postoperative imaging for patients 1 and 3. For patient 2, calculations to assess skeletal alignment were based on customized donor and recipient reference points. Angular, translational, and volumetric calculations were made to compare CSP data to postoperative actual results.

Literature Review

A comprehensive review of the literature was performed using PubMed with the following search terms: “face transplant” OR “facial transplantation” OR “face transplantation” OR “face allotransplantation” OR “facial allotransplantation” OR “face vascularized composite allotransplantation” OR “facial vascularized composite allotransplantation”; 708 articles were identified. Duplicates were removed. Non-English language articles, non–human studies, strictly cadaveric studies, review articles, and book chapters were excluded. Remaining titles and abstracts were screened, and all studies reporting on CSP in facial transplantation were included. If relevance could not be determined from the abstract alone, the full text was retrieved. References were also reviewed. The full texts of 9 articles were included.[5,6,8,13,17–21] Google search identified publications describing 4 additional face transplants mentioning aspects of CSP, including a conference abstract and 3 news publications.[22–25] Details relevant to CSP were collected including computerized preoperative planning and the use of CAD/CAM cutting guides. No quantitative comparative analysis was performed in view of the heterogeneity of the data collected.

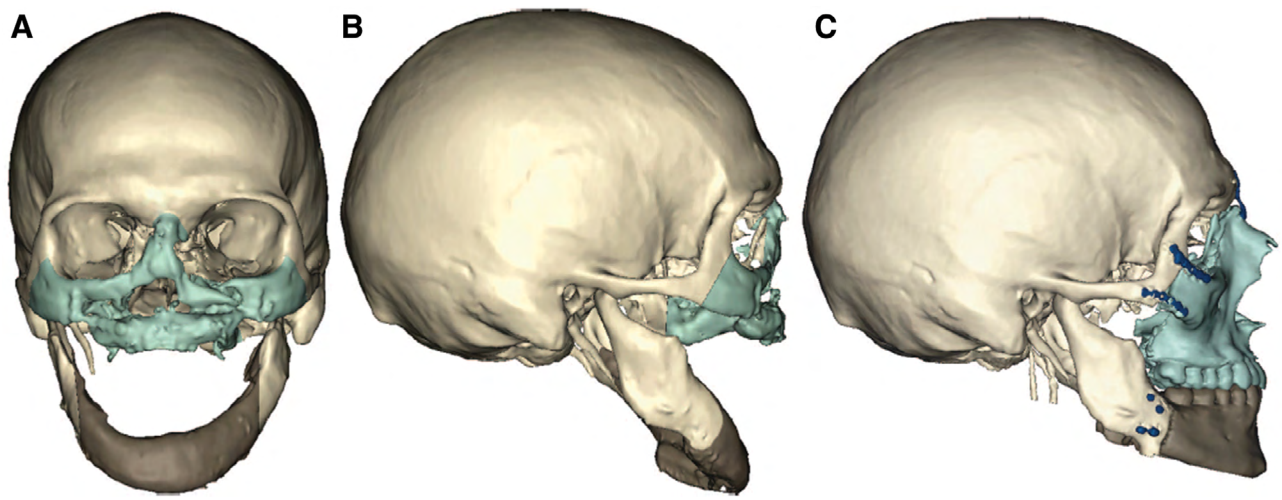

Fig. 2. Computed tomographic imaging of patient 1 before (A, frontal view, B, lateral view) vs. after face transplantation (C, lateral view). Printed with permission and copyrights retained by E.D.R.

RESULTS

Patient 1

Patient 1 is a 37-year-old man who had sustained a ballistic facial injury requiring over 20 major reconstructive procedures including 2 separate free fibula tissue transfers to his maxilla and mandible. A matching 21-year-old male donor with irreversible traumatic brain injury was identified. Total face, double jaw, and tongue transplantation was performed in March 2012[5] (Figs. 2–4).

Preoperative 3D craniofacial CT scan and formal angiography were performed. The donor underwent placement of titanium intermaxillary fixation screws (Synthes, Inc., West Chester, Pa.) to facilitate subsequent intraoperative surgical navigation (iNtellect Cranial Navigation Software; Stryker Navigation, Kalamazoo, Mich.), and CT data for both subjects were uploaded to the surgical modeling software [Synthes ProPlan CMF/SurgiCase Connect (Materialise, Leuven, Belgium)] for CSP. The donor and recipient facial skeletons were virtually superimposed, and osteotomies were planned. Recipient-specific cutting guides were prefabricated accordingly and sterilized for operative use.

The CSP was then executed, beginning with donor allograft procurement.[5,9,11] Bilateral mandibular sagittal split osteotomies were performed. Donor Le Fort III osteotomies were guided by intraoperative navigation (iNtellect Cranial Navigation Software). Before division of the vascular pedicles, the donor maxillary segment was tailored to a stereolithographic model representing the planned recipient skeletal resection. Recipient osteotomies were performed using the prefabricated cutting guides, and rigid skeletal fixation was performed.[5] The postoperative CT scan was noted to match the preoperative CSP with minimal variations (Table 2).

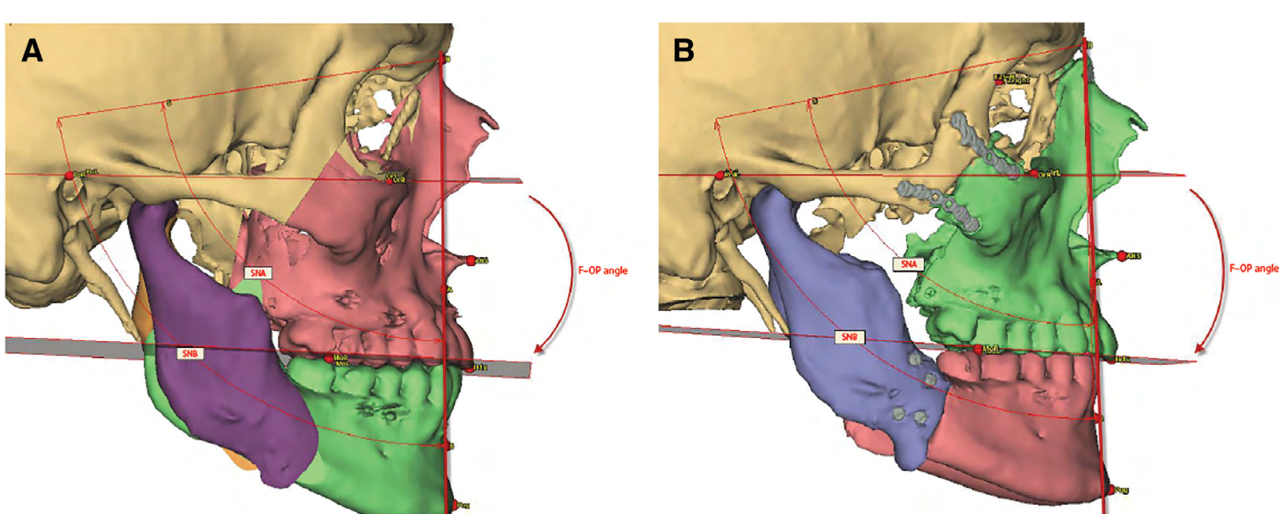

Fig. 3. CSP for patient 1. A, Lateral view, CSP before transplantation. B, Initial postoperative CT scan results. F-OP angle indicates Frankfort–occlusal plane angle; SNA, sella-nasion-A; SNB, sella-nasion-B. Printed with permission and copyrights retained by E.D.R.

Fig. 4. Patient 1 before (A) and 4 years and 2 months (B) following total face, double jaw, and tongue transplantation. Printed with permission and copyrights retained by E.D.R.

Table 2. Patient 1: Cephalometric Data for Preoperative Computerized Surgical Plan, Posttransplant Results, and Postskeletal Revision Results

						Postskeletal Revision	
	Predicted	Posttransplant (POD1)	Difference (Predicted – Posttransplant POD1)	Posttransplant (POD 148)	Difference (Predicted – POD 148)	POD 190 (Postrevision POD 1)	Difference (Predicted* – Postrevision)
SNA	81.73	83.18	−1.45	82.54	−0.81	86.99	−5.26
SNB	82.21	86.02	−3.81	88.31	−6.1	86.45	−4.24
Frankfort–OP angle	2.4	3.17	−0.77	2.98	−0.58	5.09	−2.69

All values are reported in degrees.
*Refers to pretransplant CSP.
OP, occlusal plane; SNA, sella-nasion-A; SNB, sella-nasion-B.

On postoperative day (POD) 1 following FT, the patient was in normal class I occlusion, in accordance with the surgical plan. He subsequently gradually developed class III malocclusion [**see figure, Supplemental Digital Content 1,** which demonstrates computed tomography of patient 1 before (A) and after (B) Le Fort III advancement performed on posttransplant day 189 for class III malocclusion, ***http://links.lww.com/PRSGO/B177***]. By POD 148, sella-nasion–A point angle had changed by −0.64 degree, sella-nasion–B point angle by 2.29 degrees, and the Frankfort–occlusal plane angle by −0.19 degree. After failed orthodontic management, a revisional Le Fort III advancement was performed on POD 189 using CSP. The midface was advanced to meet the mandible in class I occlusion without altering the existent mandibular position and temporomandibular condyle–fossa relationship.[26] Maxillomandibular fixation was applied and bicortical fixation was achieved at each zygoma body and at the nasofrontal region with parietal calvarial bone grafting into the osteotomy sites. Cephalometric measurements on POD 190 revealed a sella-nasion–A point angle of 86.99 degrees, sella-nasion–B point angle of 86.45 degrees, and a Frankfort–occlusal plane angle of 5.09 degrees[26] (Table 2).

Patient 2

Patient 2 is a 41-year-old male firefighter who had sustained a full facial and total scalp burn injury in 2001 while in the line of duty. He underwent over 70 reconstructive procedures before total face, eyelids, ears, scalp, and skeletal subunit transplantation in August 2015[6] (Figs. 5–6). The donor was a matching 26-year-old man with irreversible traumatic brain injury. Both the recipient and donor underwent 3D craniofacial CT scans and formal angiography.

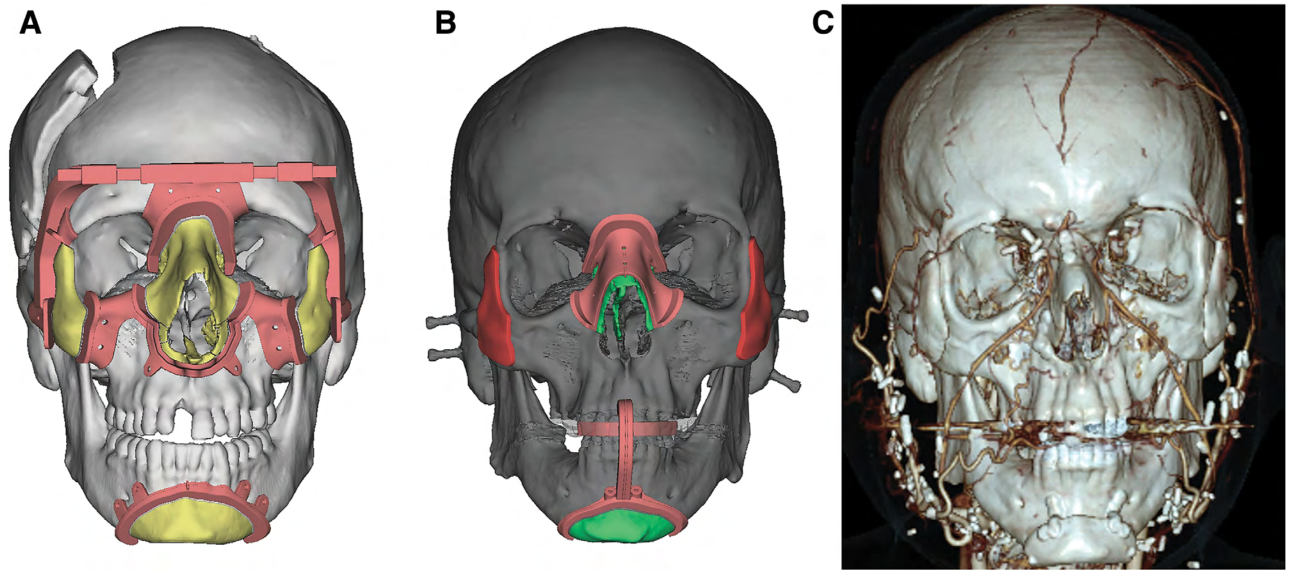

Fig. 5. Computerized surgical planning for patient 2. A, Donor planned osteotomies and customized cutting guides. B, Recipient planned osteotomies and customized cutting guides. C, Postoperative 3D computed tomographic imaging for patient 2 on postoperative day 32, showing the nasal, mandibular, and bilateral zygomatic skeletal subunits included in the allograft. Printed with permission and copyrights retained by E.D.R.

Fig. 6. Patient 2 before (A) and 2 years (B) following total face, eyelids, ears, scalp, and skeletal subunit transplantation. Printed with permission and copyrights retained by E.D.R.

The CT data were uploaded to a surgical modeling software system (Medical Modeling, Inc., Golden, Colo.), and CSP was initiated (Fig. 5A). Orbitozygomatic skeletal tangential osteotomies were designed along a steep angle to a superficial coronal plane, and a genioplasty osteotomy was planned. Donor facial skeletal subunits were virtually superimposed onto the recipient-planned osteotomies. Cutting guides were designed, prefabricated, and sterilized for operative use. Recipient preparation, allograft procurement and transfer, and rigid skeletal nasal, mandibular, and bilateral zygomatic subunit fixation were performed.[6,10,12] Postoperative CT was performed on

Table 3. Patient 2: Translational and Volumetric Differences Between Preoperative Computerized Surgical Plan and Posttransplant Results on POD 8

Parameter	Difference (Predicted – Posttransplant, POD 8)
Translation (mm)	
Nasal segment	1.67*
Genial segment	0.78*
Volume (mm^3)	
Nasal segment	151
Genial segment	–493
Left zygoma	–218
Right zygoma	–448

*Average difference, calculated as the mean of the differences between predicted and actual results at 4 reference points on each donor skeletal segment relative to the recipient skeletal fixation bed (See Figure, Supplemental Digital Content 2).

POD 8 to evaluate adherence of the surgical outcomes to the preoperative CSP and demonstrated mean positional differences ranging 0.78–1.67 mm and volumetric differences ranging 151–493 mm^3 (Table 3) (**see figure, Supplemental digital content 2,** which demonstrates patient 2. Computerized representation of translational movements of the allograft's skeletal elements in relation to the recipient skeleton. Distances are measured at 4 reference points on each skeletal element of the allograft relative to the recipient skeleton. Averages are calculated and compared between the CSP and postoperative CT results, ***http://links.lww.com/PRSGO/B178***).

Patient 3

Patient 3 is a 25-year-old man who had sustained extensive ballistic facial injury in June 2016, requiring multiple procedures including maxillary, mandibular, zygomatic, and right orbital floor open reduction and internal fixation with debilitating functional deficits and exposed hardware. In preparation for FT, the patient underwent hardware removal, bilateral naso-orbito-ethmoid osteotomies, medial canthal tendons repositioning, and bilateral orbital floor reconstruction with alloplastic titanium implants. A matching 23-year-old male brain-dead donor was identified, and partial face and double jaw transplantation was performed in January 2018[13] (Figs. 7–9).

Three-dimensional craniofacial CT scans and formal angiography were obtained for both subjects. The donor CT was obtained after performing dental impressions and placing titanium skeletal anchorage screws. CT data were uploaded to the surgical planning software (ProPlan CMF; Materialise, Inc., Plymouth, Mich.) (Fig. 7) (**See Video [online],** which demonstrates patient 3. Preoperative CSP for partial face and double jaw transplant). Osteotomies were planned, and customized donor- and recipient-specific cutting guides were designed, 3D-printed, and sterilized.

Bilateral mandibular sagittal split and Le Fort III osteotomies in both the donor and recipient were completed based on the preoperative CSP and using the prefabricated cutting guides. The donor maxillary segment was tailored to a stereolithographic model of the planned recipient skeletal defect. The dentition was placed in a prefabricated dental splint, and the previously placed maxillary and mandibular anchorage screws were used to secure the occlusion. Intraoperative navigation was used to confirm appropriate position of the skeletal segments (Brainlab, Inc., Chicago, Ill.). Rigid fixation of the allograft was completed at the bilateral zygomatic bodies and mandibular segments. Intraoperative and postoperative CT scan on POD2 confirmed allograft positioning and skeletal contact (Fig. 8); sella-nasion–A point angle was 83.3 degrees, a difference of −6.2 degrees from preoperative CSP, sella-nasion–B point angle was 81.8 degrees, a difference of −7.1 from CSP, and the Frankfort–occlusal plane angle was

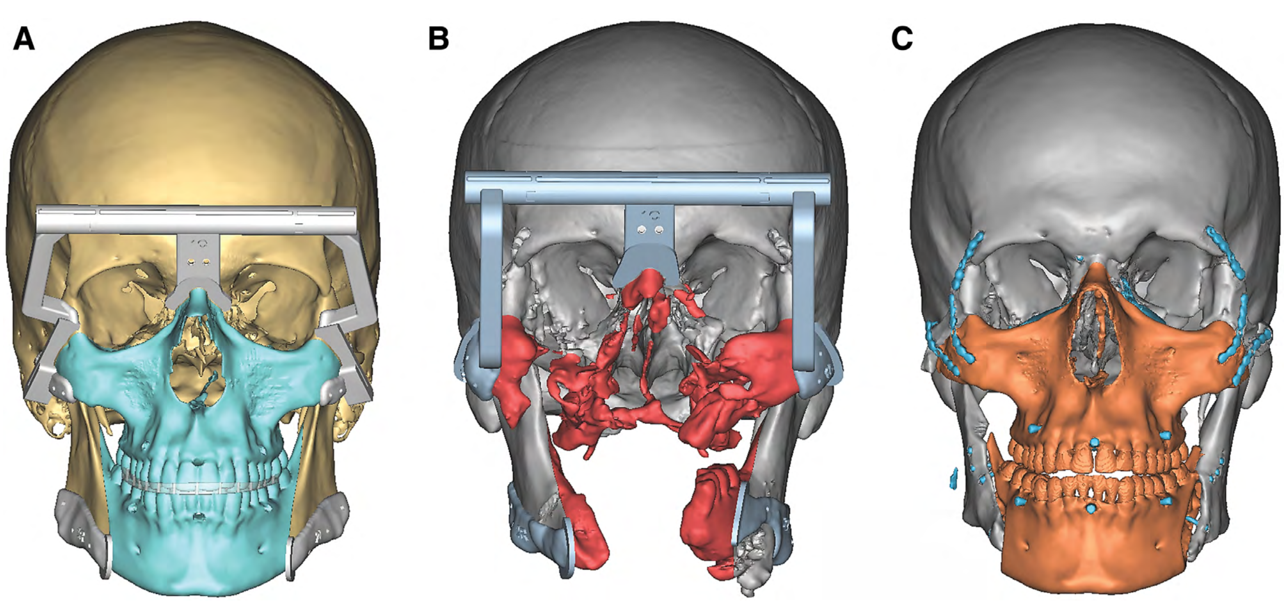

Fig. 7. Computerized surgical plan for patient 3. A, Donor planned osteotomies and customized cutting guides. B, Recipient planned osteotomies and customized cutting guides. C, Postoperative CT imaging result. Printed with permission and copyrights retained by E.D.R.

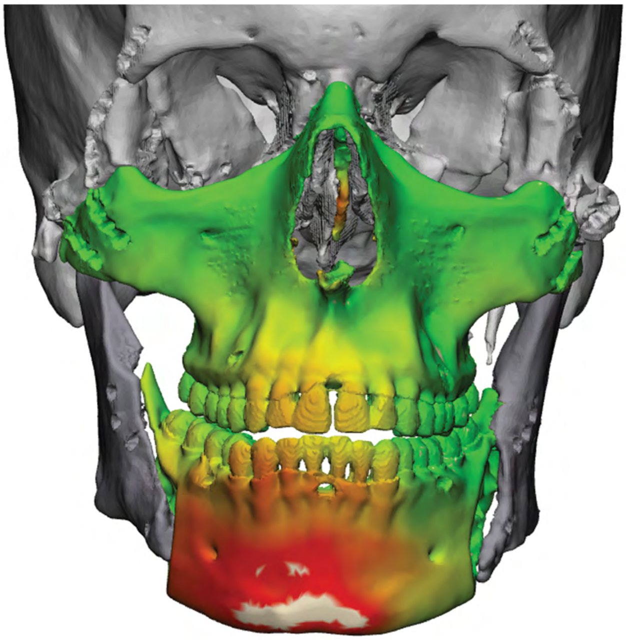

Fig. 8. Patient 3. Representative heat map analysis of planned vs. actual positions of allograft skeletal segments in the recipient. Spectrum ranges from green (smallest difference) to red (largest difference). Printed with permission and copyrights retained by E.D.R.

3.5 degrees, a difference of 8.3 from CSP (Table 4). On POD 11, the patient underwent hyoid and genioglossus advancement for floor of mouth dehiscence and palatal wound dehiscence repair. Despite normal occlusion at the conclusion of FT, he developed class II malocclusion and an open bite. Orthodontic treatment was initiated with successful correction of the occlusion by 10 months post-FT. On POD 108, he underwent left coronoidectomy and open reduction and internal fixation of left mandibular nonunion with appropriate recovery.

DISCUSSION

Forty-four procedures performed in 43 patients have established the feasibility of FT as a comprehensive reconstructive solution for patients with composite defects not amenable to satisfactory autologous reconstruction.[1,27,28] The procedure continues to adapt to increasingly complex clinical scenarios, with opportunities for improvement in technical, functional, and esthetic outcomes. CSP and CAD/CAM technology have been adopted in craniomaxillofacial surgery including oncologic reconstruction, craniosynostosis, and implant-based procedures.[29,30] CSP allows for increased accuracy and decreased intraoperative time and decision-making despite potential limitations in cost and availability.[29,30] Detailed reports of CSP use in FT are scarce. Our overall evolving experience with FT planning and execution has resulted in a gradual decrease in reliance on cadaveric simulation, from 10 mock transplants and a research procurement before the senior author's first FT in 2012 to 6 mock transplants and no research procurement before the third FT in 2018. Additionally, our systematic incorporation of CSP into FT has allowed for improved operative efficiency and accuracy by providing valuable information to supplement intraop-

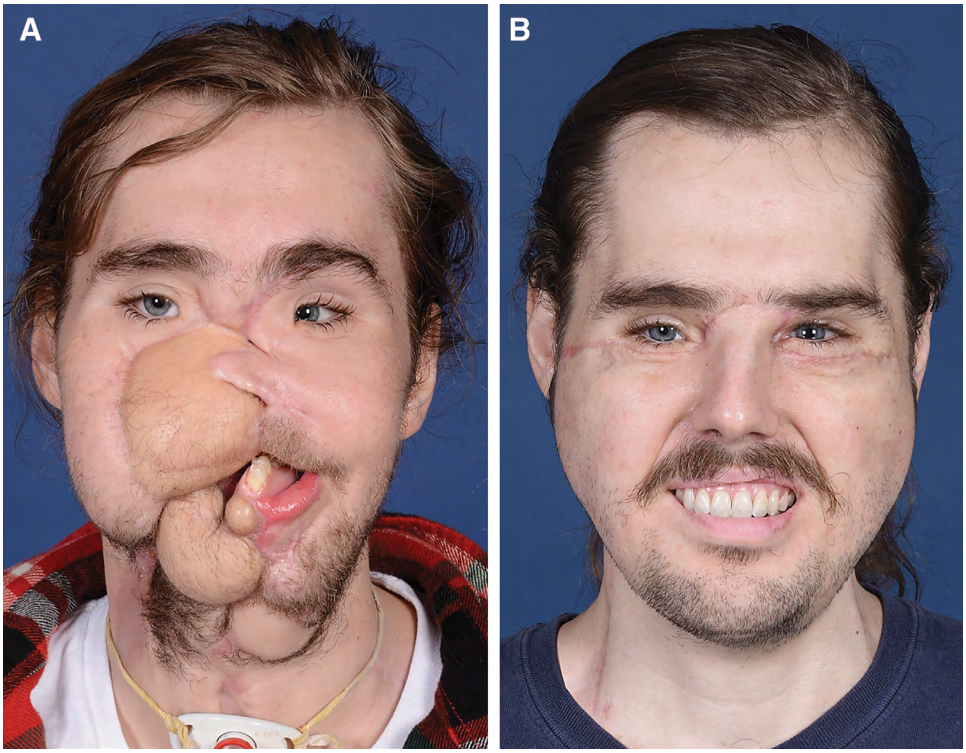

Fig. 9. Patient 3 before (A) and 9 months (B) following partial face and double jaw transplantation. Printed with permission and copyrights retained by E.D.R.

Table 4. Patient 3: Cephalometric Data for Preoperative Computerized Surgical Plan and Posttransplant Results on POD 2

Cephalometric Parameter	Predicted	Posttransplant	Difference (Predicted – Posttransplant, POD 2)
SNA	77.1	83.3	−6.2
SNB	74.7	81.8	−7.1
Frankfort–OP angle	11.8	3.5	8.3

All values are reported in degrees.
OP, occlusal plane; SNA, sella-nasion-A; SNB, sella-nasion-B.

erative decision-making. It has also allowed for improved communication and a more objective evaluation of surgical outcomes based on cephalometric analysis.

Since the first case in 2005, FT teams have used magnetic resonance imaging and/or 3D CT scans for preoperative evaluation. Devauchelle et al[17] delineated the contour of their allograft based on a rigid metallic pattern manufactured on the recipient to match the exact dimensions and shape of the defect. In 2008, Siemionow et al[8,18] used a defect template they had pretested in mock cadaveric FTs to facilitate allograft procurement. Reconfirmation of the 3D graft architecture and size was performed using a stereolithographic model based on the patient's CT. Pomahac et al[19] used a 3D skull model to plan donor zygomatic osteotomies corresponding to the anticipated recipient defect. In 2011, Roche, Blondeel, and colleagues used CSP software and 3D-printed cutting guides in a partial FT in a 54 year-old man with ballistic injury.[20] For CSP and cutting guide prefabrication, the team used 3D CT images of the patient and his son (chosen for morphologic resemblance) rather than the actual prospective donor. This was due to concerns that donor-derived CSP and printing of customized cutting guides would be time consuming in a potential scenario of hemodynamic instability interfering with the procurement of vital organs. After planning of osteotomies, cutting guides and models of the recipient's missing facial bones were 3D-printed. The patient had class II malocclusion posttransplantation.[20]

Our protocol includes both recipient and donor CT data for CSP and CAD/CAM. The process was optimized and quantitatively evaluated through cadaveric simulation before successful translation to the clinical setting. Patients 1 and 3 received maxillomandibular transplants. For patient 1, recipient-specific cutting guides were generated while intraoperative navigation was used to gauge donor osteotomies. Postoperative CT confirmed adherence to the CSP. In patient 3's case, cutting guides were generated for both donor and recipient, whereas intraoperative CT and navigation were used to guide and confirm skeletal fixation in accordance with the CSP. In both FTs, vascular anastomoses were performed after osteosynthesis with similar ischemia times (4 hours 26 minutes and 4 hours 35 minutes). Operative time was significantly reduced from 36 to 25 hours for patients 1 and 3, respectively. This improvement is partly due to the less extensive nature of patient 3's procedure, but it can also represent the learning curve with a move toward prefabrication of customized cutting guides for both donor and recipient and the addition of confirmatory intraoperative imaging. Intraoperative judgment and considerations related to scarring, soft tissue dissection, preservation of functional structures, and maximization of bone-to-bone contact required some deviation from the original CSP. Importantly, CSP cannot replace clinical judgment and experience, but it can contribute to increased accuracy and efficiency. Fitting a maxillomandibular allograft to a recipient's cranial base is particularly challenging, but the inclusion of both jaws and the use of CSP and cephalometric analysis have allowed us to achieve normal occlusion at the completion of FT.[4] Yet, both patients 1 and 3 subsequently developed malocclusion. Posttransplant malocclusion is not an uncommon complication in maxillomandibular FT, and its gradual postoperative development has also been observed by other teams.[31] A possible contributing factor could be the absence of proprioceptive feedback and motor tone during the early postoperative months as nerves regenerate. During that period, condylar-glenoid and maxillomandibular relationships can change in response to gravity, forces imparted by the soft tissue envelope, and speech and masticatory rehabilitation. For patient 1, orthodontic treatment was started at 5 months post-FT and failed. Le Fort III advancement using CSP was thus performed a month later with successful results. Patient 3's malocclusion was diagnosed in the second week post-FT and successfully corrected with early initiation of orthodontic treatment, avoiding major orthognathic revision surgery. In the future, preemptive application of orthodontic elastics immediately posttransplantation may be crucial in preventing the gradual development of malocclusion during the slow sensory-motor recovery that occurs in the first 6–9 months. Patient 2's defect did not involve bone loss, but his facial allograft was designed to include skeletal subunits to augment facial projection while preserving retaining ligaments and muscular insertion sites. CSP was instrumental to the design and safe execution of nasal, zygomatic, and genial osteotomies. Minimal translational and volumetric differences were noted between CSP and postoperative result. Few other teams have used CSP in bone including FTs. In 2016, Lassus et al[21] used donor and recipient 3D CT data for CSP and 3D printing of customized cutting guides for a Lefort II–based FT, also completing skeletal fixation before vascular anastomoses. Total surgical time was 19 hours and ischemia time of 3 hours 15 minutes. The patient had temporary temporomandibular joint pain and motion restriction as a result of imperfect mandible positioning. More recent transplants have reportedly used CSP and CAD/CAM, with no detailed description of their CSP methodology in the peer-reviewed literature.[22–25]

To the best of our knowledge, this is the largest and most detailed series describing CSP and CAD/CAM use in FT. Further validation remains to be performed. As CSP was integrated in our cadaveric rehearsals, comparison to control procedures performed without CSP was not available. Furthermore, the limited worldwide experience in FT includes heterogeneous defects and allograft designs with inconsistent reporting of preoperative preparation, operative execution, and postoperative outcomes, precluding comparative analyses on a larger scale. Two of the cases described in this series represent the only documented use of intraoperative navigation in clinical FT. The use of surgical navigation systems has expanded from intracranial and spinal applications to craniomaxillofacial surgery, providing real-time intraoperative guidance with 1–2 mm precision.[32–40] Intraoperative CT has been shown to facilitate immediate revision during orbital, zygomaticomaxillary complex, and mandibular angle fracture repair and bimaxillary repositioning osteotomies.[41–43] For patient 1, navigation was used to guide the donor Le Fort III osteotomies. For patient 3, it was combined with intraoperative CT following recipient defect creation for real-time image-guided allograft inset and skeletal fixation. A Computer-Assisted Planning and Execution workstation has been described by Gordon et al[44] and piloted in swine and human cadaveric simulations of Le Fort-type face transplants with satisfactory accuracy.[45,46] The experimental system seeks to dynamically integrate CSP, CAD/CAM, and surgical navigation. It enables intraoperative revision of CSP based on real-time cephalometric and occlusion analyses and positional tracking of cutting guides, combined with the use of custom prebent fixation plates and palatal splints. While that system has not reached clinical applicability, future iterations may provide more cohesive integration of the technologic elements described in our series for further advances in computer-assisted clinical FT.

CONCLUSIONS

A CSP protocol developed through cadaveric simulation and clinical implementation allows for refinement of operative flow, technique, and outcomes in partial and full FT. Standards for functional and esthetic outcomes are bound to evolve with the field's growth, and computerized planning and execution offer a reproducible approach to FT through objective quality assurance.

Eduardo D. Rodriguez, MD, DDS
Hansjörg Wyss Department of Plastic Surgery
Helen L. Kimmel Professor of Reconstructive Plastic Surgery
NYU Langone Health
222 E 41st Street, 6th Floor
New York, NY 10017
E-mail: eduardo.rodriguez@nyulangone.org

Statement of Conformity: This study was conducted in accordance with the Declaration of Helsinki.

REFERENCES

1. Rifkin WJ, David JA, Plana NM, et al. Achievements and challenges in facial transplantation. *Ann Surg.* 2018;268:260–270. .
2. Mohan R, Borsuk DE, Dorafshar AH, et al. Aesthetic and functional facial transplantation: a classification system and treatment algorithm. *Plast Reconstr Surg.* 2014;133:386–397.
3. Lantieri L, Grimbert P, Ortonne N, et al. Face transplant: long-term follow-up and results of a prospective open study. *Lancet.* 2016;388:1398–1407. .
4. Dorafshar AH, Brazio PS, Mundinger GS, Mohan R, Brown EN, Rodriguez ED. Found in space: computer-assisted orthognathic alignment of a total face allograft in six degrees of freedom. *J Oral Maxillofac Surg.* 2014;72:1788–1800.
5. Dorafshar AH, Bojovic B, Christy MR, et al. Total face, double jaw, and tongue transplantation: an evolutionary concept. *Plast Reconstr Surg.* 2013;131:241–251. .
6. Sosin M, Ceradini DJ, Levine JP, et al. Total face, eyelids, ears, scalp, and skeletal subunit transplant: a reconstructive solution for the full face and total scalp burn. *Plast Reconstr Surg.* 2016;138:205–219. .
7. Kollar B, Pomahac B. Facial restoration by transplantation. *Surgeon.* 2018;16:245–249. .
8. Siemionow MZ, Papay F, Djohan R, et al. First U.S. Near-total human face transplantation: a paradigm shift for massive complex injuries. *Plast Reconstr Surg.* 2010;125:111–122. .
9. Brown EN, Dorafshar AH, Bojovic B, et al. Total face, double jaw, and tongue transplant simulation: a cadaveric study using computer-assisted techniques. *Plast Reconstr Surg.* 2012;130:815–823. .
10. Sosin M, Ceradini DJ, Hazen A, et al. Total face, eyelids, ears, scalp, and skeletal subunit transplant cadaver simulation: the culmination of aesthetic, craniofacial, and microsurgery principles. *Plast Reconstr Surg.* 2016;137:1569–1581. .
11. Bojovic B, Dorafshar AH, Brown EN, et al. Total face, double jaw, and tongue transplant research procurement: an educational model. *Plast Reconstr Surg.* 2012;130:824–834. .
12. Sosin M, Ceradini DJ, Hazen A, et al. Total face, eyelids, ears, scalp, and skeletal subunit transplant research procurement: a translational simulation model. *Plast Reconstr Surg.* 2016;137:845e–854e.
13. Kantar RS, Ceradini DJ, Gelb BE, et al. Facial transplantation for an irreparable central and lower face injury: a modernized approach to a classic challenge. *Plast Reconstr Surg.* 2019. Forthcoming.
14. Kantar RS, Rifkin WJ, Diaz-Siso JR, et al. Quality improvement in facial transplantation: standard approach for novel procedures. *Plast Reconstr Surg Glob Open.* 2018;6:e1653.
15. Kantar RS, Gelb BE, Hazen A, et al. Facial transplantation: highlighting the importance of clinical vigilance in donor selection. *Plast Reconstr Surg.* 2018;142:611e–612e.
16. Gelb BE, Diaz-Siso JR, Plana NM, et al. Absence of rejection in a facial allograft recipient with a positive flow crossmatch 24 months after induction with rabbit anti-thymocyte globulin and anti-CD20 monoclonal antibody. *Case Rep Transplant.* 2018;2018:7691072. .
17. Devauchelle B, Badet L, Lengelé B, et al. First human face allograft: early report. *Lancet.* 2006;368:203–209. .
18. Siemionow M, Papay F, Alam D, et al. Near-total human face transplantation for a severely disfigured patient in the USA. *Lancet.* 2009;374:203–209. .
19. Pomahac B, Lengele B, Ridgway EB, et al. Vascular considerations in composite midfacial allotransplantation. *Plast Reconstr Surg.* 2010;125:517–522. .
20. Roche NA, Vermeersch HF, Stillaert FB, et al. Complex facial reconstruction by vascularized composite allotransplantation: the first Belgian case. *J Plast Reconstr Aesthet Surg.* 2015;68:362–371. .
21. Lassus P, Lindford A, Vuola J, et al. The Helsinki face transplantation: surgical aspects and 1-year outcome. *J Plast Reconstr Aesthet Surg.* 2018;71:132–139. .
22. The Washington Post. His face was severely damaged on a hunt. Now he's the world's oldest face transplant recipient. 2018. Available at: https://www.washingtonpost.com/news/to-your-health/wp/2018/09/14/his-face-was-severely-damaged-on-a-hunt-now-hes-the-worlds-oldest-face-transplant-recipient/?utm_term=.3251d0275559. Accessed January 17, 2019.
23. Cleveland Clinic Newsroom. Cleveland Clinic Performs Third Face Transplant. Available at: https://newsroom.clevelandclinic.

org/2017/07/18/cleveland-clinic-performs-third-face-transplant/. Accessed January 17, 2019.

24. My News Desk. A face transplant operation is a demonstration of advanced surgery and high technology. 2018. Available at: http://www.mynewsdesk.com/planmecagroup/pressreleases/a-face-transplant-operation-is-a-demonstration-of-advanced-surgery-and-high-technology-2485664. Accessed January 17, 2019.
25. Amer H, Jowsey-Gregoire SG, Rosen CB, et al. Mayo clinic's first face transplant: one year outcome. *Transplantation.* 2018;102:S433.
26. Mohan R, Fisher M, Dorafshar A, et al. Principles of face transplant revision: beyond primary repair. *Plast Reconstr Surg.* 2014;134:1295–1304.
27. Lindford AJ, Mäkisalo H, Jalanko H, et al. The Helsinki approach to face transplantation. *J Plast Reconstr Aesthet Surg.* 2019;72:173–180.
28. CNN. Man's second face transplant is a world first. Available at: https://www.cnn.com/2018/04/17/health/second-face-transplant-bn/index.html. Accessed January 17, 2019.
29. Suchyta M, Mardini S. Innovations and future directions in head and neck microsurgical reconstruction. *Clin Plast Surg.* 2017;44:325–344.
30. Rodby KA, Turin S, Jacobs RJ, et al. Advances in oncologic head and neck reconstruction: systematic review and future considerations of virtual surgical planning and computer aided design/computer aided modeling. *J Plast Reconstr Aesthet Surg.* 2014;67:1171–1185.
31. Krezdorn N, Alhefzi M, Perry B, et al. Trismus in face transplantation following ballistic trauma. *J Craniofac Surg.* 2018;29:843–847.
32. Zhang JS, Qu L, Wang Q, et al. Intraoperative visualisation of functional structures facilitates safe frameless stereotactic biopsy in the motor eloquent regions of the brain. *Br J Neurosurg.* 2018;32:372–380.
33. Zhang S, Gui H, Lin Y, et al. Navigation-guided correction of midfacial post-traumatic deformities (Shanghai experience with 40 cases). *J Oral Maxillofac Surg.* 2012;70:1426–1433.
34. Du JP, Fan Y, Wu QN, et al. Accuracy of pedicle screw insertion among 3 image-guided navigation systems: systematic review and meta-analysis. *World Neurosurg.* 2018;109:24–30.
35. He Y, Zhang Y, An JG, et al. Zygomatic surface marker-assisted surgical navigation: a new computer-assisted navigation method for accurate treatment of delayed zygomatic fractures. *J Oral Maxillofac Surg.* 2013;71:2101–2114.
36. Andrews BT, Surek CC, Tanna N, et al. Utilization of computed tomography image-guided navigation in orbit fracture repair. *Laryngoscope.* 2013;123:1389–1393.
37. Yu H, Shen SG, Wang X, et al. The indication and application of computer-assisted navigation in oral and maxillofacial surgery-shanghai's experience based on 104 cases. *J Craniomaxillofac Surg.* 2013;41:770–774.
38. Azarmehr I, Stokbro K, Bell RB, et al. Surgical navigation: A systematic review of indications, treatments, and outcomes in oral and maxillofacial surgery. *J Oral Maxillofac Surg.* 2017;75:1987–2005.
39. Marmulla R, Hilbert M, Niederdellmann H. Inherent precision of mechanical, infrared and laser-guided navigation systems for computer-assisted surgery. *J Craniomaxillofac Surg.* 1997;25:192–197.
40. Strong EB, Rafii A, Holhweg-Majert B, et al. Comparison of 3 optical navigation systems for computer-aided maxillofacial surgery. *Arch Otolaryngol Head Neck Surg.* 2008;134:1080–1084.
41. Cuddy K, Khatib B, Bell RB, et al. Use of intraoperative computed tomography in craniomaxillofacial trauma surgery. *J Oral Maxillofac Surg.* 2018;76:1016–1025.
42. Heiland M, Schmelzle R, Hebecker A, et al. Intraoperative 3D imaging of the facial skeleton using the SIREMOBIL iso-C3D. *Dentomaxillofac Radiol.* 2004;33:130–132.
43. Klatt JC, Heiland M, Marx S, et al. Clinical indication for intraoperative 3D imaging during open reduction of fractures of the mandibular angle. *J Craniomaxillofac Surg.* 2013;41:e87–e90.
44. Gordon CR, Murphy RJ, Coon D, et al. Preliminary development of a workstation for craniomaxillofacial surgical procedures: introducing a computer-assisted planning and execution system. *J Craniofac Surg.* 2014;25:273–283.
45. Murphy RJ, Gordon CR, Basafa E, et al. Computer-assisted, le fort-based, face-jaw-teeth transplantation: a pilot study on system feasiblity and translational assessment. *Int J Comput Assist Radiol Surg.* 2015;10:1117–1126.
46. Hashemi S, Armand M, Gordon CR. Development and refinement of computer-assisted planning and execution system for use in face-jaw-teeth transplantation to improve skeletal and dento-occlusal outcomes. *Curr Opin Organ Transplant.* 2016;21:523–529.