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Cervical Spondylosis: Three-dimensional Gradient-Echo MR with Magnetization Transfer

Elias R. Melhem, Mark L. Benson, Norman J. Beauchamp, and Roland R. Lee

PURPOSE: To compare a three-dimensional Fourier transform (3DFT) gradient-echo pulse sequence with magnetization transfer at a short echo time against standard 3DFT gradient-echo technique in the evaluation of cervical spondylosis, specifically addressing the effects of motion and susceptibility artifacts on the dimensions of the neural foramina and contrast at the cerebrospinal fluid (CSF)–spinal cord interface. **METHODS:** Ten patients with clinically suspected cervical spondylosis were examined with axial MR imaging using both our standard 3DFT gradient-echo sequence and a 3DFT gradient-echo sequence with a short echo time plus magnetization transfer. Two neuroradiologists measured the transverse dimensions of 22 diseased neural foramina and graded the contrast at the CSF–spinal cord interface. **RESULTS:** Sixteen of 22 affected neural foramina were larger in the transverse dimension when the magnetization transfer technique was used than when the standard 3DFT gradient-echo sequence was used. In 9 of 10 patients superior contrast was seen at the CSF–spinal cord interface on images obtained with the magnetization transfer technique. **CONCLUSIONS:** In the cervical spine, 3DFT gradient-echo imaging with magnetization transfer improves contrast and sharpness of the CSF–spinal cord interface at short echo times. This results in less exaggeration of the neural foraminal stenosis as compared with that seen with standard 3DFT gradient-echo techniques owing to the diminished effects of motion and susceptibility artifacts.

Index terms: Magnetic resonance, magnetization transfer; Spine, inflammation; Spine, magnetic resonance

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Low-flip-angle three-dimensional Fourier transform (3DFT) gradient-echo magnetic resonance (MR) imaging is currently the preferred MR imaging technique for evaluation of degenerative cervical spine disease owing to its improved spatial resolution and signal-to-noise ratio as well as its decreased intersection cross-talk and volume averaging effects as compared with two-dimensional Fourier transform (2DFT) gradient-echo MR imaging (1). However, 3DFT gradient-echo MR imaging has shown signifi-

cant sensitivity both to susceptibility artifacts, which are inherent in gradient-echo imaging techniques, and to motion and aliasing artifacts, which result from implementation of an extra phase-encoding gradient along the section-select direction (2). These artifacts have been shown to have a detrimental effect on image quality, sharpness, and contrast of the cerebrospinal fluid (CSF)–spinal cord interface (myelographic effect), and on the dimensions of the neural foramina (2, 3).

The purpose of this study was to compare a 3DFT gradient-echo pulse sequence with magnetization transfer against our standard 3DFT gradient-echo technique in the evaluation of cervical spondylosis.

Subjects and Methods

Using a 1.5-T superconductive MR magnet and a phased-array surface coil, we examined the cervical spines of two healthy volunteers using axial 3DFT gra-

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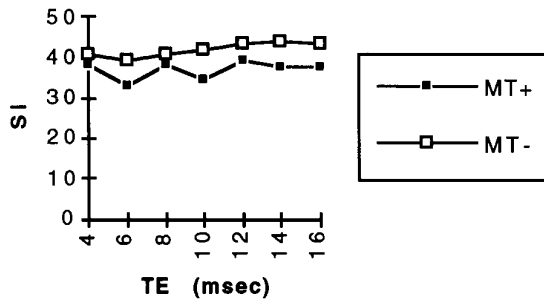
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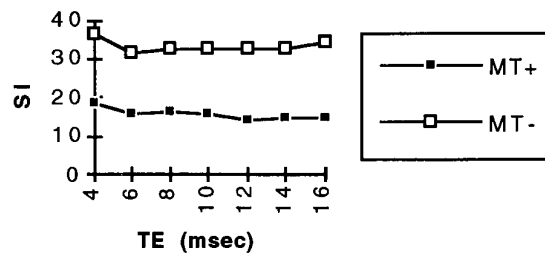
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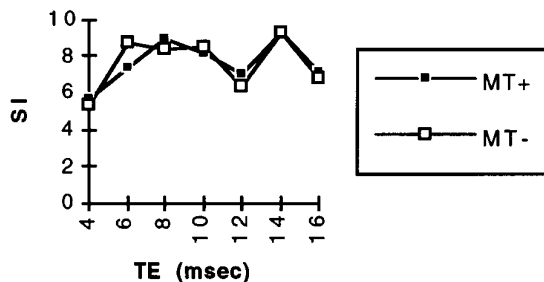
3DFT GRE [SI (CSF) vs TE]



3DFT GRE [SI (cord) vs TE]



3DFT GRE [SI (bone) vs TE]



3DFT GRE [SI (disk) vs TE]

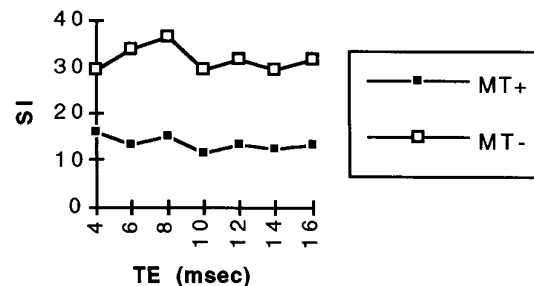


Fig 1. Plots of signal intensity (SI) of CSF, spinal cord, bone, and disk versus TE using the 3DFT gradient-echo (GRE) (repetition time = 40, flip angle = 5°) technique with and without magnetization transfer (MT) for imaging a healthy volunteer. Note the similarity in SIs of CSF and cortical bone for both techniques at various TEs and the appreciable drop in SIs of spinal cord and disk with the MT technique.

dient-echo sequences with and without magnetization transfer (average repetition time [TR] = 40, flip angle = 5°, number of excitations = 1, matrix = 128 × 256 × 32, field of view = 24 cm, bandwidth = ±16 kHz, section thickness = 1.5 mm) while varying the echo time (TE) from 4 to 16 milliseconds by increments of 2 milliseconds. Flow-compensation gradients were not applied in order to maintain consistency within and between the two methods, especially since these gradients could not be applied at short TE values. The transmitter and receiver gains were set to the same values during the scanning procedures. Signal intensities of a region of interest (3 mm³) in the CSF, spinal cord, disk, and cortical bone were determined for each TE (Figs 1 and 2) and compared for both techniques.

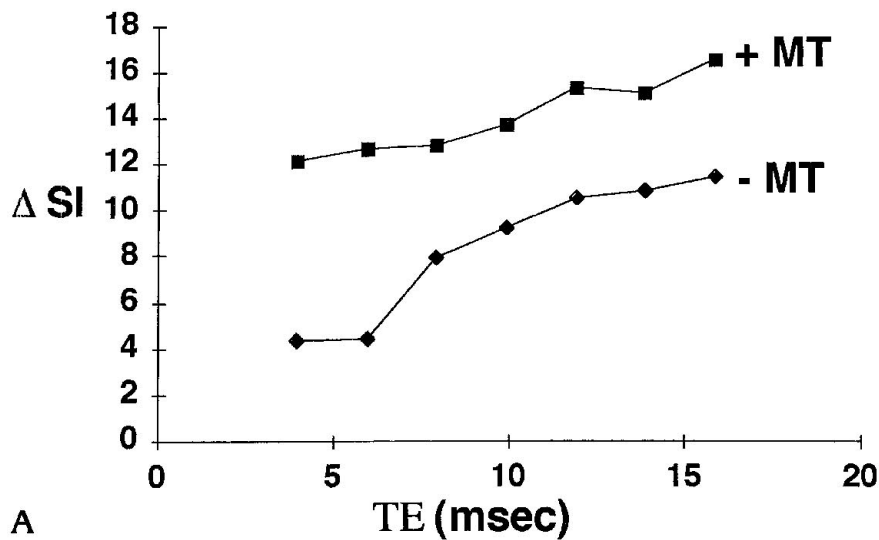
Ten patients with clinically suspected spondylosis of the cervical spine were examined prospectively in the axial plane using both the 3DFT gradient-echo sequence with magnetization transfer at parameters of 39/6 (TR/TE) and 5° flip angle, determined from imaging the healthy volunteers, and the standard 3DFT gradient-echo sequence at parameters of 35/15, 5°, keeping constant the field of view at 24 cm, the matrix at 128 × 256 × 64, the number of excitations at 1, the bandwidth at ±16 kHz, and the section thickness at 1.5 mm. Flow-compensation gradients were applied to the latter technique, and the order of the two

techniques was alternated. The magnetization transfer pulse consisted of a 0.5 cycle sinc-shaped pulse with a 14-millisecond duration (42% duty cycle), 180-Hz bandwidth, and a 90° flip angle. The pulse was applied at a frequency 1.2 kHz below water resonance.

A staff neuroradiologist identified 22 diseased neural foramina and two other staff neuroradiologists independently measured the narrowest dimension at the midtransverse level of the affected neural foramina. The contrast and sharpness of the CSF-cord interface at every level of the 10 imaged cervical spines were evaluated and the lowest representative grade was recorded based on a previously established scale as follows: 1 = CSF isointense with and indistinguishable from cord, 2 = CSF slightly hyperintense relative to cord, 3 = high-signal CSF with indistinct cord contour, 4 = high-signal CSF and sharply defined cord margin (4).

Results

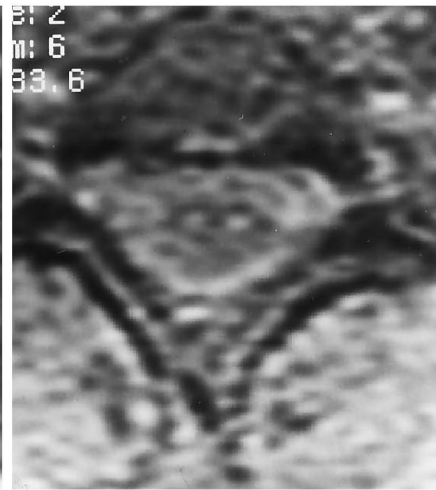
When the plots of signal intensity were compared with the TEs for the two techniques (Fig 1), the following three observations were made: The signal intensities of CSF, spinal cord, disk, and cortical bone did not vary



A



B



C

Fig 2. A, Plot of CSF-cord contrast (ΔSI) versus TE with and without magnetization transfer (MT). Note that the CSF-cord contrast (ΔSI) with the MT technique at a short TE (4 milliseconds [msec]) is greater than the maximum CSF-cord contrast (ΔSI) with the standard 3DFT gradient-echo technique at all the evaluated TEs (4 to 16 milliseconds).

B and C, Axial 1.5-mm-thick MR images obtained at the same level in a healthy volunteer using the 3DFT gradient-echo technique with magnetization transfer (TE = 4) (B), and without magnetization transfer (TE = 4) (C). Note that the image obtained with the magnetization transfer pulse (B) has superior contrast at the CSF-cord interface.

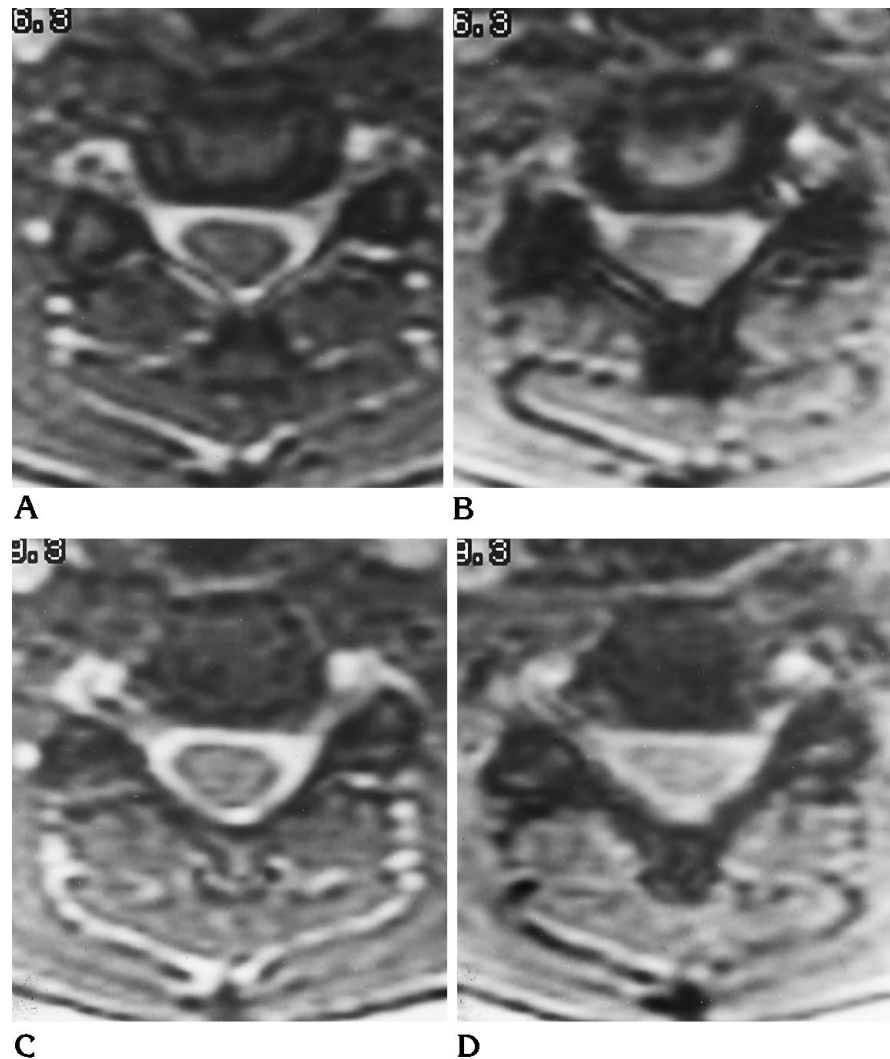
significantly with increases in TE for either method; the signal intensities of CSF and cortical bone were similar for both techniques; and there was an appreciable drop in the signal intensities of the spinal cord and disk on the 3DFT gradient-echo technique using magnetization transfer as compared with the standard 3DFT gradient-echo sequence. Thus, the difference in signal intensity (12.0) between the CSF and spinal cord seen when using the magnetization transfer technique at the shortest TE (4 milliseconds) was greater than the maximum difference in signal intensity (10.0) seen when using the standard 3DFT gradient-echo technique at all the applied TEs (4 to 16 milliseconds) (Fig 2).

Wilcoxon's signed rank test showed a statistically significant difference in the measured transverse dimensions of the affected

neural foramina ($P < .01$) between the two methods, with a good level of agreement between the two observers ($\kappa = .50$) (5). Sixteen of the 22 affected neural foramina were larger in transverse dimension (Fig 3), 5 were equal in transverse dimension, and only 1 was smaller in transverse dimension (according to one observer) on images obtained with the magnetization transfer technique. In the latter group, one patient moved during the examination.

The lowest assigned grade to the contrast and sharpness of the CSF-spinal cord interface was higher with the 3DFT gradient-echo magnetization transfer technique than with the 3DFT gradient-echo sequence without magnetization transfer in 9 of 10 patients. The difference was most pronounced at levels with moderate to severe spinal stenosis (Figs 4 and 5).

Fig 3. Pairs of 1.5-mm-thick axial MR images were obtained from two patients (A and B; C and D). Images were obtained at the same level in the same patient, with the 3DFT gradient-echo (TR = 40, flip angle = 5°) technique with magnetization transfer at TE = 6 (A and C) and without magnetization transfer at TE = 15 (B and D). The neural foramen appears larger in transverse dimension on the magnetization transfer short-TE images (A and C) than on the images obtained without magnetization transfer (B and D) owing to a decrease in diamagnetic susceptibility artifacts at the bone-soft tissue interface.



Discussion

Axial 3-D gradient-echo MR imaging at variable flip angles has been shown to be superior to standard spin-echo and 2DFT gradient-echo techniques in the evaluation of spondylotic changes in the cervical spine (1, 6). It has also been shown to approximate the accuracy of thin-section computed tomographic myelography (the standard of reference) in detecting and determining the cause of neural foraminal narrowing, especially at low flip angles (7).

Initial trials with large flip angles and short TRs in the steady state failed to produce the expected myelographic effect (signal intensity $\propto T2/T1$) needed for effective evaluation of the cervical spine (8). This was attributed to disruption of the steady state and to saturation effects related to the pulsatile motion of CSF (Fram EK, Karis JP, Evans A, et al, "Fast Imaging of

CSF: The Effect of CSF Motion," *Proceedings of the Annual Meeting of the Society of Magnetic Resonance in Medicine, New York, August 1987*, 314 [abstract]). An optimal myelographic effect has been achieved with the use of small flip angles (5°) in 3DFT gradient-echo imaging, which renders the difference in signal intensity between CSF and adjacent soft tissue dependent on T2* differences and nearly independent of steady-state effects. These T2* differences are exaggerated by increases in TE. Furthermore, the need for flow-compensation gradients to reduce CSF signal dephasing caused by in-plane and out-of-plane motion has necessitated additional increases in TE in order to achieve an adequate myelographic effect (2).

The relatively long TE (15 milliseconds) and the extra phase-encoding gradient (along the section-select direction) used in axial 3DFT

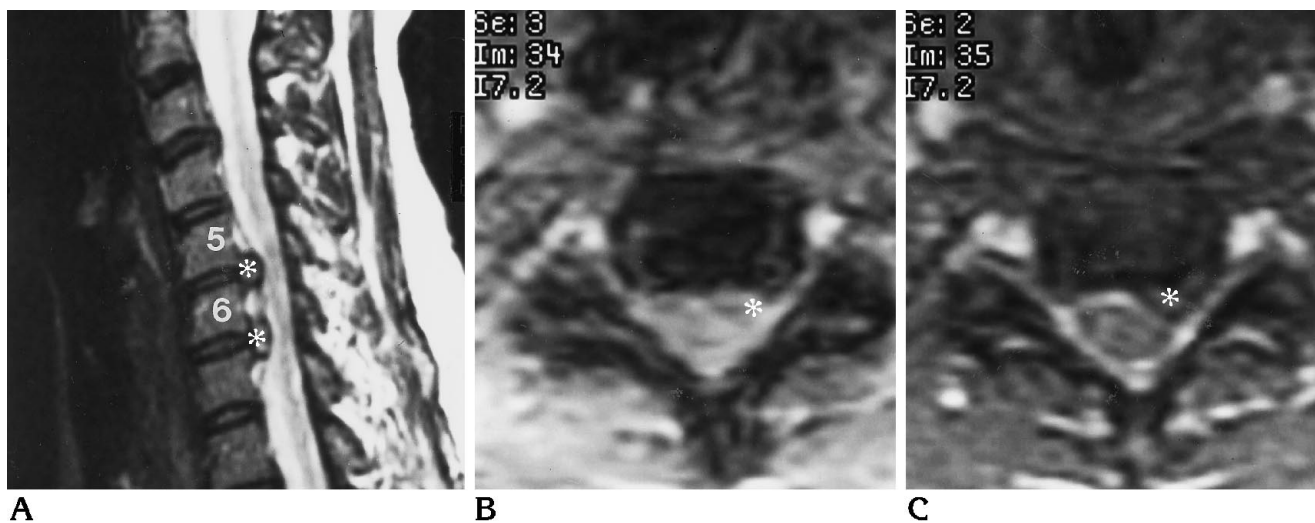


Fig 4. A, Left parasagittal 2DFT T2-weighted fast spin-echo MR image of the cervical spine shows a moderate-size left paracentral disk herniation at the C5-6 and C6-7 levels with posterior displacement of the posterior longitudinal ligament. B and C, Axial MR images 1.5 mm thick at the C5-6 level in the same patient obtained with the 3DFT gradient-echo technique (40/15, 5°) (B) and with the 3DFT gradient-echo plus magnetization transfer technique (40/6, 5°) (C). In C, there is significant improvement in the definition of the herniated disk, the posterior longitudinal ligament, and the CSF-cord interface.

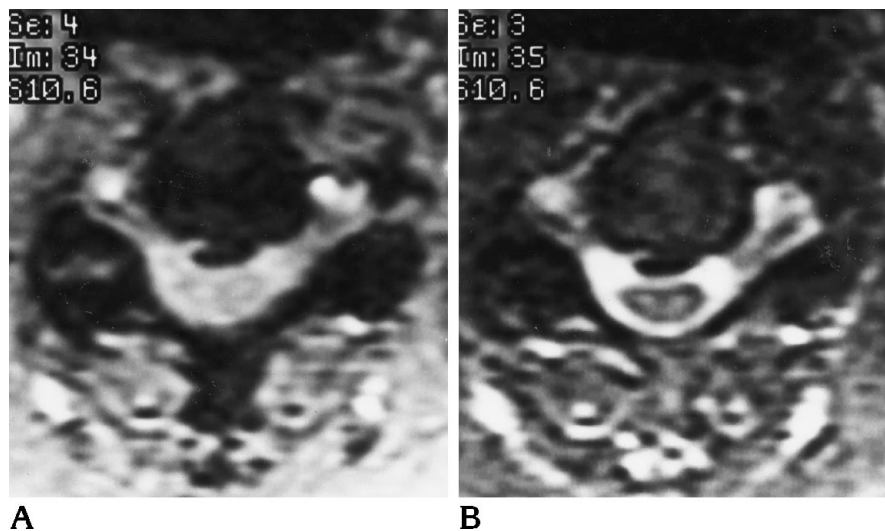


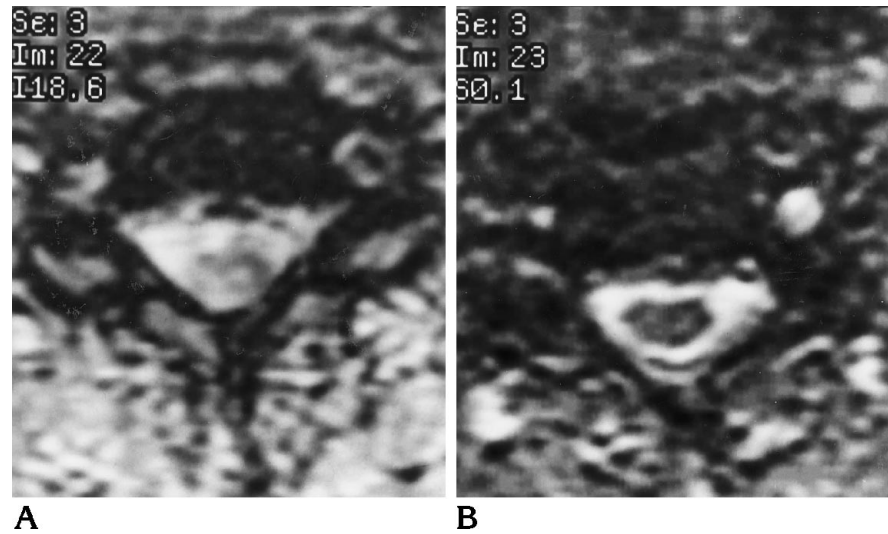
Fig 5. Another example of definite improvement in the contrast and sharpness of the CSF-cord interface, in a patient with moderate spinal canal stenosis caused by a spondylotic bar, when using the 3DFT gradient-echo plus magnetization transfer technique (40/6, 5°) (B) as compared with the 3DFT gradient-echo technique without magnetization transfer (40/15, 5°) (A).

gradient-echo MR imaging of the cervical spine has made this technique sensitive to motion and susceptibility artifacts. Motion artifacts in MR imaging of the cervical spine may be created when the patient moves, breathes, or swallows, or they may result from pulsatile CSF and cardiovascular flow. Several approaches and methods have been devised to suppress these sources of motion and their effects on MR imaging of the cervical spine. These include physical restraint, respiratory and cardiac gating, prevertebral saturation pulses, and gradient-moment nulling (9, 10). Despite these methods, anticipated patient movement during the exam-

ination is considered by some a relative contraindication to the use of 3-D techniques for the evaluation of cervical spondylosis (2).

We have been able to improve the contrast between CSF and soft tissue (the myelographic effect) at short TEs (4 to 6 milliseconds) by selectively suppressing the signal from soft tissue with the use of magnetization transfer (11). This is achieved by saturating a pool of macromolecule-bound protons that are in equilibrium with water molecules (free proton pool), presumably by means of dipolar cross-coupling and chemical exchange interaction (12). The extremely short T2 (less than 1 millisecond) of

Fig 6. Axial MR images 1.5 mm thick obtained in an uncooperative patient show preservation of the contrast and sharpness of the CSF–cord interface when using the 3DFT gradient-echo plus magnetization transfer technique (40/6, 5°) (B) as compared with the 3DFT gradient-echo technique without magnetization transfer (40/15, 5°) (A), despite patient motion during the examination.



the macromolecular pool imparts a broad MR spectral density (linewidth) to the bound protons. This is in contrast to the very narrow linewidth of free protons. The application of an off-resonance radio frequency pulse enables us to saturate selectively the bound protons and monitor the indirect effect on the free proton pool via the equilibrium state (13).

The insensitivity of the signal intensities of CSF and cortical bone to the magnetization transfer effects at the evaluated TE range is caused by a lack of macromolecules in the CSF and by a lack of free protons in cortical bone. The selective saturation of the soft tissue adjacent to the CSF is well seen in Figure 1. This resulted in an improvement of CSF–spinal cord contrast in our healthy volunteers by an average factor of 2.0 as compared with the technique in which magnetization transfer was not used. This marked increase in CSF–spinal cord contrast caused by the magnetization transfer pulse has decreased the reliance on T2* contrast to enhance the myelographic effect and has made the effects of motion artifacts (especially CSF pulsatile motion) on image contrast less visible (Figs 4 and 5). Moreover, the magnetization transfer pulse may have a direct CSF flow-compensatory effect. Note, however, despite the reduction in the signal intensity of the disk caused by the magnetization transfer effect, there continues to be an appreciable difference in signal intensity (although not as great as for the standard gradient-echo technique) between disk and cortical bone, thus maintaining our ability to differentiate between the two as an underlying

cause for spinal and neural foraminal narrowing in cervical spondylosis.

The advantages of being able to use short TEs with the new techniques and still maintain good myelographic effect are obvious. The decreased sensitivity to motion artifacts (Fig 6) obviated the use of prevertebral saturation pulses and flow-compensation gradients in imaging our study group while improving contrast and sharpness at the CSF–spinal cord interface. Unlike with the use of standard 3DFT gradient-echo techniques, the CSF–cord contrast is maintained in regions of moderate to severe spinal stenosis with the magnetization transfer technique (Figs 4 and 5) despite decreased amounts of CSF surrounding the cord, loss of flow-related enhancement, and excessive dephasing due to acceleration and jerky flow of CSF (4).

It has been suggested that diamagnetic susceptibility effects at the bone–CSF and bone–neural foramina interfaces overestimate spinal and neural foraminal narrowing (2, 3). These effects are exacerbated by superimposed motion (2). In our prospective analysis of the 10 patients with suspected cervical spondylosis, we attributed the statistically significant differences in the dimensions of the examined neural foramina noted between the two techniques to differences in the respective TEs. In only one patient was the dimension of the neural foramina smaller on images obtained with the magnetization transfer technique, and this is may have been caused by excessive patient motion during the examination.

Recent work by Finelli et al (14) evaluated the effect of variations in magnetization transfer power and section-select flip angles on 2DFT gradient-echo imaging of the cervical spine. These authors reported an ability to increase the flip angle in 2DFT gradient-echo imaging to approximate the Ernst angle of CSF while maintaining the spinal cord-CSF contrast by using a magnetization transfer pulse. Also, they reported a 2.2- to 2.4-fold increase on 2DFT gradient-echo images and a 1.4-fold increase on 3DFT gradient-echo images in the spinal cord-CSF contrast-to-noise ratio as compared with conventional gradient-echo techniques. However, the possibility of trading the improved contrast achieved by the magnetization transfer pulse for shorter TEs was not evaluated. We prospectively demonstrated the advantages of short TEs in the examination of neural foramina.

Finally, other MR imaging techniques have been developed that achieved an adequate myelographic effect at large flip angles (40°) and short TEs (7 milliseconds) by allowing, with the use of special gradient structuring, the transverse equilibrium to be maintained in the presence of motion (8, 15). However, these techniques have proved to be very sensitive to local field inhomogeneities.

In conclusion, we propose combining the advantages of 3-D imaging at short TEs achieved by selective magnetization transfer effects on soft tissues of the cervical spine. This technique produces less exaggeration of neural foramina narrowing and improved CSF-cord contrast as well as reduced sensitivity to motion and susceptibility artifacts, making it useful in evaluating cervical spondylosis in patients in whom movement is anticipated and in those who have had previous cervical spine surgery.

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