The virtual cranio-facial patient project
Le projet de patient virtuel dans le domaine cranio-facial

One of the research goals at the Craniofacial Virtual Reality Laboratory and the Integrated Media Systems Center at the University of Southern California is to build a virtual craniofacial patient from CT data, digital teeth models, and human jaw motion tracking. First, two different techniques to acquire three-dimensional soft-tissue representations will be presented. Then, automatic segmentation of the upper and lower jaws will be introduced, followed by three-dimensional reconstruction of these structures. Preliminary results on integrating high-quality digital teeth models with CT reconstructed models will be shown. Finally, an integration of the three-dimensional CT data and an ultrasound motion tracking device for human jaw, allows for visualization of jaw movement in three dimensions.

This research is a first step on building a complete craniofacial virtual patient, which will enable other researchers to develop methods for surgery simulation, treatment planning and other research topics.

Keywords: 3D modeling, CT, dentition models, jaw movement.

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1. INTRODUCTION

Accurate patient-specific three-dimensional representations or computer models are necessary for surgery simulation, treatment planning and diagnostic research to advance.

Recent developments in technology and software are providing better data and methods to facilitate research in biomedical modeling and simulation. In the area of segmentation, original methods involved the time-consuming task of manually tracing structures from slice to slice. This process is now possible with significantly less interaction from the user. Programs such as 3D Slicer (Gering et al 1999), Mimics (Materialise N.V., Heverlee, Belgium) and Amira 2.3 (TGS Inc., 5330 Carroll Canyon Road, San Diego, CA 92121-3758) provide semi-automatic image-processing-based segmentation and modeling from CT images. These programs use the Generalized Marching Cubes algorithm to create a polygonal wireframe mesh of the segmented area and export a model in STL or other formats.

In this paper we present automatic segmentation of the mandible from CT images using the Amira 2.3 program. Previous reports have utilized manual methods to segment the mandible from MRI (Krebs et al 1995) and CT images (Korioth & Hannam 1990, Shigeta et al 2003). Segmentation of the mandible contains common problems with this process in areas where anatomic structures contact and/or overlap and in areas that have indistinct borders. The other regions of difficulty are the condylar heads that rest in the radiographically dense temporal fossa resulting in borders that are often indistinct. As a result, many of the published reports present mandibles that lack parts of the dentition and the mandibular condyles.

Dental crown morphology on CT images is lacking detail due to limitations of the technology and interferences from metal and other materials. Yet this information is highly desirable for certain types of clinical procedures, such as dental implants, cleft palate or orthognathic surgery. An approach to resolve this situation is to integrate accurate 3-D dental crowns with the CT images, however this involves the process of registration of the two very different datasets. There is very limited work in this area, with a previous method described using metallic (Curry et al 2001) or ceramic markers (Terai et al 1999),(Nishii et al 1998). placed on the skeleton and dentition prior to CT imaging and production of the dental models. The spherical markers are located in both datasets and manually registered resulting in 2mm and 2 degrees mean error with maximum errors of 4.2 mm and 4 degrees (Terai et al 1999). Recent advances have allowed for production of very accurate 3-D dental models by destructive scanning, laser scanning or direct imaging of the teeth. However they only feature the tooth crowns without the roots or skeletal information. In this paper, computer methods to integrate the high-resolution 3-D dental models with the CT volume are presented.

Accurate simulation of mandibular movement is fundamental in diagnosis and treatment simulations such as planning for orthognathic surgery involving autorotation of the mandible, wherein this movement must be accurately predicted. However, movement of the mandible is very complex and not easily recorded. For these reasons, its movement has historically been simplified to rotation about a single axis. However, this approach can lead to severe mal-positioning of the jaws, because the simulated axis of rotation is not related to the true path of mandibular motion (Nattestad et al 1991, Nattestad & Vedtofte 1994). More recently light and ultrasonic systems have been developed to record mandibular position and movement (Shigeta et al 2003). Opticoelectric systems using CCD cameras to track light-emitting diodes on a headframe and face bow (Miyawaki et al 2001) have been developed (Tokiwa et al 1996). The mean measurement error of this system is 150 ± 10 μm (Tokiwa et al 1996).

However, this approach is time-intensive, requires attachment of intrusive hardware on the patient and involves a complex arrangement of cameras. Since, a newer approach utilizing ultrasonic sensors attached to a headframe and emitters firmly attached to the mandibular dentition has been developed and is commercially available: JMA (Zebris GmbH, Germany). The advantages of this system is the ease-of-use, significantly less hardware and an accuracy of ~100 μm. Both systems provide 3-D mandibular motion capture and report on the changes of coordinates positions with motion. One of the goals of our research is to describe developed methods for simulation of mandibular motion on a 3-dimensional model of the craniofacial skeletal complex. This method applies the 3D ASCII motion data from the ultrasonic jaw motion tracker to the mandible of a craniofacial model created from a CT image.

2. MATERIALS

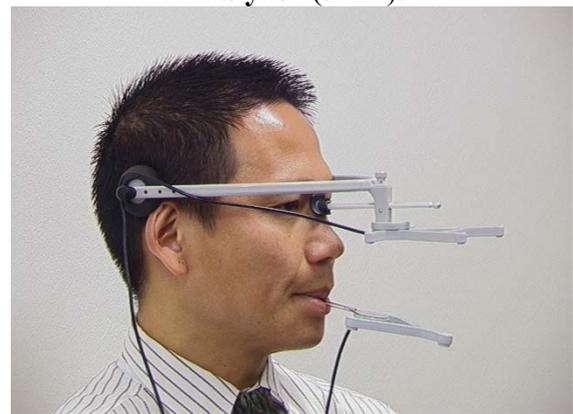*CT:* The data consisted on two kinds of CT image sequences:
   a) GE HiSpeed RP helical CT scanner (General Electric Company). The GE CT sequence imaged the whole head with slices taken at 1mm, containing in total 129 slices (12 bits) in DICOM format.
   b) the dental CT NewTom 9000 (QR srl, Via Silvestrini 20, Verona, Italy). The Newtom CT sequence imaged only 13cm and was reconstructed to provide 285 slices of 0.33mm thickness (8 bits) in BMP format.

Digital dentition models: To obtain high accuracy digital tooth crowns models, an impression of the patient imaged with the Newtom CT was sent to OrthoCad (Cadent, 640 Gotham Parkway, Carlstadt, NJ 07072-2405). Digital models of the lower and upper crowns were returned in STL format. Accurate 3-D models of the dentition can be obtained from several sources including also eModels (GeoDigm Corporation, 1630 Lake Drive West, Chanhassen, MN 55317) and SureSmile OraScanner (OraMetrix, Inc., Headquarters, 12740 Hillcrest Road, Dallas, TX 75230).

Jaw motion: Mandibular motion was recorded using the Jaw Motion Analyzer (JMA) (Zebris GmbH, Germany) and the software provided (WinJaw). JMA is an ultrasonic motion capture device depicted in Figure 1. The ultrasound emitter array is bonded to the labial surfaces of the mandibular teeth using a jig customized with cold cure acrylic. The sensors are located on a head frame secured to the patient's head. The spatial coordinates of the three emitters during motion are saved in an ASCII file.

Figure 1: Ultrasonic Jaw Motion Analyzer (JMA).

Software: Pre-existing software methods and programs were used when possible. When necessary, new software was implemented. In this project, the following software tools were used: a) DICOM2 from S. Barre (http://www.barre.nom.fr/medical/dicom2/) to convert DICOM 12-bit images to BMP 8-bit image format; b) Amira version 2.3 (TGS Inc., 5330 Carroll Canyon Road, San Diego, CA 92121-3758) for 3D visualization, segmentation and modeling of the lower jaw; c) 3D Studio MAX 3.1 (Autodesk, Inc., 111 McInnis Parkway, San Rafael, CA 94903, USA) for animation of the lower jaw and creation of videos.

3. METHODS

3.1. Soft-tissue reconstruction

CT:
Recent advances in volume rendering technology and graphic cards have provided a myriad of software to visualize CT data in three-dimensions. Amira 2.3 (cited above) allows the user to create an iso-surface at certain gray value (Figure 2). The user can also display soft tissue or bone tissue in real-time by changing the opacity value for visualization, diagnosis or treatment planning in full three dimensions.

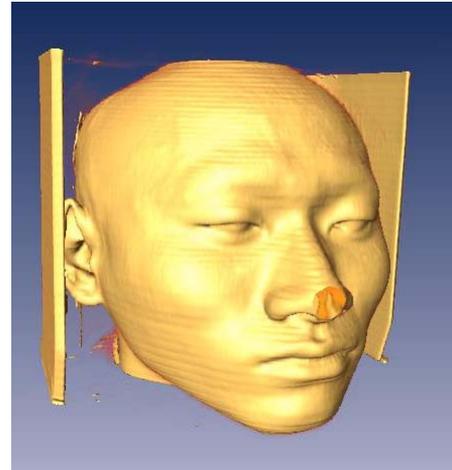**Figure 2: Iso-surface of the soft-tissue** (GE CT data) computed with Amira 2.3.

Structured-light imaging device:
Previous reports have demonstrated 3-dimensional facial imaging in a clinical setting however some of the anthropometric measurements were proven to be unreliable (errors higher than 1.5mm) (Aung et al 1995, Cavalcanti et al 1999). In addition, recent advances in imaging systems have made 3-dimensional imaging accessible to many healthcare professionals, yet these systems lack validation for specific clinical purposes.

In previous work (Enciso et al 2003) we validated a structured-light imaging system (Eyetronics, NV, Kapeldreef 60, 3001 Heverlee, Belgium) using a mannequin head with pre-labeled anthropometric markers and the Microscribe 3Dx digitizer-probe (Immersion Corp., 801 Fox Lane, San Jose, CA 95131, USA). The overall mean absolute error combining frontal, left and right side was of 0.48 mm, with standard deviation of 0.40 mm, and maximum absolute error of 1.55 mm.(Enciso et al 2003).

Figure 3 shows an example of a 3D model acquired with the Eyetronics device.

Figure 3: Structured-light imaging device.
Example of 3D mesh reconstruction using Eyetronics device (textured wireframe, shaded and textured views), courtesy of Alex Shaw, CVRL, USC.

3.2. Segmentation and modeling of the jaws

Figure 4: Segmentation: The original CT slices on the left are replaced by "phantom" slices on the right to facilitate separation of the mandible and the temporal bone (top row), and the lower and upper teeth (bottom row). To stop the growing algorithm the upper part of the mandible (in pink: top left) and the upper part of the lower teeth (in yellow: bottom left) are set to black in the "phantom slices" (right column).
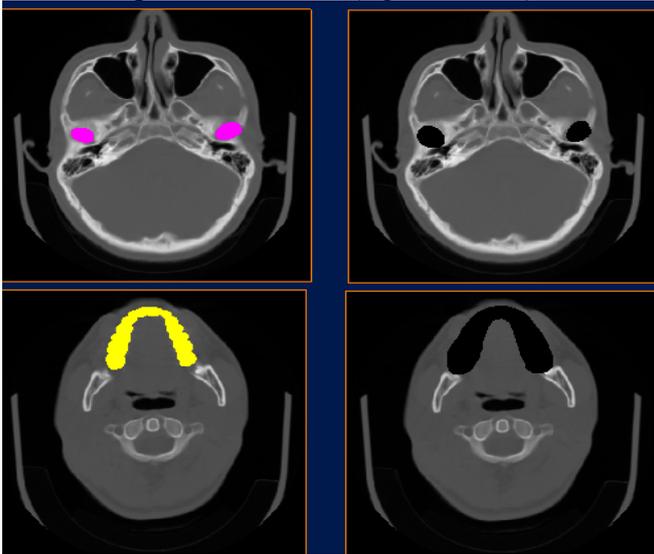
Figure 5: Automatic polygonal 3D mesh reconstruction using Amira 2.3.

Creation of a separate 3D polygonal mesh for the lower jaw is needed for animation. Therefore the mandible must be segmented from the CT volume. While the Amira 2.3 program provides computer tools for segmentation and jaw modeling, the software cannot distinguish between the maxilla and mandible or upper and lower teeth (in particular, in the area where teeth contact and overlap). To overcome this problem, two "phantom" slices were inserted in the image stack to facilitate separation: one to separate the upper part of the mandible from the temporal bone (Figure 4 top right) and one to separate the upper from the lower teeth (Figure 4 bottom right). The phantom slices were created by manually adjusting the greyscale value of the anatomic region of interest on a terminal slice to be sufficiently different than the remaining slices. This difference in greyscale was sufficient to terminate the segmentation routine. The interocclusal slice could be avoided if the patient was imaged with the teeth apart or if a radiolucent interocclusal splint was used to separate the teeth.

After the two phantom slices have been inserted in the stack of CT images, the user selects a point on any region in any slice containing the mandible and the software will automatically segment or label every slice in the volume. The same procedure can be applied to the maxilla. Using the Amira 2.3 program a 3D polygonal mesh (STL model) was created with the Generalized Marching Cubes Algorithm and decimated for later use (Figure 5).
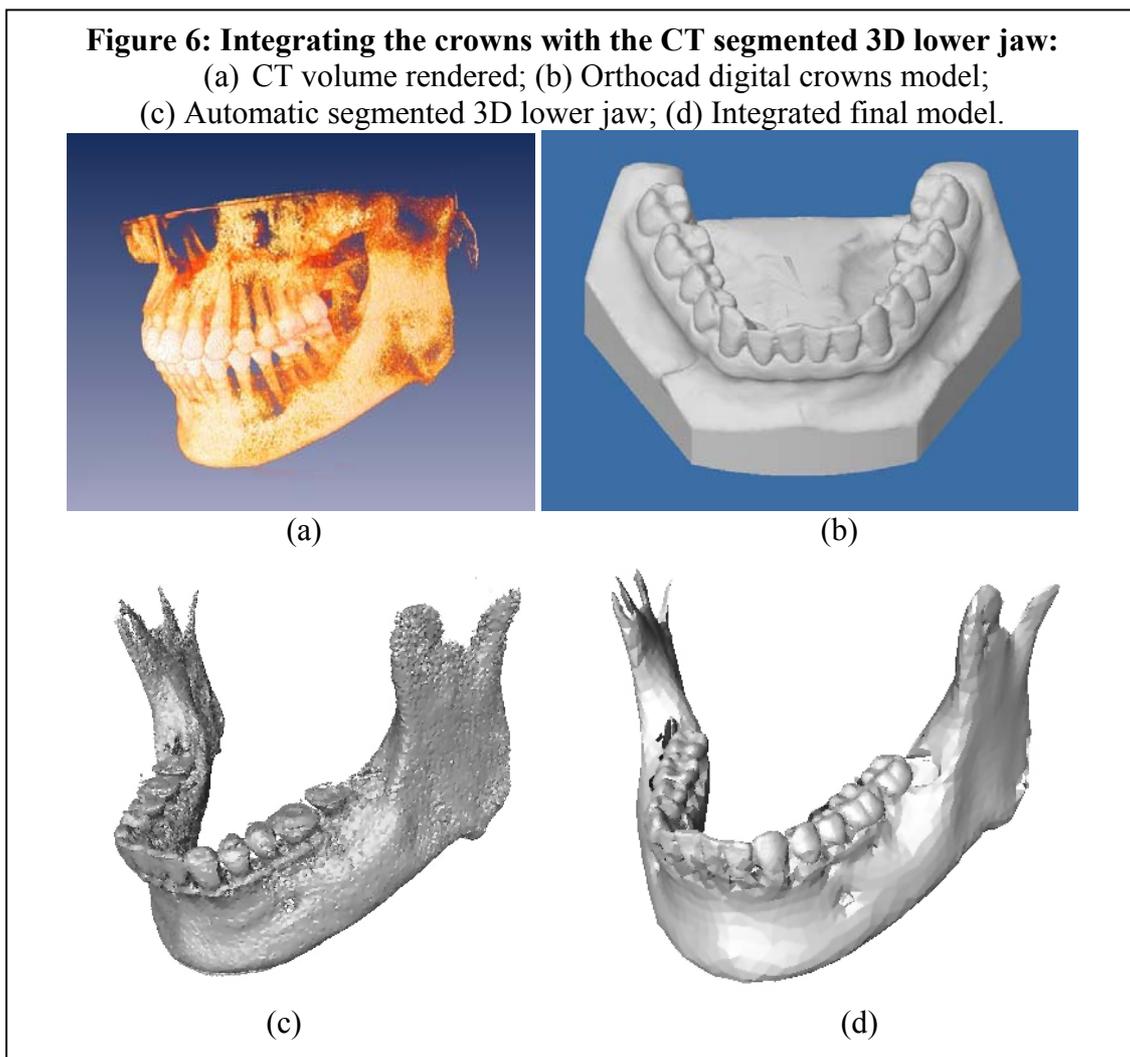
3.3. Integrating the digital teeth models

While the volume rendered image of the dental Newtom CT (Figure 6a) shows high detailed root information, the 3D model of the crowns in the reconstructed lower jaw (Figure 6c) is not as detailed as the digital crowns model from OrthoCad (see Figure 6b). Therefore, steps were carried out for fitting the digital crowns model onto the 3D jaw model. The resultant integrated 3D model is shown in Figure 6d.

The crowns digital model (Figure 6b) and the reconstructed 3D jaw model share the same metric but the software Amira 2.3 scales the jaw model. First, this homogeneous scaling was computed as follows:
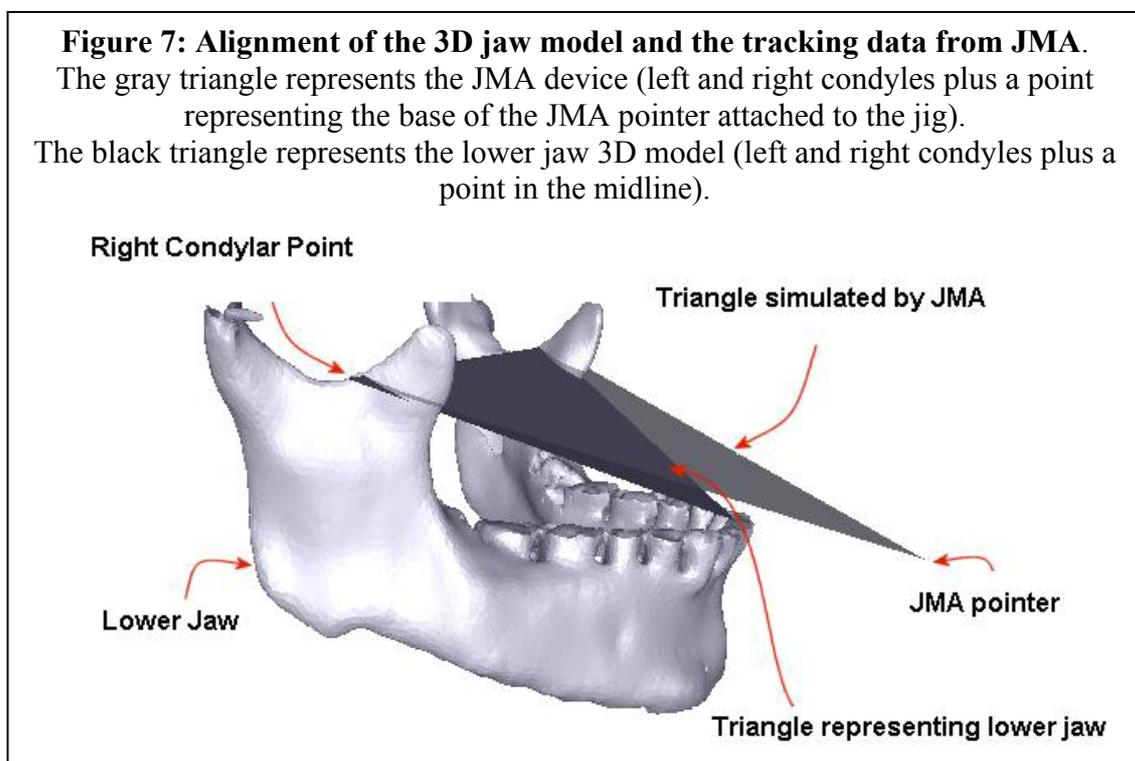
- The crown models are rotated in 3D such that the vector representing the frontal patient perspective gets aligned with one of the coordinate axes.
- Three corresponding points on the lower jaw and the crowns are manually selected, and the scaling factor is computed as the ratio between the X and Y distances along the axes. In the Newtom data, the two ratios are the same.

The 3D jaw models are then scaled accordingly. The crude teeth from the 3D model of the lower jaw are removed in Amira 2.3 and replaced with the 3D crown models, which are manually aligned (Figure6d).

Figure 6: Integrating the crowns with the CT segmented 3D lower jaw:
(a) CT volume rendered; (b) Orthocad digital crowns model;
(c) Automatic segmented 3D lower jaw; (d) Integrated final model.

(a)   (b)

(c)   (d)

3.4. Animation

The Jaw Motion Analyzer tracks the position in space of three points defining the triangle shown in gray in Figure 7: left and right condylar points (selected on the patient with a JMA T-pointer) and the tip of the JMA short pointer attached to the jig. Ideally the JMA device will output the path of three points easily identified in the 3D jaw model (i.e. ceramic markers rigidly attached to the jig). The lower jaw is represented by three points selected by the user in the computer (second triangle shown in black in Figure 7): left and right condyles and one point in the midline (between the two central teeth). The two triangles are not similar, and the best registration has to be found. First, we aligned the two bases. Second, we computed a similar triangle (same three angles) to the one simulated by JMA. Then, we found the rigid displacement between the JMA triangle and the new defined triangle (one homogeneous scale, rotation and translation). This gives us a good approximation of the alignment of the two models.

Figure 7: Alignment of the 3D jaw model and the tracking data from JMA.
The gray triangle represents the JMA device (left and right condyles plus a point representing the base of the JMA pointer attached to the jig).
The black triangle represents the lower jaw 3D model (left and right condyles plus a point in the midline).

The JMA device stores in a ASCII file the 3D positions of the tracked points sequentially with respect to time. A transformation matrix (rigid displacement) is computed for every successive position of the JMA triangle and recursively applied to all the points on the lower jaw. In fact, the lower jaw 3D model is treated as a single object in 3D Studio Max and the transformation matrix computed is applied to this object as a whole (see Figure 8 for some results).

4. RESULTS AND DISCUSSION

The overall goal of this research project is to utilize multi-media imaging of the skeleton, dentition and motion to construct a Virtual Craniofacial Patient model. This patient-specific model serves as the basis for applications such as diagnosis and treatment simulation as well as advanced functions such as biomechanical testing and tissue engineering. The integration of CT data with 3D dental crown information as well as mandibular motion is the first step.

Our methods can be applied to different scans as demonstrated through the paper for traditional helical CT and cone-beam CT. The presented modeling and animation results are descriptive studies and are ongoing research efforts in the process of further development and validation.

Segmentation of the Mandible
The GE CT data was **automatically** processed to provide the resultant polygonal 3D mesh reconstruction (Figure 5). To automatically separate the lower jaw from the upper jaw, two "phantom" slices were introduced (Figure 4): one separating the mandible from the temporal bone and one separating the lower and the upper teeth. The current method suffers from data loss in these two slices. The interocclusal slice could be avoided if the patient was imaged with the teeth apart or if a radiolucent interocclusal splint was used to separate the teeth.

Integration of 3D Dental Crowns with the CT Volume
The NewTom CT volume (Figure 6a) was processed and segmented to provide the polygonal 3D mesh of the lower jaw (Figure 6c). The 3D model of the lower crowns from OrthoCad (Figure 6b) was fitted to the lower jaw (Figure 6d). In this process the key issues are registration and consideration of distortions related to the imaging modality. Registration relies upon common features present in both datasets. To overcome this problem, metallic (Curry et al 2001) and ceramic markers (Terai et al 1999, Nishii et al 1998) placed on the dental arches for CT imaging and the dental impression have been used. This approach holds promise for future research on validation of the integration methods.

Animation of the Mandible
The segmented lower jaw was animated with the JMA motion data (Figure 8). The JMA device tracks three points over time and the transformation relating the position of the triangle over time is computed. After aligning the jaw models with the triangle representing the tracked points from JMA (see Figure 7), the transformation is applied to the jaw model. Ongoing research is to automatically transfer the jaw models to the animation space. Ceramic markers will be used as registration points to be tracked by the JMA and will be used for aligning the two coordinate systems.

The goal of constructing a Virtual Craniofacial Patient model is an ambitious interdisciplinary collaborative effort requiring both clinical and computer science knowledge. This goal will be accomplished in small steps such as those described above and with further development and advances the goal will be achieved. Realistic patient-specific models can greatly benefit patient care, education and research.

Figure 8: Jaw animation in 3D Studio Max: resting position, maximum opening, opening, and right and left lateral movements. Two different patients imaged with two different scanners are shown: (top row) CT Newtom data; (middle and bottom rows) CT GE data.
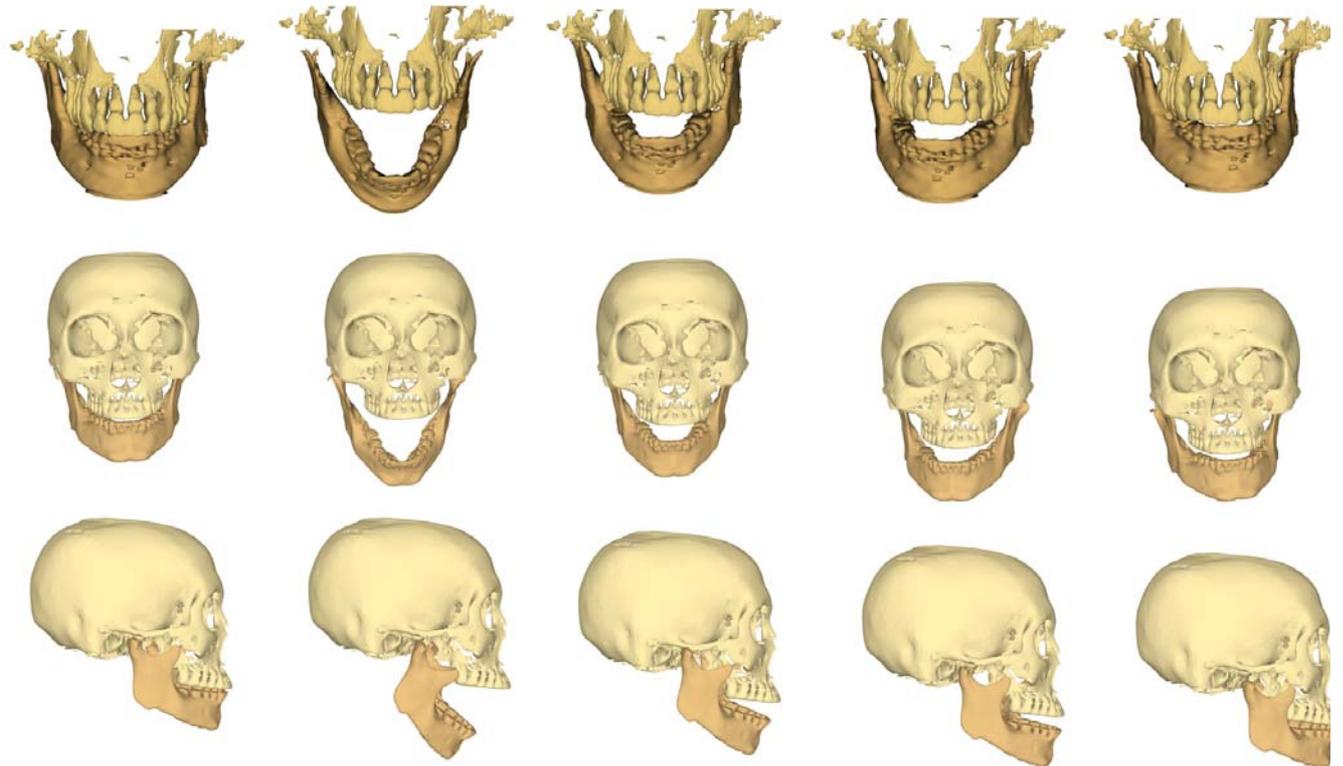
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