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Original Article

Dentistry Section

Imaging of Temporomandibular Joint: Approach by Direct Volume Rendering

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ABSTRACT

Background: The purpose of this study was to conduct a morphological analysis of the temporomandibular joint, a highly specialized synovial joint that permits movement and function of the mandible.

Materials and Methods: We have studied the temporomandibular joint anatomy, directly on the living, from 3D images obtained by medical imaging Computed Tomography and Nuclear Magnetic Resonance acquisition, and subsequent re-engineering techniques 3D Surface Rendering and Volume Rendering. Data were analysed with the goal of being able to isolate, identify and distinguish the anatomical structures of the joint, and get the largest possible number of information utilizing software for post-processing work.

Results: It was possible to reproduce anatomy of the skeletal structures, as well as through acquisitions of Magnetic Resonance Imaging; it was also possible to visualize the vascular, muscular, ligamentous and tendinous components of the articular complex, and also the capsule and the fibrous cartilaginous disc. We managed the Surface Rendering and Volume Rendering, not only to obtain three-dimensional images for colour and for resolution comparable to the usual anatomical preparations, but also a considerable number of anatomical, minuter details, zooming, rotating and cutting the same images with linking, graduating the colour, transparency and opacity from time to time.

Conclusion: These results are encouraging to stimulate further studies in other anatomical districts.

Keywords: Computer generated, Magnetic resonance imaging, Three-dimensional Imaging, TMJ

INTRODUCTION

TMJ is complex synovial joint which include the condyle of the mandible and the articular fossa of the temporal bone. TMJ is divided with fibrocartilagenous disk in upper and lower part. Radiography and conventional tomography are unable to demonstrate soft tissue of TMJ. Computerized Tomography (CT) is limited in the evaluation of inner structure of TMJ. The magnetic resonance imaging (MRI)demonstrate internal anatomic structure of TMJ with great precision.

In the last years, the reconstruction and the representation of anatomical districts in three dimensions (3D) have significantly meliorated the study of human anatomy, producing realistic, interactive features, especially relative to gross anatomy [1-6].

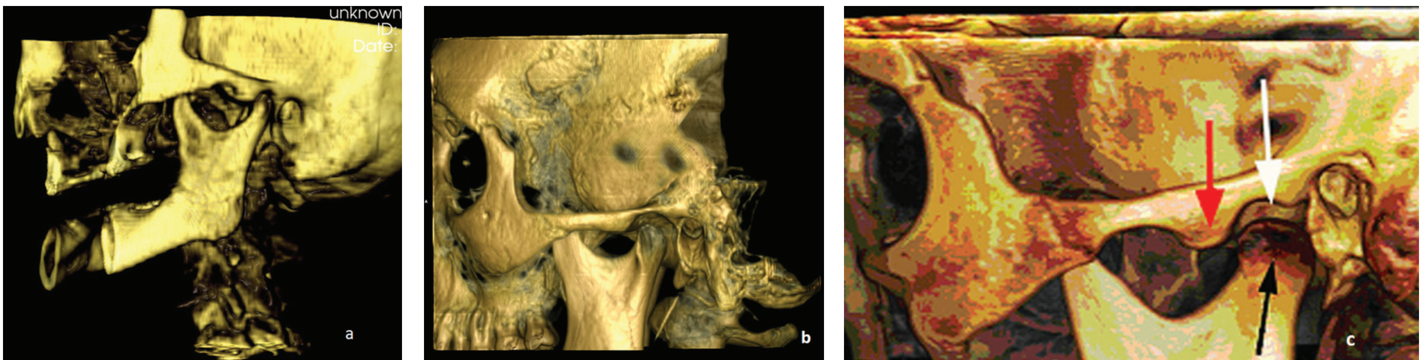
Traditional two-dimensional (2D) methods based on X-ray absorption exclusively; do not completely reveal all the complex non-calcified tissues, such as tendons, ligaments, adipose tissue, and cartilage. That's why it is necessary to complete the study by multiple diagnostic techniques, as well as MRI or CT [7]. However, routine axial CT scans do not highlight regions of complex anatomy, such as articular facets of the joints or muscle insertions.

About this problem, the study of temporomandibular joint does not permit a clear visualization of all structures because of the heterogeneity of elements such as ligaments, articular surfaces and articular disk. To obviate this limitation, we aimed at revising this joint using direct volume rendering (DVR) which allows a complete analysis of temporomandibular joint [8].

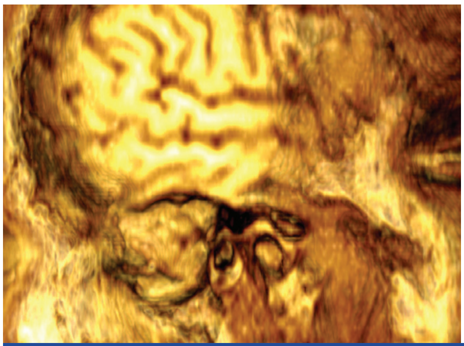
DVR is a visualization technique that allows, for example, to display all the unknown information in three-dimensional data sets of CT [9], or MRI [10-12], and reducing margin of error ($p < 001$) in comparison to axial, shaded surface display ad maximum intensity projection [13,14].

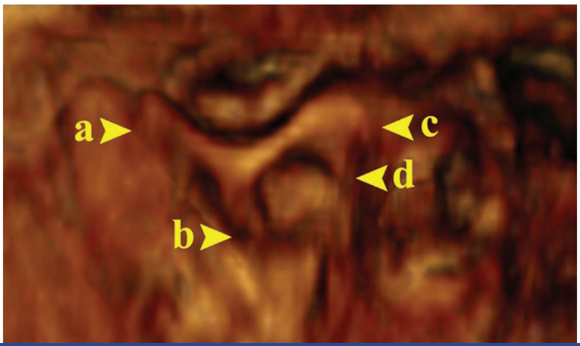
Previously, we tested direct volume rendering on various region of human body; these studies permitted to obtain high quality images that meliorated the knowledge of gross anatomy. In particular, we studied organs with homogeneous tissues, such as brain, succeeding to separate and visualize only white matter or only gray matter; furthermore, we studied knee and ankle joint visualizing ligament or muscle or bone, separately or contemporarily [15,16].

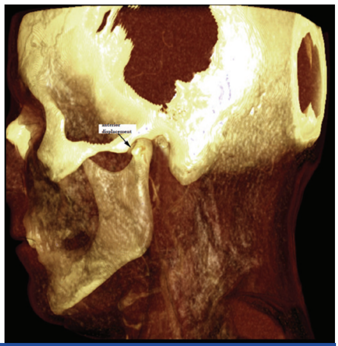
Ishimaru et al., have described some methods for the application of volume rendering to temporomandibular joint study, using a



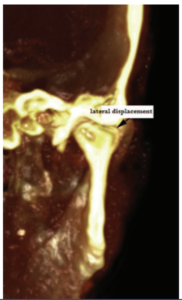
[Table/Fig-1a]: Sagittal T1-weighted MR images shows the articulation between zygomatic process of the temporal bone with the temporal process of the zygomatic bone **[Table/Fig-1b]:** Magnifying the joint, these articular surfaces are better visible **[Table/Fig-1c]:** The articular surfaces of the temporomandibular joint are better visible. Red arrow shows the articular tubercle of temporal bone; white and black arrows show the articular surface of temporomandibular joint

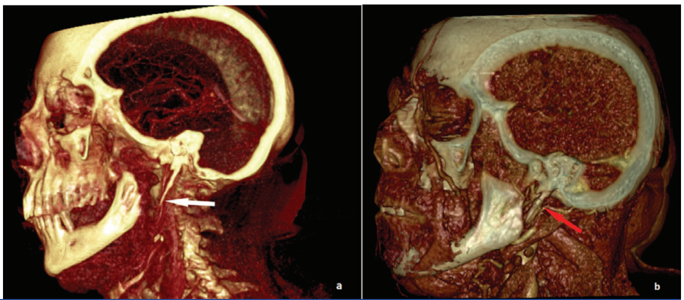




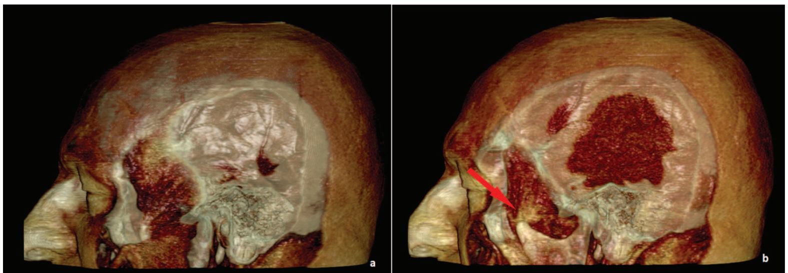


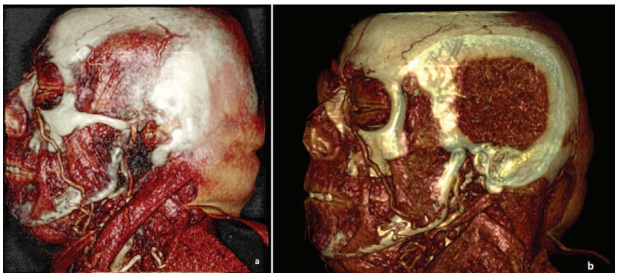
[Table/Fig-2]: Three-dimensional images in different view of the temporomandibular joint of a 32-year old healthy female. Sagital T1-weighted MRI images show the temporomandibular joint with soft tissues and the articular disc between articular surfaces **[Table/Fig-3]:** Three-dimensional image of the temporomandibular joint of a 32-year old healthy female. Sagital T1-weighted MRI images shows the ligament of the articular disc **[Table/Fig-4]:** Three-dimensional image of the temporomandibular joint of a 39-year old female showing anterior displacement





[Table/Fig-5]: Three-dimensional image of the temporomandibular joint of a 34-year old male showing medial displacement, **[Table/Fig-6]:** Three-dimensional image of the temporomandibular joint of a 43-year old female.showing lateral displacement **[Table/Fig-7]:** Three-dimensional image of the temporomandibular joint of a 33-year old female showing posterior displacement **[Table/Fig-8]:** Three-dimensional image of the temporomandibular joint of a 43-year old healthy male. Sagital T1-weighted MRI images show in A the stylomandibular ligament (white arrow), in B the sphenomandibular ligament (red arrow)





[Table/Fig-9]: Three-dimensional image of the temporomandibular joint of a 43-year old healthy male. Sagital T1-weighted MRI images show in A temporalis muscle and its muscularis fascia, in B the insertion of this muscle on coronoid process of the mandibular bone (red arrow) **[Table/Fig-10]:** Three-dimensional image of the temporomandibular joint of a 52-year old healthy female. Sagital T1-weighted MRI images show in A the masseter muscle and in B, avoiding sternocleidomastoid muscle, the posterior belly of digastric muscle

[Table/Fig-11]: Three-dimensional image of the temporomandibular joint of a 52-year old healthy female.Horizontal T1-weighted MRI images shows the masseter muscle and medial pterygoid muscle

computerized simulation of an arthroscopy (virtual arthroscopy) by a reworking of three-dimensional images available from Internet [17,18]; however, the images obtained in such study, in our opinion, still have poor accuracy in the visualization of the ligaments or articular surfaces.

The aim of this study is to test new parameters of 3D direct volume rendering appropriate for the temporomandibular joint structures in order to meliorate the visualization methods and to better evaluate the articular morphology, its internal structures and its modifications.

MATERIALS AND METHODS

We studied and analysed for 20 months the TMJ of 20 consecutive adult patients (age range: 30–58y, 10 males, 10 females) suffering from various craniofacial diseases and disorders who had concurrent MRI and CT images. Ten patients underwent MRI, and ten underwent CT. We included the subjects underwent to CT because we're already clinically analysed for different craniofacial diseases and the other 10 patients were included to be underwent to MRI after clinical analysis and suspect serious craniofacial diseases. All subjects gave written informed consent before beginning the study. The Medical Ethics Committee of the Policlinico "G. Martino" approved the study protocol, which conformed to the principles of the Declaration of Helsinki for human research. The research was carried out at "Centro Neurolesi Bonino Pulejo – Messina Italy.

For our study we used MRI equipment Intera Philips Gyroscan 1.5 TL, relise 12.1, flex coil sinergy M (tmj study). The thickness of the slice was 1.8 mm at intervals of 1 mm. T1-weighted and T2-weighted sequences were carried. Volumetric sequences have been acquired on sagittal plans.

The cross-talk artifacts was reduced by conducting the examination using the linear method, rather than the interleave method [19].

For the CT technique a four-channel CT scanner (Philips MX8000) has been used. Proton density weighted image (PDWI) is not included in the routine sequence.

MRI technique

Three-dimensional double echo steady state (DESS) sequences were used for cartilage examination. Sagittal, coronal, transverse, and oblique coronal multiplanar reconstruction images were reformatted from MRI, acquired by one stack of 1.50-mm slices. Each sequence was characterized by a TR of 17.21 ms, TE of 5.14 ms, flip angle of 27%, slice thickness of 1.3 mm, voxel size of 0.6 × 0.6 × 1.5 mm, and a 25% distance factor.

For other images of the ATM, we used turbospin-echo images (TSE-T2) weighted in 512 dpi. These images were characterized by an echo train length of 11, section thickness of 1.5 mm, field of view of 12.75 cm, image matrix of 384 × 384 pixels, bandwidth of 75.8 KHz, section-selection and refocusing-pulse durations of 2 ms, signal acquisition of 2, and a total acquisition time of 22.5 min.

Digital MRI data were acquired in pixel resolutions of either 256 × 256 or 512 × 512 in 16 bits of grey and converted to 8 bits of grey TIFF files.

CT technique

For the CT technique we used a four-channel CT scanner (Mx8000 Quad; Philips Medical Systems, Best, Netherlands). The scanning and reconstruction parameters were the following: peak:140 KV, 150– 200 mAs, resolution: ultrahigh, beam collimation 2 x 0.5 mm, effective section width 0.6 mm, nominal section width 0.5 mm reconstruction increment 0.2 mm, Pitch 0.825–0.925. The section thickness and reconstruction interval were selected in a way that our data have nearly isotropic voxels.

Rendering technique

The reconstruction was performed with fields of view of 8 × 8 cm, with the result that the voxel size of the in-plane became 0.41 × 0.41 mm with a 512 × 512 matrix. Once MRI scan was acquired, the data was sent to the workstation Apple Mac Pro Eight-Core 2.8 GHz Xeon Desktop Computer powered by two 2.8 GHz Quad Core 45-nm Intel Xeon E5462 (Harpertown/Penryn) with ATI Radeon HD 2600 XT 256 MB Mac OS X v10.5 Leopard, 12 MB of L2 cache per processor (each pair of cores shares 6 MB), 128-bit SSE4 SIMD engine, 64-bit data paths and registers, Energy efficiency optimization, 1600 MHz, 64-bit dual independent frontside buses, where the images were viewed as consecutive axial section and so performed manually for each axial image by editing with Osirix 3.3.1.

RESULTS

By volume rendering technique, we were able to provide three-dimensional images of structures of the temporomandibular joint. In this way, the modifications of the algorithms and the implementations of computing signal gradients permitted to obtain a more realistic view of the anatomical structures.

In particular, applying the parameters to bone structure and analyzing the skull from the left side, it was possible to highlight the head of the mandible articulating with mandibular fossa of the temporal bone; in this image also the coronoid process of the mandible was clearly visible. Moreover, it was possible to highlight the articulation between zygomatic process of the temporal bone with the temporal process of the zygomatic bone [Table/Fig-1a]. By meliorating these parameters, and analyzing the right temporomandibular joint, the articular surfaces were better visible; besides the articular cavity was also clearly observable [Table/Fig-1b]; by a magnification of the joint also other bone structures were clearly visible, as well as articular tubercle [red arrow in Table/Fig-1c], or the tympanic part with external acoustic meatus and suprameatal triangle. By these parameters the joint between temporal and zygomatic bones were better visible and also the articular surface of temporal and mandibular bones (white and black arrows) [Table/Fig-1c].

By modifying the algorithm, switching on the gradient and scalar opacity in order to evidence soft tissues, it is possible to highlight the articular disc between the condyle, articular eminence, and glenoid fossa [Table/Fig-2]. Setting the parameters in order to better visualize the soft tissue, the ligaments of the discs are clearly identifiable; particularly visible are the short anterior ligament (a), long anterior ligament (b), short posterior ligament (c), and long posterior ligament (d) [Table/Fig-3].

In addition a study of the disc-condyle relationship on both sides of TMJ was investigated. The disc positions of the TMJ were classified according to the criteria reported by Takase et al., Normal disc position was defined when in the closed position, the junction of the posterior band with the retrodiscal area was located above the apex of the condylar head (12 o'clock position ±10o). Anterior disc displacement was defined when the posterior band was located anterior to the superior part of the condyle in all sagittal sections. Medial disc displacement and lateral disc displacement were defined when the disc crossed over one of the lines through the condylar poles in the coronal plane [20].

Of 40 joints anterior displacement was found in 10 joints [Table/Fig-4], medial displacement was found in 2 joints [Table/Fig-5], lateral displacement was found in 4 joints [Table/Fig-6], and posterior displacement was found in 1 joint [Table/Fig-7].

Further modifications of the parameters allowed to highlight the ligaments of the temporomandibular joint; in this way it was possible to analyse the stylomandibular ligament (white arrow) [Table/Fig-8a], which stretches from the apical part of the styloid process of the temporal bone to the angle of the mandible. Moreover, by the same parameters, also the sphenomandibular ligament is visible; in particular, its origin from the spine of the sphenoid bone is clearly identifiable (red arrow) [Table/Fig-8b].

Applying the parameters to the muscular structures, it was possible to highlight the temporalis muscle and its muscularis fascia and all its fibers [Table/Fig-9a]; cutting this surface plan, its insertion on coronoid process of the mandible was clearly visible (red arrow) [Table/Fig-9b].

Finally, using other algorithms, also the masseter muscle was visible; in details its origin from the zygomatic process of the maxilla was clearly identifiable, from the anterior two-thirds of the lower border of the zygomatic arch [Table/Fig-10a]. In this image it was also possible to highlight the muscle fibres of the buccinator muscle which originates from the outer surfaces of the alveolar processes of the maxilla and mandible. Cutting previous three-dimensional image in order to evidence other muscular structures, and then also avoiding sternocleidomastoid muscle, it was possible to visualize the posterior belly of digastric muscle [Table/Fig-10b].

By rotating previous image and visualizing this region in horizontal section, most muscles are visible. In this section, masseter muscle and medial pterygoid muscle are particularly highlighted [Table/Fig -11].

DISCUSSION

In the present report we have showed a new approach to study the morphology of human TMJ directly on the living, by reconstruction and 3D visualization, obtaining a viable alternative to traditional anatomical studies on the corpses.

Volume rendering permits to obtain three-dimensional images with a higher resolution, proving to be an extremely useful tool in highlighting anatomical characters. Interpolation and extraction of the volume region of interest from our data sets enabled us to visualize the 3D images on a computer screen, with the possibility of making enlargements or reductions, translations and rotations. In this way, it is possible to obtain faithful images comparable to the usual anatomical preparations; moreover, by zooming, rotation and cut, it was possible to highlight several anatomical details of the TMJ.

All 3D rendering techniques are based on mathematical formulas to determine, for each pixel, what portion of the memorized data should be displayed on the screen and how that portion should be weighed to represent spatial relationships better. Voxel selection is usually accomplished by projecting lines (rays) through the data set corresponding to the pixel matrix of the desired 2D image [21].

On this basis, here we studied the morphology of TMJ of living humans along arbitrarily positioned cutting planes. Using this technique, every single part of the joint can be virtually removed in order to analyse and visualize the inner structures better [22].

To obtain our three-dimensional images, the necessary steps to be performed are as follows: data acquisition, interpretation of the results with re-sampling and editing by filtering, segmentation, classification and 3D reconstruction [21]. The image was acquired through normal diagnostic procedures, as magnetic resonance MRI or TC, and then was 'purified' by filtering systems.

In particular, in this study, to analyse the TMJ structures, we used acquisition techniques such as DESS and turbo spin-echo (TSE-T2 weighted) that could be utilized with good results in post-processing. However, for the reconstruction of articular cartilage images, the three-dimensional spoiled gradient-recalled (3D-SPGR) could also be used, giving good results in the postprocessing phase and allowing for the visualization of high-quality images [23].

3D-SPGR method is an imaging technique for identifying and characterizing physeal growth arrest following physeal plate aggression [24]. Fluctuating equilibrium MR imaging can also be used for the evaluation of the cartilage structures in the TMJ as it provides highest cartilage signal-to-noise ratio (SNR) and contrast-to-noise ratio efficiencies although it has worst fat suppression [25].

After the steps of acquisition and filtering, it is necessary to follow the segmentation step which provides a very good discrimination between bone and surrounding tissues subdividing the image into homogenous areas followed by cataloguing and incorporation of every single area [26].

The latter step provides the final images, associating each voxel with a colour and partial opacity, and blending them. The ultimate aim of this report is to render the image in such a way that its 3D nature can be perceived. In order to better understand the real structure and morphology of the TMJ in living humans, we studied the knee joint with a volume rendering technique, making a comparison with anatomical structures of dissection images.

Our results revealed the real anatomical morphology of the TMJ, evidencing bone structures, ligaments, muscles and vessels contemporarily. We were also able to show other inner structures of the joint, such as the articular disc. On these bases, in our images it is possible to visualize the origin and insertion of sphenomandibular and stylomandibular ligaments, or the exact relationship between head of the mandible and the mandibular fossa of the temporal bone. Modulating the parameters of the algorithms, we can also show several structures of TMJ contemporarily, e.g. temporalis muscle and its fascia, or its insertion on coronoid process; furthermore, by specific algorithm it is possible to visualize the articular disc between mandible and temporalis bone.

This technique, although is mainly focused on creating a database of 3D high-quality images, it provides a substantial contribution to medicine, opening several scenarios in didactic, research, and clinical field.

About didactic field, we intend to meliorate the database of digital images adding innovative images on TMJ; in this way it will possible to introduce a new method of studying anatomy [4], avoiding the dissection but nevertheless always on living humans. Thus, it is realisable a true dissections accomplished by virtual material for a better 3D understanding of the human body.

Then, our results demonstrate that the use of volume rendering allows specialists to approach the study of the TMJ with a non-invasive method, without the aid of invasive techniques, which entailed a high level of risk, for diagnosis or presurgery planning [27].

CONCLUSION

Several radiographic methods are used to assess the TMJ, an area that is difficult to be imaged due to factors like superimposition of adjacent structures and morphological variations. The complexity of the TMD however, demands a clear and precise image of the region for effective management of the patient. 3D images can be integrated in practical studies, seminars and lectures; then, the anatomy of the TMJ, as well as the anatomy of several anatomical districts can be studied by comparing our virtual images with those of atlases of human anatomy and real preparations; moreover, it will possible to create a direct internet resource or printouts of the images, permitting students to continue learning and studying at home. About clinical field, this method can be used to define the true position of the condyle in the fossa, which often reveals possible dislocation of the disk in the joint, and the extent of translation of the condyle in the fossa. Another advantage is the ability to visualise soft tissue around the TMJ in cases of trauma, pain, dysfunction, fibro-osseous ankylosis and in detecting condylar cortical erosion and cysts. This method can be used to supply surgeons with a valid support in planning surgical interventions. Besides, this technique also permits to young surgeons the opportunity to gain experience, using preoperative analysis systems with a more realistic evaluation of the risks involved.

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