Int J CARS (2007) 2:203–210
DOI 10.1007/s11548-007-0130-4

ORIGINAL ARTICLE

3D-visualization of the temporomandibular joint with focus on the articular disc based on clinical T1-, T2-, and proton density weighted MR images

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Received: 24 July 2007 / Accepted: 17 October 2007 / Published online: 10 November 2007

Abstract
Objective An approach of 3D-visualization of the temporomandibular joint (TMJ) with special focus on the articular disc based on magnetic resonance imaging (MRI) was developed for the purpose of diagnosis support.
Materials and methods Mandibular condyle and fossa were reconstructed as 3D-surfaces. Articular disc, retrocondylar tissue, and the lateral pterygoid muscle were visualized by means of direct volume rendering. By simultaneous visualization of both, the bony surfaces and the soft tissue, anterior disc displacement could be recognized in 3D-context. Additional superposition of the 3D-visualization with the original 2D-MRI slices allowed for a combination with conventional diagnostics. The method was tested for clinical T1-, T2-, and proton density weighted MRI data from four independent medical institutions.
Results For all cases, the skeletal anatomy could be reproduced. Applied validation approaches showed good results. Anterior disc displacement could be clearly depicted as well as the incidence of reduction of the disc. By several experienced observers, the approach was rated as significant.
Conclusion Although partially non-standard in the clinical routine the new method provided promising results for efficient diagnosis support. Its validity in the medical practice, namely, its impact for dislocation/deformity of the mandibular disc will be further analyzed.

Keywords MRI · Temporomandibular joint · Articular disc · 3D-reconstruction · Visualization

Abbreviations

TMJ	Temporomandibular
MRI	Magnetic resonance imaging
CT	Computer tomography
CBCT	Cone-beam computer tomography
PDWI	Proton density weighted images
T2WI	T2-weighted images

This paper has been written on behalf of a publication request following Cars 2006 conference held in June 2006 in Osaka, Japan. The title of the talk at Cars 2006 conference was “An approach for three-dimensional rendering of the mandibular disc based on high-resolution MR images” authored by Kober C, Hayakawa Y, Kinzinger G, Yamamoto M, Sano T, Sader R, see Int J Comput Assist Radiol Surg 2006 1(Suppl 1): 405–406. I apologize for the delay which was caused by very dense time schedule. In return, the article is a considerable extension of the work presented at Cars 2006.

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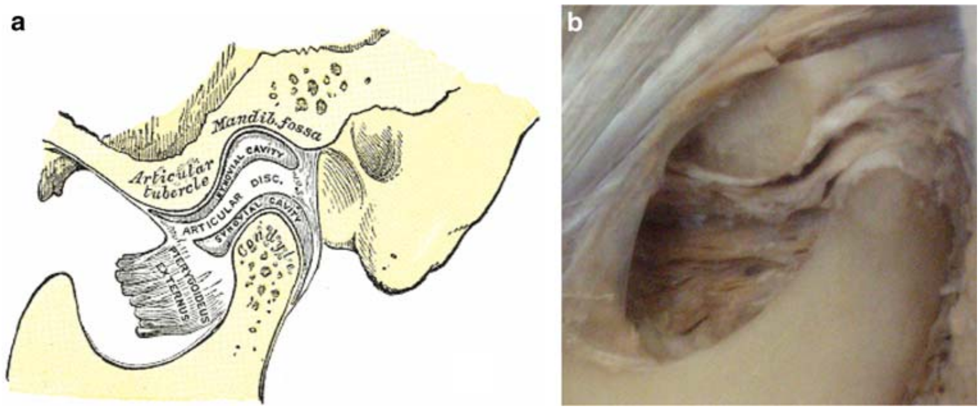

Fig. 1 Anatomy of the TMJ, **a** sagittal cut through the articular capsule [1]; **b** human preparation with opened articular capsule, preparation: Anatomische Anstalt der Universität München, photograph: C. Kober

Introduction

The temporomandibular joint (TMJ) is one of the most complicated joints in the human body. The skeletal anatomy consists in the anterior part of the mandibular fossa of the temporal bone and the articular tubercle above and the mandibular condyle below. The attachment of the condyle to the skull is formed by the articular capsule in the sense of a thin, loose envelope made of fibrous membrane surrounding the joint and incorporating the articular eminence. A parasagittal cut through the articular capsule reveals the articular disc which divides the joint into two sections, see Fig. 1a for an anatomical drawing resp. Figure 1b for a human preparation. It shows biconcave shape and attaches to the condyle medially and laterally. The anterior portion of the disc splits in the vertical dimension, coincident with the insertion of the superior head of the lateral pterygoid muscle. The posterior portion also splits in the vertical dimension, and the area between the split continues posteriorly and is referred to as the retrodiscal tissue. Unlike the disc itself, this piece of connective tissue is vascular and innervated [1].

According to [2], between 5% and 15% of the people in the United States experience pain associated with TMJ disorders which range from "jaw clicking" to severe facial pain, limitations of mandibular motility, or even noticeable hearing loss. TMJ disorders are caused by earlier trauma from a severe blow to the jaw, degeneration of the joint, osteoarthritis, rheumatoid arthritis, or other forms of inflammation.

In actual radiology, MRI (magnetic resonance imaging), CT (computer tomography), especially CBCT (cone beam computer tomography), and ultrasound are discussed as diagnostic tools for the TMJ [3–8]. For soft tissue abnormality of the TMJ, MRI has evolved as the prime diagnostic tool [4,5]. Depending on the state of the disorders and the available medical equipment, various examination schemes have been developed over the last decade. Due to the frequent occurrence of TMJ disorders and for the sake of patients' convenience, fast examination time and cost-efficiency of the radiological data acquisition are highly favored. Detailed research has been carried out concerning the choice of MRI protocols where T1-, T2-, or proton density (PD) weighted MR images were discussed in the literature [9–11]. As regards MR image positioning, the acquisition of parasagittal images oriented according to the individual angle of the mandibular condyle [12] or parasagittal images supplemented with coronal images has proven as good clinical standard usually provided with 3 mm slice thickness. Nevertheless, in spite of detailed research, there are still severe limitations in the diagnostic value of MRI with regard to the diagnosis of TMJ disorders [13].

Mostly, for medical 3D-rendering, shaded surface reconstruction is applied based on manual or (semi-) automatic segmentation. Concerning TMJ and articular disc based on MRI, see [14–22] for this kind of research. Basically, segmentation consists in reduction of the considered images to binary data separated into black and white according to a user defined strategy. If tissue differentiation is enough clear, as for bony organs in computer tomography data for instance, shaded surface reconstruction is generally accepted. However, MRI-data with 3 mm slice thickness with additional gap of 10–20% yield very scarce spatial information on the TMJ the articular disc. Furthermore, exact tissue classification is unclear. This renders segmentation tedious, error-prone, and highly user dependent.

The objective of this work is an alternative approach for 3D-rendering the articular disc based on TMJ MRI-data stemming from the clinical routine. The scarceness of spatial anatomical information due to the high slice thickness is overcome by a combined application of different visualization techniques. Input data from four independent hospitals or research institutions characterized by varying quality and resolution were processed. The focus was put on anterior disc displacement with and without reduction. The present study is an extension of the results presented in [23,24] where a first version of the approach was tested for a case based on high-resolution MR images from Tokyo Dental College.

Methods

MR-image acquisition

For the sake of illustration of the validity and the significance of the approach, MR images from four independent medical hospitals or research institutions with varying quality and resolution were examined.

High-resolution MR images from Tokyo Dental College, Chiba, Japan

As in [23,24], the method was demonstrated for high-resolution MR-imaging carried out using a 1.5-T MRI scanner system (Magnetom Symphony Maestro Class, Siemens, Erlangen, Germany) with the use of bilateral surface coils, "Double Loop Array," as receivers. Oblique sagittal cross-sectional plane images oriented according to the individual angle of the mandibular condyle were obtained, at closed and open mouth position (Fig. 4a, b). The slice thickness in each sliced image was 3 mm with additionally 20% gap. Proton density weighted images (PDWI) and T2-weighted images (T2WI) were simultaneously taken by the double-echo sequence [9]. The settings of TR/TE were 3,300 /14 ms (PDWI) and 3,300/85 ms (T2WI). The matrix was 512 × 512 pixels and the FOV was 150 mm. Four cases with various pathological findings were examined. For some cases, coronal and axial MR images were also acquired (PDWI and T2WI).

T1-weighted MR images from RWTH Aachen, Germany

Within an orthodontic MRI study [10,11], the temporomandibular joints of mostly juvenile or young adult patients were analyzed at different dates of an orthodontic treatment by means of a Philips Gyroscan NT/Interna MRI machine (1.5 T, Philips Medical System, Eindhoven, Niederlande, Spin-Echo-Sequence). Bilateral C4 surface coils were used. Axial, frontal, and parasagittal T1-weighted MR images were acquired with 256 × 256 pixel matrix and 3 mm slice thickness and additionally 0.3 mm gap, at closed mouth position. Additionally, T2-weighted MR images were acquired at open mouth position. MRI data of patients with anterior disc displacement with and without reduction as well as without pathological findings were processed (Fig. 3a, b).

T2-weighted fat suppressed high resolution MR images from University Hospital Basel, Switzerland

(Courtesy: Dr. C. Leiggener)

From clinical routine, several cases with TMJ disorders (anterior disc displacement with and without reduction) and one control case were provided (1.5 T, GE Medical Systems, SE scanning sequence). Using bilateral surface coils axial, coronal, and parasagittal T2-weighted fat suppressed MR images were acquired with 512 × 512 pixel matrix and 3 mm slice thickness with additionally 0.3 mm gap, at closed and open mouth position. For one case (anterior disc displacement without reduction), additionally kinematic parasagittal MR images were obtained. Proton density weighted 3D-MRI-data sets were continuously recorded at seven time steps with 256 × 256 pixel matrix, 3 mm slice thickness, and 0.3 mm gap [25].

Research MR images from the University of Zurich, Switzerland

For research purposes about TMJ function [16,26], T1-weighted MRI data of a healthy volunteer were acquired with 2 mm slice distance and 256 × 256 pixel matrix, at closed mouth position. Additionally, 3D-reconstructions of both joints comprising condyle and mandibular fossa, were delivered in stl-format. The reconstructions were performed according to the algorithm described in [15,16]. MRI scans were recorded by means of a 1.5- T system (Gyroscan ACS-II Philips Medical System, Best, Netherlands) using a body coil and a FFT protocol (gradient recalled echo).

3D-surface reconstruction of mandibular condyle and fossa

If lower resolution was provided the MR images were resampled to 512 × 512 pixel matrix. After preparatory image processing, such as Gaussian smoothing and contour filtering, the mandibular condyle and fossa were semiautomatically segmented. The segmented slices were interpolated using a cubic algorithm to isotropic voxel size of about 0.2–0.3 mm in each direction. A first polygonal surface model was performed by means of the Amira built in surface reconstruction algorithm [27,28]. Stepwise simplification and surface smoothing down to about 2,500 faces for the condyle and about 9,000 faces for the fossa, similar as in [29,30], delivered an acceptable 3D-reconstruction of the skeletal anatomy (Figs. 2a, 3c, d, 4c, d). For validation purpose, the 3D-reconstructions performed by means of the MRI data from Zurich were superposed to the polygonal surface models delivered by the Zurich group which were built according to [16,26].

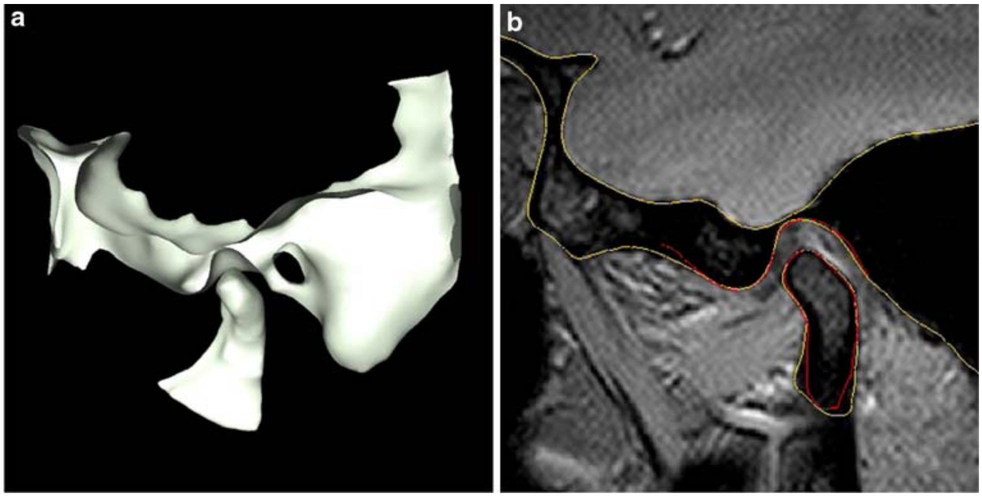

Fig. 2 3D-Reconstruction and its validation **a** right mandibular condyle and fossa with the latter sagitally cut (*medial view*) based on T1-weighted MRI-data from the University of Zurich; **b** MRI slice (Univ. Zurich) with contours produced by an intersection of the MRI slice with the surface models from Zurich (*red line*) and from Osnabrueck (*yellow line*)

Rendering of the temporomandibular joint with special focus on the articular disc

For this purpose, the voxels representing the soft tissue around the condyle limited by the mandibular fossa were segmented from the (to 512 × 512 pixel matrix resampled, see before) MRI data. Anatomically, this region concerned the articular capsule including the disc, the retrodiscal tissue, the acoustic meatus, the lateral pterygoid muscle, and also to some extent the temporal muscle. As before, this segmentation was interpolated using a cubic algorithm to isotropic voxel size of about 0.2–0.3 mm in each direction and moderately smoothed. Thereafter, the MRI data were resampled to the same dimensions as the (interpolated) segmentation. By means of the segmentation, the voxels of the concerned soft tissue were isolated from the MRI data and inverted which means that the new gray value of a special voxel is given by the maximal value of the original voxels (within the segmented region) minus the original gray value of the considered voxel.

For the visualization, these voxels were subjected to direct volume rendering which is a very intuitive method for visualizing 3D-scalar fields. Each point in a data volume is assumed to emit and absorb light. The amount and color of emitted light and the amount of absorption is determined from the scalar data by using a color map which includes alpha values [27,28]. For colored rendering, bichromatic color maps proved to be very appropriate, namely a green—blue one, or an orange—black one. For the sake of anatomical orientation, the polygonal models of the mandibular condyle and fossa were simultaneously rendered either as shaded or as transparent surfaces. For the sake of clear visibility of the disc, the soft tissue (subjected to volume rendering) and the mandibular fossa (in shaded or transparent surface rendering) were sagittally clipped. The clipping plane was scrollable, and both, medial and lateral clipping was possible. The mandibular condyle was not clipped in order to provide orientation about the position of the clipping plane with regard to the skeletal anatomy. (Figs. 3e, f, 4e, f).

For a combination with conventional diagnosis using 2D-gray images, it is possible to superimpose the 3D-visualization by the original 2D-MRI slices, in transparent or opaque rendering and scrollable by the user. The 3D-visualization can be totally or partially switched on and off. Needless to say, standard interactive 3D-manipulations as rotation, translation, and zooming are possible.

The method consists in a combination of well validated tools of image processing, 3D-reconstruction, and visualization. Besides initial semiautomatic segmentation of the (few) original slices, the method does not comprise any further user dependent step. Although at the moment still a prototype the application is not very time consuming. Further, it can be easily automated. The geometry reconstruction from 3D image data and all visualizations were performed using the visualization tool box Amira 4.1 [27,28].

Results

3D-reconstruction of the skeletal anatomy

In spite of the high sagittal slice distance and gap, satisfactory polygonal surface reconstruction of the skeletal anatomy was possible (see Figs. 2a, 3b, c, 4b, c).

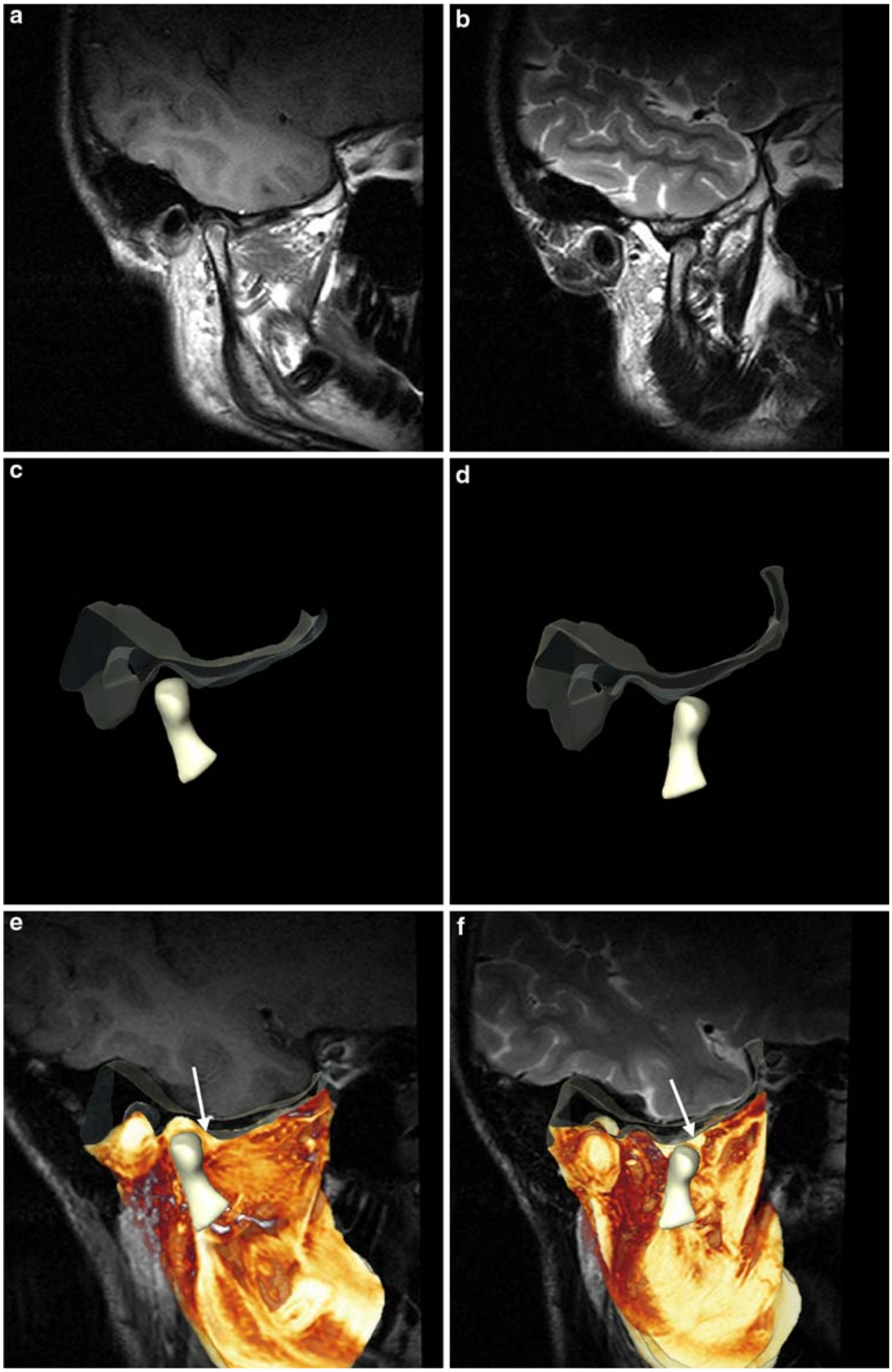

Fig. 3 **a, b** MR images of right joint at closed **a** and open **b** mouth position; **c, d** 3D-reconstruction; **e, f**: visualization (patient: male, 19 Y, physiological TMJ condition without abnormalities, MRI data from RWTH Aachen)

For the sake of validation, the surface models from Zurich and the ones from Osnabrueck were superposed. Visual inspection of the superposition showed good agreement of both models though they were built using different reconstruction algorithms. For a more quantitative analysis, the contours derived by means of an intersection of the models with an MRI slice were compared (Fig. 2b: Zurich model: red line, Osnabrueck model: yellow line). The contours at the

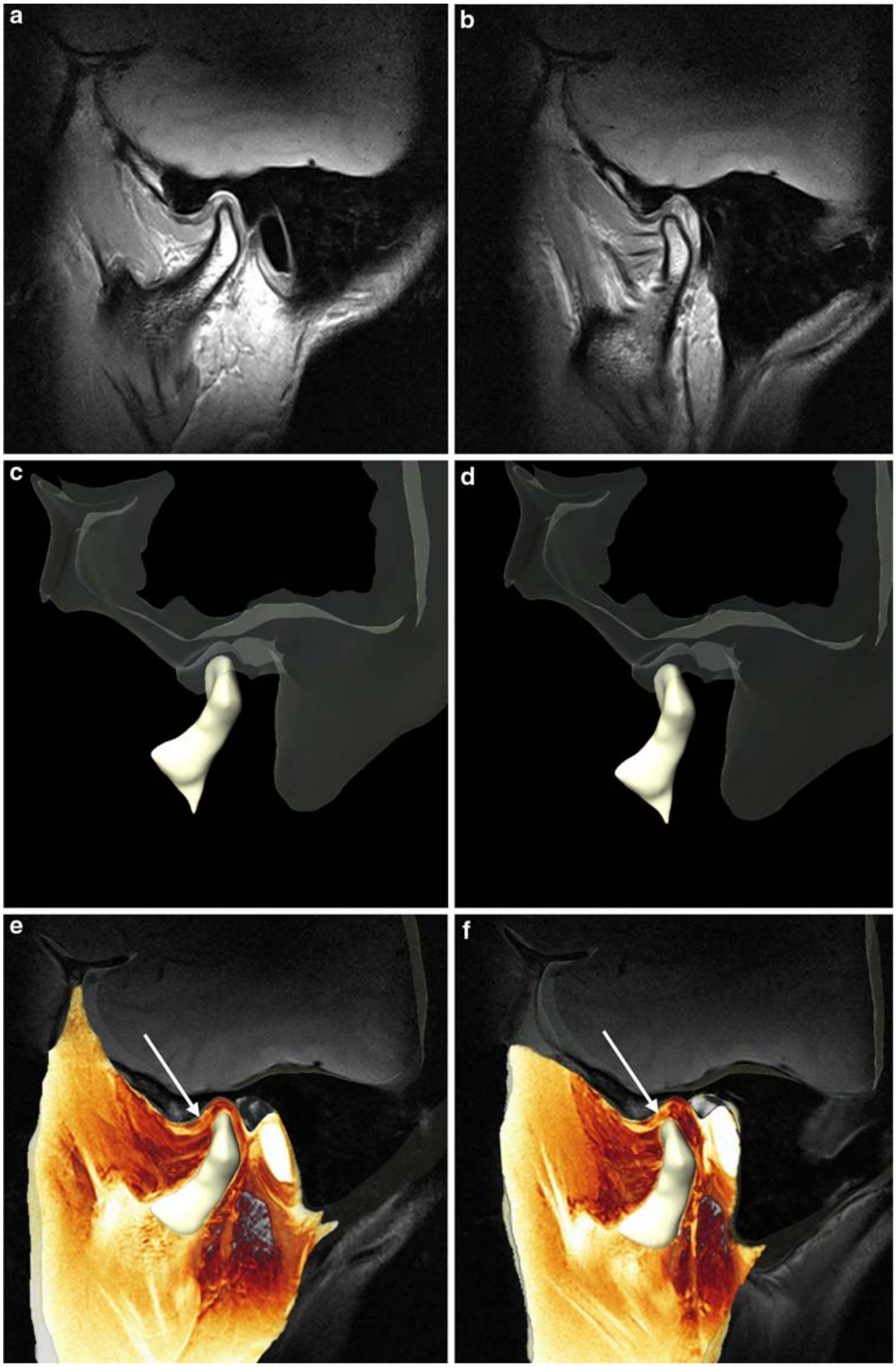

Fig. 4 **a, b** Proton density weighted MR images of left joint at closed **a** and open **b** mouth position; **c, d** 3D-reconstruction; **e, f** visualization (patient: male, 37 Y, anterior disc displacement with reduction, MRI data from Tokyo Dental College)

condylar head as well as at the mandibular fossa showed a deviation of less than 1 pixel. The deviations at the condylar neck were due to the different reconstruction algorithms.

Further validation of the surface reconstruction has been provided in [23]. There, condylar surfaces based on PDWI and the T2WI images as well as on MR images acquired at open and closed mouth position of the same joint were superposed.

The MRI protocols from Tokyo Dental College were optimized with respect to imaging the condition of the articular disc. For this reason and also caused by the high gap of 20%, the reconstructions of the condylar neck showed some distortions.

3D-visualization with special focus on the articular disc

For all cases, it could be clearly depicted whether anterior disc displacement occurred or not as well as the incidence of reduction of the disc at open mouth position. In Fig. 3a–f, a case without pathological findings is depicted based on T1-weighted (closed mouth) resp. T2-weighted (open mouth) MRI data from RWTH Aachen. The articular disc at physiological position can be clearly recognized at closed mouth position as well as at open mouth position. Additionally, the visualization provides some information about the condition of the retrodiscal tissue. In contrast the left joint presented in Fig. 4a – f based on proton density weighted MR images from Tokyo Dental College shows anterior disc displacement with reduction. The joint was not fully opened due to patient's pain. The disk is located between the posterior slope of the eminence and the condyle. There is notable difference in the condylar shape depicted in Fig. 3 (without pathological findings) and in Fig. 4 (anterior disc displacement with reduction).

For the high-resolution MR images from Tokyo Dental College, University Hospital Basel, or University of Zurich, the visualization revealed some inner structure of the disc. Comparison and superposition of the visualization based on PDWI and T2WI images of same joints (MRI data from Tokyo Dental College) delivered corresponding results and served, by this, as vice versa validation of the approach. Besides the TMJ, the approach enabled visualization of the lateral pterygoid muscle and, to some extent, also of the temporal muscle which was especially applicable for the MRI data from the University Hospital Basel [25].

The significance of the approach was rated by several independent experienced observers (oral surgeons, medical practitioners, orthodontists) as promising with regard to diagnosis of anterior disc displacement with and without reduction. For the case from University Hospital Basel where kinematic MRI data were provided, first dynamic 4D-visualization of TMJ movement was possible although the data were suffering from distortion and misalignment [25].

Discussion

An approach for diagnosis support for anterior disc displacement within the TMJ was reported. By the superimposition with the original MRI slices, it can be combined to conventional diagnosis. The approach has been tested by cases from four independent hospitals and medical research institutions based on T1-, T2-, and proton density weighted MRI data. The positive feedback of the medical observers encourages further development. Nevertheless, keeping in mind the results of [9], clinical validation is an ongoing task.

The method consists in a chain of well validated tools of image processing, 3D-reconstruction, and visualization. Besides initial semiautomatic segmentation of the (few) original slices, the method actually does not comprise any further user dependent step. As several validation approaches showed satisfactory results (see also [23]) reproducibility of the results has been provided. Actually, the method is implemented as a proto type in Amira 4.1, but it can be easily automated.

Besides ongoing validation of the clinical impact of the approach, actual and future work is spent on the extension of the diagnostic significance. By a slight modification, an impression of joint effusion can be given [23]. Actual activity is dedicated to simultaneous visualization of disc displacement and joint effusion by means of multiple data set processing. Furthermore, the approach is going to be extended to an examination of medial or lateral disc displacement based on coronal MRI images. First tests have already been successfully performed. With regards to the 3D-reconstruction of the skeletal anatomy, a combined processing of axial, coronal, and parasagittal images is under development in order to enhance the accuracy. First tests proved the extension of the method to the analysis of condylar bone adaptation as very promising. In the course of the project, the significance of the approach will be continuously evaluated based on a visual rating system similar to the one applied by Widmalm et al. [13].

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