Published in final edited form as:

Plast Reconstr Surg. 2015 August ; 136(2): 350–362. doi:10.1097/PRS.0000000000001455.

Optimizing Hybrid Occlusion in Face-Jaw-Teeth Transplantation: A Preliminary Assessment of Real-Time Cephalometry as Part of the Computer-Assisted Planning and Execution Workstation for Craniomaxillofacial Surgery

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Abstract

Background—The aesthetic and functional outcomes surrounding Le Fort–based, face-jaw-teeth transplantation have been suboptimal, often leading to posttransplant class II/III skeletal profiles, palatal defects, and “hybrid malocclusion.” Therefore, a novel technology—real-time cephalometry—was developed to provide the surgical team instantaneous, intraoperative knowledge of three-dimensional dentoskeletal parameters.

Methods—Mock face-jaw-teeth transplantation operations were performed on plastic and cadaveric human donor/recipient pairs ($n = 2$). Preoperatively, cephalometric landmarks were identified on donor/recipient skeletons using segmented computed tomographic scans. The computer-assisted planning and execution workstation tracked the position of the donor face-jaw-teeth segment in real time during the placement/inset onto recipient, reporting pertinent hybrid cephalometric parameters from any movement of donor tissue. The intraoperative data measured through real-time cephalometry were compared to posttransplant measurements for accuracy assessment. In addition, posttransplant cephalometric relationships were compared to planned outcomes to determine face-jaw-teeth transplantation success.

Results—Compared with postoperative data, the real-time cephalometry–calculated intraoperative measurement errors were 1.37 ± 1.11 mm and 0.45 ± 0.28 degrees for the plastic

The first two authors should be considered co–first authors.

Disclosure: Dr. Gordon is a consultant for Stryker CMF. All other authors have no conflicts of interest to report.

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skull and 2.99 ± 2.24 mm and 2.63 ± 1.33 degrees for the human cadaver experiments. These results were comparable to the posttransplant relations to planned outcome (human cadaver experiment, 1.39 ± 1.81 mm and 2.18 ± 1.88 degrees; plastic skull experiment, 1.06 ± 0.63 mm and 0.53 ± 0.39 degrees).

Conclusion—Based on this preliminary testing, real-time cephalometry may be a valuable adjunct for adjusting and measuring “hybrid occlusion” in face-jaw-teeth transplantation and other orthognathic surgical procedures.

The reconstruction of severe midfacial defects was revolutionized by the introduction of Le Fort–based, face-jaw-teeth transplantation in 2008.^{1–3} Since then, a number of face-jaw-teeth transplantations have been reported.⁴ Recent face-jaw-teeth transplantations demonstrate improved patient survival and enhanced aesthetics; however, posttransplant results seen to date achieve only class II or III skeletal relation, with significant malocclusion, suboptimal masticatory function, dentofacial disharmony, and palatal defects between the donor/recipient maxillary segments.

To emphasize post–face-jaw-teeth transplantation occlusal outcomes, we previously investigated Le Fort–based allotransplantation⁵ in cadavers to describe a phenomenon termed “hybrid occlusion” (Table 1).^{5,6} Hybrid occlusion is the result of the posttransplant relation between two human jaws of varying anthropometrics (i.e., a native jaw and an allograft jaw). It was noted that although hybrid malocclusion and poor facial skeletal relationship may be prevented with adequate planning, they are often considered important only after transplantation.⁵ Many face-jaw-teeth transplantations require dentoskeletal adjustments, which create the high possibility of debilitating malocclusion, incomplete palates, potential malocclusion-related facial pain, and need for revision surgery.

The intraoperative use of dental casts, “hybrid splints,” and other intraoral orthognathic devices in face-jaw-teeth transplantation may potentially improve post–face-jaw-teeth transplantation hybrid occlusion, facial projection, and skeletal harmony.⁵ However, these devices pose numerous shortcomings. Fabrication of these components is very time consuming considering the time-sensitive transplant timeframe; generally, face-jaw-teeth transplantation occurs within 24 to 36 hours of donor identification. Moreover, both device fabrication and operation require access to dental specialists (maxillofacial prosthodontists and oral/maxillofacial surgeons), which may be difficult given the time constraint. As is often the case with any form of orthognathic surgery, unexpected intraoperative adjustments of the surgical plan may be required based on many factors, including osteotomy success, unexpected dental caries, or soft-tissue/masticatory muscle hindrance. These intraoperative obstacles may significantly diminish the value of prefabricated occlusal splints. For instance, the first reported face-jaw-teeth transplantation in 2008⁷ required extracting all donor teeth (except for the central incisors) because of extensive caries found on radiographic evaluation. In addition, conventional dental devices may not account for the lateral orbital (frontozygomatic) and/or nasofrontal donor tissue positioning, both of which are critical sites for rigid fixation.⁷

With this in mind, our objective was to develop a novel technology, the computer-assisted planning and execution workstation, to assist Le Fort–based, maxillofacial

transplantation.^{8,9} The resulting system creates a patient-specific plan and uses trackable cutting guides (for both donor and recipient) to effectively perform face-jaw-teeth transplantation. Intraoperatively, the computer-assisted planning and execution workstation offers real-time position feedback of the donor fragment. However, for obtaining appropriate occlusion, visualization of the skeletal anatomy would not be enough given the precise measurements pertinent to orthognathic surgery. Therefore, we hypothesized that by combining the positional hard-tissue information with validated orthognathic measurements (i.e., real-time cephalometrics), one could quantify the on-table hybrid occlusion during face-jaw-teeth transplantation following standard-of-care principles.

An essential tool of orthodontists, cephalometry can be rooted to works of Leonardo da Vinci (1452 to 1519; Italian) and Albrecht Dürer (1471 to 1528; German), both of whom attempted to quantify craniofacial relations for artistic progress.¹⁰ Over the ensuing several centuries, anthropologists measured aspects of dry skulls to determine human developmental patterns. Subsequent to the discovery of x-rays, August J. Pacini, M.D. (1888–?), was likely the first to publish on using radiographs to measure live human skeletal relations^{11,12} in an accurate, in vivo longitudinal study of human skull development. Broadbent's seminal work was the first to present cephalometric radiography as a technique for measuring jaw relation with respect to the head,¹³ and Björk identified a set of common landmarks and measurements.¹⁴ Following these breakthroughs, normative cephalometric values^{10,15–17} were established for diagnosis and treatment planning in orthodontics, orthognathic surgery, and plastic surgery.¹⁸ With the rise of three-dimensional cephalometrics in the recent decades,^{19,20} we now hope to introduce real-time cephalometry through the novel application of intraoperatively derived, dynamic cephalometrics for guiding orthognathic surgery.

This article demonstrates the real-time application of cephalometrics and orthognathic principles in craniofacial reconstruction surgery for intraoperative adaptability and outcome prediction, referred to throughout as real-time cephalometry. In addition, we report our preliminary evaluation of realtime cephalometry in the laboratory and further describe relevant dental concepts applicable to face-jaw-teeth transplantation and hybrid occlusion.

Materials and Methods

The development and utility of the computer-assisted planning and execution workstation is described in previous publications.^{8,9} Briefly, this technology provides surgeons various tools related to the planning and execution of face-jaw-teeth transplantation. Significant modules include biomechanical and geometric planning, patient-specific bone and soft-tissue cutting guides, navigation to confirm cutting guide and quantitative) of the repositioning of the donor fragment. A schematic overview and the components of the computer-assisted planning and execution system are shown in Figure 1.⁸ Preoperative planning is conducted on segmented patient computed tomographic scans, and intraoperative navigation is performed using an optical, three-dimensional position tracker (Polaris; NDI, Waterloo, Ontario, Canada). The position tracker helps to localize instrumentation and cutting guides with respect to the donor/recipient craniums.

This proof-of-concept study involved a single jaw-face-jaw transplantation performed using two different plastic human craniofacial skeletal models, and a cadaveric procedure using two elderly (aged 72 and 80 years), Caucasian, female cadaver head specimens. High-resolution computed tomographic scans ($0.45 \times 0.45 \times 0.6$ mm) were obtained on a SOMATOM Definition Flash scanner (Siemens Healthcare, Erlangen, Germany) of both donor and recipient. Bony segmentation using commercial image-processing software (Mimics; Materialise, Leuven, Belgium) generated surface models of the relevant anatomy (i.e., cranium, mandible, maxilla). Subsequently, virtual osteotomies were made using the same software, and a planned, hybrid, posttransplant result was obtained in which the dental arches were aligned. The goal of planning was to achieve an adequate occlusal plane and the greatest possible dental intercuspation.

Following the computer-assisted planning and execution system protocol, patient-specific, navigated cutting guides were mounted to the appropriate nasofrontal and zygomatic locations of both donor and recipient (Fig. 2). These trackable cutting guides were fabricated using additive manufacturing—also known as three-dimensional printing—with stereolithography.^{8,9} In the cadaveric scenario, soft-tissue cutting guides were also fabricated to guide the incision path. After performing intraoperative registration (Fig. 3), the surgeon placed the cutting guides into position, and performed the dentoskeletal osteotomies. Note that for the human cadaver study, extensive recipient midfacial trauma (Fig. 4) was simulated using a scalpel, osteotomes, and surgical saw before the face-jaw-teeth transplantation.

Following the bone cuts, the position of the donor face-jaw-teeth segment was measured using spatial relationships between the cranial reference geometry attached to the recipient and that of the donor cutting guide. The real-time cephalometry module used the real-time donor positioning information (as measured by the tracker) to transform cephalometric landmark coordinates described below (Fig. 5)^{13,14,21} onto the hybrid skull to predict relevant hybrid occlusion measurements. (See Figure, Supplemental Digital Content 1, which shows distance and angle measurements computed from specific sets of cephalometric landmarks. The legend describes the measurements depicted in the labeled images on the left, <http://links.lww.com/PRS/B351>.) The surgical team used these measurements to adjust, achieve, and confirm the hybrid relations planned before performing final fixation. Maxillomandibular posttransplant fixation of the cadaver recipient achieved using four intermaxillary fixation screws (Stryker Craniomaxillofacial; Stryker, Kalamazoo, Mich.) placed lateral to each canine helped to overcome the recipient's rigor mortis; the intermaxillary fixation screws are unnecessary in the clinical setting and are required only because of the cadaveric specimen. The planned postoperative models of both cadaver and plastic skulls were compared to posttransplant computed tomographic scans in Mimics (Fig. 6).

We have chosen a subset of standard cephalometric landmarks^{13,14} in this study (nasion, rhinion, sella, zygoma, B-point, A-point, gonion, menton, opisthion, and the anterior nasal spine) (Fig. 5 and Table 2). Altogether, these landmarks identified four angular and 14 distance measurements assessing both the functional and aesthetic outcomes of hybrid occlusion and orthognathia (see Figure, Supplemental Digital Content 1, <http://>

links.lww.com/PRS/B351) (Table 2).^{22–24} Two of the measured angles, ANB and BSA, were used to analyze facial projection, on the basis that a convex parasagittal profile would be more aesthetic compared with a concave parasagittal profile.²⁵ The remaining angle measurements, SNB and SNA, scrutinized facial projection more closely with respect to mandibular and maxillary projection, respectively.²⁶

The distance measurements assessed occlusal function (OB, OJ, and B–A) and aesthetic parameters such as facial projection (S–A, S–R, and Op–R). Also, we measured lower anterior facial height and total anterior facial height as the distances Me–ANS and Me–Na, respectively. Their ratio (lower anterior facial height–to–total anterior facial height) was calculated as a percentage. Several distance parameters exist solely on the recipient's cranium/mandible (Go–B, Go–Me, S–Na, Zy–Zy, and Op–Na). During the course of single-jaw face-jaw-teeth transplantation, these should not be altered and serve as internal controls to identify examiner measurement and virtual processing error. The posttransplant skeletal relationship considered the first molar–to–first molar relationships.

From each scanned skull, preoperative three-dimensional cephalometric landmark coordinates were identified. A virtual representation of the hybrid skull combined appropriate measurements from the recipient cranium/mandible and the donor maxilla to obtain the planned measurements. Posttransplant measurements were identified manually on segmented, post transplant computed tomographic scans. Intraoperative values computed using real-time cephalometry were compared against the posttransplant cephalometric measurements; the obtained posttransplant measurements were compared with the planned model for utility assessment of the real-time cephalometry technology for face-jaw-teeth transplantation.

Results

Overall, the real-time cephalometry navigation was successful, allowing verification of skeletal relations before rigid fixation. (See Video, Supplemental Digital Content 2, which demonstrates real-time cephalometry use as a part of the computer-assisted planning and execution system, available in the “Related Videos” section of the full-text article on PRSJJournal.com or, for Ovid users, at <http://links.lww.com/PRS/B352>.) The total computer-assisted planning and execution setup preparation required approximately 11 minutes (Table 3). The learning curve for this setup is minimal; prior studies on plastic and animal models^{8,9} helped to achieve this setup time. The registration errors were 0.727 mm and 0.306 mm for the plastic skull model donor and recipient, respectively, and 1.22 mm and 0.745 mm for the human cadaver donor and recipient, respectively.⁹ The face-jaw-teeth transplantation performed on the plastic skull retained the preoperative class I profile. The obtained human cadaver posttransplant molar relation (class I) matched the planned skeletal relation (class I), even though the donor and recipient originally exhibited class II and class I molar relations, respectively (Fig. 7), and the recipient showed a large original overjet (9.22 mm). As planned, an aesthetically superior convex sagittal projection of the midfacial skeleton was achieved, and a posterior open bite of right (3.5 mm) and left (2.00 mm) jaw was present postoperatively in the human cadaver experiment (Fig. 7). The donor osteomyocutaneous segment had a stable and firm fit at the two zygomatic and nasal

junctions of the human face-jaw-teeth transplantation, even without the use of fixation screws. Congruency between the intraoperative outcome and the stereolithographic planning model was readily apparent in the human face-jaw-teeth transplantation (Fig. 8).

The intraoperative values calculated by realtime cephalometry are compared to those measured postoperatively in both the cadaver and plastic models and reported in Tables 4 through 6. In general, the plastic model achieved better accuracy compared with the human cadaver. For distance-based cephalometric measures, the average difference comparing intraoperative to postoperative values was 1.37 ± 1.11 mm (plastic model) and 2.99 ± 2.24 mm (human cadaver). Angular-based cephalometric measures saw similar trends—the difference between intraoperative and postoperative values was 0.45 ± 0.28 degrees (plastic model) and 2.63 ± 1.33 degrees (human cadaver) (Table 4). In the human cadaver experiment, several of the real-time cephalometry measurements showed noticeable deviation between intraoperative and posttransplant measurements (Op–Na, 3.55 mm; overbite, 3.65 mm; B–A, 5.31 mm; Me–ANS, 4.38 mm; Me–ANS, 4.38 mm) (Table 5).

Overall, the majority of cephalometric measurements for the postoperative recipients followed that of the planned hybrids. Distance-based metrics showed a mean difference of 1.06 ± 0.63 mm (plastic model) and 1.39 ± 1.81 mm (human cadaver). Angular-based metrics were more accurate for the plastic model experiment, with a mean difference of 0.53 ± 0.39 degrees (plastic model) and 2.18 ± 1.88 degrees (human cadaver) (Table 4). For the human cadaver experiment, Me–Na and Op–Na distances showed the largest deviation for distance-based metrics (5.98 mm and 3.55 mm, respectively), whereas SNB and SNA had the largest angular deviation (3.03 and 4.33 degrees, respectively) (Table 5). Discrete occlusal parameters showed improvement from the planned outcome (improvement of plastic model overjet by 1.78 mm and human cadaver overjet/overbite by 0.86 and 0.89 mm, respectively) (Tables 5 and 6).

Discussion

This article presents and evaluates a novel paradigm to compute cephalometrics intraoperatively, in real time, for improved outcomes in face-jaw-teeth transplantation. This study compared cephalometric measures obtained intraoperatively using the real-time cephalometry module of the computer-assisted planning and execution system with those measured from postoperative computed tomographic images. The results showed that intraoperative real-time cephalometry predictions were similar to measurements made postoperatively. In addition, both the human cadaver and plastic skull experiments were successful face-jaw-teeth transplantations as reflected by the difference between the postoperative planned models and the obtained outcomes (Table 4 and Fig. 6).

Several cephalometric measures pertaining only to the recipient should remain constant during single-jaw face-jaw-teeth transplantation (e.g., S–Na, Go–Me). However, these control measures showed differences in both the plastic skull (0.76 mm) and human cadaver experiment (1.68 mm) (Tables 4 through 6). This difference represents imprecise landmark placement by the examiner. Future studies should compare interobserver and intraobserver errors related to the selection of landmark locations.

As expected, the human cadaver experiment was less accurate compared with the plastic model experiment, which did not show any deviations greater than 3 mm or 2 degrees from target measurements (Table 5). The plastic model experiment represents an idealized procedure with highly accurate patient-to-model registration error (0.727 mm and 0.306 mm for the plastic skull model donor and recipient, compared with 1.22 mm and 0.745 mm for the human cadaver donor and recipient, respectively), leading to improved tracking of the donor fragment when placing on the recipient. This achieves improved accuracy in comparing intraoperative to postoperative cephalometric measurements. The largest error comparing planned to posttransplant measurements in the plastic skull model (B–A, 1.97 mm) is on par with the largest error exhibited by the control measure (Go–Me, 2.24 mm). As such, the plastic model experiment may represent the potential best-case scenario for real-time cephalometry.

The human cadaver experiment comparison of post–face-jaw-teeth transplantation and planned outcome measurements showed large differences in Me–Na (5.98 mm), and SNA (4.33 degrees)/SNB (3.03 degrees) angles (Table 5). In the comparison of predicted intraoperative values relative to obtained postoperative values, overbite (3.65 mm), B–A (5.31 mm), Me–ANS (4.38 mm), and Me–Na (5.98 mm) showed the greatest variation (Table 5). The error associated with these measurements comes mainly from two sources: (1) landmark identification error and (2) navigation and registration error. Landmark identification error has been the subject of many studies.^{27–30} A meta-analysis of several studies on landmark identification and reproducibility showed total identification error of approximately 0.81 mm,³¹ which is similar to the control error for the plastic model (0.76 mm) but lower than that of the human cadaver (1.86 mm). Navigation error can be attributed, in part, to the intraoperative patient-to-model registration error of 1.22 and 0.745 mm for the human cadaver donor and recipient, respectively.⁹

Aside from the mentioned variations, one of the three aspects of hybrid occlusion (Table 1), bilateral posterior contact between recipient and donor dental arches, was not established in the human cadaver (lateral open bites of 3.5 mm and 2 mm on the right and left, respectively) (Fig. 8). However, this was predicted in the planned model (Fig. 6), and was inevitable because of the size mismatch between the two dental arches involved.

Future studies on real-time cephalometry can extend these results and address certain limitations of the study. The current study used same-sex cadaveric donors (elderly female cadavers); however, prior research eliminated donor-to-recipient sex mismatch as a contraindication for face-jaw-teeth transplantation,³² showing that it is possible to use size-mismatched donor/recipient pairs. In addition, the human cadaver recipient's maxilla and mandible were fixated postoperatively to counteract the mandibular retraction caused by rigor mortis; this is atypical and would not be necessary in a typical study. However, this should not have introduced deviation from normal postoperative occlusion (free of rigor mortis), as the obtained outcome very similarly resembled the planned outcome. In the future, we hope to improve occlusion optimization by integrating real-time navigation of soft-tissue and masticatory insertions in real-time cephalometry.³³

This work presents a proof of concept for the inclusion of navigation technologies such as real-time cephalometry and computer-assisted planning and execution. Although the sample size is small—one plastic model experiment and one cadaveric experiment—the results speak to the benefits of such a technology. Future studies should include more specimens, and compare the results of the computer-assisted technologies to more conventional approaches not using computer assistance. These studies should also consider the impact the computer-assisted planning and execution system has on the overall surgical time; although the setup adds minimal time to surgery, the resulting information gain and time reduction achieved through intraoperative feedback may serve to reduce overall surgical time.

It should be noted that the development of real-time cephalometry and future reliance on similar technologies does not reduce the importance of collaboration between the craniofacial surgeon and dental specialists (maxillofacial prosthodontists or oral and maxillofacial surgeons). To the contrary, this collaboration is crucial for the fabrication of a planned model. Even in the case of an edentulous patient, dental expertise is essential to ensure optimal maxillomandibular relations (e.g., freeway space, midline, and occlusal plane adjustments) and maximize the success of future occlusal procedures (i.e., denture/obturator placement, orthognathic surgery, and implant placement). Moreover, the pretransplant involvement of dental specialists in face-jaw-teeth transplantation will help give insight regarding expectations for what can be achieved following transplantation with regard to occlusion and subsequent dental reconstruction.³² This recommended transition from the use of dental appliances to navigational technology, such as the one presented here, emphasizes the need for implementing more time-efficient, adaptable, and error-proof methods.

Conclusions

Orthognathic principles are an indispensable utility in predicting and achieving appropriate post-transplant dentofacial-skeletal relations.^{34–38} However, the conventional use of mechanical dental appliances (e.g., occlusal splints) poses numerous inherent limitations, including long construction time with limited intraoperative adjustability. Moreover, if the mechanical appliance fractures or fails, the surgeon is left with few (if any) options for realtime feedback. As such, this pilot study suggests that real-time cephalometry can overcome several limitations of conventional dental appliances used in face-jaw-teeth transplantation (and other orthognathic operations) while still achieving appropriate face-jaw-teeth transplantation outcomes with respect to orbital volumes, airway patency, facial skeletal appearance, and hybrid occlusion. Moreover, this technology can be adapted for use with more traditional orthognathic cases that do not have the complexity of a hybrid jaw introduced in face-jaw-teeth transplantation. We believe that computer-assisted technologies such as real-time cephalometry may represent the next stage in assistive surgical guides offering virtual planning, intraoperative adaptability, and outcome confirmation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Other funding sources include the American Society of Maxillofacial Surgery (2011 research award), American Association of Plastic Surgeons (2012–14 Academic Scholar Award), Independent Research and Development funds from the Johns Hopkins Applied Physics Laboratory, and the 2014 Abell Foundation Award presented by the Johns Hopkins Alliance for Science and Technology development.

This study was made possible, in part, by the Johns Hopkins Institute for Clinical and Translational Research, which is funded in part by the National Center for Advancing Translational Sciences, a component of the National Institutes of Health, and National Institutes of Health Roadmap for Medical Research. Its contents are solely the responsibility of the authors and do not necessarily represent the official view of the Johns Hopkins Institute for Clinical and Translational Research, the National Center for Advancing Translational Sciences, or National Institutes of Health (National Center for Advancing Translational Sciences grant UL1TR000424-06).

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Fig. 1. Schematic overview of computer-assisted planning and execution and its components. *OR*, operation. (Revised with permission from 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.)

Fig. 2.
Cutting guides designed to fit directly on the cadaver recipient and place with navigation from the attached cranial reference.

Fig. 3. Digitization of the donor's craniomaxillofacial skeleton (*left*) and real-time cephalometry calculation of pertinent dento-facial-skeletal relations (*right*).

Fig. 4.
Extensive midfacial defect created in recipient before face-jaw-teeth transplantation.

Fig. 5.

Landmarks used for cephalometric analysis (Broadbent BH. A new x-ray technique and its application to orthodontia. *Angle Orthod.* 1931;1:45–66; and Björk A. *The Face in Profile: An Anthropological X-Ray Investigation on Swedish Children and Conscripts*. Lund: Berlingska Boktryckeriet; 1947). (†Landmarks previously used in Santiago GF, Susarla SM, Al Rakan M, et al. Establishing cephalometric landmarks for the translational study of Le Fort-based facial transplantation in swine: Enhanced applications using computer-assisted surgery and custom cutting guides. *Plast Reconstr Surg.* 2014;133:1138–1151.)

Fig. 6.

Lateral view of the human cadaver before transplantation (donor and recipient), after transplantation, and the planned outcome. The *red dots* denote the measured landmark positions in each model (*above*). Frontal three-dimensional reconstruction of the human cadaver recipient before transplantation, after transplantation, planned outcome, and donor before transplantation. Note the sites of rigid fixation in a Le Fort–based face-jaw-teeth transplantation. The *red dots* denote the measured landmark positions in each model (*below*).

Fig. 7. One of the three aspects of hybrid occlusion, bilateral posterior contact between recipient and donor dental arches, was not established in the human cadaver face-jaw-teeth transplantation (gaps of 3.5 mm and 2 mm on the right and left bites, respectively).

Fig. 8.

Three-dimensional reconstruction of the obtained hybrid (*red*) superimposed on top of the planned hybrid (*bone colored*), accenting the differences between the two (*above*). The predicted model held next to the postoperative recipient. Note the congruency in the zygomaxillary junction (*below*).

Table 1
Comparison between the Standard Dentofacial Occlusion Scheme Described by Edward Angle and the Proposed Hybrid Occlusion Scheme for Osteocutaneous, Maxillofacial Allotransplantation

	Angle Classification	Hybrid Occlusion
Outcome classes	Three main types: class I, II, and III	Defined as either “optimal” or “suboptimal”
Assessment keys	Based exclusively on first maxillary molar meso–buccal cusp to first mandibular molar buccal groove	Defined as (1) bilateral posterior contact, (2) overbite/overjet 2 mm, and (3) proper midline symmetry with centric relation
First introduction to literature	Introduced by Angle [*] for dental examination	Introduced in Gordon et al., 2011 [†] for optimizing occlusal outcomes related to osteocutaneous, maxillofacial allotransplantation
Context	Important for outcomes related to orthognathic surgery	Important for outcomes related to maxillofacial or mandibulofacial allotransplantation

^{*} Angle EH. Classification of malocclusion. *Dental Cosmos* 1899;41:248–264.

[†] Gordon CR, Susarla SM, Peacock ZS, et al. Osteocutaneous maxillofacial allotransplantation: Lessons learned from a novel cadaver study applying orthognathic principles and practice. *Plast Reconstr Surg*. 2011;128:465e–479e.

Table 2
Cephalometric Measurements and Their Use in This Study

Measurement Type	Landmark Measurement	Landmark/Measurement Abbreviation	Cephalometric Significance	Purpose in This Study
Distance	Gonion to B-point	Go-B	Control	Occlusal parameter
	Gonion to menton	Go-Me		
	Sella to nasion	S-Na		
	Zygoma to zygoma	Zy-Zy		
	Opisthion to nasion	Op-Na		
	Overjet	OJ	Occlusal parameter*	
	Overbite	OB		
	B-point to A-point	B-A		
	Sella to A-point	S-A	Facial projection	
	Sella to rhinion	S-R		
	Opisthion to rhinion	Op-R		
	Lower anterior facial height (LAFH): menton to anterior nasal spine (ANS)	Me-ANS	Facial height	
	Total anterior facial height (TAFH): menton to nasion	Me-Na		
	Ratio of LAFH to TAFH	Me-ANS/Me-Na		
Angle	A-point-nasion-B-point	ANB	Facial projection;	Aesthetic/function parameter
	B-point-sella-A-point	BSA	orthognathic skeletal relationship	
	Sella-nasion-B-point	SNB	Mandibular projection; orthognathic skeletal relation	
	Sella-nasion-A-point	SNA	Maxillary projection; orthognathic skeletal relation	

* Tonni I, Pregarz M, Ciampalini G, Constantinides F, Bodin C. Overjet and overbite influence on cyclic masticatory movements: A CT study. *ISRN Radiol.* 2013;2013:932805; Glaros AG, Brockman DL, Ackerman RJ. Impact of overbite on indicators of temporomandibular joint dysfunction. *Cranio* 1992;10:277-281; John MT, Hirsch C, Drangsholt MT, Mancil LA, Setz JM. Overbite and overjet are not related to self-report of temporomandibular disorder symptoms. *J Dent Res.* 2002;81:164-169.

Table 3
Comparison of Computer-Assisted Planning and Execution–Real Time Cephalometry
and Conventional Face-Jaw-Teeth Transplantation Techniques

	Conventional	CAPE–Real-Time Cephalometry
Use of dental appliances to optimize occlusion	Necessary	Redundant
Basis of intraoperative adjustment to surgical plan because of unexpected findings	Based on direct visualization and approximation	Based on optimization of real-time calculated skeletal measurements
Preoperative planning time	4.5 hr for dentate scenario (1.5 hr for cephalometric analysis, 1.5 hr for model generation, 1.5 hr for splint fabrication)*; 2 hr for edentulous scenario (1.5 hr for cephalometric, 0.5 hr for maxillomandibular fixation)*	5 hr for cephalometric analysis, virtual osteotomies and planned outcome design, and designing custom cutting guides; 12 hr for manufacturing three-dimensional skull models and cutting guides (performed overnight without supervision)
Intraoperative preparation time	5 min for dentate recipient; 30 min for edentulous recipient	11 min total (roughly 5 min for registration of each skull)
Understanding of orthognathic and occlusal principles by the surgical team	Necessary	Necessary

CAPE, computer-assisted planning and execution.

* Gordon CR, Susarla SM, Peacock ZS, et al. Osteocutaneous maxillofacial allotransplantation: Lessons learned from a novel cadaver study applying orthognathic principles and practice. *Plast Reconstr Surg*. 2011;128:465e–479e.

Table 4**Overview of Cephalometric Analysis**

	Measure Type	Human Cadaver FJTT		Plastic Skull FJTT	
		Average Difference	SD	Average Difference	SD
Intraoperative* vs. posttransplant	Distances (mm)	2.99	2.24	1.37	1.11
	Angles (deg)	2.63	1.33	0.45	0.28
	Controls (mm)	1.68	1.29	0.76	0.86
Planned vs. post-transplant	Distances (mm)	1.39	1.81	1.06	0.63
	Angles (deg)	2.18	1.88	0.53	0.39
	Controls (mm)	1.68	1.29	0.76	0.86

FJTT, face-jaw-teeth transplantation.

* Intraoperative cephalometric values were calculated by real-time cephalometry to predict the posttransplant outcome.

Table 5
Detailed Overview of the Cephalometric Analysis for the Human Cadaver FJTT

	Intraoperative vs. Posttransplant			Planned vs. Posttransplant		
	Parameter	Value Difference from Postoperative Value	% Deviation from Postoperative Value	Parameter	Value Difference from Planned	% Deviation from Planned
Distance measures, mm	Go-B	1.03	1.25	Go-B	1.03	1.27
	Go-Me	2.49	3.02	Go-Me	2.49	3.11
	S-Na	0.52	0.78	S-Na	0.52	0.79
	Zy-Zy	0.82	0.63	Zy-Zy	0.82	0.62
	Op-Na	3.55	2.60	Op-Na	3.55	2.67
	Overjet	0.39	10.42	Overjet	0.86 [*]	18.84 [*]
	Overbite	3.65	197.94	Overbite	0.89 [*]	93.40 [*]
	B-A	5.31	14.86	B-A	1.75	5.15
	Me-ANS	4.38	6.93	Me-ANS	1.24	2.00
	Me-Na	5.98	5.18	Me-Na	5.98	5.47
Angle measures, degrees	Me-ANS/Me-Na [†]	1.01% [‡]	1.84	Me-ANS/Me-Na [†]	1.86% [‡]	3.28
	S-A	2.2	2.80	S-A	0.19	0.24
	S-R	0.72	0.97	S-R	1.2	1.59
	Op-R	1.3	0.96	Op-R	0.35	0.26
	BSA	2.07 deg	11.05	BSA	0.09 deg	0.49
	ANB	1.16 deg	38.99	ANB	1.25 deg	29.65
	SNB	3.03 deg	4.11	SNB	3.03 deg	3.95
	SNA	4.27 deg	5.57	SNA	4.33 deg	5.35

FJTT, face-jaw-teeth transplantation.

^{*}These deviations represent an improvement in outcome [i.e., the obtained outcome was closer to normal range of 0–2 mm (Marchac D, Arnaud E. Midface surgery from Tessier to distraction. *Childs Nerv Syst.* 1999;15:681–694) than the planned].

[†]Note that Me-ANS/Me-Na parameter was not used in the calculations to avoid redundant calculations.

[‡]Unless mentioned, the parameters were measured in millimeters.

Table 6
Detailed Overview of the Cephalometric Analysis for the Plastic Skull FJTT

	Intraoperative vs. Posttransplant			Planned vs. Posttransplant		
	Parameter	Value Difference from Postoperative Value	% Deviation from Postoperative Value	Parameter	Value Difference from Planned	% Deviation from Planned
Distance measures, mm	Go-B	0.14	0.17	Go-B	0.14	0.17
	Go-Me	2.24	2.73	Go-Me	2.24	2.66
	S-Na	0.79	1.06	S-Na	0.79	1.08
	Zy-Zy	0.25	0.19	Zy-Zy	0.25	0.19
	Op-Na	0.37	0.26	Op-Na	0.37	0.26
	Overjet	1.99	64.36	Overjet	1.78*	36.53*
	Overbite	2.41	72.93	Overbite	1.46	78.92
	B-A	0.39	1.06	B-A	1.97	5.11
	Me-ANS	3.3	4.93	Me-ANS	0.9	1.36
	Me-Na	1.02	0.85	Me-Na	1.02	0.86
Angle measures, degrees	Me-ANS / Me-Na [†]	2.30% [‡]	4.11	Me-ANS/Me-Na [†]	0.27% [‡]	0.49
	S-A	1.03	1.20	S-A	0.52	0.61
	S-R	0.5	0.60	S-R	1.32	1.60
	Op-R	0.33	0.22	Op-R	0.6	0.41
	BSA	0.25 deg	1.26	BSA	1.07 deg	5.18
	ANB	0.78 deg	16.04	ANB	0.52 deg	9.60
	SNB	0.18 deg	0.24	SNB	0.18 deg	0.24
	SNA	0.57 deg	0.72	SNA	0.34 deg	0.42

FJTT, face-jaw-teeth transplantation.

* These deviations represent an improvement in outcome [i.e., the obtained outcome was closer to normal range of 0–2 mm (Marchac D, Arnaud E. Midface surgery from Tessier to distraction. *Childs Nerv Syst.* 1999;15:681–694) than the planned].

[†] Note that Me-ANS/Me-Na parameter was not used in the calculations to avoid redundant calculations.

[‡] Unless mentioned, the parameters were measured in millimeters.