Asian Biomedicine Vol. 6 No. 4 August 2012; 591 - 596

DOI: 10.5372/1905-7415.0604.095

Brief communication (Original)

A pilot study of four-dimensional visualization of mandibular and temporomandibular joint movement

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Background: Mandibular movements are reliable indicators of mandibular system disease and changes in movements can be useful to estimate treatment effect. Detection of mandibular movement is important.

Objectives: We evaluated four-dimensional (4D) visualization of mandibular and temporomandibular joint movement using 320-row computed tomography (CT).

Methods: A stepwise mouth gag was placed between mandibular and maxillary incisors to control mouth opening (0.5-cm increments) in healthy volunteers and one temporomandibular disorder (TMD) patient. A 320-row CT Joint-Move and Shot sequence was used for scanning with an image taken after each increment. 4D reconstruction was used to establish volume data.

Results: 4D visualization of joint and dentition in a rest state and in a state of mandibular movement from multiple angles and in different planes demonstrated differences between healthy subjects and the subject with TMD. The effective dose per scan was approximately 17% of the 16-slice spiral CT.

Conclusion: 4D visualization of mandibular movement can be achieved through 320-row volume CT, which may provide a diagnosis of temporomandibular joint disorder and assessment of treatment effects.

Keywords: Four-dimensional visualization, mandible, temporomandibular joint, 320 CT

Mandibular movement is a complex phenomenon involving the mandible, masticatory muscles, and the temporomandibular joint (TMJ). It is central to mastication, swallowing, and linguistic function [1, 2]. In clinical practice, abnormalities in mandibular movement are reliable indicators of mandibular system disease and changes in motion can be used to evaluate treatment effects [3-5]. Previous studies of mandibular movement used mandibular movement tracking devices to record motion [6, 7]. Computer simulation and modeling techniques have also been used [8, 9]. However, these techniques are limited in accurately tracking mandibular and temporomandibular joint movement.

The emergence of 320-row dynamic volume computed tomography (CT) greatly advances the ability to visualize patient-specific mandibular movement [10, 11]. With its wide (16 cm) anatomic coverage, 320-row CT can scan the mandibular system in a single gantry rotation, providing physiological as well as anatomical information that cannot be obtained using conventional 64-slice scanners.

Motor function impairment and postinjury recovery cannot be evaluated from static images because bone and joint abnormalities typically only emerge in a dynamic state. Until now, however, this technology has been mainly used for neuroimaging [10, 11]. Its use in obtaining dynamic images, especially the movement bones and joints, has not been fully explored. This study evaluated 4D 320-row dynamic volume CT for comparisons of mandibular movement in healthy subjects and a subject with temporomandibular joint disorder.

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Materials and methods

Study participants

This study included 10 healthy male volunteers and one male patient with temporomandibular disorder (TMD). Their age range was from 20 to 30 years, with a mean age of 24.8 years. Inclusion criteria for healthy volunteers included: 1) no systemic diseases; 2) facial symmetry without any deformity; 3) no previous history of maxillofacial trauma or surgery; 4) no temporomandibular joint discomfort, noise, or limited mouth opening; 5) no abnormal habits including lateral chewing preference, bruxism, or clenching. The study was approved by our Hospital Institutional Review Board. All participants signed an informed consent agreement.

Study procedure

A stepwise Plexiglas mouth gag was constructed for insertion between mandibular and maxillary incisors (**Figure 1**). There were a total of 10 steps (height and width of each step was 0.5 cm and length was 1.0 cm). A subject's mouth opening was increased by 0.5 cm with each step forward (maximum degree of mouth opening was 5 cm). A subject's mouth opening was decreased by 0.5 cm with each step backwards. Sequential images in an occlusal position were taken with the mouth closed followed by 0.5-mm increments (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 cm) and in an open mouth position followed by 0.5-mm decrements (4.0, 3.5, 3.0, 2.5, 2.0, 1.5, 1.0, 0.5, and 0 cm).

Scanning procedures

A single 320-row CT system (Toshiba, Aquilion One) was used to capture up to 16 cm coverage in one rotation. The Joint-Move and Shot sequence was used for dynamic scanning, with the following scan parameters: tube voltage 120 kV, tube current 50 mA, FOV 240 mm, gantry rotation time 0.5 s. Each scan included 16 cm, covering the mandible and temporomandibular joint.

Dynamic reconstruction was used to establish a number of volume data sets. The volume data at all mouth opening and closing positions were selected on an Aquilion One or Vitrea 2.1 workstation and automatically imported into the 3D mode. The volume VR images of each position were then obtained and displayed in a film-mode sequence.

The weighted CT dose index was used to calculate the dose length product (DLP) value with a range of 16 cm. The effective radiation dose was obtained using multiple DLP values and a coefficient (0.0021). The effective dose delivered during the entire process of the movement imaging was compared with the effective dose of a single 16-slice spiral CT examination.

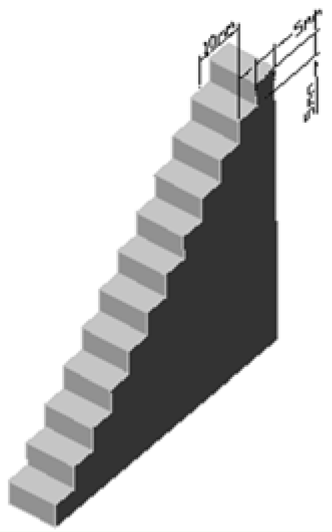

Figure 1. Nonmetallic stepwise mouth gag

Results

CT images of the mandible in open or closed positions

We first tried to compare the difference of occlusive position of mandible between normal patients and the TMD patient. **Figure 2** shows frontal and lateral CT images of a normal volunteer and patient with TMD in the occlusive position. This 23-year-old male patient had temporomandibular joint disorder with left lateral chewing for more than 2 years, snapping sound in maximum mouth opening, no pain, and obvious left-side shift of the mandible during mouth-opening and -closing movement. Condylar processes were located within the glenoid fossa, and dislocation of the anterior teeth was 0.2 cm in the patient with TMD.

Subsequently, the temporomandibular joint position in different and the sequential open position were examined. In open positions at 1.5 cm (**Figure 3A**) and 4 cm (**Figure 3B**), the condylar process in the TMD patient crossed the articular eminence and was displaced toward the midline. In the anteroposterior position the left-side shift of the mandible was obvious in the TMD patient, the midline displacement was 1.2 cm. In the lateral position the condylar process in the TMD patient went across the articular eminence and was displaced toward the inner side. The condylar process was located posteroinferiorly to the articular eminence in healthy subjects (**Figure 3A**). At the 4 cm open position, the anteroposterior position a left-side shift of the mandible was observed in the TMD patient, the midline displacement was 0.7 cm. There was no midline displacement in normal subjects. In the lateral position the condylar process of the TMD patient shifted toward the inner side of the zygomatic arch. The condylar process was located anteroinferiorly to the articular eminence in healthy volunteers (**Figure 3B**). In healthy volunteers, the condylar process was located posteroinferior or anteroinferior to the articular eminence, and there was no midline shift.

Mandibular motion in the anteroposterior position

An obvious side shift was observed with mandibular movement in the TMD patient; the mandible was returned to a midline position at the maximum mouth opening. Based on the 4D visualization of mandibular and temporomandibular joint movement using 320-row computed tomography, with mandibular movement in the right lateral position, the condylar process shifted toward the inside in the TMD subject. In the left lateral position, the condylar process shifted toward the inside. Mandibular movement was observed from different angles in a 360-degree rotation video of the mandible. Evaluation of the mandibular movement video in different planes showed bilateral condylar processes were in the same horizontal plane in normal subjects whereas they were not in the same horizontal plane in the TMD subject.

The effective dose of a single volume scan of the 320-row CT system was $73.4 \times 0.0021 = 0.154$ mSv. The dynamic volume scan was performed at 18 positions, and the total radiation dose was $0.154 \times 18 = 2.77$ mSv. The effective dose of 16-slice spiral CT examination for the mandible was 0.95 mSv.

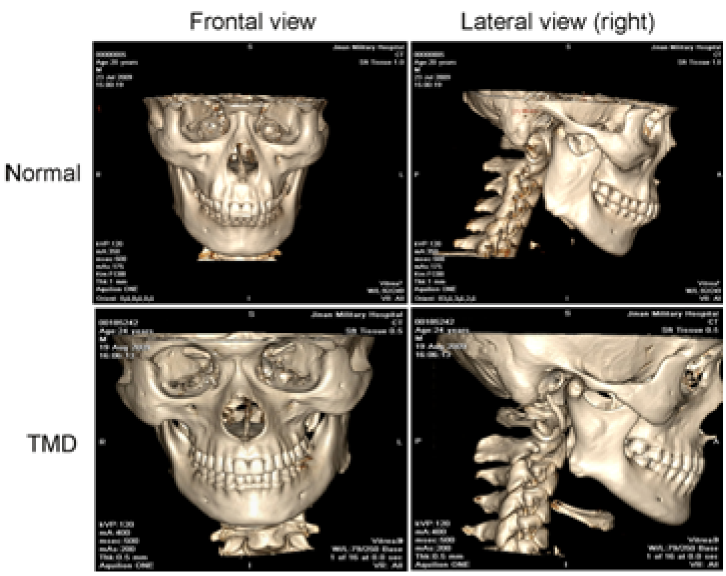

Figure 2. CT images in an occlusive position: condylar processes were located within the glenoid fossa in healthy subjects and the TMD patient. The dislocation of the front teeth was 0.2cm in the TMD patient.

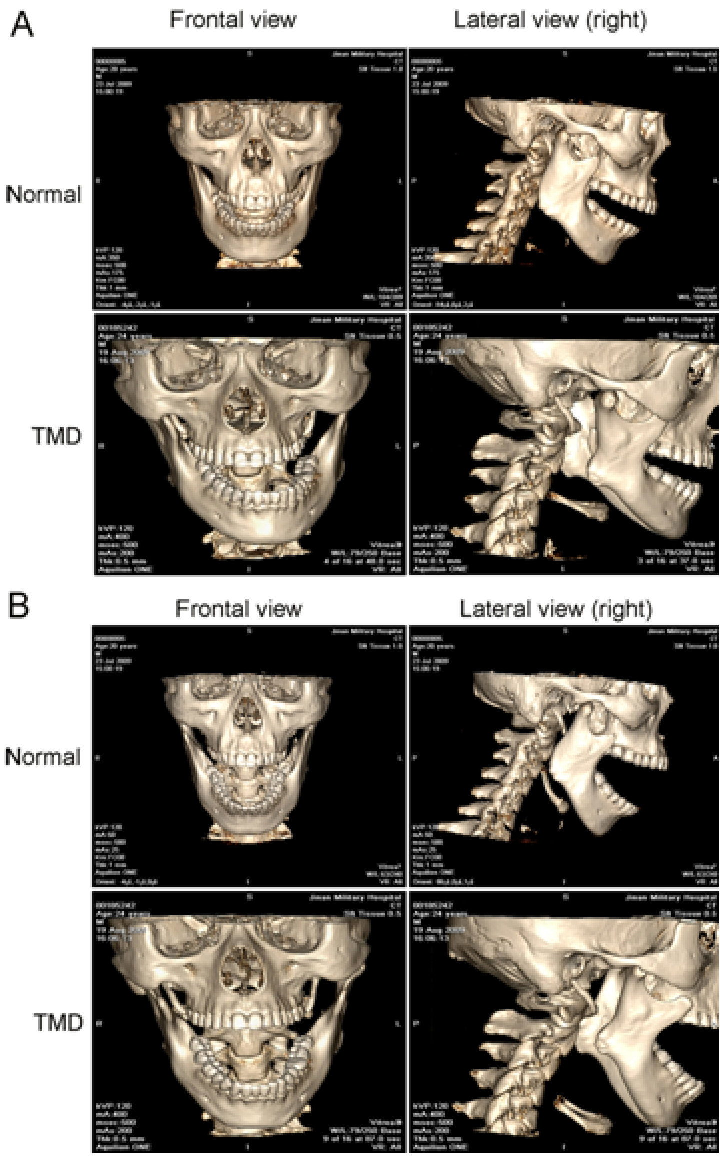

Figure 3. CT images in an open position. **A:** At 1.5 cm open in frontal view, **B:** At 4 cm open

Discussion

In this study, dynamic scanning using a 320-row CT system was conducted on healthy subjects and a TMD subject with 0.5-cm increments of mouth opening. 4D images of the TMJ and mandible in motion and in a rest state were obtained from multiple angles and in different planes. Specifically, this study showed differences between healthy subjects and the TMD subject in the position and movements of the mandible and condylar process, which provide diagnostic and prognostic information. On opening, the condylar process in the TMD subject crossed the articular eminence and was displaced interiorly. Other images showed that bilateral condylar processes were in the same horizontal plane in normal subjects whereas they were not in the same horizontal plane in the TMD subject.

Since its introduction into clinical practice in 1972, computed tomography has greatly improved the specificity and sensitivity of diagnosis of temporomandibular joint and mandibular diseases because of the accurate determination of the scope of lesions and degree of injury. The images obtained from two-dimensional axial CT, spiral CT with multiplanar reconstruction and three-dimensional reconstruction can be combined for analysis. However, these techniques are inherently limited in evaluating complex mandibular movement such as the position of the mandible, the relationship between the mandible and associated muscles during mandibular movement, and the track of the mandible during mastication and speech. Static images are insufficient to describe the complex motion associated with TMJ and mandibular excursions. More recently, methods combining 3D CT imaging and motion tracking data (both optoelectric and electromagnetic) have been introduced to study TMJ kinematics [13]. However, combining 3D images with kinematic data recordings may affect the overall accuracy and precision of the data collection method. MRI can show the relative moving relationship between disks and soft tissue while CT is more appropriate to show moving relationship between disk and bone joint. The 4D relative moving relationship and position between the mandibular and temporomandibular joints can be used to evaluate the status of the disease progress and treatment.

Use of dynamic CT imaging to precisely reconstruct maxillofacial motion has been constrained, in part, because of potential radiation exposure to the patient. Consequently, in recent years researchers have conducted studies of mandibular motion using virtual restoration of mandibular movement derived from cephalograms or CT images [14-16]. However, models and simulations are intrinsically imperfect representations of complex patient-specific movements both statically and dynamically.

The emergence of 320-row dynamic volume CT makes visualization of both mandibular structures and movement possible by achieving 16-cm coverage through the use of a large area detector with a minimum gantry rotation time. Studies have shown that 320-row CT multidetector CT is capable of quantifying characteristics of the trabecular bone network in long bones [17]. Neuroimaging studies using a new 320-row CT scanner has demonstrated its utility in providing perfusion imaging of the entire neurocranium and dynamic CT angiography of the intracranial vessels [18]. Results presented here demonstrate that 320-row CT (Aquilion One) can realize truly dynamic volume imaging (i.e., 4D dynamic observation) of mandibular movement. This imaging modality can be used to monitor changes in the mandibular movement track, such as the degree of mouth opening and the type of mouth opening, to facilitate diagnosis of some oral and facial diseases including mandibular fracture, temporomandibular joint disorders, and temporomandibular joint tetanus. Treatment effect evaluation is also possible.

As 4D 320-row CT imaging requires the application of a continuous scan, a low tube current and low tube voltage technique is used to keep radiation exposure within reasonable limits [19]. It is thus not surprising that detail conspicuity may be reduced in comparison with standard 3D CT in return for kinematic information. However, 320-row CT offers a unique capability to capture 3D CT data and dynamic volume imaging with clinically acceptable radiation dose levels. In this study, the radiation dose was reduced by approximately 80% compared with 16-slice CT, but a similar image quality to 16-slice CT was obtained. The total radiation dose was 2.77 mSv. The increase in the image noise during 320-row CT is negligible relative to the image quality [20]. Healthy subjects were scanned a maximum of 18 times during imaging receiving a maximum radiation dose equal to that delivered by three 16-slice CT scans, which approximates the dose delivered in coronary angiography.

Several challenges need to be resolved before widespread adoption of this technology into clinical practice. Radiation exposure needs to be further minimized. Although the radiation dose is within a clinically acceptable range, the radiation dose is three-fold higher than that delivered by common CT. Another challenge is that the normal range of mandibular protraction and lateral movement is approximately 1 cm, which cannot be artificially controlled. Therefore, mandibular protrusion and lateral excursion cannot be reflected in the images. For patients with preoperative fracture, the mandibular movement cannot be accurately manifested before surgery because of limited mouth opening and pain.

Further research should center on mapping the tracks of mandibular and temporomandibular joint movement based on 4D 320-row CT imaging. Dynamic 3D data can be quantified using the 3DMax. Research should also focus on a better and more intuitive, understanding of the relationship between local anatomical structures and motor function. Toward this end, a preliminary database of quantified reference value ranges of normal populations needs to be established. In addition, new diagnostic criteria and treatment effect evaluation should be established for common oral diseases related to motor function such temporomandibular joint fractures and temporomandibular joint disorders.

In summary, this study evaluated 4D images of mandibular movement using 320-row CT and reproduced the state of movement of the mandible and the temporomandibular joint. 4D images that can display mandibular and temporomandibular joint movement directly are beneficial for the clinical diagnosis of temporomandibular joint disorders and mandibular diseases and the evaluation of treatment effect. Our results may provide a new approach for future studies on mandibular movement.

Acknowledgements

Chongjian Fu and Xuelei Huang contributed equally to this work. All authors have no conflict of interest to declare.

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