Dynamic Magnetic Resonance Imaging Technique for the Study of the Temporomandibular Joint

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Aims: *Echo planar imaging (EPI) is an ultrafast magnetic resonance imaging (MRI) technique that can scan a single frame in less than a second. The aim of this study was to use the EPI technique to develop a new dynamic MRI protocol for the temporomandibular joint (TMJ).* **Methods:** *Basic fast-field echo and EPI pulse sequences were used for dynamic studies of the TMJ. The subjects were instructed to perform spontaneous, continuous, slow opening/closing movements without visual or audio feedback. Different scanning parameter settings were explored to optimize the results.* **Results:** *With an opening/closing movement of approximately 6 to 7 seconds per cycle, the proposed protocol yielded a good insight into the relative motion between condyle and disc. It was also possible to see the deformation of the disc during movement.* **Conclusion:** *The EPI technique is a non-invasive technique that can be used for dynamic imaging study of a slow but continuous, uninterrupted jaw movement.*
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Key words: temporomandibular joint, echo planar imaging, magnetic resonance imaging, motion, dynamic imaging

Imaging of the temporomandibular joint (TMJ) is often performed to study the causes of internal derangement, which is most often caused by an abnormal disc-condyle relationship. Imaging techniques that can capture the dynamics of the disc-condyle relationship during motion are therefore valuable in efforts to understand the problem. At present, there are 3 imaging techniques that can be used for a dynamic analysis of the disc-condyle complex: arthrography combined with fluoroscopy,[1,2] pseudodynamic magnetic resonance imaging (MRI),[3,4] and the MRI MOVIE technique.[5,6] The advantage of arthrography is its high sampling rate, so that the motion recorded with this technique can be considered as continuous. The obvious disadvantage is the invasiveness of the procedure, given the need to use x-rays and to inject a contrast medium into the joint space, which according to a study on jaw motion does not alter the joint biomechanics to a degree that invalidates the arthrographic diagnosis.[7] The arthrographic technique has been partially replaced by MRI because the latter is not invasive.

With the pseudodynamic MRI technique,[3,4] also called CINE, a MRI series of images is scanned at different degrees of mouth opening, recorded on a storage medium, and played back continuously to provide the illusion of jaw motion.[3,4] The greater the number of opening steps imaged, the better the movement details, but the imaging time is lengthened. On the other hand, the events occurring between different steps can be lost if the opening increments are too large. It is therefore not surprising that the diagnostic value of pseudodynamic MRI has been questioned,[8] the main problem being that this procedure does not record actual movement.

Another technique is the MRI MOVIE technique.[5,6] Its basic idea is to record a series of images with a biologic signal to trigger the scans during several cycles at progressively increasing time intervals from the trigger pulses. The series of images is then replayed sequentially, as in the CINE technique. In the MRI MOVIE technique, it is assumed that all cycles recorded are identical. For example, electrocardiograph signals are used to trigger heart scans to image cardiac function.[9] This idea has also been applied to the TMJ[5,6] by the use of a pressure sensor to detect mandibular movement and to generate pulses that trigger the scans. However, the entire time needed to record 3 TMJ images is about 4 minutes—still too long to take snapshots of changes in the disc-condyle relationship.

Improvements in MRI technology allow images to be taken in a much shorter time with a satisfactory signal-to-noise ratio. The echo planar imaging (EPI) technique can reduce the scanning time to less than 1 second,[10,11] and optimally dimensioned coils can increase the signal-to-noise ratio. These ultrafast techniques are ideal for dynamic studies and have already been successfully applied to dynamic imaging of the heart,[9] vocal cords,[12] and other joints.[13] However, in most cases these ultrafast techniques have been used simply to obtain fast scans in combination with either MRI MOVIE or CINE MRI procedures, so that they did not in fact record continuous and spontaneous movements.

The goal of this study was to develop a protocol that allows us to image jaw motion continuously, thus avoiding the need to constrain the masticatory system, as with mouth-opening devices or blocks. The purpose of this technical communication is to present this new dynamic MRI technique for the study of TMJ movement.

Materials and Methods

Subjects

Magnetic resonance imaging was performed on 8 subjects (age range 19 to 50 years, 3 males and 5 females). One had a normal joint (patient 3); 3 had an anterior disc displacement with reduction (patients 1, 6, and 7); 2 had an anterior disc displacement without reduction (patients 2 and 5); 1 had an anterior disc displacement with and without reduction, ie, sometimes the mouth opening was locked (patient 8); and 1 had TMJ osteoarthrosis without pain (patient 4). The patient number corresponds to the numbering of the dynamic MRI sequences that accompany this article and are displayed on the Internet (location is indicated in the Results section).

MRI Scanning

The MRI was performed on a 1.5 Tesla MRI scanner (Philips Gyroscan NT) with a pair of 8-cm TMJ coils using an ultrafast EPI technique. The EPI technique is an accelerated procedure that is combined with standard MRI pulse sequences (such as spin echo, gradient echo, and inversion recovery) to keep the familiar tissue contrast characteristics.[11] The acceleration is achieved based on the idea of building a complete image after a single excitation of the spins instead of building only 1 line after 1 excitation, as in the conventional MRI technique.[10,11] Practically speaking, with the EPI technique the phase and frequency encoding gradients are switched rapidly after the 180-degree radiofrequency pulse within 1 single repetition time (T_R). This technique requires a very rapid switching of large gradients. Since the sampling period is reduced, the signal-to-noise ratio is reduced with respect to the standard technique.

Since the goal of this work was to record jaw movements continuously, it was necessary to develop a protocol providing a fast scanning time and to minimize motion artifacts while maintaining a signal-to-noise ratio sufficient to allow the examiner to interpret the images. The following scanning parameters provided good results in about 80% of the patients. Most of the unsatisfactory results rose either from motion artifacts that were too large or signal-to-noise ratios that were too low.

- Pulse sequences: fast-field echo (FFE) with EPI acceleration
- Repetition time (T_R): 60 ms

- Echo time: (T_E): 17 ms
- Flip angle: 20 degrees
- Field of view (FOV): 140 mm
- Rectangular FOV: 50%
- Slice thickness: 5 mm
- Scan percentage: 80%
- Scanning matrix: 128
- Reconstruction matrix: 256
- Number of signal averages (NSA): 4

With these parameters, a single scan lasts 0.5 seconds. This necessitates, of course, the execution of slow movements. Indeed, a good compromise between image quality and movement duration was obtained with opening/closing cycles of about 6 to 7 seconds. Since each scan starts immediately after the previous scan, it takes approximately 20 seconds to image 3 to 4 opening/closing cycles, with 60 images.

Experimental Recording Technique. Subjects were positioned in the conventional way in the MRI gantry and were instructed to remain still and to gently close the teeth in maximum intercuspation. The scanning session began with a preliminary axial scan (axial localizer), which determined the angulation of the long axis of the condyle. Then the scanning plane was re-oriented perpendicular to the long axis. Eventually, the subject was instructed via microphone to open and close the mouth slowly, without any visual or audio feedback.

Image Processing. All raw image data were exported to a Pentium-class personal computer and converted into single-window bitmap frames by means of self-developed software, which performed the following tasks: *(1)* extraction of the binary data for every single frame, *(2)* conversion of the 16-bit pixel values into 8-bit gray level values by linear mapping, *(3)* resizing of the images from the resolution of 256 × 256 pixels to 512 × 512 pixels through bilinear interpolation, and *(4)* insertion of the bitmap file header. The frames were converted into AVI files by means of Adobe Premiere software (Adobe Systems Inc) according to the Intel Indeo codec, which can run on any personal computer.

Results

The frames of the dynamic MRI and the corresponding static MRIs of 2 subjects are shown in Figs 1 and 2. Dynamic recordings and static images taken at maximum intercuspation of these 2 patients (described below), as well as those of the 6 other subjects, can be accessed in the "What's New" section at the following World Wide Web address: http://www.quintpub.com. They can be played back on a personal computer with Microsoft Internet Explorer.

Patient 1

Figures 1a to 1c show 3 contiguous sagittal static images of a TMJ of a 25-year-old patient with loud clicking in the late stage of mouth opening, taken at maximum intercuspation. The completely anteriorly displaced disc is visible. The 14 single frames of an open/close movement of 7 seconds are shown in Figs 1d to 1q and represent a typical dynamic MRI sequence. The quality of the single images is not as good as that of the static images, not only because of the lower signal-to-noise ratio but also because of motion artifacts. However, they are of sufficient quality to view both the changes in the disc position relative to the condyle and the disc deformation during opening. The anteriorly displaced disc is pushed past the tubercle, where it bends into a U form. Then the disc-condyle relationship is reduced, while the bent disc returns to its normal shape.

Patient 2

Figures 2a to 2c show 3 contiguous sagittal static images of a TMJ of a 22-year-old female patient with an anterior disc displacement without reduction. Figures 2d to 2r show a series of frames of an opening/closing cycle in which the movement of the disc can be seen.

Discussion

The ideal imaging technique for dynamic studies of the disc-condyle relationship should: *(1)* be noninvasive, *(2)* have a high sampling rate, *(3)* yield images with a high signal-to-noise ratio, *(4)* be easy to perform, and *(5)* allow spontaneous movements to be recorded. It is clear that none of the techniques available today can meet all these requirements. The main disadvantage of the presented EPI protocol is the low sampling rate, which requires slow movements. In addition, the signal-to-noise ratio is far lower than optimal.

Similar to static MRI, a compromise should always be obtained between spatial resolution, signal intensity, and scanning time. For dynamic imaging, the scanning time must be short; therefore, the compromise must be on the other 2 factors.

Figs 1a to 1c Static MRI of patient 1.

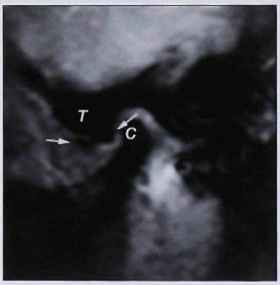


Fig 1d

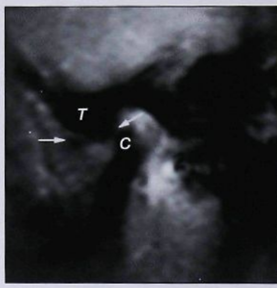


Fig 1e

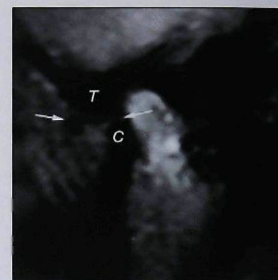


Fig 1f

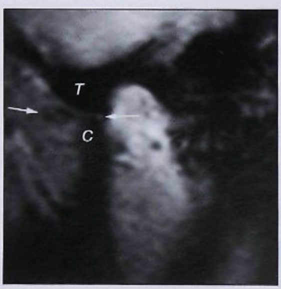


Fig 1g

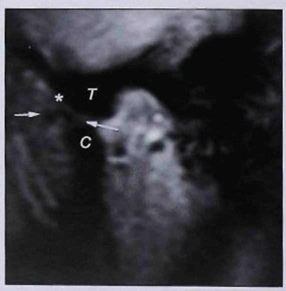


Fig 1h

Figs 1d to 1q Dynamic MRI sequence of patient 1. The arrows indicate the anterior and posterior border of the disc; an asterisk marks the image with the bent disc. C = condyle; T = tubercle.

Unfortunately, the small size of the TMJ makes these compromises more critical. The following strategies were used to reduce the scanning time. A short T_R of 60 ms and a small flip angle of 20 degrees were used to shorten the FFE protocol established for static recordings. A further reduction in scanning time of 50% was obtained by the use of a scanning matrix of 128 lines instead of 256 lines. Figure 3 shows one of the 20 images taken during an extremely slow opening/closing movement, which lasted 24 seconds. This is the best echo planar image obtained so far, but it was obtained with a scanning time of about 1.3 seconds per frame, which is far too long for a dynamic study.

To further lower the scanning time, the horizontal FOV was reduced by 50%, thus producing a

Fig 1i

Fig 1j

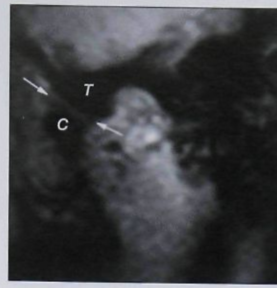


Fig 1k

Fig 1l

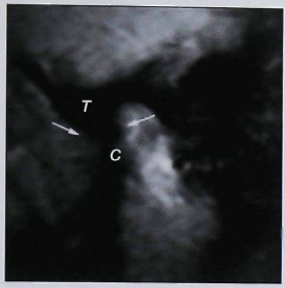


Fig 1m

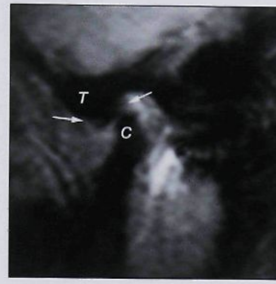


Fig 1n

Fig 1o

Fig 1p

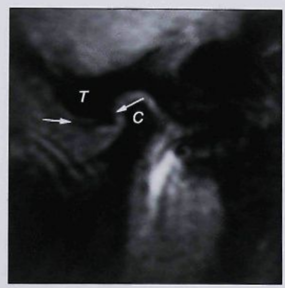


Fig 1q

rectangular image instead of a square image, and the scan percentage was set to 80%. The first approach can halve the scanning time, and the second approach can reduce it by a further 20%. Thus, the scanning time was shortened by a total of 60%. Figure 4 shows an image scanned with this protocol during a relatively slow opening/closing movement lasting 10 seconds. The scanning time of approximately 0.5 seconds allowed us to take 20 images during the whole cycle. Note that the image is rectangular (50% FOV) and that motion artifacts do not hinder interpretation of the image.

Theoretically, the signal-to-noise ratio is decreased by a factor inversely proportional to the square root of the FOV reduction, in this case by

Figs 2a to 2c Static MRI of patient 2.

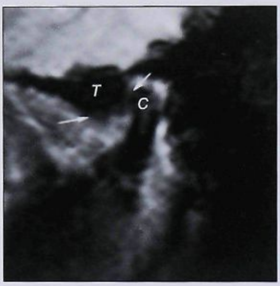


Fig 2d

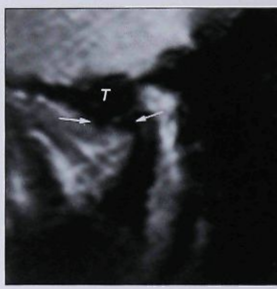


Fig 2e

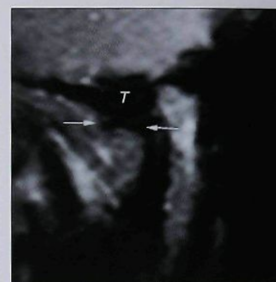


Fig 2f

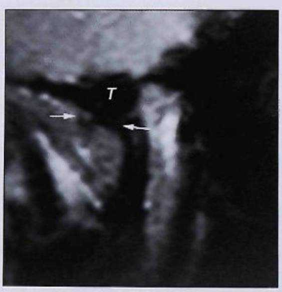


Fig 2g

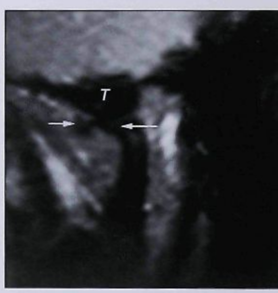


Fig 2h

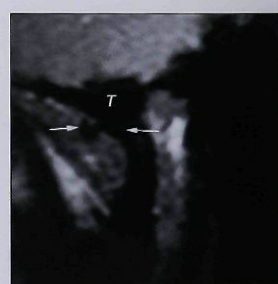


Fig 2i

Figs 2d to 2r Dynamic MRI sequence of patient 2. The arrows indicate the anterior and posterior border of the disc. C = condyle; T = tubercle.

Fig 2j

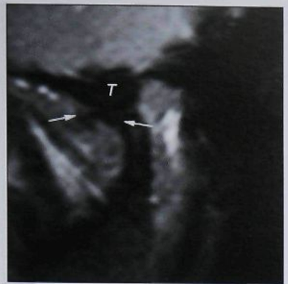


Fig 2k

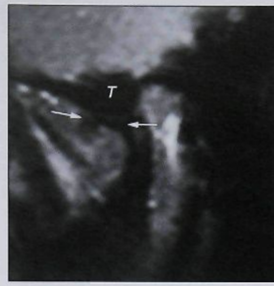


Fig 2l

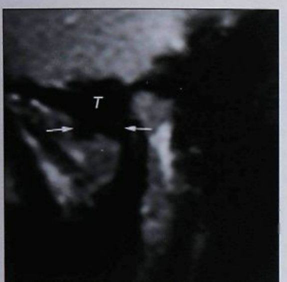


Fig 2m

Fig 2n

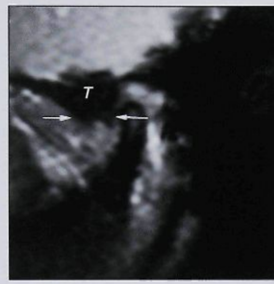


Fig 2o

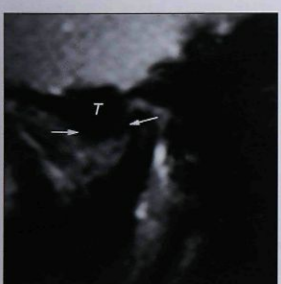


Fig 2p

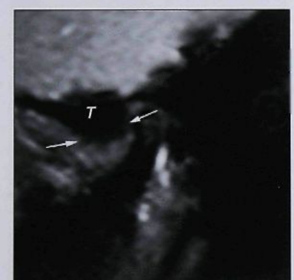


Fig 2q

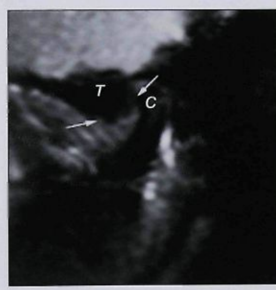


Fig 2r

the square root of 2. This effect can be seen in Fig 4, which has higher noise than Fig 3. To counteract this, we selected a thicker slice (5 mm) and 4 excitations (NSA). Obviously, an increased slice thickness enhances the partial volume effects, thus reducing the spatial resolution. An NSA of 4 means that a volume element is scanned 4 times and that these 4 signals are averaged to determine its intensity with lower noise, since noise occurs randomly. However, this approach not only increases the scanning time but also increases the motion artifacts, because the positions of the condyle are not identical during these 4 excitation periods. Another method of increasing the signal-to-noise ratio is to enlarge the FOV while keeping the same number of pixels; however, because of the small size of the TMJ, this strategy would have blurred the anatomic details.

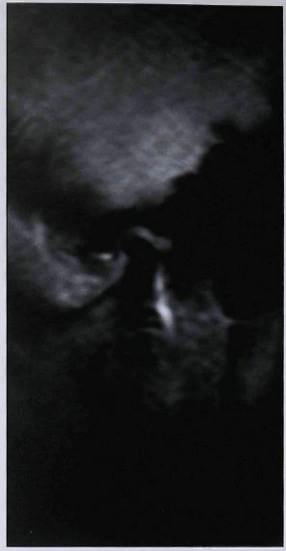
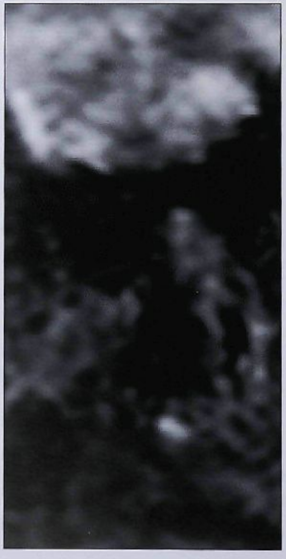


Fig 3 *(Left)* Example of an image taken during a very slow opening movement of a TMJ with an anteriorly displaced disc. Scanning time was about 1.2 seconds. Because of the low noise level, the details are well defined.

Fig 4 *(Right)* Image obtained with a scanning time of 0.5 seconds and a rectangular field of vision. The noise level is higher than that of the image shown in Fig 3, but the motion artifact is negligible.



Figs 5a and 5b Images scanned with the quickest protocol tried so far (scanning time of 0.16 seconds per frame). *(Left)* Already the quasi-static image has a low signal-to-noise ratio, so that the anatomic details are hardly recognizable. *(Right)* Figure 5b was scanned during a movement performed at normal speed. The motion artifact is so pronounced that no anatomic detail can be seen.

The speed limits for dynamic studies of the TMJ have been investigated intensively in this work. The fastest protocol used so far produced an image in 0.16 seconds and allowed the subject to open and close at a normal pace. The protocol used the following parameters: FOV = 70 mm, T_R = 20 ms, T_E = 17 ms, 50% rectangular FOV, 80% scan percentage, scanning matrix = 64, reconstruction matrix = 128, and NSA = 3. Figure 5a shows a static image and Fig 5b shows an image taken during motion. Both scans are of poor quality because of the low signal-to-noise ratio, and Fig 5b is almost unintelligible because of the large motion artifact.

The dynamic MRI scanning technique presented certainly opens up exciting new perspectives, such as the ability to observe the deformation of the disc. However, in addition to the main limitation, ie, the impossibility of recording movements at normal velocity, some other limitations must be pointed out. Dynamic MRI provides information in only 1 arbitrarily determined section and therefore does not allow for the study of events that occur in the medial and lateral part of the joint. This, in addition to the coarse resolution of this technique, does not allow precise 3-dimensional measurements within the TMJ, as is possible with dynamic sterometry.[14]

The protocol proposed in this paper with a scanning time of 0.5 seconds yielded the best result so far. The sampling rate is still too low to study masticatory movements. However, if the patient is able to perform slow movements, this technique is a useful imaging alternative. The protocol proposed here has never been used on different machines, and since different MRI scanners have different hardware configurations, it might need some modifications when used on other MRI scanners. Furthermore, the EPI technique is very sensitive to magnetic susceptibility, ie, it requires highly homogenous magnetic fields. It is possible that the instantaneous conditions in the MRI scanner or some other unknown factors might affect the homogeneity of the electromagnetic field, leading to unpredictable results.

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