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Magnetic Resonance with Marked T2-Weighted Images: Improved Demonstration of Brain Lesions, Tumor, and Edema

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The object of this study was to determine the sensitivity of magnetic resonance (MR) for imaging intracranial lesions with heavily T2-weighted images compared with that of computed tomographic (CT) and T1-weighted images. Fifty-five patients with known intracranial pathology consisting of primary neurogenic tumors, brain infarcts, demyelinating disease, and metastases were studied by MR and CT. Patients were studied with either 0.6 or 1.5 T systems with T1- and T2-weighted radiofrequency pulse sequences. The heavily T2-weighted images were found to be superior to the T1-weighted images in terms of sensitivity, with 168 lesions found versus 86 by CT and 104 by T1-weighted imaging.

In our preliminary work with different pulse sequences, more lesions were imaged on heavily T2-weighted images with a long echo time (TE) than on less markedly T2-weighted images with a short TE. We applied this to detection sensitivity in metastatic disease, primary malignancy of brain, multiple sclerosis (MS), and infarcts; comparison was made with computed tomography (CT) and T1-weighted images. We also tried to determine the spin-echo (SE) pulse sequence that could best differentiate tumor from edema.

Subjects and Methods

Of 55 patients examined, 14 had known primary malignancies: six of the lung with 20 brain metastases, four of the breast with 25 metastases, and four from other sources with nine metastases. Metastatic disease to the brain was diagnosed by surgical excision, biopsy, or autopsy in seven patients (50%) and by clinical and CT evidence of metastatic disease that responded to chemotherapy or radiotherapy in the other seven patients (50%). In all of the 10 patients with primary brain tumors, the diagnosis was confirmed histologically.

The 12 patients with MS had histories strongly suggestive of the disease, and positive correlative tests including Tourtelotte protein greater than 3.7 mg/day, positive oligoclonal bands, positive visual-evoked potential examinations, and/or positive brainstem auditory-evoked potential examinations. Nineteen patients had a clinical history of brain infarction or of transient ischemic attacks. In eight of these patients, infarcts were demonstrated with CT. The other 11 patients had angiographic findings of occlusive disease of the artery supplying the territory of the defect imaged on magnetic resonance (MR).

The patients were examined on a 0.6 T or 1.5 T superconductive MR prototype system manufactured by Technicare using either an anisotropic (modified three-dimensional) technique with 8 mm section thickness or a single- or multislice single-echo technique with a 10 mm section thickness. The TEs and repetition times (TRs) and magnetic field strengths are listed in table 1. We separated images into relatively T1- and T2-weighted. We used short TE, short TR (i.e., TE, 30–60 msec, with TR of 0.25–1.0 sec) as relatively T1-weighted, where cerebrospinal fluid (CSF) signal was clearly less intense than that of brain. Relative T2-weighting, where CSF was clearly more intense than brain, had longer TEs and TRs (TE 120 msec or greater with a TR of 1.0 sec or greater). Pulse sequences near crossover points of CSF and brain intensities (i.e., TE 90 msec, TR 1.0 sec, and TE 30 msec, TR 2 sec) have both T1- and T2-weighting and were not separated as a category in lesion identification.

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TABLE 1: **Echo Times, Repetition Times, and Magnetic Field Strengths Used in Imaging Brain Lesions and Differentiating Tumor from Edema**

Imaging Parameters	No. of Patients (n = 55)			
	Metastases	Primary Tumor	Multiple Sclerosis	Infarction
Total	14	10	12	19
0.6 T/1.5 T system	11/5*	8/2	9/5*	12/7
Single or multislice single echo:				
30 or 60 msec TE; 0.25–5 sec TR	1/3	7/1	0/3	3/9
30, 60, or 120 msec TE; 1.0 sec TR	1/0	2/1	4/0	3/0
60, 120, 180, 210, or 240 msec TE; 1.5–3.0 sec TR	4/3	4/3	4/4	8/10
Anisotropic—30, 60, 90, and 210 msec TE:				
0.5 sec TR	0/0	1/0	1/0	0/0
1–1.2 sec TR	7/0	1/0	2/0	3/0
1.5 sec TR	1/0	1/0	2/0	2/0

* Two patients examined in both 0.6 and 1.5 T units.

TABLE 2: **Identification of Brain Lesions by CT and T1- and T2-Weighted MR Imaging**

Disease	No. of Patients	No. of Lesions Seen by:		
		CT	T1	T2
Metastasis	14	36	44	54
Primary brain tumor	10	9	9	14
Multiple sclerosis	12	17	21	49
Infarction	19	24	30	51
Total	55	86	104	168

TABLE 3: **Identification of Brain Lesions on T2-Weighted MR Images but Not on CT Scans or T1-Weighted Images**

Disease	No. of Patients	No. of Lesions Seen by:	
		T2 not CT	T2 not T1
Metastasis	14	18	10
Primary brain tumor	10	5	5
Multiple sclerosis	12	32	28
Infarction	19	27	21
Total	55	82	64

TABLE 4: **Parameter Weighting and Location of Brain Lesions Identified by MR but Not by CT Imaging**

Disease	No. of Lesions			
	Seen by MR but Not CT	Supra-/Intra-tentorial	T1- and T2-Weighted	T2-Weighted Only
Metastasis	18	14/4	7/2	7/2
Primary brain tumor	5	5/0	0/0	5/0
Multiple sclerosis	32	30/2	5/0	25/2
Infarctions	27	23/4	6/0	17/4
Total	82	72/10	18/2	54/8

Note.—No lesions were seen only on T1-weighted images.

For anisotropic scans, we used a Y matrix of 64, X matrix of 128, Z matrix of 32 (pixel size of 3.64 × 1.82 mm). One data point per buffer was used for this technique. The data accumulation time for a 1 sec TR was 64 (Y matrix) × 32 (Z matrix) × 1 (TR) × 1 data point per buffer equals 34 min. Multiecho multisection imaging was not available at the time of this study. In the single-echo, multislice mode, the Y matrix was 128, the X matrix 256 (pixel size 1.82 × 0.91 mm), and the number of data points per buffer varied between 2 and 8. The most common data acquisition time for the T1-weighted images was 128 (Y matrix) × 0.5 (TR) × 4 (signal averages) equals 4.3 min, and for T2-weighted images, 128 (Y matrix) × 2 (TR) × 4 (signal averages) equals 17 min.

In 48 of 57 patients, CT was performed with a Picker 1200 scanner with a sampling matrix of 512 × 512 and a display matrix of 256 × 256 to conserve disk storage space. The other CT scans were obtained on a variety of systems at referring centers. Each section was obtained in 3.4 sec at 80 mA, 130 kVp, and was 1 cm in slice thickness. One hundred ml of intravenous contrast material was used in 13 of 14 patients with metastases, all patients with primary neurogenic tumors and multiple sclerosis, and in 14 of 19 patients with infarction. The contrast material used at our center contained a total of 37 g I (MD 76) and was injected as a bolus 15 min before the examination. Delayed scanning was not performed.

Results

Table 2 summarizes the number of lesions seen on CT and T1- and T2-weighted MR images in the four disease groups studied.

In group 2, two lesions in a patient with an optic glioma were demonstrated with CT and MR. In one patient with a dysgerminoma, four areas of subarachnoid seeding were demonstrated on T2-weighted MR images that had not appeared on either the CT scan or T1-weighted MR image.

In groups 1 and 2, tumor and edema were differentiated by CT in 25 (55%) of 45 lesions, by MR T1-weighted images in 23 (43%) of 53 lesions, and by T2-weighted images in 27 (39%) of 68 lesions. In all cases in which tumor and edema were differentiated by contrast-enhanced CT they were differentiated as well by MR. None of the cases had histologic confirmation of the tumor-edema margin so that it is not possible to be certain of the exact border between tumor and edema in any of these cases. On T1-weighted images, tumor and edema were differentiated by subtle differences in signal intensity. On T2-weighted images, gross tumor and edema were differentiated more clearly by a rim of decreased signal around the tumor. In only one lesion in a patient with metastatic breast carcinoma, tumor and edema differentiated on CT and T1-weighted images could not be differentiated on the T2-weighted image. On the T2-weighted image, however, tumor and edema could be differentiated in all other patients in whom it had been seen on either the CT or the T1-weighted images.

Table 3 summarizes the number of patients in whom lesions were demonstrated on T2-weighted images but not on CT scans, and on T2-weighted but not T1-weighted images. All lesions demonstrated by CT were also seen by MR imaging. All lesions demonstrated on T1-weighted images also appeared on T2-weighted images. Table 4 summarizes the

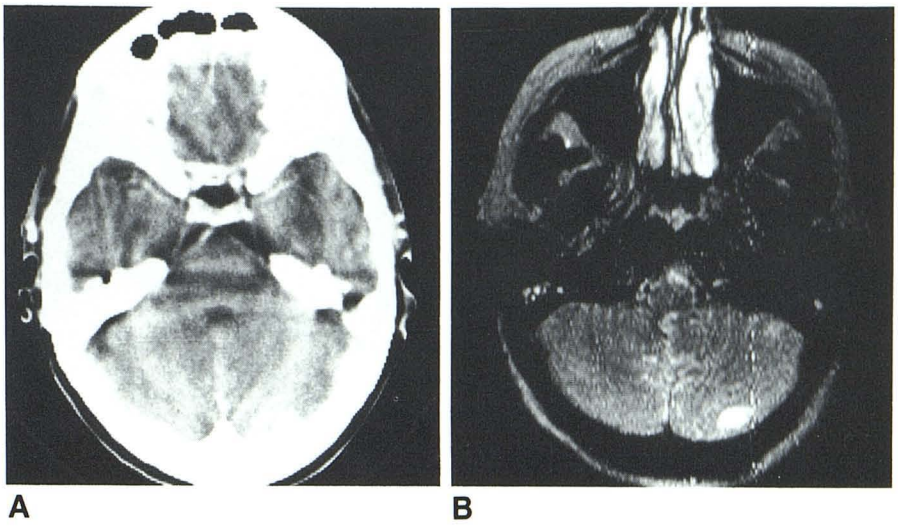


Fig. 1.—56-year-old woman with breast carcinoma. CT showed two supratentorial lesions. Six lesions were seen with MR. **A**, CT scan at level of fourth ventricle and at other levels in posterior fossa were interpreted as normal. **B**, SE scan, 120 msec TE, 2 sec TR, four buffers, 0.6 T. Metastatic lesion in posterior aspect of left cerebellar hemisphere.

numbers of lesions seen supratentorially versus infratentorially by MR imaging that were not seen by CT.

All lesions demonstrated with a T2-weighted SE pulse sequence were seen best using TEs of 120–210 msec with TRs of 1–2 sec. With smaller or larger TEs and TRs, the conspicuity of lesions was decreased.

In MS, lesions were demonstrated in the three patients with normal CT scans, while more lesions were seen by MR than by CT in six of the remaining nine patients.

Discussion

Heavily weighted T2 images showed more metastatic lesions, MS plaques, and infarcts than either T1-weighted images or CT.

At the beginning of the study, patients with known metastatic disease to the brain demonstrated by CT were studied with MR imaging to determine if more lesions could be seen. Near the end of our study, we examined patients with suspected intracranial metastases and known malignancies outside of the brain who had normal cranial CT scans. This explains why only one of our 14 patients with metastatic brain disease had no visible metastasis on CT.

In one patient with metastatic disease, the CT scan was normal, but MR imaging demonstrated three metastatic lesions; in two cases, CT demonstrated one metastasis, but two and four lesions, respectively, were seen with MR. We detected more brain metastases with MR than with CT in 50% of the patients with known extracranial primary malignancies (fig. 1). In patients with primary malignancy outside of the brain, therapy is altered by the presence of brain metastases; some surgeons remove a single brain metastasis, but two or more metastatic lesions are not resected. If additional clinical studies continue to show that MR imaging can be used to detect lesions and alter therapy in a high percentage of patients with primary malignancies that have a predilection for cranial metastases (i.e., lung carcinoma), then it is likely that MR of the brain will be indicated in all patients with primary malignancies that have such a predilection.

Previous reports in which T1-weighted images with inversion-recovery pulse sequences or T1-weighted SE pulse sequences were used have shown that in most cases it is difficult to differentiate tumor from edema [1–3]. With CT, tumor and edema often cannot be differentiated without the use of contrast material, which leaks through the blood-brain barrier into the tumor. All lesions having apparent differentiation between tumor and edema by CT were also differentiated by MR imaging. The lower percentage of differentiation of tumor from edema on T2-weighted images is explained by the fact that more small lesions were seen with MR imaging. In one patient only, tumor and edema were not differentiated on T2-weighted but were differentiated on the T1-weighted image. The explanation for the area of low signal intensity surrounding the apparent region of tumor, separating it from edema on the T2-weighted images, is unknown (fig. 2).

Although CT has shown lesions in patients with MS and is reported to show more MS lesions with delayed scans and higher doses of contrast material [4–6], its diagnostic usefulness is limited. In a large percentage of patients (25%), the CT scan was normal, but MS lesions were demonstrated with MR imaging (fig. 3). Since more MS lesions are detectable with MR (fig. 4), MR will probably become a major diagnostic test and also will be used for serial evaluation of different therapies. The lack of ionizing radiation, of course, is an important advantage.

With MR, brain infarctions can be detected within hours [7], whereas with CT, they are usually detected only after 1–3 days, depending in part on the size of the infarct and the contrast resolution of the CT scanner. With heavily T2-weighted images, more and smaller lesions can be identified than with T1-weighted images or with CT (fig. 5). However, it is possible that the additional lesions seen by MR represent areas of ischemia rather than complete infarcts.

Although heavily T2-weighted images have a high sensitivity, the specificity is low. Almost all pathologic brain lesions that we have observed on heavily T2-weighted images have

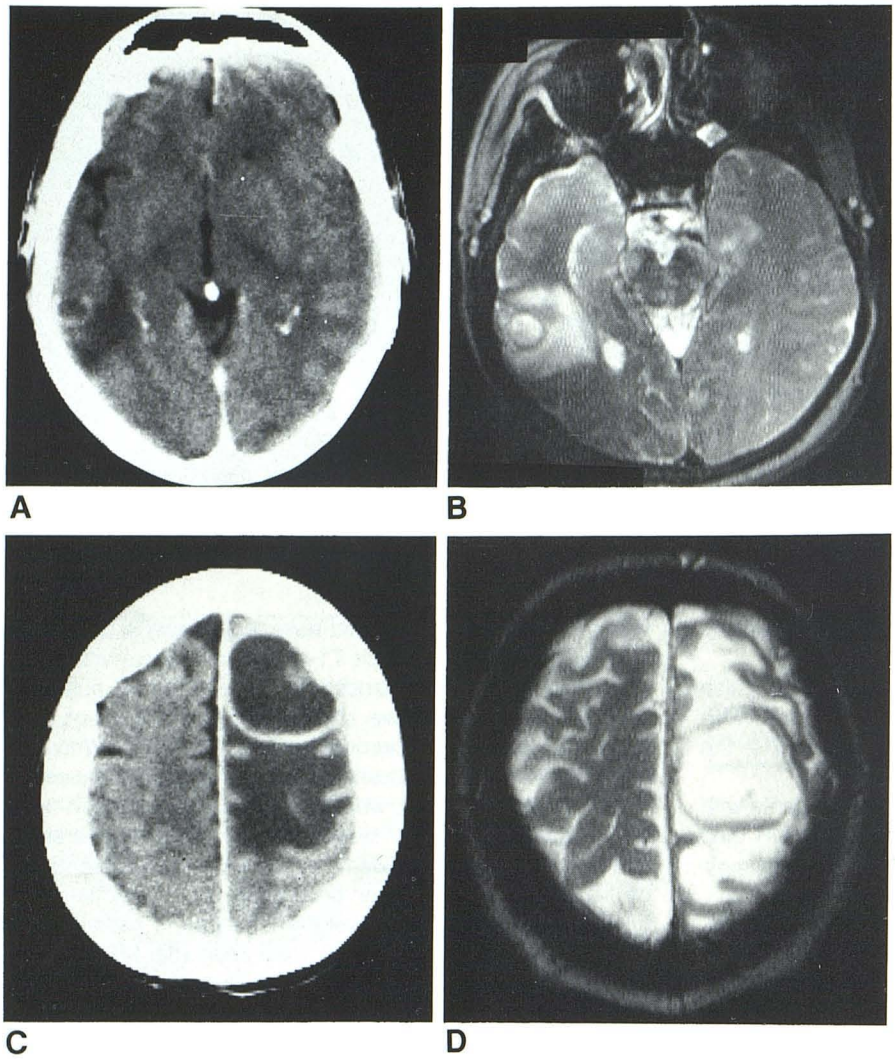


Fig. 2.—52-year-old man with bronchogenic carcinoma. Two lesions seen with CT, three with MR. **A**, CT scan. Rim of enhancement adjacent to temporal bone surrounded by edema. **B**, SE scan, 120 msec TE, 2 sec TR, four buffers, 1.5 T. Lesion in **A** has rim of decreased signal surrounded by area of increased signal from edema. **C**, CT scan. Frontal metastatic lesion with rim of enhancement surrounded by edema. **D**, SE scan, 120 msec TE, 2 sec TR, four buffers, 1.5 T. Lesion corresponds to lesion in **C**. Tumor and edema can be clearly differentiated. CT was performed with 20° angulation and MR at 0° to orbitomeatal lines. This is why lesion appears at different locations in the two images.

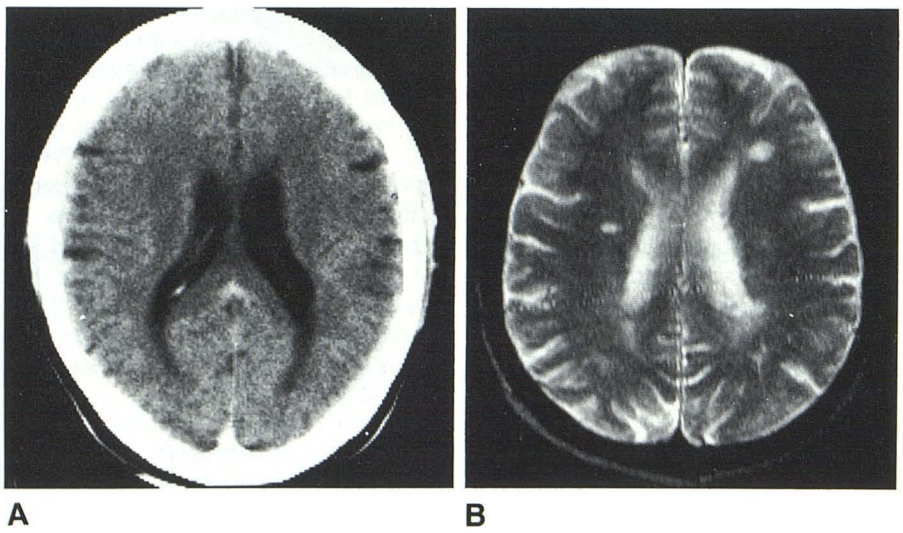


Fig. 3.—52-year-old man with 5 year history of signs and symptoms of MS. **A**, Normal CT scan at level of lateral ventricles. **B**, SE scan, 120 msec TE, 2 sec TR, four buffers, 0.6 T. Two areas of increased signal in periventricular region on this T2-weighted image. T1-weighted images were normal.

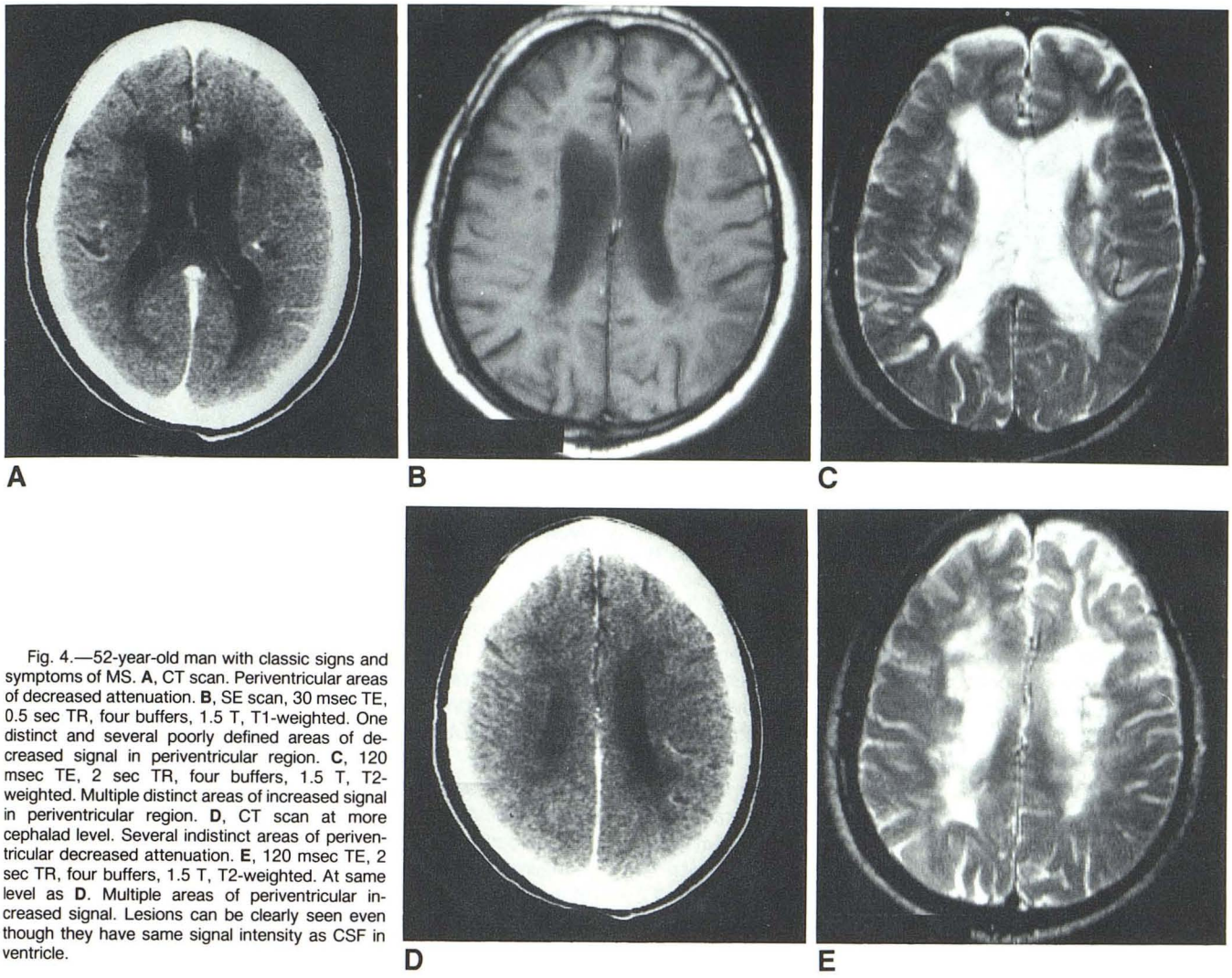


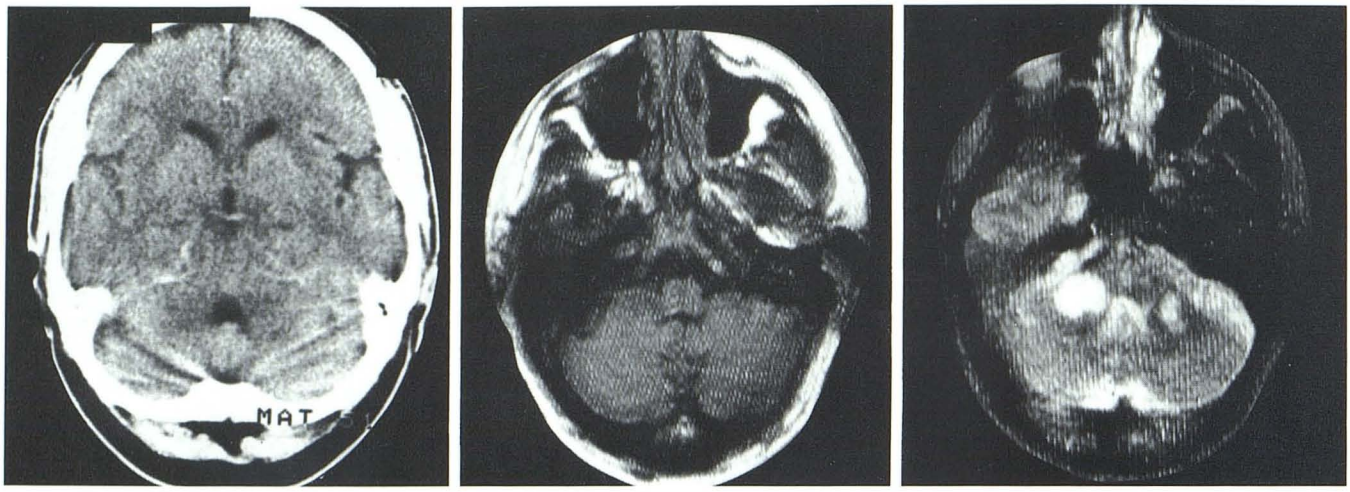
Fig. 4.—52-year-old man with classic signs and symptoms of MS. **A**, CT scan. Periventricular areas of decreased attenuation. **B**, SE scan, 30 msec TE, 0.5 sec TR, four buffers, 1.5 T, T1-weighted. One distinct and several poorly defined areas of decreased signal in periventricular region. **C**, 120 msec TE, 2 sec TR, four buffers, 1.5 T, T2-weighted. Multiple distinct areas of increased signal in periventricular region. **D**, CT scan at more cephalad level. Several indistinct areas of periventricular decreased attenuation. **E**, 120 msec TE, 2 sec TR, four buffers, 1.5 T, T2-weighted. At same level as **D**. Multiple areas of periventricular increased signal. Lesions can be clearly seen even though they have same signal intensity as CSF in ventricle.

been increased in signal. Two exceptions are calcified lesions and vessels with rapid blood flow. Calcified lesions may have variable amounts of paramagnetic material, resulting in variable signal; and blood vessels with rapid flow usually give a low signal because the MR signal is disrupted by protons moving out of the section or changing in position within the section of the examination, before their signal is detected [9, 10].

With T1-weighted images, we did not detect any lesions that could not be detected with T2-weighted images also. In one lesion in a patient with metastatic parotid tumor, the tumor was seen more clearly on the T1- than on the T2-weighted image. Past studies have shown that the benignancy versus malignancy of lesions identified on MR does not result in a consistent pattern of T1 and T2 values. It is hoped that future work with varying pulse sequences including those in the intermediate range may aid in specificity.

With heavily T2-weighted images, it is often impossible to distinguish metastatic lesions, MS, primary tumors, infection, and hemorrhage. The presence or absence of mass effect, as with CT, helps to differentiate tumors, infarcts, and MS plaques. Confinement of the lesion to the white matter and periventricular region points to MS. A potential use of the paramagnetic materials in the brain may be to help identify the etiology of lesions demonstrated with MR.

On T2-weighted images, the increased signal of metastatic lesions, primary brain tumors, MS plaques, and edema is most likely due to increased free water in these lesions, which is related to a variable degree of breakdown of the blood-brain barrier. We have found that heavily T2-weighted images give the greatest conspicuity between these lesions and the surrounding brain. The explanation for this is related to T1 and T2 relaxation rates, signal-to-noise ratios, and contrast-to-noise ratios, which in part depend on the magnetic field strength of the system [10]. With increasing field strength, T1 values increase about 30% from 0.5 to 1.4 T, while T2 values stay the same or decrease slightly [11]. At the pulse sequences used in our examinations, the relative gray scale



A B C

Fig. 5.—60-year-old man with persistent dizziness for 1 year with recent onset of slurred speech and blurred vision. Angiogram showed occlusion of basilar artery. **A**, Normal CT scan at level of fourth ventricle. **B**, 30 msec TE, 0.5 sec TR, four buffers, 1.5 T. This and all other T1-weighted images were normal. **C**, 120 msec TE, 2.0 sec TR, four buffers, 1.5 T. Areas of increased signal in cerebellar peduncles.

appearance for T1- and T2-weighted images as we have defined them did not change significantly between 0.6 and 1.5 T for the purpose of lesion identification. However, the crossover points for intermediately weighted images did change with increasing magnetic field strength. Lesions are seen less well when the SE radiofrequency pulse technique is selected near the crossover point of CSF and brain, such as at about 60 msec TE and 1.5 sec TR for a 0.6 T MR unit.

T1 relaxation rates represent an exponential growth of magnetization. The longer the TR, the stronger the signal. T2 relaxation rates, however, represent an exponential decay of magnetization. The longer the TE, the greater the signal loss and, therefore, the lower the signal-to-noise ratio of any given tissue. On a heavily T2-weighted image with a long TE, the image is less pleasing esthetically because of the lower signal-to-noise ratio of the tissue. However, with heavily T2-weighted images, lesions having increased free water content have a greater conspicuity because water has a much longer T2 relaxation time than does brain. In general, short TEs and short TRs produce T1-weighted images and long TEs with long TRs produce T2-weighted images.

Signal-to-noise ratios increase linearly with increasing field strength from 0.15 to 1.5 T [10, 12]. Although the difference in signal intensities between tissues such as gray matter and white matter and between lesions and surrounding normal tissues may decrease with increasing field strength above about 0.5 T, the contrast-to-noise ratio increases with increasing field strength up to at least 1.5 T.

The pulse parameter settings for a heavily T2-weighted image that will give the best conspicuity differ from one MR system to another. With our previous use of an MR system operating at 0.15 T, a heavily T2-weighted image did not give the best conspicuity of lesions because the lesion's signal decayed so much that it could not be differentiated from that of brain. The 0.15 T system had better differentiation of lesions on T1-weighted images (with a higher signal-to-noise ratio) in contrast to the 0.6 and 1.5 T systems, where there was better conspicuity of lesions with T2-weighted images.

The greatest lesion conspicuity occurs with an SE radiofrequency pulse technique, using TEs of 120–210 msec with TRs of 1–2 sec on a 0.6 T or 1.5 T MR system. When using these TRs, if the TEs are lengthened beyond 210 msec, the lesion conspicuity decreases because there is too much noise in the image or the contrast is too great for the dynamic range of the system.

With the SE technique, images acquire more T2-weighting by increasing the TR or the TE. Increasing the TR results in a linear increase in scanning time for both volume and multislice data acquisition techniques. It is more efficient to increase TE than TR to yield more T2-weighted images, since increasing TE does not alter the data acquisition time. The time for data acquisition for a section is Y matrix × TR × data points per buffer for either single slice or multislice technique and Y matrix × TR × data points/buffer × Z matrix for a volume acquisition technique. If the Z matrix is equal to the Y matrix, then the volume technique is isotropic and the images can be displayed in axial, coronal, sagittal, or oblique projections. However, for good-resolution images with isotropic techniques, the acquisition time becomes excessive. If the Z matrix is not equal to the Y matrix, then the volume technique is anisotropic and the images are acquired and displayed in one plane only.

After reviewing the literature and our own results, we conclude that heavily T2-weighted imaging is the most sensitive MR technique for detecting metastatic lesions to the brain, primary brain tumors, MS, infarcts, and inferentially all lesions of the brain. The sensitivity of the T2-weighted image is high but its specificity is low. Almost all brain lesions described in the literature have an increased signal relative to normal brain on a T2-weighted image (long TR, long TE). The

sensitivity of T1 SE images is not as high as that of T2-weighted images for the detection of lesions. Although the specificity of MR remains in doubt, it is hoped that it will improve with further experimentation in signal acquisition.

The main impetus for the development of paramagnetic ions for MR of the brain was to find a substance that would leak through the blood-brain barrier and enable differentiation of tumor from edema [13, 14]. Using the heavily T2-weighted SE pulse technique, there appears to be no longer a need to develop paramagnetic substances for this particular purpose. Paramagnetic ions for the examination of the brain may be useful in low-field-strength magnets where additional contrast from the paramagnetic material might make possible the demonstration of lesions that would not otherwise be seen and the detection of meningiomas and gray matter infarcts.

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