A New Technique for the Creation of a Computerized Composite Skull Model

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Purpose: The goals of this study were to develop a technique for creating a computerized composite skull model and to test its accuracy. The computerized composite skull model is the combination of a 3-dimensional (3D) computed tomography (CT) bone model with digital dental models.

Materials and Methods: A dry skull with intact dentition was used in development of the technique. The creation of the computerized composite skull model was divided into 3 steps. The first step was to create digital dental models. The second step was to create a 3D CT bone model of the craniomaxillofacial skeleton. The last step was to incorporate the digital dental models into the 3D CT skull model, creating a computerized composite skull model. The accuracy of the computerized composite skull model was assessed. Bone-to-bone, tooth-to-tooth, and bone-to-tooth measurements were made on the computerized composite skull model and the dry skull. Pearson correlation coefficient and linear regression tests were performed.

Results: A technique to create a computerized composite skull model was developed. This computerized model not only represented bony structures from CT data but also reproduced dentition from digital dental models. For the bone-to-bone measurements, the mean difference between the computerized composite skull model and the dry skull was 0.5 ± 0.6 mm. For the tooth-to-tooth measurements, the mean difference was 0.1 ± 0.2 mm. For the bone-to-tooth measurements, the mean difference was 0.2 ± 0.3 mm.

Conclusions: This study showed the feasibility of creating a computerized composite skull model as well as its accuracy.

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The reconstruction of complex craniofacial malformations continues to challenge modern surgeons. Current surgical procedures are designed to reestablish aesthetic and functional anatomy. To accomplish this, precise surgical planning is necessary.

Computers are increasingly used as a tool for surgical planning in orthognathic and craniofacial surgery. The advent of computed tomography (CT), in conjunction with appropriate computer software and hardware, has created a number of options for the planning and treatment of congenital and traumatic craniofacial deformities.[1-5] CT imaging is excellent for generating bone models. However, a significant disadvantage of CT is that it is not capable of accurately representing the teeth.[6] Furthermore, orthodontic metal brackets and dental restorations may cause severe scattering during CT scanning. Because of these limitations, current surgical planning still uses conventional dental model surgery to establish the occlusion and to fabricate surgical splints.[4,5] Plaster dental models, mounted on articulators, are the most accurate replicas of the patients' teeth. Nonetheless, these models lack bony support. The limitation of conventional dental model surgery is that the planner cannot visualize the surrounding bony structures, which are critical in the treatment of complex craniofacial deformities.

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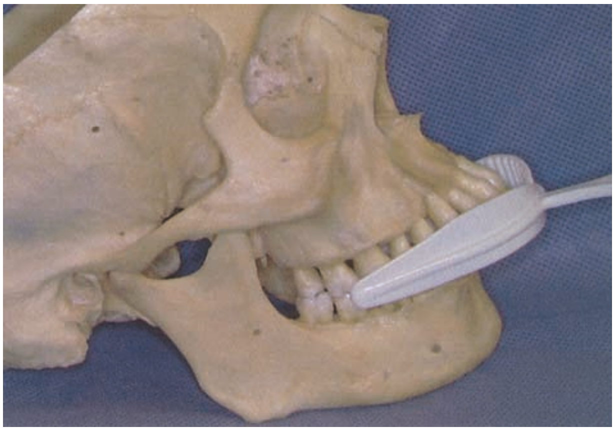

FIGURE 1. A dry skull with Triple Tray in place.

The inherent problems of surgical planning with CT and plaster dental models can be solved if there is a way to incorporate an accurate rendition of teeth into the computerized 3-dimensional (3D) bone models. Accurate digital dental models can be obtained by scanning dental impressions with a laser surface scanner. The digital dental models can then be incorporated into a computerized 3D bone model, creating a composite skull model, which will resolve the limitations of current planning systems. The present study was designed to develop a technique to create a computerized composite skull model and to test its accuracy.

Materials and Methods

To create and test the accuracy of this technique, a dry skull with intact dentition was used. The study was completed in 4 steps. The first step was to create digital dental models of the dry skull. The second step was to create from the dry skull, a computerized 3D CT skull model. The third step was to incorporate the digital dental models into the 3D CT skull model, creating a computerized composite skull model. The final step was to assess the accuracy of the computerized composite skull model.

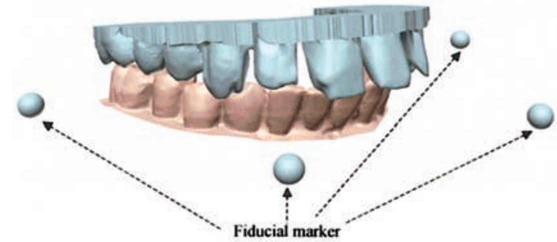

FIGURE 3. Digital dental models with 4 fiducial markers created by a laser surface scanner from simultaneous upper and lower dental impressions.

CREATION OF DIGITAL DENTAL MODELS

Before dental impressions were obtained, fiducial markers were inserted into a radiolucent full-arch dental impression tray (Triple Tray; ESPE America, Norristown, PA) (Fig 1). This triple tray was used to take simultaneous impressions of the maxillary and mandibular arches. Four 4.0-mm titanium spheres were mounted on the Triple Tray as fiducial markers. One pair was at the canine region, and another pair was at the molar region (Fig 2). Dental impressions were then taken with polyether impression material (Impregum; ESPE America) in the conventional manner (Fig 2).

The dental impressions with the 4 fiducial markers were scanned using a 3D laser surface scanner (Geodigm Corp, Minneapolis, MN). The accuracy of the laser scanner was 0.01 mm. Data were saved in stereolithography (.STL) format with its full resolu-

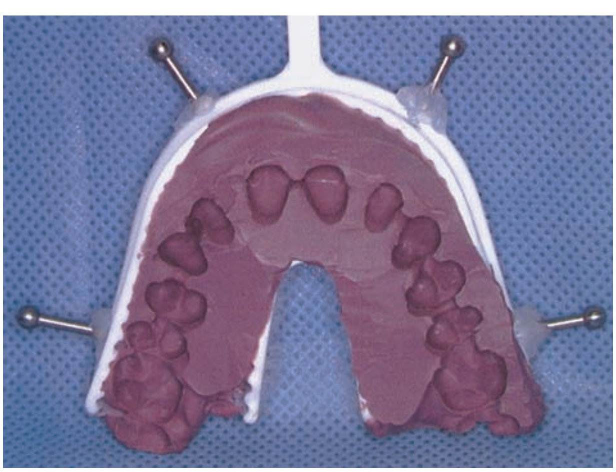

FIGURE 2. Simultaneous upper and lower dental impressions made with a Triple Tray and 4 fiducial markers.

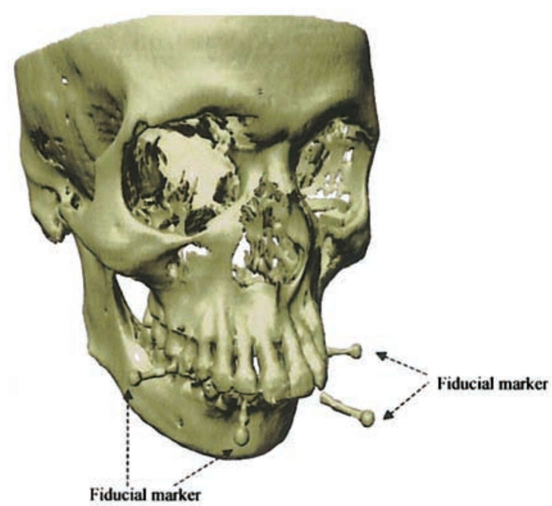

FIGURE 4. The 3D CT skull model with 4 fiducial markers reconstructed from a CT scan of the dry skull.

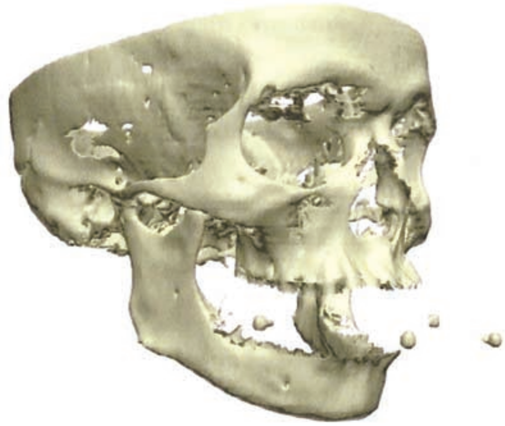

FIGURE 5. The 3D CT bone model with teeth removed and 4 fiducial markers in place.

tion. Using a custom computer program, the scanned impressions were turned inside out to generate positive models of the teeth from the negative models of the impressions. Digital dental models with 4 fiducial markers were created (Fig 3).

CREATION OF 3D CT SKULL MODELS

The dental impressions with fiducial markers were again placed into the maxillary and mandibular dental arches of the dry skull. The dry skull then underwent CT scanning with a 16-bit 512 × 512 matrix at a slice thickness of 1.0 mm, field of view of 190 mm, kVp of 140, and mA of 250. The digital CT data were directly transferred from the CT scanner to a personal computer using a 5.25-inch Magneto-Optical disk (Sony Corp, Tokyo, Japan). The threshold of the bony structures was carefully chosen and verified on a layer-by-layer on the CT data to ensure the bony structures were properly segmented. A 3D CT skull model with 4 fiducial markers was then reconstructed via a divide-and-conquer technique (Marching Cubes algorithm[7]). Because of the large size of the volumetric dataset, the less critical region in the computer skull model from the inferior piriform aperture level to the forehead

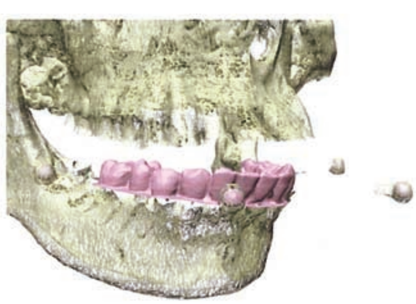

FIGURE 6. The 3D CT bone model rendered in wire-frame format to precisely align fiducial markers from the 3D CT bone model and the digital dental models.

FIGURE 7. The creation of a computerized "composite skull model" after the digital dental models were incorporated into the 3D CT of the craniofacial skeleton and the fiducial markers were removed.

was decimated and the total numbers of triangles were reduced to 210,000 via the Decimation algorithm[4,8] (Fig 4).

INCORPORATION OF DIGITAL DENTAL MODELS INTO A 3D CT BONE MODEL

The 3D CT skull model was imported into custom computer software. The teeth of the CT skull model were removed, leaving the fiducial markers in place (Fig 5). After this, the digital dental models were imported and placed into the CT skull models by aligning the corresponding fiducial markers (Fig 6). The fiducial markers were then removed, creating the computerized composite skull model (Figs 7 and 8).

ASSESSMENT OF ACCURACY OF "COMPOSITE SKULL MODEL"

Measurements were made on the computerized composite skull model and directly on the dry skull

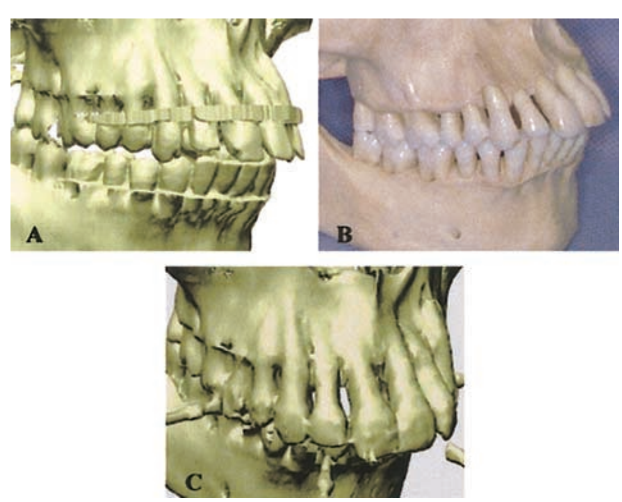

FIGURE 8. The oblique views of the teeth from computerized "composite skull model" (*A*), dry skull (*B*), and 3D CT bone model directly reconstructed from CT scans (*C*).

Table 1. DEFINITIONS OF MEASUREMENTS BY CATEGORY

Category	Landmark	Definition
Bone to bone	R Po-Me	Right porion to menton
	L Po-Me	Left porion to menton
	L Go-Me	Left gonion to menton
	R Go-Me	Right gonion to menton
	Go-Go	Right gonion to left gonion
	Zy-Zy	Right zygomatic arch to left zygomatic arch, smallest distance
	L Po-L Or	Left porion to left orbitale
	R Po-R Or	Right porion to right orbitale
	Maxilla width	Smallest width of maxilla at Le Fort I level
	Mandible width	Smallest width of mandible, ramus to ramus
Tooth to tooth	U3-U3	Upper right cuspid to upper left cuspid, buccal surfaces
	L3-L3	Lower right cuspid to lower left cuspid, buccal surfaces
	U6-U6	Right upper first molar to left upper first molar, buccal surfaces
	LL6-LR3	Lower left first molar to lower right cuspid, buccal surfaces
	LR6-LL3	Lower right first molar to lower left cuspid, buccal surfaces
	UR6-UL3	Upper right first molar to upper left cuspid, buccal surfaces
	UL6-UR3	Upper left first molar to upper right cuspid, buccal surfaces
	U2-U2	Upper right lateral to upper left lateral, distal surfaces
Bone to tooth	LU3-L Or	Upper left cuspid tip to left orbitale
	RU3-R Or	Upper right cuspid tip to right orbitale
	Na-RU3	Nasion to upper right cuspid
	Na-LU3	Nasion to upper left cuspid
	Na-RU6	Nasion to upper right first molar
	Na-LU6	Nasion to upper left first molar
	RL3-Me	Right lower cuspid tip to menton
	LL3-Me	Left lower cuspid tip to menton

using a digital Boley gauge, which was accurate to 0.01 mm. All measurements were performed by the same investigator (A.R.), and each measurement was repeated 3 times on different days. A 1-way analysis of variance was used to calculate the intraobserver reliability.

The measurements were grouped into 3 categories: bone-to-bone, tooth-to-tooth, and bone-to-tooth (Table 1). The bone-to-bone measurements were made between 2 bony landmarks and were used to assess the accuracy of the 3D skull model. The tooth-to-tooth measurements were made between 2 dental landmarks and were used to assess the accuracy of the digital dental models. The bone-to-tooth measurements were made from a bony landmark to a dental landmark and were used to assess the accuracy of the alignment of the digital dental models with the 3D CT skull model.

Pearson correlation coefficient was obtained and linear regression analyses were performed to identify any possible differences between the computerized composite skull model and the dry skull. Statistical analysis was performed using SPSS 10.0 (SPSS Inc, Chicago, IL)

Results

A technique for creating a computerized composite skull model was developed. This computerized model not only represented bony structures from CT data but also reproduced dentition from digital dental models.

There were no significant differences among the 3 measurements made by the examiner; therefore, the 3 measurements were averaged for each item (Table 2).

For the bone-to-bone measurements, the mean difference between the computerized composite skull model and the dry skull was 0.5 ± 0.6 mm (Table 2). There was a high degree of correlation between these 2 sets of data. The correlation coefficient (r) was 1.00, and the regression coefficient (β) was 0.99.

For the tooth-to-tooth measurements, the mean difference was 0.1 ± 0.2 mm (Table 2). There was high degree of correlation between these 2 sets of data; r was 1.00 and β was 1.00.

For the bone-to-tooth measurements, the mean difference was 0.2 ± 0.3 mm (Table 2). There also was a high degree of correlation between these 2 sets of data; r was 1.00 and β was 1.01.

Discussion

Current computerized 3D surgical planning systems allow surgeons to perform virtual osteotomies and to predict surgical outcomes.[3,4] A drawback of the current systems is that they require the use of plaster dental model surgery to establish the occlusion and to fabricate surgical splints.

Table 2. COMPARISON OF COMPOSITE SKULL MODEL WITH DRY SKULL

Category	Landmark	Composite Skull Model Distance (mm)	Dry Skull Distance (mm)	Difference
Bone to bone	R Po-Me	129.30	129.62	0.32
	L Po-Me	127.81	129.15	1.34
	L Go-Me	80.04	81.54	1.50
	R Go-Me	79.54	78.87	−0.67
	Go-Go	95.03	95.79	0.76
	Zy-Zy	120.86	121.51	0.65
	R Po-R Or	80.21	80.54	0.33
	L Po-L Or	80.39	80.58	0.19
	Maxilla width	66.38	66.66	0.28
	Mandible width	95.49	95.75	0.26
Mean difference			0.50	
SD			0.62	
Pearson correlation coefficient (r)			1.00	
Regression coefficient (β)*			0.99	
Significance			.00	
Tooth to tooth	U3-U3	43.71	43.78	0.07
	U6-U6	60.81	60.90	0.09
	L3-L3	32.13	32.04	−0.09
	LL6-LR3	49.91	49.49	−0.42
	LR6-LL3	50.53	50.66	0.13
	UR6-UL3	57.73	57.59	−0.14
	UL6-UR3	58.75	58.52	−0.23
	U2-U2	34.54	34.63	0.09
Mean difference			−0.06	
SD			0.19	
Pearson correlation coefficient (r)			1.00	
Regression coefficient (β)*			1.00	
Significance			.00	
Bone to tooth	RU3-R Or	53.92	54.59	0.67
	LU3-L Or	55.10	55.10	0.00
	Na-RU3	85.69	85.70	0.01
	Na-LU3	85.93	86.02	0.09
	Na-RU6	86.30	86.25	−0.05
	Na-LU6	87.03	87.28	0.25
	RL3-Me	46.83	47.04	0.21
	LL3-Me	46.72	47.42	0.70
Mean difference			0.23	
SD			0.30	
Pearson correlation coefficient (r)			1.00	
Regression coefficient (β)*			1.01	
Significance			.00	

NOTE. See Table 1 for explanation of landmark abbreviations.
*Dependent variable: composite skull model.

Surgeons have always had difficulty in simultaneously displaying bony structures and accurate teeth. Several investigators have attempted to incorporate dental models into physical bone models.[9-14] Different methods were developed for replacing the teeth with plaster dental models in 3D milled or stereolithographic models. These methods solved the problem of simultaneously displaying bony structures and accurate teeth. However, all of these methods were based on physical models, which were not suitable for computerized virtual osteotomies. An additional shortcoming was the distortion of stereolithographic models due to the character of the material (SLA-resin) and reslicing procedure.

The authors developed a technique for creating a computerized composite skull model and showed its accuracy. The results indicate that the values for the composite skull model were the same as those for the dry skull.

The tooth-to-tooth measurements showed a high degree of accuracy (mean difference, 0.1 mm). These findings support the use of laser surface scanning as a way of obtaining accurate digital dental models directly from dental impressions.

The bone-to-tooth measurements also showed a high degree of accuracy (mean difference, 0.2 mm). This confirmed the accuracy of the authors' fiducial marker system.

The difference in the bone-to-bone measurements was slightly greater (mean difference, 0.5 mm) than the tooth-to-tooth measurements. These findings are similar to those found by other investigators.[6] Regardless of how small the field of view is, the precision of CT is limited by the layer thickness during scanning.[6,9] CT scanners capture images layer by layer, and data between image layers are reconstructed with the use of mathematic algorithms.[7] Currently, the most precise CT scanners scan at a minimum interval of 1.0 mm. At this scanning interval, they are not capable of accurately reproducing the teeth to the degree that is necessary for surgical planning. The occlusion between maxillary and mandibular teeth requires a high degree of precision; even a small error may result in malocclusion.

The use of our computerized composite skull model has the potential to eliminate plaster dental model surgery. With this method, it becomes possible to perform presurgical planning entirely in the computer. However, the current design of an impression tray with fiducial markers is not practical for clinical use; it was used only to test a technique of incorporating digital dental models into a 3D CT bone model. We are currently redesigning a new impression tray with fiducial markers, based on the same theory, for clinical use. In the future, it also will be possible to establish the occlusion and to design surgical splints digitally. The physical surgical splints will then be fabricated using rapid prototyping techniques. If necessary, physical models of the craniofacial skeleton can also be fabricated stereolithographically.

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