Methods for managing 3-dimensional volumes

Asem Awaad Othman,a Amr Ragab El-Beialy,b Sahar Ali Fawzy,c Ahmed Hisham Kandil,c Ahmed Mohammed El-Bialy,c and Yehya Ahmed Mostafad

Cairo, Egypt

The introduction of 3-dimensional (3D) volumetric technology and the massive amount of information that can be obtained from it compels the introduction of new methods and new technology for orthodontic diagnosis and treatment planning. In this article, methods and tools are introduced for managing 3D images of orthodontic patients. These tools enable the creation of a virtual model and automatic localization of landmarks on the 3D volumes. They allow the user to isolate a targeted region such as the mandible or the maxilla, manipulate it, and then reattach it to the 3D model. For an integrated protocol, these procedures are followed by registration of the 3D volumes to evaluate the amount of work accomplished. This paves the way for the prospective treatment analysis approach, analysis of the end result, subtraction analysis, and treatment analysis. (Am J Orthod Dentofacial Orthop 2010;137:266-73)

With the introduction of 3-dimensional (3D) technology, producing a patient’s 3D virtual image became an achievable reality. However, to make the 3D volume versatile and usable, we need diagnostic tools that enable us to detect defective skeletal and dental areas. We also need tools that allow us to detach, manipulate, and adjust various parts of the dentofacial skeleton, and then reattach them. In this article, a technique for these tasks is introduced.

MATERIAL AND METHODS

Acquisition of the patient’s 3D virtual model is the foundation. Computed tomography (CT) slices of the patient’s head (soft and hard tissues) are obtained in digital imaging and communication in medicine (DICOM) format. These cuts are then compiled to create a 3D model. By using a ray-casting volume-rendering technique, a digital 3D replica is built.1 This volume-rendering formula provides more information of the anatomic details of the dentofacial skeleton for better visualization of the 3D model of the head (Fig 1). Surface-rendering formulas are available for additional manipulation. For automatic separation of the mandible from the skull, a consistent interocclusal clearance is essential throughout the arch length, to facilitate the training of the artificial intelligence. Hence, an important prerequisite of the imaging procedure is to acquire the CT images with the teeth in disclusion. This dental separation should be within the interocclusal freeway space, where the condyles experience pure rotation around the condylar hinge axis. In such position the condyles are functionally centered in the glenoid fossa (centric relation), hence, the facial pattern of the patient is preserved, and a reproducible posture is obtained, in addition to elimination of functional occlusal shifts due to premature occlusal interferences. Subsequent localization of the condylar hinge axis allows for mandibular rerotation into maximum interdigitation when necessary.

On the contrary, capturing the CT images without interocclusal separation produces slides with blended maxillary and mandibular teeth. This results in loss of anatomic details and in turn, jeopardizes the accuracy of the dental measurements. Through occlusal separation, occlusal details are visible, and the maxillary and mandibular separation is technically precise.

For occlusal separation, the patient wears a custom-made mandibular splint during radiographic image acquisition. The splint is fabricated with a vacuum-pressing machine. A 2-mm hard plastic sheet is custom made on the patient’s mandibular model. The splint is then tried in the patient’s mouth. The patient is instructed to occlude on an articulating paper to mark the points of initial contact. Marks on the splint are accurately and mildly ground to guide the maxillary teeth into their shallow grooves and avoid eccentric occlusions. Such manipulations of the splint will reduce its thickness to 1 mm. Hence, a minimal posterior dental separation is obtainable with the mandible maintained in centric relation.
The algorithm used for automatic mandibular separation stems from a previous approach for fully automatic identification of 2-dimensional (2D) cephalometric landmarks. This approach was developed by unifying an active appearance model and simulated annealing for automatic cephalometric landmarks localization on 2D lateral radiographic images (Fig 2). The results showed that the active appearance model followed by
simulated annealing can give more accurate results than an active shape model. This technique was extended to obtain landmarks for both lateral and frontal images. Our approach depends on determining the landmarks from the 2D model and then processing them to generate their corresponding landmarks on the 3D model. This procedure starts by building digital reconstructed radiography from the patient’s 3D images. This means generating the lateral and posteroanterior cephalograms from the 3D model of the patient’s head (Fig 3, A and B). These cephalograms are fed into the computer for automatic 2D landmark identification with the previously mentioned technique (Fig 3, C and D). Identical automatically detected landmarks on the lateral and frontal cephalograms are processed to generate their equivalent lines on the 3D model of the patient’s head (Fig 4). Because point landmarks on the 2D images are represented as lines on the 3D model, the generated lines will be perpendicular on the y-z and x-z planes, respectively. Hence, the intersection of the two generated lines is a point on the 3D image. Thus each landmark generated from equivalent frontal and lateral landmarks, is represented as a corresponding landmark on the 3D skull model (Fig 5).

Using this technique, the mandibular landmarks from 3D cephalometry were automatically selected. This represents the initial data to accomplish the mandibular separation. In addition, a faster operation is guaranteed by automatically determining an imaginary boundary box for the mandible from the 3D cephalometric landmarks. Hence, a fully automated approach is developed for mandibular separation (Fig 6). Likewise, the fully automatic parting of the maxilla with its attached dental structures begins with the training of the artificial intelligence. In this approach, the landmarks allocated on the 3D image with the boundary points of the maxilla are used to separate the maxilla in the 3D model. The boundary points of the maxilla are learned from the lateral cephalometric image generated from the 3D image. The generated maxillary contour fed into the computer makes it possible to trace the maxillary border with subsequent maxillary separation (Fig 7).

Both techniques used for automatic separation of the mandible and the maxilla can be used for symmetric and asymmetric patients, since the technique is boundary oriented.

Separation of the dentition from the adjoined skeletal base facilitates the dental manipulation. The difficulty of extracting the teeth from CT images is due to the similarity in intensity with the surrounding bone.
The technique depends on the fact that the dental enamel can be allocated easily because of its maximum intensity in the image and is automatically extracted by the threshold segmentation technique.\textsuperscript{9,10} The crowns are used to complete the segmentation of the roots by checking the connectivity for each pixel in the root data with the crown pixel in the tooth data. The segmentation technique depends on manually assigning a centroid for each tooth. Using K-means clustering (a method for clustering objects into arbitrary number
of classes \([K]\), where classes are defined by their means) and the connected component algorithms, tooth boundaries are identified. By using region-growing techniques, the whole dentition can be separated from the rest of the skeletal base (Fig 8). Subsequent separation of individual teeth and the ability to color each tooth separately facilitates implementation and simulation of the various orthodontic applications (Fig 9). Further maneuvering of the dental units separately, simulation of the extraction procedure, and virtual aligning of the teeth are the beginning of the virtual digital computer-based 3D diagnostic setup (Fig 10).

For virtual orthognathic surgical planning, a cutting tool is constructed. This knife-like tool allows tailored cutting in the 3D volume (Fig 11). This procedure permits the disconnection of any skeletal unit from the rest...
of the skull in the desired customized osteotomy lines (Fig 12). Subsequent spatial handling and manipulation of the separated 3D skeletal unit are feasible. Reattachment of the skeletal unit to the rest of the skull in the desired spatial position simulating the orthognathic surgical protocol is then possible. This regimen could be applied to simulate many orthognathic surgical procedures.

The superimposition of the 3D volumes is called registration. Because separation and manipulation of the maxilla, mandible, and dentition is possible by using the above-mentioned protocols, simulation of the orthodontic treatment is completed on the separated areas. Reattachment of the previously separated and manipulated skeletal and dental regions permits visualization of the final outcome of the treatment. Registration of the corrected 3D volume on the original unmodified 3D volume of the patient is done. The 3D skull volumes will automatically fit on most skull regions that have not been manipulated (occipital bone, frontal bone, and anterior cranial base) irrespective of the dental misfit in orthodontic patients or the skeletal and dental misfit in orthognathic patients. An attempt to use the unmanipulated regions of the skull in the registration procedure was done, comparing various registration protocols. The principal curvatures technique, used for the automatic registration procedure, yielded the best automatic registration procedure (Fig 13). The difference between the modified and unmodified virtual models shows the amount of work the orthodontist must complete (subtraction analysis). Moreover, the capability of superimposition of the 3D volumes before and after treatment is used to assess the treatment results.

**DISCUSSION**

The introduction of virtual 3D volumes and the massive amount of information that could be extracted from it imposes the necessity for new vision and new technology for orthodontic diagnosis. Because treatment of the 3D virtual images of the orthodontic patients is possible, introducing new 3D handling tools is timely.

We described many methods that have been developed. The ultimate aim is to create an integrated process for virtual orthodontic treatment. The process enables the creation of a virtual 3D model and automatic 3D landmark identification, thus identifying the problems in each area. In addition, this diversity of tools enables, through various algorithms, the separation of the maxillary, mandibular, and dental units. Accordingly, the defective regions are extracted from the 3D volume. Correction of the defect of the skeletal or dental units is executed, until the best orthodontic or orthognathic outcome is achieved. Reattachment of the skeletal unit to the virtual 3D of the patient in the desired position rebuilds the volume. This facilitates execution of the treatment plan.

The treatment of the patient’s virtual 3D image allows building up a view of the final treatment result...
rather than pondering the outcome. Hence, the treatment decision is based on correcting the defect within the limits of the surrounding environment (alveolar bone, soft tissue, and muscular boundaries). Therefore, the orthodontist’s expectations can be virtual reality before treatment. The time-saving benefit of this procedure is priceless.

The capability to visualize the end result beforehand in a 3D format paves the way for a focused approach to use current orthodontic tools to achieve the planned result. With the end result in mind, communication between the orthodontist and the patient, especially before orthodontic treatment, is much simpler, not to mention the gain in patient cooperation.

Previous attempts have been made to use 3D CT images to simulate orthognathic surgical procedures. However, the consensus of opinion is that the CT image with its inherent limited special resolution and partial volume averaging effects produces distorted occlusal surface details, occlusal configuration, and intercuspatation. This limitation motivated the introduction of the 3D surface-scanning system of orthodontic models with a slit laser surface scanning system to obtain occlusal surface details. This procedure resulted in separate skull and dental models, and started a chain of technical difficulties. A problem of image fusion of different 3D modalities emerged. An accurate but complicated approach has been applied for intermodality registration techniques to register the virtual dentition model to the virtual skull model. However, this approach is confined to mandibular jaw surgeries, whereas the maxilla is used as the reference for registration. Untested
modification of the technique is advocated when maxillary surgery is needed with no fixed reference for orientation of the fiducial markers. Even though this protocol is efficient and essential for research work, it is inapplicable for routine clinical implementation. As a solution to this limitation, we offer a simpler approach with minimal intermaxillary separation of 1 mm. We believe that this modification does not disrupt facial esthetics and condylar position. Moreover, maximum intercuspsation can be achieved by localizing the condylar hinge axis and subsequent rotation of the mandible into the intercuspsal position, a research point that is beyond the scope of this article, not to mention the elimination of functional occlusal shifts and the ease of automatic mandibular separation. However, a limitation to our approach is the need for massive training of the artificial intelligence to refine the results, and the fewer occlusal details that are acquired in comparison with laser scanning.

In an analogous registration approach, 3D model superimposition was performed by Cevdanes et al to evaluate condylar position after 1-jaw and 2-jaw surgeries. The surface of the cranial base was used as the registration guide, since it is unaltered by these surgeries, unlike the maxilla and the mandible. Alterations in the 3D position of the mandibular rami and condyles were measured. Color-map tool on the 3D display were used to facilitate eyeballing the differential magnitude and direction of mandibular displacement.

Similarly, Terajima et al used the 3D models of 10 normal Japanese women. They established 3D standard values of the maxillofacial skeletal and facial soft-tissue morphology. The 3D spatial coordinate system was defined on the 3D CT image. They created a 3D analysis system based on linear measurements to compare preoperative and postoperative patient coordinates with standard values. The superimposed images were registered by matching parts that were not altered by the surgery (supraorbital and forehead regions).

There is a significant benefit in sharing visual and quantitative 3D information from this simulation system among orthodontists and surgeons.

CONCLUSIONS

The proposed process involves detaching, manipulating, and reattaching targeted regions of a 3D image. The registration techniques show the changes needed to arrive at the best outcome, in addition to evaluation of the treatment outcome. Achieving this will enable optimal use of the Prospective Treatment Analysis approach and the end-result analysis, simulated annealing, and treatment analysis.

We thank Earlene Gentry, technical editor and freelance writer (Cairo Foreign Press Association), and former editor of the Fulbright Chronicle (Egypt), for her assistance in revising and editing this manuscript.

REFERENCES

9. Othman AA. A novel approach for developing a complete automatic 3D cephalometric analysis system and a mandible, maxilla and dentition separation system [thesis]. Systems and Biomedical Engineering Department, Faculty of Engineering, Cairo, Egypt: Cairo University; 2007.