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Functional magnetic resonance imaging of temporomandibular joint disorders

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SUMMARY Fifty-eight temporomandibular joints (TMJs) from 40 patients with TMJ-related symptoms were examined by means of magnetic resonance scans with modified gradient echo sequences and a special double coil. This technique yielded a good spatial resolution of the intra-articular soft tissues, especially the articular disc and the bone structure of the TMJ. In combination with an incremental jaw opener, the disc-condyle complex was analysed in various closed and open mouth positions, depending on the clinical examination. Open mouth movement with differentiation of disc-condyle rotational and translation movement was demonstrated.

Disturbances of TMJ motion showed interrupted condylar translation combined with mandibular deviation during open mouth movement (n = 8/58). Early phases of internal derangement of the TMJ with partial anterior disc displacement with (n = 12/58) or without (n = 2/58) reduction, total anterior disc displacement without reduction (n = 10/58), disc deformation (n = 10/58), disc adhesion (n = 2/58), condylar hypermobility (n = 6/58), condylar displacement (n = 8/58), and late phases of internal derangement of the TMJ with osteoarthrosis (n = 14/58) were clearly identified. Bilateral TMJ disorder was found in 72.5 per cent of the patients. By using motion-adapted, semi-dynamic magnetic resonance imaging (MRI), it is possible to improve the understanding of the complexity of TMJ movements.

Introduction

Disturbances of the stomatognathic system have a multifactorial aetiology (Laskin, 1969). Between 35 and 72 per cent of humans show symptoms of TMJ disorders with a prevalence in young women at 20–35 years of age (Schiffmann and Fricton, 1988; Mohlin *et al*., 1991). This is supported by clinical studies where a female to male ratio of 3:1 to 9:1 was found in subjects seeking treatment (Hansson and Nilner, 1975). In contrast, epidemiological investigations have shown no differences in the sex and age distribution of subjects with TMJ disorder (Helkimo, 1974; Rieder *et al*., 1983).

Internal derangement of the TMJ is a progressive, degenerative disease marked by morphological and structural changes in the TMJ and related anatomy. The normal anatomical relationship of the intra-articular components is altered (Schellhas, 1989; Wilkes, 1989). Other authors have concluded that the progressive development of TMJ disease (TMD) does not always occur (Dijkstra *et al*., 1993; de Leeuw *et al*., 1993). However, there are different opinions on the course of TMD and knowledge is limited (Stegenga *et al*., 1989; Randolph *et al*., 1990).

Different imaging techniques with various levels of validity have been used in the study of TMJ disorders. Conventional radiography has been shown to be of limited value in the evaluation of bony structures and only allows assessment of the overall amplitude of joint movements. TMJ radiographs with lateral cephalometric tomograms provide information concerning joint space, condylar shape, and position, but no information about the soft tissue components of the joint. Computed tomography is more precise in visualizing cortical bone or maxillofacial fractures. This technique is useful when pathological conditions such as congenital skeletal anomalies, maxillofacial trauma with the presence of fractures, osteoarthrosis, osteomyelitis, and tumours with condylar destruction are suspected (Baily *et al*., 1990; Palacios *et al*., 1990).

Magnetic resonance imaging (MRI) visualizes disc morphology and position, and facilitates an interpretation of topographic changes in osseous, muscular, and meniscoligamentous structures of the TMJ. Therefore, MRI in the open and closed mouth position is the method of choice in imaging TMJ disorders (Murakami *et al*., 1993; Matsuda *et al*., 1994; Rao, 1995).

The aim of this study was to analyse the TMJ at various degrees of mouth opening using fast MRI, because this method yields more information on disc and condyle mobility than purely static MRI examinations.

Subjects and methods

Forty patients showing signs and symptoms of internal derangement of the TMJ were examined by means of sagittal MRI using a 1.5 Tesla Magnetom SP-63 (Siemens, Erlangen, Germany). Seventy per cent of the patients were female. The mean age of all subjects was 38 years. Eighteen patients were investigated synchronously on both sides (36 TMJs) and 22 subjects unilaterally, at the affected joint only (22 TMJs).

Prior to MRI, each patient was examined clinically in order to objectively assess muscle physiology, joint function, and occlusal relationships. The TMJ was palpated and auscultated in order to detect joint clicking, crepitation, or myofacial pain. The inter-incisal distance, the maximum angle of mouth opening, and deviations were recorded. These measurements determined the inter-incisal distance at which TMJ symptoms such as joint clicking, crepitus, or pain occurred during mandibular excursion. The fully closed position in inter-cuspal relationship and the individual, maximum open mouth position were included in each examination. For documentation, the clinical examination form of the German Association of Dentomaxillary Science (DGZMK) was used.

The MRI consisted of a gantry, an operating console, and a computer room network. All three components were electronically interfaced to receive the raw MRI data signals originating from the tissue sample and then to computer encode the signals into an image.

The MRI unit had a super-conductive field strength with the direction of the static magnetic field parallel to the long axis of the patient. Three electromagnetic gradient coils surrounded the patient. The distribution of the gradient of the magnetic field in each plane allows spatial localization of the visualized region.

The patients were investigated in a supine position. A dual surface coil was positioned with its central opening directly over the subject's TMJ area. An axial 5-mm localizing image section was obtained through the mandibular condyle level to indicate the sagittal image orientation of the TMJ. Following this, a series of nine sagittal images for each mandibular position were then obtained. In most subjects, the intra-articular structures of the TMJ were best visualized in the central slice. A corresponding slice was therefore selected for all mouth opening steps in each subject.

Various mouth opening positions were investigated using a hydraulic calibrated jaw opener (Vogl and Eberhard, 1993). This appliance allowed reproducible and stable TMJ articulation. The device was made of plexiglass with connected hydraulic cylinders applied for transformation of force. The subjects were instructed to open their mouths passively, using the jaw opener to the increments determined in the clinical examination. With a cinematographic (CINE) program, appropriate sagittal images were selected and sequentially arranged for a CINE display of TMJ function. CINE MRT was performed by means of a gradient echo FISP-2D (fast imaging with steady precision) in different mandibular positions. In this gradient echo sequence, the 180-degree rephrasing pulse used in spin echo sequences is eliminated, and angles less than 90 degrees are used instead of the 90 degree pulse flip angle. Selected representative slices were loaded into a standard programme that allowed fast serial observation of the slices in a pseudo movie mode. The interval of the images displayed on the workstation could be varied individually; no additional software was needed.

Gradient echo sequences were obtained in two acquisitions with a repetition time (TR) of 300 milliseconds, an echo time (TE) of 150 milliseconds, a flip angle of 40 degrees, a section thickness of 4 mm, and a matrix of 256–256. The TMJ coil had a signal to noise ratio of 202 and a field of view of 3–4 cm. Six to nine different TMJ positions, with an acquisition time of 1 minute 19 seconds for each MRI measurement, were examined.

Like other authors (Katzberg *et al*., 1986; Kaplan *et al*., 1987), we examined the posterior band of the disc normally situated above the uppermost portion of the condyle. In order for disc reduction to occur and for the disc to translate to the normal position under the temporal eminence, the condyle must pass under the posterior band of the disc during mouth opening. Here, the disc was usually situated with the intermediate zone above the condyle.

Table 1 MRI findings of 58 TMJs in 40 subjects.

Normal TMJ	9
Unstable disc position (disc hypermobility)	2
Partial anterior disc displacement with reduction	12
Partial anterior disc displacement without reduction	2
Total anterior disc displacement without reduction	10
Disc deformation	20
Disc adhesion	2
Osteoarthrosis	14
Condylar displacement	8
Condylar hypermobility	6
Disturbances in condylar motion	8

Multiple findings within the same subject were registered.

Results

The use of a fast MRI technique, with a very short time of measurement, made it possible to examine children, geriatric, or handicapped subjects. The incidence of motion artefacts could be reduced to 5 per cent due to the stable construction of the device and the defined bite position.

Gradient echo sequences clearly identified disc, condylar position and morphology, fibrocartilaginous remodelling of the articular surfaces, abnormal condylar shape, cortical erosion, limitation in translation, and disc alterations in all subjects (Table 1). The dynamic display of TMJ alterations (Figure 1) makes it necessary to investigate different mouth positions. The condylar position in central occlusion (Figure 1a) was determined by the occlusal relief of the dentition. The second mandibular position (Figure 1b) showed an inter-occlusal space of 2–3 mm. Physiologically, there was only a slight condylar distraction between these two lower jaw positions. Changes in vertical dimension with joint compression or changes in the sagittal plane indicated excessive malocclusion or a loss of dental occlusion, which made oral rehabilitation necessary. Most subjects with TMJ disorders were treated with a splint in order to reduce the symptoms and to achieve a correct disc-condyle relationship. The recapture of an anteriorly dislocated disc by means of anterior repositioning appliances was only successful in some subjects, depending on the degree of displacement (Figure 1c). Completely displaced discs with positions before or beyond the eminence could not be recaptured by means of conventional treatment. Various open mouth positions allowed an interpretation of disc mobility and condylar limitations (Figure 1d–h).

The CINE mode of the normal TMJ subjects showed rotational condyle movement corresponding to an inter-incisal distance of 0.5–2.0 cm during the early phase of mouth opening. Mandibular positions with an inter-incisal distance larger than 2.0 cm showed a continuous translational condylar movement beyond the articular eminence at the maximum open mouth position (normally 4.0 cm). The subjects with normal TMJ (9/58) and disc hypermobility (2/58), and five subjects with partial anterior disc displacement with reduction showed no clinical signs or symptoms of TMD. Anterior disc displacement with reduction showed an abrupt change in the disc-condyle relationship during mandibular translation. The dislocated disc was reduced initially (10/58) or intermediately (12/58) during open mouth movement. The range of mandibular motion was usually not limited. Joint

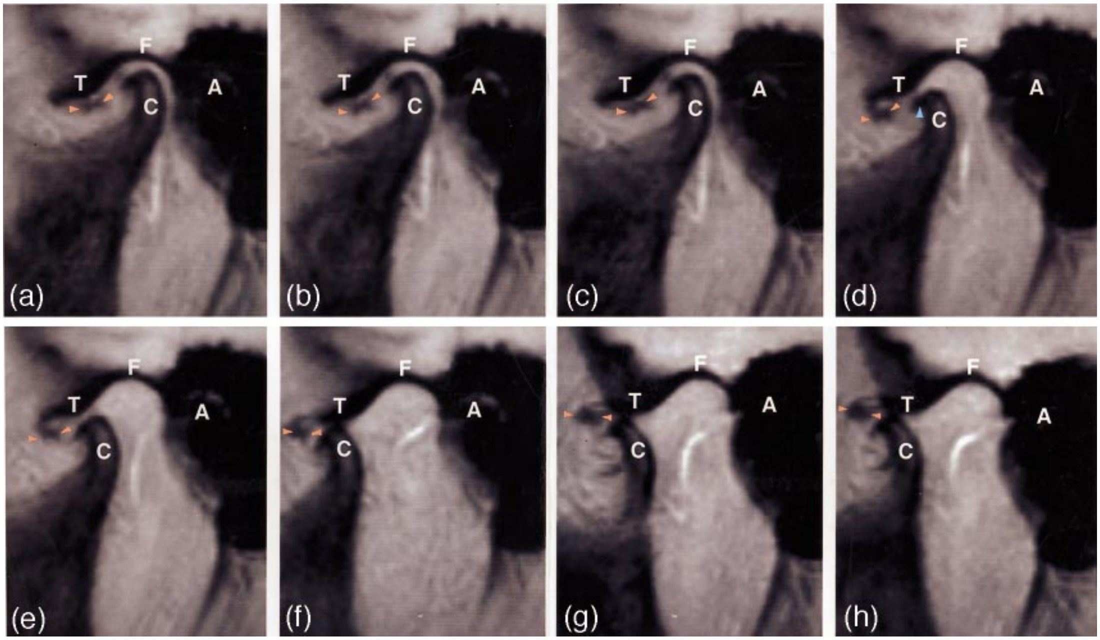

Figure 1 CINE imaging of the left TMJ of a 28-year-old female. Total anterior disc displacement without reduction by disc deformation and disturbances of coordinated TMJ motion during mouth opening movement. FISP-2D, TR milliseconds/TE milliseconds = 300/15. (a) In central occlusion there was a slight posterosuperior condylar displacement, with osteophytosis in the anterior part of the articulating surface of the condyle (blue triangle), and a completely anteriorly dislocated disc. The anterior (red left triangle) and posterior bands (red right triangle) of the disc can be clearly identified. The disc was shortened and slightly deformed. (b) There was a short vertical condylar distraction at this mandibular position with no occlusal tooth contact. (c) With the use of a maxillary occlusal splint, the condylar position improved (compared with Figure 1a) by means of slight distraction in the vertical plane and anterior condyle positioning. The anterior and posterior joint spaces are almost equal. In this subject, a correct disc-condyle relationship with recapturing by means of a protrusive splint was not possible. (d) During an open mouth position of 0.5 cm (inter-incisal distance), there was onset of condylar translation, loss of rotational condylar movement, and wide condylar translation from the glenoid fossa to a pre-tubercular position. The displaced disc was pushed forward by condylar translation. There was no approximation between the disc and condyle during translational movement as a diagnostic criterion of over-stretching of the superior stratum. (e) At an open mouth position of 1.0 cm, there was condylar rotational movement. (f) With an open mouth position of 2.0 cm, condylar translation continued. The disc was pushed to the joint capsule and was compressed. (g) Open mouth position at 3.0 cm: condylar translation was interrupted and there was rotational condylar movement. The deformed disc was located anterior to the eminence. (h) Open mouth position of 4.0 cm: at maximum mouth opening, there was a predominantly rotational movement with very short forward translation of the condyle. The condyle was located in a normal position under the apex of the eminence. Anterior band of the disc (left red triangle); posterior band of the disc (right red triangle); osteophytosis (blue triangle); A, external auditory canal; C, condyle; F, fossa; T, eminence.

clicking was found at various stages of open mouth movement. Subjects with anterior disc displacement without reduction (10/58) showed an abnormal disc-condyle relationship, which continued in all jaw positions adopted during opening movements (Figure 1). The disc was completely in front of the condyle and the anteriorly located disc was pushed further forward during condylar excursions (Figure 1d–h). Changes in disc position and morphology were seen by MRI during translational movement of the condyle which compressed the anteriorly dislocated disc (Figure 1e–h). The condyle moved antero-inferiorly, beyond the articular eminence. At no point during opening did the condyle pass under the disc to achieve a normal relationship. In the acute phase, mandibular movements were painful, and mouth opening was limited with deviation to the affected side. Lateral jaw movements to the contralateral side were also limited. In the chronic phase, the range of TMJ motion was not significantly limited. In some subjects, the anteriorly dislocated disc mechanically prevented the condyle from moving through its full forward excursion. In this closed lock derangement, the subject was not able to fully open their mouth.

A wide, completely anteriorly dislocated meniscus showed no effective ligamentous connection between the condyle and the bilaminar zone. There was no adjustment of the anteriorly dislocated disc and the condyle during the intermediate or late condyle translation movement (Figure 1d–h). Restricted condylar movements with uncoordinated patterns appeared in the late phase of open mouth movement. The perforated meniscus was pressed into the joint capsule by sub-tubercular condylar movement. Disc avulsion was a traumatic insult or a late effect of severe internal derangement caused by over-stretching of the menisco-ligamentous structure. Inflammatory processes of the upper joint compartment, such as arthritis or trauma, caused disc immobility (2/58), which was verified by a lower signal in the upper joint space. Condylar displacement (8/58) constricted the joint space. Condylar hypermobility (6/58) showed a wide range of open mouth movement with an inter-incisal distance greater than 4 cm.

In severe internal derangement, the disc remained irregularly shaped. The biconcave configuration was lost and, in most subjects, the disc was shortened. It was not possible to identify the intermediate zone. Here, the meniscus was clearly seen as a low signal structure against the higher signal intensity background of the synovium. It was found that the deformed disc had an even lower signal intensity than the normal disc.

Subjects with clinically evident joint symptoms such as clicking, crepitation or tenderness on palpation also demonstrated pathological MRI findings. As far as configuration, position, and function of the disc were concerned, there were often disturbances of occlusal relationships between the upper and the lower arches. Intra-articular adaptation processes such as osteophytosis (Figure 1) at the condylar articulation surface or at the glenoid fossa caused crepitation or irregular condylar movements. Disturbances of condyle movement (8/58) were seen as disc adhesions; anterior disc displacement without reduction often combined with osteoarthrosis. In all subjects with osteoarthrosis (14/58), disc displacement and disc distortion occurred together. No disc alteration (20/58) without disc displacement was found. More than one abnormality was found in 72.5 per cent of the subjects.

During the movement cycles, the identification and differentiation of condylar rotation and translation phases was possible at each step of mouth opening. Unilateral disturbances of condylar movement with interrupted translation and rotational movements, which restricted condylar mobility, caused an incongruent motion of both condyles manifesting as deviations. The disc-condyle relationship, and its functional and anatomical changes through the range of TMJ movements were analysed and interpreted.

Discussion

MRI allowed accurate representation of the discal-retrodiscal junction and yielded valuable therapeutic information on the tissue structure of the disc and the ligaments. Westesson and Paesani (1993) reported limited demarcation of the disc and the retrodiscal tissue in a subject with fibrotic adaptation. The integrity of the inferior aspect of the posterior attachment of the disc to the condyle is essential for maintaining the disc in its position superior to the condyle. The efficacy of the ligamentous connection is responsible for the reduction of a partially or completely anteriorly displaced meniscus. As the disc is displaced forward, there is stretching of the fibres of the bilaminar zone. Insufficient ligamentous structures cause anterior disc displacement without reduction. The increasingly stretched elastic fibres of the bilaminar zone are unable to exert a restraining force on the disc as the condyle translates forward.

Arthrography is performed especially to determine the status of the condyle–glenoid–fossa eminence relationship in the closed, semi-open, and open mouth positions. Inferior joint compartment arthrography, dual-space or single contrast arthrography combined with fluoroscopic joint dynamics may be used to confirm the integrity and competency of the retrodiscal tissue. The diagnostic accuracy of arthrotomography has been reported to range from 79 to 97 per cent (Palacios *et al.*, 1990).

With this technique, it is possible to determine disc position and anterior disc displacement with or without reduction, such as a distorted disc shape. Arthrography is considered a valuable alternative in subjects where MRI is contraindicated, e.g. in those with claustrophobia, or where ferromagnetic clips or a cardiac pacemaker are fitted. Some authors consider arthrography more effective in detecting disc perforation, adhesions, and capsule perforations than MRI (Nakasato *et al.*, 1991; Van Hoe *et al.*, 1992, 1993).

Due to recent advances in MRI of the TMJ and the introduction of surface coils allowing precise visualisation of intra-articular structures, especially of the articular disc, MRI is excellent in evaluating disc position and changes in disc morphology. However, it also involves the problem of over-diagnosis or false-positive MRI findings (De Laat *et al.*, 1993; Steenks *et al.*, 1994; Crowley *et al.*, 1996). The interpretation of MRI findings should only be used in addition to the clinical examination. Nevertheless, as a non-invasive, multi-planar imaging modality, it is the method of choice for TMJ evaluation. Standard MRI consists of T1-weighted images in the closed and open mouth position. T1-weighted images show a high spatial resolution and specificity in visualization of disc position and disc configuration (Brady *et al.*, 1993).

Fast imaging techniques allow the examination of disc and condylar mobility, and help to determine at which point along the path of condylar translation the reduction of the disc occurs, as well as to establish the relationship of the reduction to joint clicking and pain. Fast MRI scans with gradient echo sequences show improved differentiation of cortical and cancellous structures. The diagnosis of sclerotic changes, avascular necrosis, regressive condylar changes, or proliferative bony changes is also possible (Van der Meolen *et al.*, 1985; Vogl and Eberhard 1993; Dorsay *et al.*, 1994; Roditi *et al.*, 1997).

CINE MRI can be regarded as a supplementary diagnostic tool to static MRI. The advantage of CINE MRI in comparison with static MRI is that it allows evaluation of the degree of forward condylar excursion, differentiation of rotational and translational movements, and diagnosis of an interruption of translational movement. The functional component of internal derangement of the TMJ can be analysed by monitoring the disc condyle relationship during mandibular excursions.

Previous MRI studies have revealed that partial flip angle images provide reliable information on disc position, morphology, intrinsic signal, and a reduction in resolution in comparison with T1-weighted images (Aase *et al.*, 1986; Burnett *et al.*, 1987; Mills *et al.*, 1987; Conway *et al.*, 1988).

The CINE technique is helpful in evaluating various types of TMJ dysfunction (Behr *et al.*, 1996; Bell *et al.*, 1992) to provide information on the efficacy of treatment by monitoring disc and condyle mobility, for example, in the diagnosis and post-therapeutic evaluation of an adherent TMJ disc (Dorsay *et al.*, 1994) or a proplast Teflon TMJ inter-positional implant (Dorsay *et al.*, 1995). Dorsay and Youngberg (1995) evaluated the Burnett device while studying functional and morphological aspects of internal derangement of the TMJ with CINE MRI. They carried out off-sagittal imaging of the disc in the closed mouth position prior to appliance placement in order to detect anterior displacements with very early recapture. Behr *et al.* (1996), however, found that the dynamic information obtained by means of the CINE technique was useful for the diagnosis of disc displacement in only 14 per cent of the investigated subjects.

The CINE technique enables more information to be obtained about the disc-ligamentous-condyle complex by differentiating between various stages of TMJ movement. The morphological changes in disc configuration, over-stretching of the joint capsule in the maximum open mouth position, or compression of an anteriorly dislocated disc during various degrees of condylar translation, provides improved understanding of TMJ pathology. Magnetic resonance fast scanning is the method of choice for MRI evaluation of disc-condyle motion and effects of internal derangement on this motion.

CINE MRI evaluates the degree of forward condylar excursion, the interruption of translational motion, or condylar hypermobility. Mouth opening is achieved by a combined rotational and translational movement of the disc-condyle complex within the fossa. The relationship between condylar rotation and anterior condylar translation during deliberate opening movements shows great intra- and inter-individual variability (Salaorni and Palla, 1994). The applied MRI technique is semi-dynamic and two-dimensional only in the sagittal plane. The diagnosis of sideways disc displacements is limited, because no coronal plane was used. However, the motion artifacts increased due to the period of examination and the main interest in this investigation was the functional MRI approach.

The correlation between MRI and clinical classification shows a sensitivity of 79 per cent, and a specificity of 91 per cent for MRI relative to the clinical assessment (Brady *et al*., 1993). The comparison of prevalence of TMJ derangement in asymptomatic versus symptomatic subjects using MRI shows a significant prevalence of disc displacement in 25 out of 76 (33 per cent) asymptomatic subjects, as compared with 79 out of 102 (77 per cent) symptomatic subjects (Katzberg *et al*., 1996b). Therefore, subjects without any signs or symptoms of TMJ disorders mostly suffered from partial disc displacement that was not registered in the clinical examination. Mouth opening was within normal limits and palpation of the masticatory muscles was painless. As an unstable disc-condyle complex may jeopardize the success of orthodontic treatment or oral rehabilitation, MRI may help to detect moderate TMJ alterations at an early stage of internal derangement, thus identifying patients at risk. Therapeutic intervention may reduce or prevent subsequent destruction of the intra-articular structures. The most common predisposing factor for degenerative TMJ changes is a displaced meniscus. The most extensive soft and hard tissue changes have been found in subjects with anterior disc displacement without reduction (Hans *et al*., 1992; Muller-Leise *et al*., 1996). The indication for MRI evaluation of the TMJ should be extended to asymptomatic subjects with a history of limitation in mouth opening and pathologic radiographic morphology of the condyle (Katzberg *et al*., 1996a). Unilateral internal derangement is a predisposing factor for alterations on the unaffected TMJ side. The diagnostic value of unilateral imaging is reduced by the significant influence of the clicking or limited joint on the contralateral TMJ. Bilateral MRI scans are the most effective imaging technique to evaluate the presence or absence of TMJ pathology.

Conclusions

MRI facilitates demonstration of pathological signs of internal derangement of the TMJ, such as degenerative bone changes with osteophyte formation, condylar erosion, condylar dislocation, or various degrees of disc deformation and displacement. Functional disturbances of the TMJ cycle can be evaluated by means of the CINE technique, which examines motional and morphological aspects of internal TMJ derangement. CINE MRI provides additional information about disc and condyle mobility, disc reduction, and topographic changes in the disc condyle relationship between various stages of open mouth movement, compared with static MRI.

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