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Comparison of Lesion Enhancement on Spin-Echo and Gradient-Echo Images

Phylliss M. Chappell,[1] Norbert J. Pelc,[1] Thomas K. F. Foo,[2] Gary H. Glover, [1] S. Patricia Haros,[1] and Dieter R. Enzmann[1]

PURPOSE: To compare lesion enhancement after injection of gadopentetate dimeglumine on spin-echo and gradient-echo T1-weighted images. **METHODS**: A total of 48 contrast-enhancing intracranial lesions were evaluated using a spin-echo and two gradient-echo T1-weighted pulse sequences. Percent contrast, contrast-to-noise, and signal-to-noise measurements were made on the spin-echo T1-weighted, three-dimensional gradient-echo, and multiplanar gradient-echo sequences. **RESULTS**: The measurements were somewhat different for the following categories of lesions: extraaxial, intraaxial with edema, and intraaxial without edema. The latter group provided the greatest diagnostic challenge: three of 19 such lesions 1 cm in size or smaller could not be identified on three-dimensional gradient-echo images, and one could not be identified on multiplanar gradient-echo images. The spin-echo T1-weighted sequence demonstrated significantly higher percent contrast ($P < .05$) and greater contrast to noise ($P < .03$) than either gradient-echo sequence for these small intraaxial lesions without edema. For extraaxial and intraaxial lesions with edema, percent C was similar for spin-echo T1-weighted and three-dimensional gradient-echo images, while contrast to noise was greater for spin-echo T1-weighted images. This reflected greater tissue noise with gradient-echo sequences. **CONCLUSION**: The T1-weighted spin-echo sequence was preferred for detecting the full spectrum of contrast-enhancing lesions of the central nervous system.

Index terms: Magnetic resonance, comparative studies; Magnetic resonance, contrast enhancement; Magnetic resonance, gradient-echo; Magnetic resonance, 3-D

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Improvements in machine hardware and software have resulted in new capabilities in scanning. One goal has been faster scanning, both for T1-weighted and T2-weighted images (1, 2). The conventional spin-echo T1-weighted and T2-weighted pulse sequences have proved valuable in lesion detection and are considered the current standard by which different and newer pulse sequences should be judged. New pulse sequences need to be evaluated in the detection of contrast enhancement of lesions of the central nervous system using gadopentetate dimeglumine even if they appear to be very good surrogates for conventional spin-echo images. This comparison study used measures of contrast to evaluate differences between pulse sequences.

Materials and Methods

Thirty-two patients were randomly selected for this study and prospectively scanned on the basis of the need for administration of gadopentetae dimeglumine based on clinical history. Five patients had no demonstrable contrast-enhancing lesions; 27 had a variety of contrast-enhancing intracranial lesions (Table 1). There were 13 female patients and 14 male patients, ranging in age from 13 to 77 years (mean age 47.6 years). A total of 48 enhancing intracranial lesions were evaluated: 38 intraaxial and 10 extraaxial (Table 1).

Magnetic resonance (MR) examinations were performed with a 1.5-T magnet (General Electric Medical Systems, Milwaukee, Wis). In each patient T1-weighted spin-echo sagittal (500/20/2 [repetition time/echo time/excitations]), T1-weighted spin-echo axial (800/20), and T2-weighted axial-gated and flow-compensated spin-echo images (>2000/30,80) were obtained before the administration of

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[1] Department of Radiology, Stanford University School of Medicine Stanford, California. Address reprint requests to: Dieter Enzmann, MD, Department of Radiology, S072, Stanford University School of Medicine, Stanford, CA 94305–5105.

[2] Present address: General Electric Medical Systems, Milwaukee, WI 53201.

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TABLE 1: Distribution of intra- and extraaxial contrast-enhancing lesions

Lesion	No. of Lesions	No. of Patients
Intraaxial		
Primary tumor	13	9
Secondary tumor	10	5
Infarction	6	1
Infection	4	2
Demyelination	4	2
Cryptic arteriovenous malformation	1	1
Total	38	20
Extraaxial		
Primary tumor	6	5
Secondary tumor	3	1
Postoperative	1	1
Total	10	7

contrast material. Immediately after the intravenous administration of a single dose of gadopentetate dimeglumine (0.1 mmol/kg), the three following sequences were randomly performed in the axial plane: 1) spin-echo T1-weighted sequence (800/20) with the acquisition time of 6:53 minutes; 2) spoiled gradient-echo sequence (SPGR) (30/6) and flip angle of 30° with acquistion time of 4:07 min; and 3) multiplanar spoiled gradient-echo sequence (MPSPGR) (247/3.8) and flip angle of 60° with acquistion time of 2:09 min. The section thickness of 5 mm, field of view of 21 cm, and matrix size of 256 × 256 were held constant. These studies were performed at two sites, in an inpatient and outpatient setting. One site randomized these sequences well; the other had a predominance of the spin-echo T1-weighted sequence first. Approximately 60% of the studies were randomized; the others had a potential bias of early imaging after injection for the spin-echo T1-weighted sequence and delayed imaging for the gradient-echo sequences. However, we felt that a delay of, at most, 7 to 8 minutes after injection would not significantly alter the magnitude of contrast enhancement. It has been shown that tumor contrast enhancement does not change significantly for up to 25 minutes after injection (3). If anything, an early scan could bias the spin-echo T1-weighted image to lower degrees of enhancement because of slow buildup of tissue levels of gadopentetate dimeglumine to a stable, higher level.

One question that arises in the use of short repetition time gradient-echo imaging is the choice of flip angle. Some analytical guidance to flip angle selection is useful. If noise is constant, contrast can be defined as the difference in signal between two materials. If the two materials have longitudinal relaxation times of T_{1a} and T_{1b} and assuming equal spin-density and T_2* effects, the contrast is $\Delta S = S(T_{1a}) - S(T_{1b})$, where $S(T_1)$ is the MR signal for a particular T_1. Because of the simple and useful relationship that results, we approximate the signal difference by $\Delta S = (dS/dT_1)\Delta T_1$, where dS/dT_1 is the derivative of S with respect to T_1 evaluated at the average of T_{1a} and T_{1b}, and $\Delta T_1 = T_{1a} - T_{1b}$. This differential approximation is particularly appropriate when the T_1 difference is small, and this often matches the relevant clinical problem. Thus, differential T_1 contrast C is proportional to dS/dT_1. It has been shown that the optimum flip angle, α_o, which maximizes C, is given by (2, 4): $\cos(\alpha_o) = 2E_1 - 1/2 - E_1$, or $\alpha_o = \cos^{-1}(2E_1 - 1/2 - E1)$, where $E1 = e^{-TR/T1}$ evaluated at the average T_1. The optimum flip angle depends only on TR/T_1, just as the Ernst angle does (5). However, it is instructive to examine it as a function of TR and parametrically as a function of T_1 (Fig 1).

The flip angles for these gradient-echo sequences were calculated to achieve maximum contrast between subtle contrast-enhancing lesions and adjacent white matter as background. The calculations were based on the assumption that the goal of the imaging sequence was to detect subtle contrast-enhancing lesions in white matter, and thereby to detect lesions with a slightly shorter T_1 relaxation time than white matter. The range of T_1 relaxation times for normal white matter (T_1 = 500–700) were obtained from the literature (6–8). The graphs resulting from the calculations used to determine the optimum flip angles for the three-dimensional SPGR and two-dimensional MPSPGR sequences are shown in Figure 1.

In three additional patients with contrast-enhancing lesions, the following sequences were performed to evaluate the change in white matter background standard deviation as a function of echo time for spin-echo and gradient-echo sequences. The comparison was for spin-echo (800/12 and 800/18) and SPGR (30/12 and 30/18).

Region of interest (ROI) measurements were obtained to determine the mean signal intensity and standard deviation of spin-echo and gradient-echo images for the enhancing lesions, the adjacent background, and the air surrounding the calvarium. The ROI outlined the entire lesion if it was homogenous or the area of maximal contrast enhancement if it was inhomogenous. Identical ROIs were used for the same lesion for the three sequences. The range of ROIs

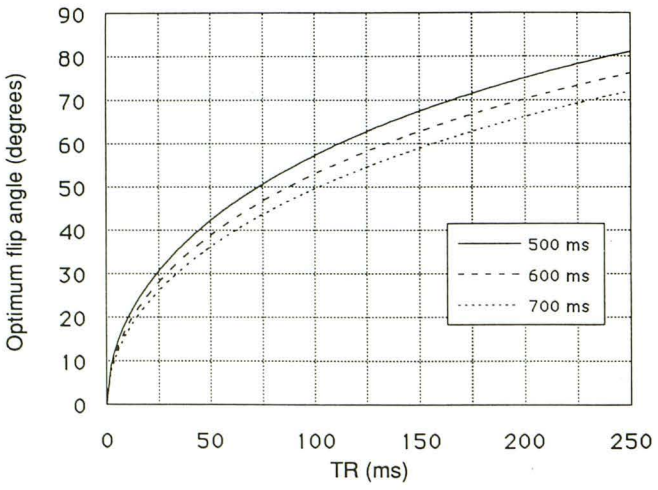

Fig. 1. Optimum flip angle as a function of TR for the SPGR sequence. Three curves are shown for three different T1 relaxation times. We felt that these relaxation times are representative of white matter at 1.5 T.

was 0.03 to 12 cm^2. Percentage of contrast was then calculated using the following formula (SI = signal intensity): $\%C = SI_{lesion} - SI_{bkgd}/SI_{bkgd}$. Noise was calculated by each of two methods (9): $Noise_{air} = SI_{air}/\sqrt{\pi}$ and $Noise_{bkgd} = StdDev_{bkgd}$. $Noise_{air}$ represented "thermal" noise. $Noise_{bkgd}$ also included tissue noise (ie, inhomogeneity of background white matter and artifacts).

ROIs selected for background signal intensity measurements were confined to cerebral white matter immediately adjacent to the lesion except for extraaxial lesions. For these, cerebrospinal fluid or gray/white matter was used. Contrast-to-noise ratios (CNR) and signal-to-noise ratios (SNR) were calculated using each of these noise measurements (10): $CNR_{air} = SI_{lesion} - SI_{bkgd}/Noise_{air}$, $CNR_{bkgd} = SI_{lesion} - SI_{bkgd}/Noise_{bkgd}$, and $SNR_{bkgd} = SI_{lesion}/Noise_{bkgd}$.

The detectability of contrast-enhancing lesions on T1-weighted spin-echo and gradient-echo sequences was compared by comparing mean percentage of contrast, CNR_{air}, CNR_{bkgd}, and SNR_{bkgd} of four groups of lesions: 1) extraaxial lesions, 2) all intraaxial lesions, 3)intraaxial lesions with edema, and 4) intraaxial lesions without surrounding edema. All values are mean ± SEM (Table 2). Statistical analysis was performed using an analysis of variance and paired *t* tests.

Results

Extraaxial Lesions

The mean and SEM for percentage of contrast, CNRs, and SNR are shown in Table 2 and Figure 2. The mean percent contrast for extraaxial lesions was statistically comparable for spin-echo (79.1 ± 14.0%) and SPGR T1-weighted (67.9 ± 19.1%) sequences. Both had significantly higher percentage of contrast than the MPSPGR (27.3 ± 14.6%) sequence ($P = .01$). For spin-echo and SPGR images the CNR_{air} was comparable and did not discriminate between the sequences. The spin-echo T1-weighted CNR_{bkgd} was higher than the CNR_{bkgd} of both SPGR and MPSPGR, but this just failed to reach statistical significance ($P = .07$). No lesions were missed by any sequence in this group.

TABLE 2: Mean ± SEM of the measures for T1-weighted, spin-echo, SPGR, and MPSPGR images

Lesion	T1-Weighted	SPGR	MPSPGR
Extraaxial			
Contrast (%)	79.1 ± 14.0	67.9 ± 19.1	27.3 ± 14.6
CNR_{air}	35.7 ± 3.8	30.0 ± 5.9	17.3 ± 12.4
CNR_{bkgd}	29.5 ± 8.6	11.7 ± 3.7	11.9 ± 8.5
SNR_{bkgd}	61.9 ± 12.9	29.8 ± 6.5	59.3 ± 16.7
All intraaxial			
Contrast (%)	51.4 ± 4.7	48.5 ± 7.9	24.5 ± 4.3
CNR_{air}	26.4 ± 2.4	24.8 ± 3.2	26.7 ± 4.9
CNR_{bkgd}	24.5 ± 4.0	10.0 ± 1.7	10.8 ± 1.6
SNR_{bkgd}	75.0 ± 10.4	37. ± 3.8	66.3 ± 7.0
Intraaxial with edema			
Contrast (%)	61.8 ± 7.9	74.0 ± 12.5	33.2 ± 5.4
CNR_{air}	30.6 ± .8	31.3 ± 4.8	23.6 ± 3.5
CNR_{bkgd}	29.4 ± 5.3	13.5 ± 2.7	14.4 ± 2.2
SNR_{bkgd}	83.4 ± 12.2	34.7 ± 4.6	67.7 ± 10.6
Intraaxial without edema			
Contrast (%)	41.0 ± 3.7	22.9 ± 4.8	15.9 ± 6.2
CNR_{air}	22.3 ± 2.5	18.3 ± 3.6	29.7 ± 9.1
CNR_{bkgd}	19.6 ± 5.6	6.4 ± 1.6	7.1 ± 2.2
SNR_{bkgd}	66.5 ± 16.7	40.7 ± 5.9	52.6 ± 7.9

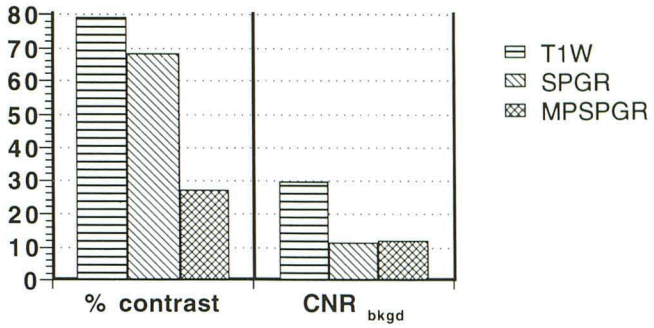

Fig. 2. Percentage of contrast and CNR for extraaxial lesions for the three pulse sequences. T1W indicates T1-weighted.

Intraaxial: All Lesions

The mean percentage of contrast for all intraaxial lesions was statistically comparable on T1-weighted spin-echo (51.4 ± 4.7%) and SPGR (48.5 ± 7.9%) sequences. Both had significantly higher mean percentage of contrast than the MPSPGR (24.5 ± 4.3%) sequence ($P = .001$). The CNR_{bkgd} was statistically higher with the T1-weighted spin-echo sequence (24.5 ± 4.0) compared with either SPGR (10 ± 1.7) or MPSPGR (13.3 ± 1.6) ($P < .05$). The mean CNR_{air} again was comparable for each technique.

Intraaxial: Lesions with Edema

Intraaxial lesions were separated into those with and without surrounding edema, because this affected lesion detectability (Fig 3). For intraaxial lesions with edema the mean percentage of contrast was comparable for spin-echo (61.8 ± 7.9%) and SPGR (74 ± 12.5%) sequences. Both demonstrated significantly higher percentage of contrast than the MPSPGR (33.2 ± 5.4%) sequence ($P < .05$) (Fig 4). The CNR_{bkgd} also showed a difference with the T1-weighted spin-echo sequence being statistically higher (29.4 ± 5.3) than either SPGR (13.5 ± 2.7) or MPSPGR

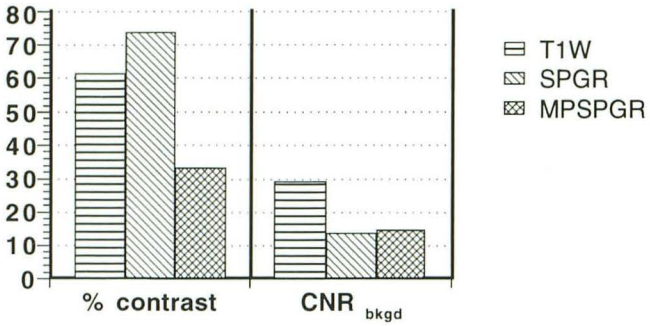

Fig. 3. Percentage of contrast and CNR for intraaxial lesions with edema for the three pulse sequences. T1W indicates T1-weighted.

(14.4 ± 2.2) ($P < .002$). The CNR_{air} was comparable for each technique.

Intraaxial: Lesions without Edema

The detectability of intraaxial lesions without surrounding edema was significantly better with the T1-weighted spin-echo sequence and demonstrated a statistically significantly greater percentage of contrast (41.0 ± 3.7%), than either gradient-echo sequence (SPGR: 22.9 ± 4.8% and MPSPGR: 15.9 ± 6.2%) ($P < .05$) (Figs 5, 6, 7, and 8). The CNR_{bkgd} was also statistically higher for the T1-weighted spin-echo sequence (19.6 ± 5.6) than either SPGR (6.4 ± 1.6) or MPSPGR (7.1 ± 2.2) ($P < .03$). The CNR_{air} was again comparable for each technique. Three small lesions, of a total of 19 measuring 1 cm or smaller, were not visualized on the SPGR images. One of these 19 was not visualized on the MPSPGR sequence. There were no lesions identified on either gradient-echo sequence that were not visualized on the spin-echo T1-weighted images. In this group, two quantitative measures favored the T1-weighted spin-echo sequence.

Effect of Echo Time on Spin Echo and Gradient Echo

There was no significant change in the standard deviation of background signal or CNR_{bkgd} in the comparison of spin-echo and gradient-echo sequences using echo-time values of 11 and 18.

Discussion

Conventional spin-echo T1-weighted and T2-weighted images have become standard clinical pulse sequences in the diagnosis of disease of the central nervous system and the de facto standard of reference. These pulse sequences, however, have long scanning times and thus a number of faster, substitute pulse sequences have been developed to produce images similar to spin-echo T1-weighted and T2-weighted images. A generic group of SPGR sequences have been developed to generate T1-weighted-like images, with the advantages being a shorter clinical scanning time and 3-D Fourier transform feasibility (1, 2). Although these gradient-echo images have T1-weighting, the use of gradient echoes does produce image differences from spin-echo T1-weighted sequences. Before a new pulse sequence can be judged a substitute for the conventional spin-echo T1-weighted sequence, it should be compared prospectively.

In choosing to use such a newer sequence, several trade-offs need to be considered, and these trade-offs must be accurately defined. Some image degradation caused by magnetic susceptibility effects around bone and air was expected and present with gradient-echo sequences (Fig 9). The disturbing finding in this study, however, was that the 3-D gradient-echo sequence failed to detect small contrast-enhancing lesions seen on conventional spin-echo T1-weighted images. This occurrence was limited to small, moderately contrast-enhancing lesions (<1 cm) in the brain parenchyma not associated with surrounding edema. This, therefore, would be a clinical problem in the detection of conditions such as metastatic disease, infection, demyelination (multiple sclerosis), and possibly leptomeningeal disease. This diagnostic drawback was not encountered with larger intraaxial lesions, which typically have surrounding edema, or with extraaxial lesions. In such lesions, morphologic change in addition to contrast enhancement aided in the detection of the lesion. The lesions that cause no morphologic change and in which detection depends solely on contrast enhancement were the lesions that caused problems for the gradient-echo sequences tested.

The reason for the failure to detect small contrast-enhancing lesions using gradient-echo T1-weighted sequences is not clear. This problem was investigated by Rand (11) using theoretical calculations; that study concluded that the reduced-contrast enhancement was related to saturation effects (ie, the short repetition time of the 3-D SPGR). In our investigation, a long repetition time gradient-echo T1-weighted sequence was included for that reason (MPSPGR) and, although this sequence showed more lesions than

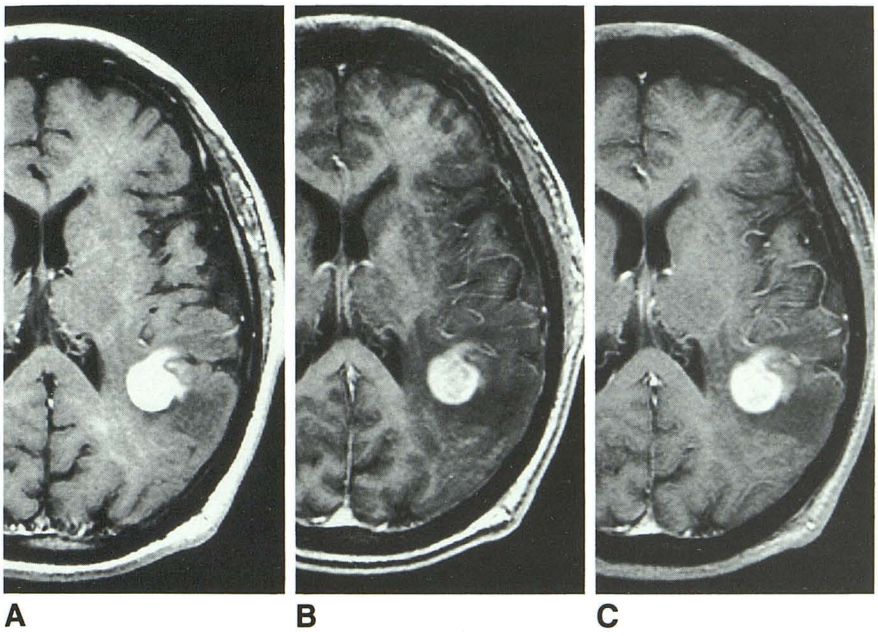

Fig. 4. Comparison of spin echo (800/20) (*A*), 3-D SPGR (30/6) (*B*), and MPSPGR (247/3.8) (*C*) sequences in detecting a contrast-enhancing lesion representing central nervous system lymphoma in the parietal lobe. For large contrast-enhancing lesions with surrounding edema as in this patient, all three pulse sequences adequately detected the lesion.

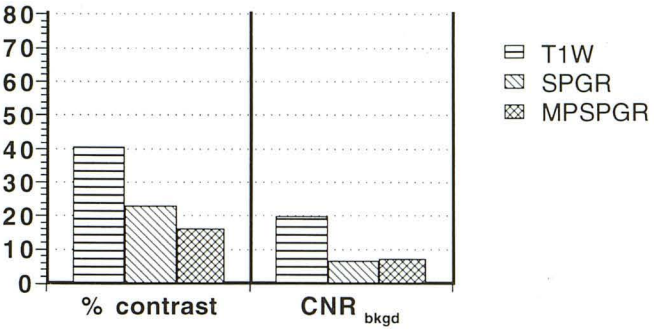

Fig. 5. Percentage of contrast and CNR for intraaxial lesions without edema for the three pulse sequences. T1W indicates T1-weighted.

SPGR, it did not detect one lesion, and the degree of contrast enhancement (percentage of contrast, CNR_{bkgd}) was not superior to the SPGR sequence. The gradient-echo sequences consistently had lower CNRs than the spin-echo images. In comparing CNR_{air} and CNR_{bkgd}, it became apparent that background noise (ie, SD) was greater with gradient-echo sequences, and thermal noise (air) remained unchanged. This difference in the pulse sequences was detected only when background noise was used in the CNR calculation. This effect can make detection of lesions of similar intensity to background difficult and appears to be one reason that lesion detectability was lower with gradient-echo sequences.

A recent nonrandomized comparison study of spin-echo T1-weighted and one type of gradient-echo T1-weighted sequence did not find differences as described in this study (12). That study's conclusion, however, was not that the gradient-echo sequence would replace the spin-echo sequence, but only that it would play a major role in contrast-enhanced MR. In that study, the spatial resolution of the spin-echo and gradient-echo images differed. If our lesion data are combined and if CNRs are calculated, then our study also shows no statistically significant differences in CNR between spin-echo and SPGR images (28.4 versus 25.9, respectively). Our results, however, indicate that thermal noise is not a good discriminator between spin-echo and gradient-echo sequences because it is not sensitive to differences in tissue noise. Separation of lesions by their imaging characteristics was important in identifying the small enhancing lesions without edema as a subgroup that revealed the drawback of gradient-echo T1-weighted images. Another investigation of gradient-echo T1-weighted images also revealed the potential for compromised lesion detection, with two lesions not being seen on the gradient-echo images (13).

T1-weighted images are often judged visually by the degree of gray-white matter contrast. Although this is important for evaluating morphology, it may not be the most important attribute for detecting gadopentetate dimeglumine contrast enhancement. The 3-D SPGR image had the greatest gray-white differentiation, in part because of the relatively higher white matter signal intensity. Lesions on gradient-echo images are of relatively lower signal intensity than white matter compared with spin-echo T1-weighted im-

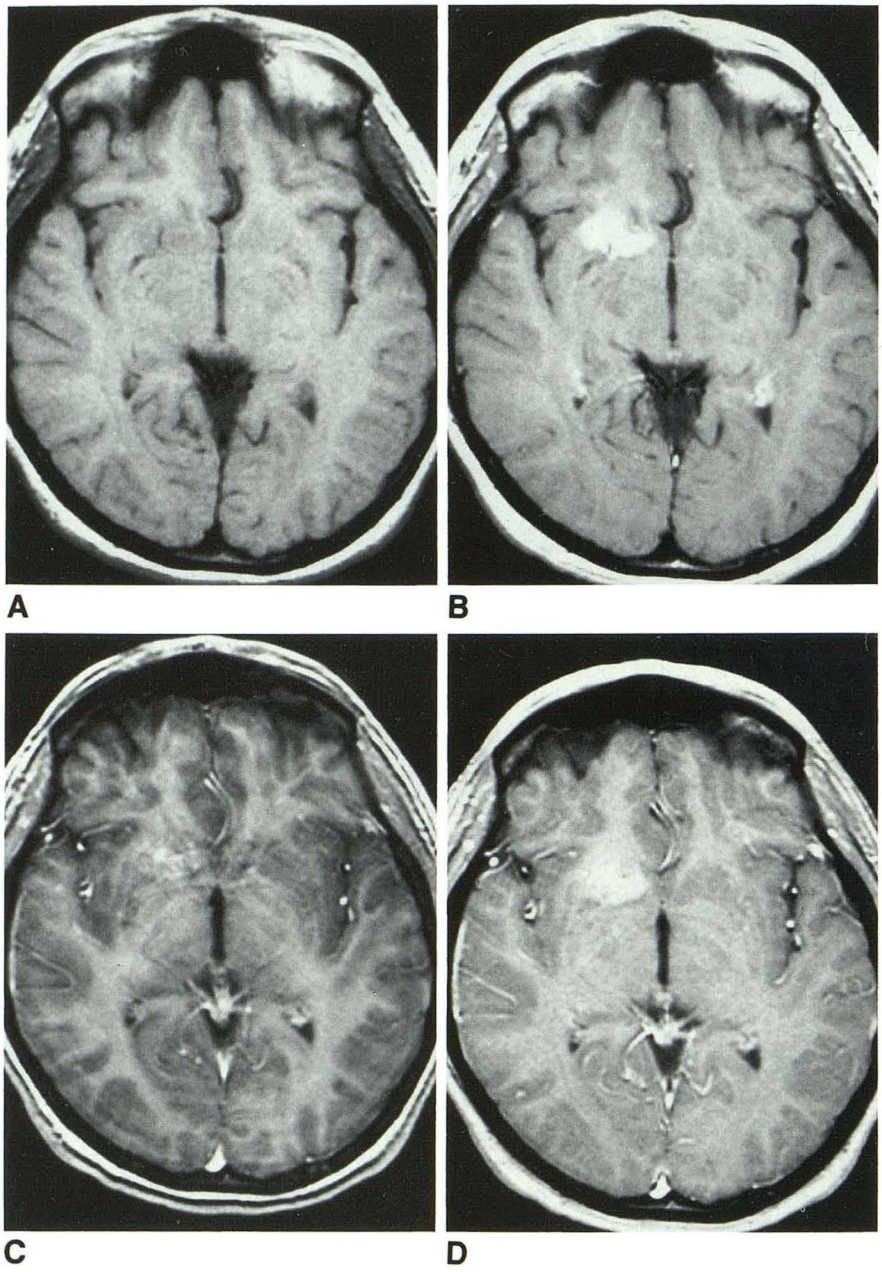

Fig. 6. Comparison of lesion detectability using spin-echo (800/20) (*A* and *B*), 3-D SPGR (30/6) (*C*), and MPSPGR (247/3.8) (*D*) techniques for a relatively large contrast-enhancing vascular malformation, which does not have surrounding edema. The precontrast spin-echo sequence shows a small linear signal void indicative of a vessel in the interior of the vascular malformation. This was a typical venous angioma on angiography. Postcontrast T1-weighted spin-echo scan (*B*) shows relatively uniform, intense enhancement. The 3-D SPGR sequence (*C*) exhibits much less contrast enhancement although the lesion is still detectable. The MPSPGR image (*D*) shows greater enhancement than the SPGR sequence but less than the spin-echo sequence. Both gradient-echo sequences have the characteristic high signal in cerebral vessels.

ages. This lower baseline signal, however, may make contrast enhancement more difficult to detect in white matter. If small lesions are of lower signal intensity than white matter on precontrast images and then increase in signal intensity up to a level equivalent to normal white matter, contrast enhancement may be more difficult to detect. Unfortunately, our study design did not include precontrast SPGR and MPSPGR scans. The phenomenon of contrast enhancement bringing lesion signal intensity up closer to a level of adjacent background does appear to play a role in the difficulty of detecting contrast enhancement of lesions without associated edema.

The visual cues used to detect lesions differ for the type and location of central nervous system lesions. Lesions difficult to detect are small, cause no morphologic change, and exhibit only a small change in signal intensity (ie, contrast enhancement) in comparison with surrounding tissue. If these can be considered the most difficult diagnostic problem for central nervous system contrast enhancement, then percentage of contrast and CNR_{bkgd} measurements provided good discrimination between the three pulse sequences.

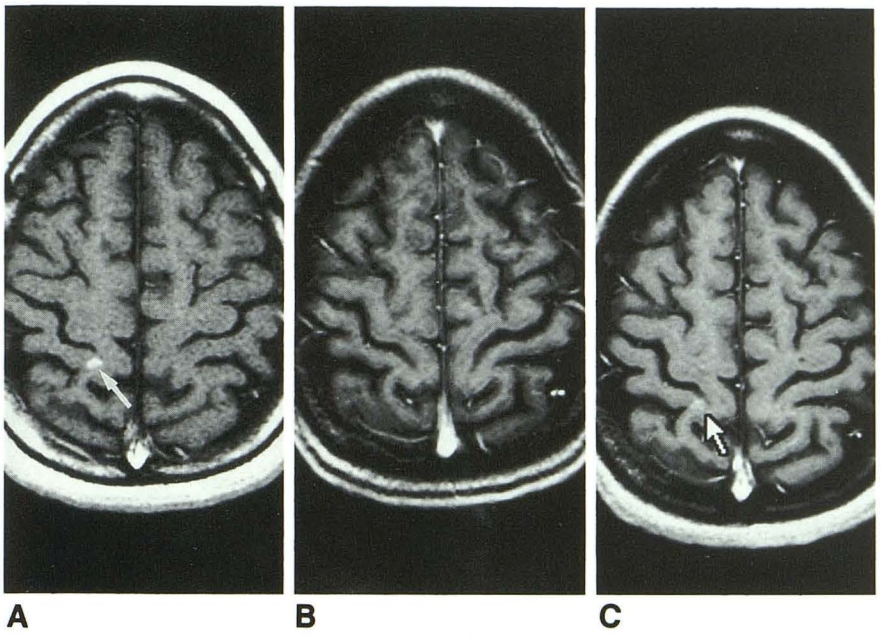

Fig. 7. In this patient with multiple sclerosis, the 3-D SPGR image (30/6) (*B*) did not show the lesion that was well seen on the spin-echo sequence image (800/20) (*arrow, A*). This contrast-enhancing plaque did not have surrounding edema. The MPSPGR sequence (247/3.8) (*C*) fell between these two images in that the contrast enhancement was detectable (*arrow, C*) but less so than in the spin-echo image (*A*). This represented a lesion not detected by the 3-D SPGR sequence. The section level between these sequences was virtually identical (note the sulcal pattern). Note also the 3-D SPGR image has the greatest gray-white differentiation.

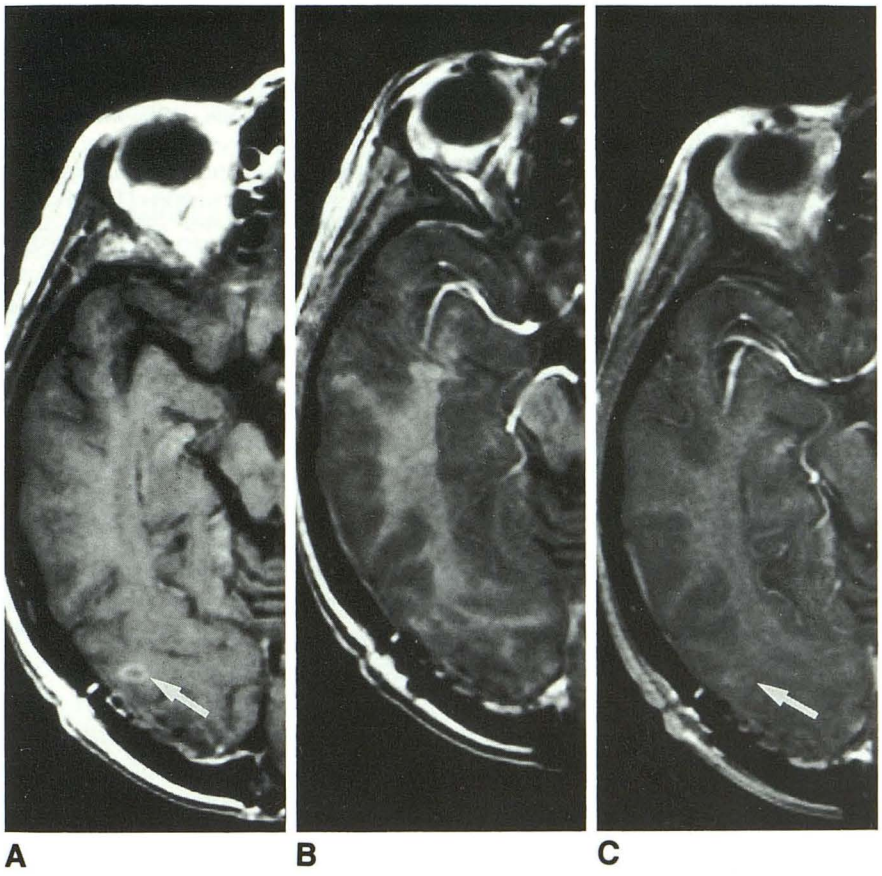

Fig. 8. An example of a contrast-enhancing lesion, recurrent primitive neuroectodermal tumor without surrounding edema, not detected by the 3-D SPGR sequence (*B*). A well-defined elliptical rim of contrast enhancement was identified on the spin-echo image (800/20) (*arrow, A*). This lesion was not identified on the 3-D SPGR image (30/6) (*B*). This recurrent tumor was only poorly visualized on the MPSPGR image (247/3.8) (*arrow, C*). Note the relatively high signal of white matter on the 3-D SPGR image, which resulted in good gray-white differentiation but poor visualization of enhancement.

Use of tissue noise (background standard deviation) as a measure of noise may be more appropriate than the electronic noise (air) measurement in comparing spin-echo and gradient-echo sequences because there appears to be a differential effect on background.

Although the gradient-echo T1-weighted images are not a complete replacement for spin-echo T1-weighted images, they do have clinical application. The 3-D capability allows thinner sections. This, in combination with good gray-white discrimination, provides excellent morpho-

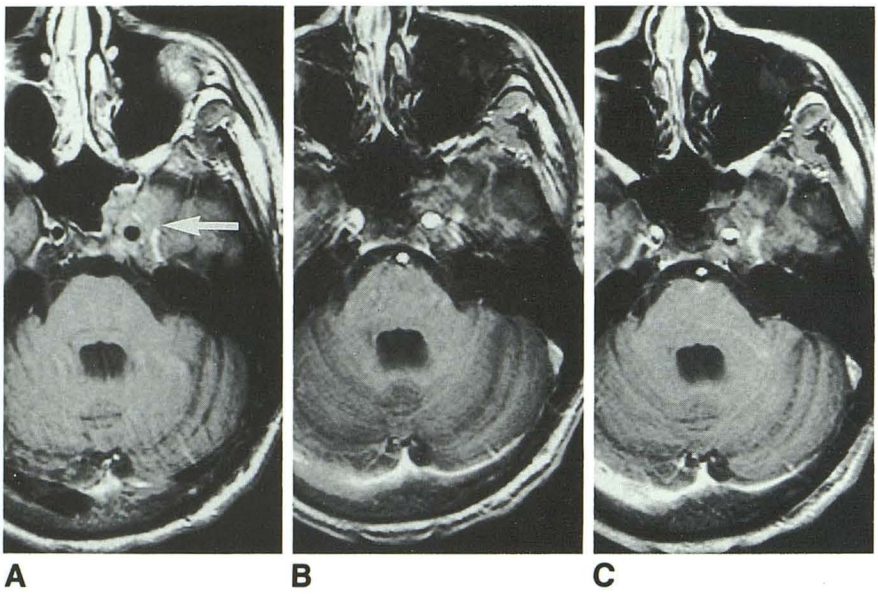

Fig. 9. Patient with metastatic Ewing sarcoma to the left cavernous sinus. The spin-echo image (800/20) (*arrow, A*) best demonstrated the enlarged cavernous sinus and its lateral border. Both gradient-echo sequences, 3-D SPGR (30/6) (*B*) and MPSPGR (247/3.8) (*C*), fail to show clearly the enlarged cavernous sinus or its lateral border. Presumably this is related to magnetic susceptibility effects caused by adjacent air in this sphenoid sinus and bone in the skull base.

logic detail, which can be useful in evaluating subtle mass effects, measuring gray and white matter volumes, or for evaluating cortical gray matter for suspected cortical dysplasia. For post-contrast scans they can be used for follow-up of extraaxial or intraaxial edematous lesions and they are advantageous for generating a 3-D data set that can be used for treatment planning (12).

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