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Spinal Cord Lesions in Patients with Multiple Sclerosis: Comparison of MR Pulse Sequences

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PURPOSE: To compare T2-weighted conventional spin-echo (CSE), fast spin-echo (FSE), short-tau inversion recovery (STIR) FSE, and fluid-attenuated inversion recovery (FLAIR) FSE sequences in the assessment of cervical multiple sclerosis plaques. **METHODS:** Twenty patients with clinically confirmed multiple sclerosis and signs of cervical cord involvement were examined on a 1.5-T MR system. Sagittal images of T2-weighted and proton density–weighted CSE sequences, T2-weighted FSE sequences with two different sets of sequence parameters, STIR-FSE sequences, and FLAIR-FSE sequences were compared by two independent observers. In addition, contrast-to-noise measurements were obtained. **RESULTS:** Spinal multiple sclerosis plaques were seen best on STIR-FSE images, which yielded the highest lesion contrast. Among the T2-weighted sequences, the FSE technique provided better image quality than did the CSE technique, but lesion visibility was improved only with a repetition time/echo time of 2500/90; parameters of 3000/150 provided poor lesion contrast but the best myelographic effect and overall image quality. CSE images were degraded by prominent image noise; FLAIR-FSE images showed poor lesion contrast and strong cerebrospinal fluid pulsation artifacts. **CONCLUSIONS:** The STIR-FSE sequence is the best choice for assessment of spinal multiple sclerosis plaques. For T2-weighted FSE sequences, shorter echo times are advantageous for spinal cord imaging, long echo times are superior for extramedullary and extradural disease. FLAIR-FSE sequences do not contribute much to spinal imaging for multiple sclerosis detection.

Index terms: Sclerosis, multiple; Spinal cord, magnetic resonance; Magnetic resonance, comparative studies

Isolated spinal cord involvement occurs in 15% to 20% of patients with multiple sclerosis (1). Magnetic resonance (MR) imaging has proved to be the method of choice for depicting these lesions (2–4). With standard T2-weighted conventional spin-echo (CSE) sequences, however, intrinsic plaques can be detected in only about 50% to 60% of multiple sclerosis patients who have clinical findings that are highly suggestive of spinal cord lesions (2, 5). Recent hardware and software developments, such as multiarray coils and fast spin-echo (FSE) sequences, have improved the quality of spinal MR images (6) and might also be advantageous for depicting multiple sclerosis plaques. However, the FSE technique offers a number of additional sequence parameters that influence image contrast, and the diagnostic efficacy of FSE sequences is therefore still subject to scientific investigation. Moreover, short-tau inversion recovery (STIR) sequences and fluid-attenuated inversion recovery (FLAIR) sequences have also been introduced for MR imaging of the spinal cord (5, 7, 8) and have been reported to improve the diagnostic efficacy of this technique. FLAIR and STIR sequences can also benefit from the FSE technique (9, 10). Thus, a number of imaging techniques are available for spinal cord imaging and for the assessment of multiple sclerosis plaques in particular. The purpose of this study was to compare the diagnostic efficacy of T2-weighted FSE, STIR-FSE, and FLAIR-FSE sequences in the assessment of cervical multiple sclerosis plaques and to com-

pare these imaging techniques with a double-echo CSE sequence.

Subjects and Methods

Twenty patients (11 women and nine men; 22 to 55 years old; mean age, 33 years) with clinically confirmed multiple sclerosis and signs of cervical cord involvement were examined with MR imaging. Thirteen patients had a relapse-remission disease course, two patients had a primary progressive disease course, and five patients had a secondary progressive course. The expanded disability status scale ranged from 1.5 to 7.5 (mean, 3.5).

MR examinations were performed on a 1.5-T superconducting system using a multiarray spine coil. T2-weighted and proton density–weighted double-echo CSE sequences, T2-weighted FSE sequences with two different sets of sequence parameters, a STIR-FSE sequence, and a FLAIR-FSE sequence were obtained. The order of the sequences was randomized for each patient. For sequence comparison, only sagittal images with a field of view of 230 mm and a matrix size of 256 × 204 were obtained. Because a section thickness of 3 mm (which we use for routine cervical FSE imaging) resulted in unacceptably high levels of image noise on T2-weighted CSE images, 4-mm-thick sections with a 10% intersection gap were used for this study. This increases partial volume artifacts but does not inhibit sequence comparison. The phase-encoding direction was anterior to posterior for the CSE sequence and feet to head for all FSE sequences. Presaturation pulses outside the field of view perpendicular to the phase-encoding direction and oversampling were used to minimize ghosting and fold-over artifacts. The anteroposterior phase-encoding direction was chosen for CSE sequences to curb fold-over artifacts that would have occurred with a single excitation and the feet-to-head phase-encoding direction. With a rectangular field of view, which is suited for the anteroposterior phase-encoding direction only, a second signal average was reasonable. For CSE sequences, a 60% rectangular field of view with a second excitation was used and provided a slightly higher signal-to-noise ratio than a quadratic field of view with only a single excitation. For proton density–weighted and T2-weighted CSE sequences, the well-established parameters of 2500/15,90/1 (repetition time[TR]/echo time [TE]/excitations) were used.

Sequence parameters for all FSE sequences were optimized in preliminary trials according to the results of previous publications and our own experience, as described below. The FSE technique offers a number of additional sequence parameters that influence image contrast, as detailed for T2-weighted FSE sequences (11). In our study, the initial T2-weighted FSE sequence was obtained with parameters that minimized contrast differences relative to the T2-weighted CSE sequence so that we could evaluate the effects of the FSE technique only. Image blurring has been observed for T2-weighted FSE sequences with a long echo train length and short TEs (11)

but this was not significant with echo trains shorter than 8. Thus, to resemble T2-weighted CSE contrast, an echo train length of 8 was used and TR/effective TE was adjusted to 2500/90. Conversely, longer TEs and longer echo trains have been advocated for FSE imaging of the cervical spine in a previous report (11). An optimization of sequence parameters along the suggestions of this publication led to a second T2-weighted FSE sequence with a TE of 150 and an echo train length of 24. This second T2-weighted FSE sequence is routinely used in our institution for evaluating degenerative disk disease. Corresponding to the TRs that were used, the first T2-weighted FSE sequence was termed *FSE-2500* and the second *FSE-3000*.

The STIR-FSE sequence was altered for spinal cord imaging by slightly increasing the effective TE to 50 and reducing the inversion time to 110. The longer effective TE increases T2 contrast relative to shorter TEs that are commonly used for musculoskeletal STIR imaging. The shorter inversion time reduces scan time because of a shorter dead time during the inversion time interval. A shorter inversion time also reduces fat suppression, but this is undesirable for cord imaging. The synergistic effects of long T1 and T2 relaxation that yield a high lesion contrast on STIR images are preserved with short inversion times (12). An asymmetric incomplete k-space sampling (one echo collected before the effective TE and six echoes collected thereafter), an echo train length of 8, and six signal averages were found to provide good overall image quality for STIR-FSE images in preliminary trials.

We did not find many reports in the literature about sequence parameter optimization of FLAIR-FSE sequences (10). The sequence parameters for the FLAIR-FSE sequence used for this study were determined as follows: For the suppression of the cerebrospinal fluid signal, an inversion time of 2000 yielded the best results. The long dead time during the inversion time interval increases scan time and must be compensated by a long echo train that can be used only with a long effective TE. Conversely, in our experience with FLAIR-FSE imaging of the brain, very long values for effective TE (of 150 or more) might reduce the contrast of some type of lesions. In preliminary trials, the best results in terms of overall image quality, lesion detectability, and scan time were provided by an effective TE of 120, which enabled an echo train as long as 18 and thus three excitations within a reasonable scan time. This set of sequence parameters for FLAIR-FSE is used for routine spinal imaging in our institution and was also used for this study. The individual sequence parameters and the scan times of all sequences used are listed in Table 1.

Technicians were advised to use a window setting that provided optimal visibility of the spinal cord lesion and to adjust the contrast of the individual sequences as much as possible. The individual sets of images were then assessed side by side independently by two experienced neuroradiologists. Since contrast differences were obvious, the interpreters could not be completely blinded to the type of sequence. In two patients, a previous MR examination

TABLE 1: MR sequence parameters compared

	Proton Density–Weighted CSE	T2-Weighted CSE	T2-Weighted FSE-2500	T2-Weighted FSE-3000	STIR-FSE	FLAIR-FSE
TR	2500	2500	2500	3000	2165	6000
TE (effective)	15	90	90	150	50	120
Inversion time	. . .	. . .	. . .	. . .	110	2000
Echo train length	. . .	. . .	8	24	8	18
Excitations	2	2	6	6	6	3
Scan time	10 min, 44s	10 min, 44 s	6 min, 25 s	5 min, 12 s	6 min, 34s	7 min

Note.—CSE indicates conventional spin-echo; FSE, fast spin-echo; STIR, short-tau inversion recovery; and FLAIR, fluid-attenuated inversion recovery.

obtained during an acute phase of the disease was available and was compared with the recent MR examination. Image assessment criteria were lesion detectability (number and contrast of lesions, with number of lesions considered more important); lesion extension; lesion delimitation; myelographic effects (cerebrospinal fluid/cord contrast and homogeneity of cerebrospinal fluid, evaluated for "bright cerebrospinal fluid" sequences only); and overall image quality (image noise, visibility of small anatomic details, image degradation by artifacts). For every patient, a ranking of sequences was established independently with regard to the individual image assessment criteria (ranked 1 for the best sequence). Sequences were then compared for both readers independently by using the nonparametric version of the Student-Newman-Keuls test (13). In addition, ghost artifacts from patient motion (swallowing, cardiac pulsation, respiration, blood flow), from cerebrospinal fluid flow, and from truncation-type artifacts were classified as absent or not disturbing (0) or as definitely reducing the diagnostic efficacy (+).

For objective image assessment, contrast-to-noise ratios between normal cord and multiple sclerosis plaques as well as between cerebrospinal fluid and normal cord were determined: the signal intensity of the different anatomic structures was assessed by using region-of-interest measurements, with the regions of interest placed identically on the different sequences. Differences between signal of normal cord (S_{cord}), signal of multiple sclerosis lesions (S_{lesion}), and signal of cerebrospinal fluid (S_{CSF}) were then related to the standard deviation (SD) of background air measured at areas free of ghost artifacts (SD_{air})

$$\left(CNR_{lesion(CSF)} = \frac{S_{lesion\ (CSF)} - S_{cord}}{SD_{air}} \right)$$

(14). Contrast-to-noise ratios (CNRs) of the individual sequences were then compared with one another by means of paired one-tailed t tests ($P < .05$). Since scan times were similar, contrast-to-noise ratios were not related to scan time. Scan time for the FSE sequences were between 5 minutes 12 seconds and 7 minutes, the CSE took about twice as long (11 minutes 44 seconds) but also provided two types of images (proton density–weighted and T2-weighted) simultaneously.

Results

Signal abnormalities within the cervical or upper thoracic cord were found in 17 (85%) of 20 patients. In all three patients without spinal cord signal abnormalities, MR images of the brain showed demyelinating lesions, which could explain the clinical findings that were attributed primarily to suspected spinal cord lesions. The expanded disability status scale of these three patients was low (1.5, 2.5, and 3.0, respectively), all three patients had a relapsing-remission disease course, and the duration of the disease from the time of its onset was short (1 month, 5 months, and 4 years, respectively). Different types of lesions were observed, from small circumscribed foci with markedly increased signal on all types of sequences to large and poorly marginated areas with only subtle signal abnormalities.

Spinal Cord Lesion Assessment

Intrinsic spinal cord lesions were seen best on STIR-FSE images (Figs 1–3), which were particularly superior in cases of large, poorly marginated plaques with only subtle signal abnormalities (Figs 3 and 4); these types of lesions were hardly visible on any other type of images. Lesions showed the highest contrast, appeared larger, and were better delimited on STIR-FSE images. In six patients, additional plaques were depicted on STIR-FSE images that would have been missed on the other types of images.

In two patients for whom a previous MR examination obtained during an acute phase of the disease was available and showed acute high-intensity multiple sclerosis plaques on T2-weighted images, those multiple sclerosis plaques showed a markedly lower contrast on the T2-weighted images of the follow-up examination. Clinically, the decrease of T2 contrast
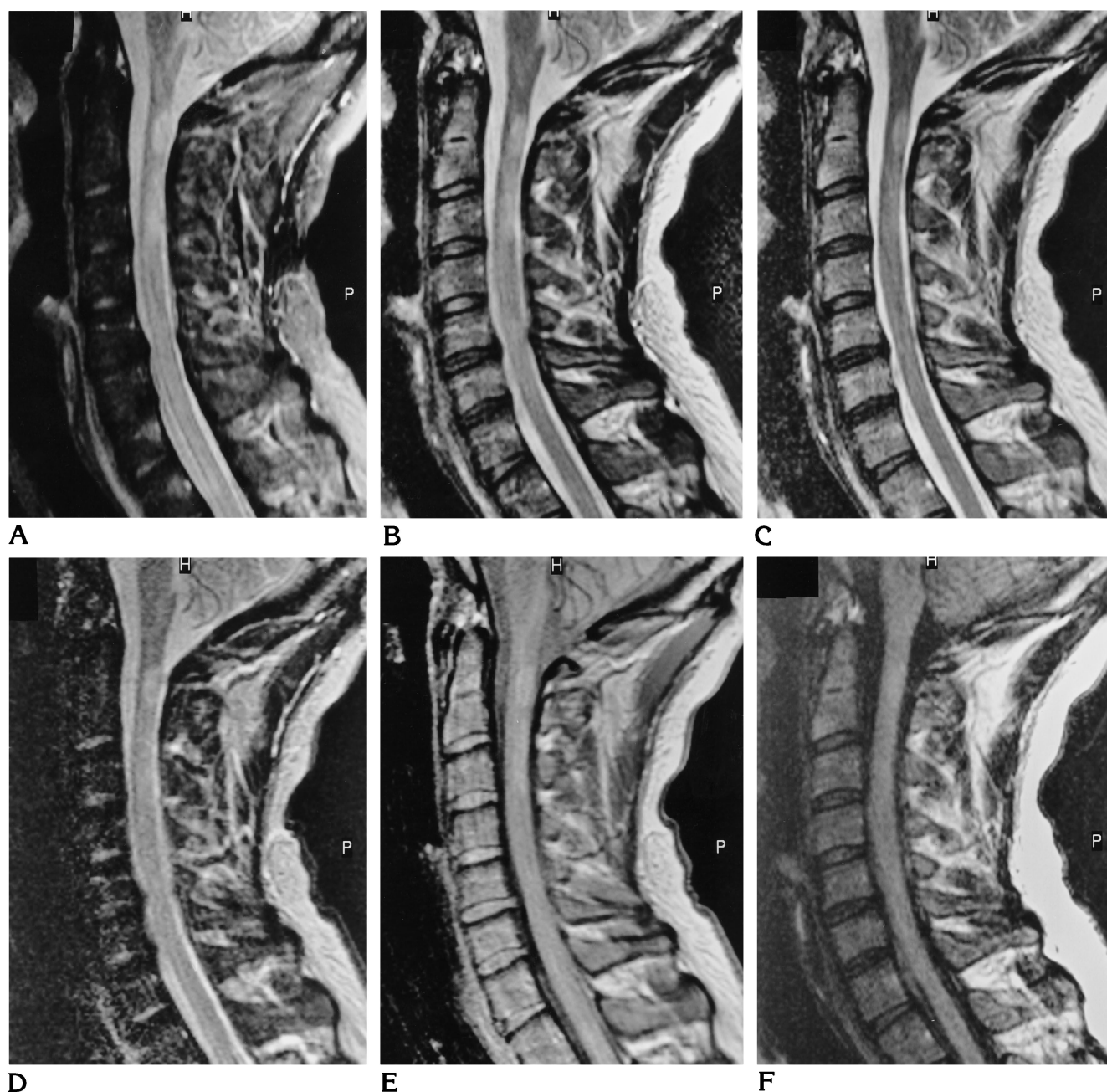
Fig 1. Thirty-one-year-old man with multiple sclerosis.

STIR-FSE image (*A*) shows high-intensity plaque within the cervical cord at the C1–2 level and a second less bright lesion at C-3. Both multiple sclerosis plaques show a lower contrast on the T2-weighted FSE-2500 image (*B*). Detectability of the C1–2 lesion is further reduced on the T2-weighted FSE-3000 image (*C*), on which the C-3 lesion is hardly visible, despite the best overall quality of all images. The T2-weighted CSE image (*D*) is degraded by prominent image noise, which greatly complicates the detection of the lesion at C-3, whereas the C1–2 lesion can be delineated. The T2-weighted FSE-3000 image (*D*) shows the best myelographic effect, with the brightest and most homogeneous cerebrospinal fluid, which is advantageous for the assessment of the disk protrusion at C5–6. Cerebrospinal fluid appears dark on proton density–weighted CSE (*E*) and FLAIR-FSE (*F*) images. Lesion contrast is poor on both of these dark-cerebrospinal-fluid sequences, but is slightly better on the proton density–weighted CSE image.
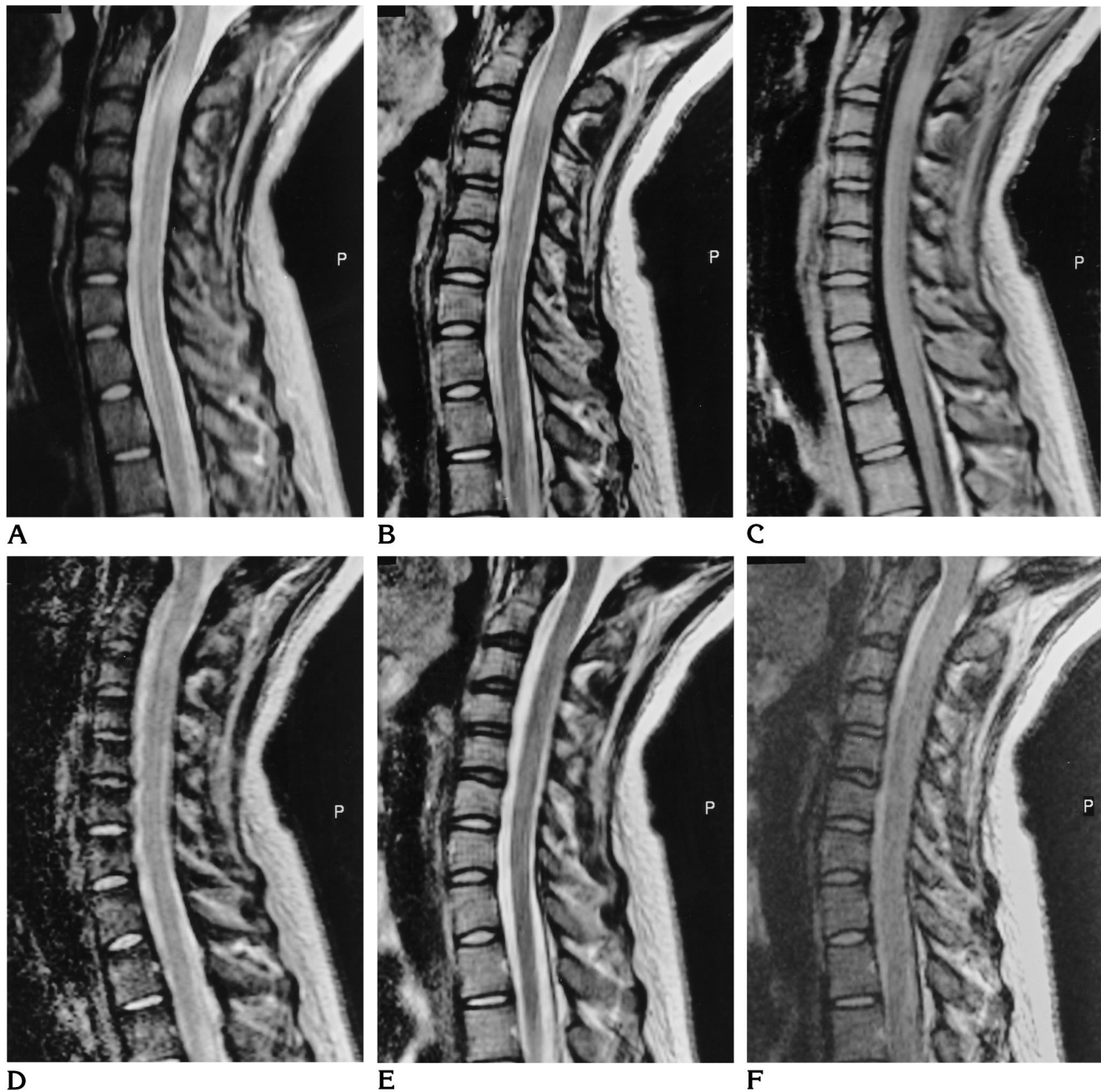
Fig 2. Twenty-year-old woman with multiple sclerosis.

STIR-FSE image (*A*) shows a poorly marginated area of increased signal at C2–3. This plaque is less well seen on T2-weighted FSE-2500 (*B*) and proton density–weighted CSE (*C*) images, poorly seen on the T2-weighted CSE image (*D*), and not seen reliably on T2-weighted FSE-3000 (*E*) and FLAIR-FSE (*F*) images. The cerebrospinal fluid signal is brightest and most homogeneous on the T2-weighted FSE-3000 (*E*) image; the FLAIR-FSE (*F*) image is degraded by extensive cerebrospinal fluid pulsation artifacts, which cause a high cerebrospinal fluid signal within large areas of the cervical subarachnoid space.
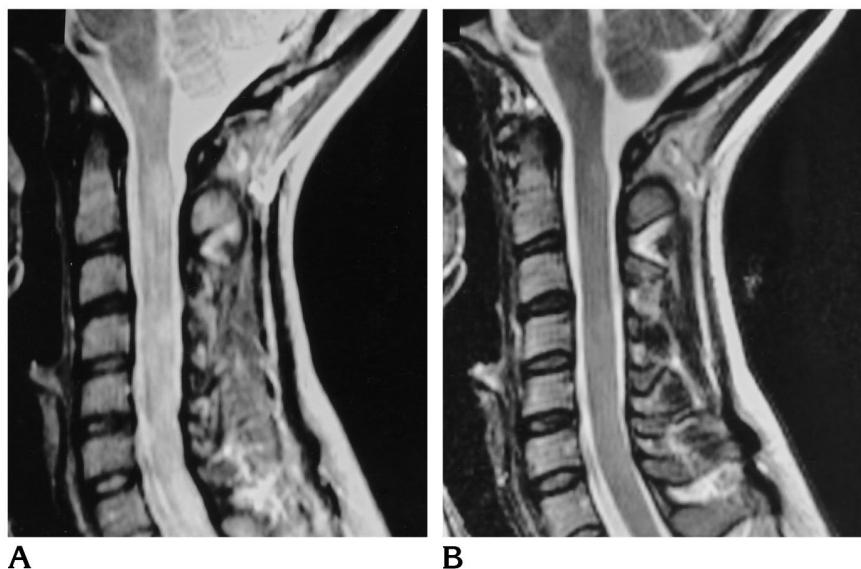
A   B

Fig 3. Twenty-eight-year-old woman with multiple sclerosis.

STIR-FSE image (*A*) shows diffuse multiple sclerosis involvement, whereas a good-quality T2-weighted FSE-3000 image (*B*) shows no definite signal abnormality within the cervical cord.
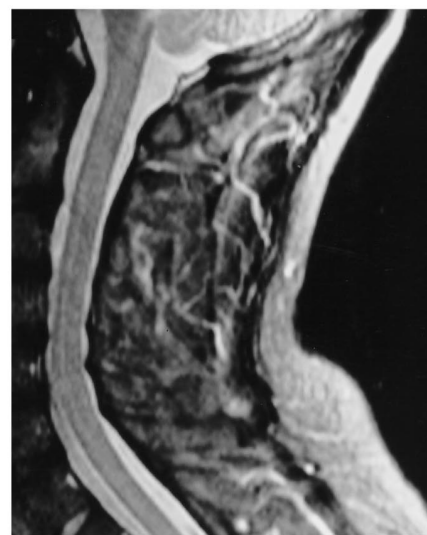
Fig 4. STIR-FSE image in a 29-year-old man with multiple sclerosis but without definite signal abnormalities within the cervical cord on any sequence. In contrast to the widespread areas of increased signal within the cervical cord seen in Fig 3A, this "normal" STIR-FSE image shows a homogeneous low-signal-intensity cervical cord.

was paralleled by a significant improvement in symptoms. At the follow-up examination, the lesions were barely visible on the FLAIR-FSE and CSE images but still excellently depicted on the STIR-FSE images.

The mean contrast-to-noise ratio between multiple sclerosis plaques and normal cord was about twice as high on STIR-FSE images as on any other sequence (highly significant *t* tests) (Table 2). The differences between the mean contrast-to-noise ratio of the remaining sequences were much lower. Intermediate contrast-to-noise ratios were found for T2-weighted FSE-2500 and T2-weighted CSE images, while the lowest contrast-to-noise ratios were found for T2-weighted FSE-3000, proton density–weighted CSE, and FLAIR-FSE images. The CNR values of the individual sequences and the statistically significant differences between the individual sequences (as tested with paired one-tailed *t* tests, $P < .05$) are listed in Table 2. The analysis of the subjective image assessment criteria provided very similar results for both readers (without significant interobserver variability) and paralleled the results of CNR measurements. The rank sums of lesion detectability, lesion extension, and lesion delimitation were ranked in the same order and were significantly

higher for STIR-FSE images than for any other sequence (Student-Newman-Keuls test, $P < .05$). The T2-weighted FSE-2500 sequence was second, followed by the T2-weighted CSE and the proton density–weighted CSE; reader 1 felt slightly more comfortable with T2-weighted CSE sequences, whereas reader 2 slightly preferred proton density–weighted CSE sequences. Regarding lesion characterization, the T2-weighted FSE-3000 sequence was rated inferior to even the CSE sequences by both readers, the FLAIR-FSE sequences were least desirable.

Overall Image Quality, Artifacts, and Myelographic Effect

Both readers rated the overall image quality of the T2-weighted FSE-3000 sequence as best (significant Student-Newman-Keuls test, $P < .05$), because this type of image was almost free of distortion artifacts and showed the least image noise, the best myelographic effect, and good visibility of small anatomic detail with no noticeable image blurring. The overall image quality of STIR-FSE and T2-weighted FSE-2500 sequences was rated as significantly inferior (Student-Newman-Keuls test, $P < 0.05$) to the T2-weighted FSE-3000 sequence by both

TABLE 2: Contrast-to-noise ratios of MS plaques

	STIR-FSE	T2-Weighted FSE-2500	T2-Weighted CSE	T2-Weighted FSE-3000	FLAIR-FSE	Proton Density–Weighted CSE
Mean contrast-to-noise ratio (lesion/normal cord)	13.87	7.43	6.46	5.64	4.69	3.97
Statistically lower than:*	…	STIR-FSE	STIR-FSE	STIR-FSE, T2-weighted FSE-2500	STIR-FSE, T2-weighted FSE-2500, T2-weighted-CSE	STIR-FSE, T2-weighted FSE-2500, T2-weighted CSE
Statistically equal to:*	…	T2-weighted CSE	T2-weighted FSE-2500, T2-weighted FSE-3000	T2-weighted, FLAIR-FSE, proton density–weighted CSE	T2-weighted FSE-3000, proton density–weighted CSE	T2-weighted FSE-3000, FLAIR-FSE
Statistically higher than:*	T2-weighted FSE-2500, T2-weighted CSE, T2-weighted FSE-3000, FLAIR-FSE, proton density–weighted FSE	T2-weighted FSE-3000, FLAIR-FSE, proton density– weighted CSE	FLAIR-FSE, proton density– weighted	…	…	…

Note.—STIR indicates short-tau inversion recovery; FSE, fast spin-echo; CSE, conventional spin-echo; and FLAIR, fluid-attenuated inversion recovery.
* Differences of contrast-to-noise ratios were analyzed by using paired one-tailed t tests ($P < .05$).

readers but still as very good. The STIR-FSE images showed some image blurring which, however, did not compromise the diagnostic efficacy even for the smallest multiple sclerosis plaques. The T2-weighted FSE-2500 images had a slightly increased image noise as compared with the T2-weighted FSE-3000 images, and the cerebrospinal fluid was less bright and less homogeneous on this type of image. A markedly and significantly lower overall image quality was found for the FLAIR-FSE and proton density–weighted CSE sequences but without significant differences between these two sequences (Student-Newman-Keuls test, $P < .05$). Overall image quality of the T2-weighted CSE sequence was rated lowest by both readers (significant Student-Newman-Keuls test, $P < .05$). FLAIR-FSE images were degraded by disturbing artifacts from cerebrospinal fluid pulsations and by image noise. On FLAIR-FSE images, cerebrospinal fluid signal was not homogeneously suppressed but showed a high signal in some areas, particularly in compartments of the subarachnoid space with a prominent flow void on bright-cerebrospinal-fluid images. This complicated image analysis and was thought to have reduced diagnostic efficacy in 13 cases. The flow voids on bright-cerebrospinal-fluid images were considered to have definitely reduced the diagnostic efficacy only on the STIR-FSE images of one patient but in none of the other images. Overall image quality of CSE images was affected by pronounced image noise, while the proton density–weighted CSE images were less severely degraded than the T2-weighted CSE images. Ghost artifacts definitely reduced the diagnostic efficacy of CSE images in four patients (T2-weighted CSE images in four patients and proton density–weighted CSE images in three patients). Truncation-type artifacts were noticeable on CSE and FSE images, but were not thought to have definitely reduced the diagnostic efficacy of any image.

The myelographic effect was assessed for the bright-cerebrospinal-fluid sequences only. The cerebrospinal fluid appeared brightest and most homogeneous on T2-weighted FSE-3000 images, which was reflected by the best subjective ranking by both readers (significant Student-Newman-Keuls test, $P < .05$) and by the highest contrast-to-noise ratio between cerebrospinal fluid and normal spinal cord (significant paired one-tailed t test, $P < .05$) (Table 3). The supe-

TABLE 3: Myelographic effect

	T2-Weighted FSE-3000	T2-Weighted FSE-2500	STIR-FSE	T2-Weighted CSE
Mean contrast-to-noise ratio	41.22	20.90	18.01	14.05
Statistically lower than:*	. . .	T2-weighted FSE-3000	T2-weighted FSE-3000	T2-weighted FSE-3000, T2-weighted FSE-2500, STIR-FSE
Statistically equal to:*	. . .	STIR-FSE	T2-weighted FSE-2500	. . .
Statistically higher than:*	T2-weighted FSE-2500, STIR-FSE, T2-weighted CSE	T2-weighted CSE	T2-weighted CSE	. . .

Note.—FSE indicates fast spin-echo; STIR, short-tau inversion recovery; and CSE, conventional spin-echo.

* Differences of CNRs were analyzed by using paired one-tailed t tests ($P < .05$).

rior myelographic effect allowed an excellent assessment of degenerative disk disease, which was found in six patients (Fig 1). Contrast-to-noise ratio measurements and subjective image assessment revealed that the myelographic effect of T2-weighted FSE-2500 and STIR-FSE sequences was significantly inferior to the T2-weighted FSE-3000 sequence but not significantly different from each other; T2-weighted CSE was significantly inferior to all other sequences (Student-Newman-Keuls and paired one-tailed t tests at $P < .05$, respectively). Despite the statistically significant differences, the myelographic effects on T2-weighted FSE-2500 and STIR-FSE images were still good enough to facilitate an exact evaluation of degenerative disk disease. T2-weighted CSE images were markedly inferior in this regard because of the pronounced image noise. The evaluation of disk protrusions was most difficult on dark-cerebrospinal-fluid images, such as on proton density–weighted CSE and FLAIR-FSE images, because the degree of narrowing of the spinal canal and the cerebrospinal fluid space could not be assessed reliably.

Discussion

Although MR imaging is the only imaging method suitable for the assessment of spinal cord multiple sclerosis plaques, its diagnostic sensitivity is still not sufficient when a conventional imaging technique is used, as only a limited percentage of these lesions can be seen (2, 5). This is a major diagnostic drawback, because 15% to 20% of spinal multiple sclerosis lesions occur without MR signal abnormality in the brain (1) and in these cases, a radiologic diagnosis cannot be established on the basis of brain MR findings. Although it is commonly ac-

cepted that the FSE technique improves the appearance of MR images, experience with FSE in imaging of the spinal cord is limited, whereas there is long-term, extensive experience with CSE sequences. With the CSE technique, commonly the anteroposterior phase-encoding direction is used, while with the FSE technique, multiple excitations and the feet-to-head phase-encoding direction are reasonable. Our results favor the feet-to-head phase-encoding direction used for FSE sequences, because it avoided the ghost artifacts seen on the CSE images. Otherwise, differences between the CSE and FSE sequences and differences between the individual FSE sequences can be attributed to the different sequence techniques and to different sequence parameters. Established sequence parameters for T2-weighted CSE and proton density–weighted CSE sequences are 2500/15,90; sequence parameters for FSE sequences are less well established. To facilitate a fair comparison of optimized sequences, parameters for all FSE sequences had been optimized in preliminary trials along the suggestions of previous publications. A significant reduction of image noise and scan time were the greatest merits of the FSE technique. However, it could be shown that the reduced image noise does not necessarily improve diagnostic efficacy, as discussed below.

With regard to lesion detection and characterization, the results of the contrast-to-noise ratio measurements and the subjective image assessment provided concordant results. The STIR-FSE sequence was considered the best in this regard, which is particularly important because STIR-FSE images showed multiple sclerosis plaques that would have been missed on the other types of images. In three patients, even STIR-FSE images revealed no definite signal abnormality. These cases, however, need

not necessarily represent false-negative MR results, because the clinical symptoms that had first fostered suspicion of spinal cord involvement could also be attributed to demyelinating lesions of the brain seen on cranial MR images. Thus, the STIR-FSE sequence, together with recent hardware developments used for this study, provides a high sensitivity for cervical multiple sclerosis plaques that significantly exceeds previously published data (2, 5). The high lesion contrast on STIR-FSE images can be attributed to the synergistic effect of prolonged T1 and T2 relaxation times (12), which characterize not only spinal cord plaques but also most other types of pathologic tissue (15). With all other types of sequences used for this study, prolonged T1 and T2 relaxation times produce antagonistic effects, and this reduces lesion contrast. The synergistic effect of long T1 and T2 are particularly advantageous in lesions with only slightly prolonged T2 relaxation times, which might be characteristic of inactive multiple sclerosis plaques. In two of our patients, a follow-up examination of active multiple sclerosis plaques revealed a marked signal decrease on T2-weighted images, which was paralleled by a significant clinical improvement. The inactive plaques, with only low T2-contrast, benefited particularly from the synergistic T2- and T1-contrast on the STIR-FSE images. Compared with conventional STIR sequences, the merits of the STIR-FSE sequence are an improved overall image quality and reduced scan times without relevant changes of the unique STIR contrast (9). The slight blurring that was observed on the STIR-FSE images in this study can be attributed to a significant T2 decay during k-space sampling (11). This might have been reduced with longer TEs, but longer TEs might have also reduced the conspicuity of some multiple sclerosis plaques. Results of the two T2-weighted FSE sequences indicate that long TEs are inadequate for seeing multiple sclerosis plaques, which we discuss in a more detailed way below. The slight blurring seen on the STIR-FSE images was a negligible problem as compared with the high lesion contrast, ability to detect small lesions, and excellent delimitation of lesions it afforded.

The two T2-weighted FSE sequences provided good image quality; the T2-weighted FSE-2500 sequence was equal to the STIR-FSE sequence, and the T2-weighted FSE-3000 was superior to the STIR-FSE sequence in this regard. However, lesion conspicuity on T2-weighted FSE sequences was markedly lower than that on STIR-FSE images. This is important, because readers might feel comfortable with a false-negative diagnosis derived from good-quality images. There was also a significant difference in lesion conspicuity between the two sets of T2-weighted FSE sequences. The T2-weighted FSE-3000 sequence showed the best overall image quality but was significantly inferior to the T2-weighted FSE-2500 sequence with regard to lesion characterization because of lower lesion contrast, smaller lesion extension, and inferior lesion delimitation. On T2-weighted FSE-3000 images, spinal multiple sclerosis plaques were masked despite the excellent overall image quality, and intrinsic cord plaques were even less visible than they were on CSE images, with greatly inferior overall image quality. Image blurring has been discussed as an explanation for the reduced contrast, particularly in regard to small lesions on FSE sequences (16). Some findings, however, suggest that the differences between the two T2-weighted FSE sequences of this study might be due to a different T2-weighting (caused by a different effective TE) rather than to image blurring. First, no image blurring was noticeable on T2-weighted FSE-3000 images. Second, there was no difference between small and large lesions. Third, a poorer delimitation on T2-weighted FSE-3000 images was always paralleled by lower lesion contrast. The maximal signal difference between two types of tissue with different T2 relaxation times is observed at an optimal TE that depends on the actual difference of T2 (10). With only slightly prolonged T2 relaxation times that might be characteristic of inactive multiple sclerosis plaques, the signal of normal cord and pathologic lesions will have already decreased at a long TE. In these cases, shorter TEs can produce a higher contrast between normal cord and pathologic lesions, because lesion signal is still preserved. The value of shorter TEs for seeing multiple sclerosis plaques has already been observed by other investigators (5, 7). Conversely, it is known that long TEs with long echo trains provide a superior myelographic effect and a better overall image quality. This has been advantageous for the assessment of degenerative disk disease (11) and was also confirmed by the results of our T2-weighted FSE-3000 sequence (11).

FLAIR-FSE sequences were of minor diag-

nostic value for imaging cervical multiple sclerosis plaques. Considering both the results of contrast-to-noise ratio measurements and subjective image assessment, the FLAIR-FSE sequence was worst or among the worst in this regard. FLAIR images not only were degraded by an incomplete cerebrospinal fluid signal suppression but also resulted in insufficient lesion contrast. CSF flow artifacts have already been observed on multisection FLAIR-FSE sequences that commonly use section-selective inversion pulses (10). Since cerebrospinal fluid pulsations are present in the cervical subarachnoid space, spins that do not "see" the inversion pulse enter the section during the inversion time interval and produce a high cerebrospinal fluid signal with the heavily T2-weighted FSE sequence that follows the inversion time interval. CSF pulsation artifacts were not observed on the conventional FLAIR sequence reported by Thomas et al (5) because a non–section-selective inversion pulse was used in that investigation. With a non–section-selective inversion pulse, however, each section "sees" a different inversion time interval. For sagittal cord imaging, in which the entire cord is covered with a few sections, this seems to be only a minor limitation (8), and a non–section-selective inversion pulse might be useful to reduce cerebrospinal fluid pulsation artifacts in multisection FLAIR-FSE imaging. Cardiac synchronization is an alternative approach to this problem and has been shown to be effective in reducing cerebrospinal fluid pulsation artifacts with T2-weighted CSE sequences (17). In addition to the cerebrospinal fluid pulsation artifacts, poor lesion contrast is another drawback of the FLAIR-FSE sequence with regard to assessment of multiple sclerosis plaques. Since the FLAIR-FSE sequence consists of an inversion pulse followed by a heavily T2-weighted FSE sequence, the explanation for the poor plaque contrast on FLAIR-FSE images seems to be the long effective TE and echo train length, analogous to the T2-weighted FSE-3000 sequence. This appears to be a major limitation of FLAIR-FSE sequences in general, because the long dead time during the inversion time interval (about 2000 milliseconds needed for cerebrospinal fluid suppression) necessitates a fast data acquisition by the FSE sequence, and a fast data acquisition requires long echo trains and a long effective TE. In addition, the inversion pulse of FLAIR sequences introduces a considerable T1

weighting, which acts antagonistically to the T2 contrast.

Summarizing, all types of multiple sclerosis plaques were best or at least equally well demonstrated by the STIR-FSE sequence, which holds true, in our experience, also for other types of intrinsic cord lesions occurring in patients with a myelopathy. Particularly if done after the evaluation of extramedullary or extradural lesions with heavily T2-weighted FSE sequences, STIR-FSE sequences might disclose additional intrinsic cord abnormalities.

Conclusions

The FSE technique improves the overall image quality of T2-weighted images as compared with CSE images. This, however, does not necessarily improve the visibility of intrinsic spinal cord lesions, such as multiple sclerosis plaques. Short TEs and short echo trains seem to be advantageous for spinal cord imaging, whereas long TEs and long echo trains are beneficial for showing extramedullary and extradural disease. STIR-FSE appears to be the sequence of choice for the assessment of spinal multiple sclerosis plaques because it provides the highest lesion contrast, which seems to be advantageous for the assessment of patients with a myelopathy. The FLAIR-FSE sequence is of minor diagnostic value for cervical multiple sclerosis plaques, owing to poor lesion contrast and cerebrospinal fluid pulsation artifacts.

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