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Optimization of Sequence Parameters in Fast MR Imaging of the Brain with FLASH

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Owing to the intrinsically complex behavior of the signal intensity of fast gradient-refocusing MR sequences, agreement as to the clinically most useful sequence parameters has not yet been reached. This study evaluates the FLASH (fast low-angle shot) sequence for gray-white matter differentiation on normal volunteers at 1.5 T. The FLASH gradient-echo sequence is essentially T1-dependent. For very fast imaging and T1 weighting, the following parameters yield the best results: a flip angle of 30–50° with TR = 20 and TE = 10. To replace T1-weighted SE by the faster FLASH sequence, the best results are achieved by a flip angle of 70–120° with TR = 150–300 and TE = 10 (or shorter, if possible). The most valuable proton-density aspect is achieved by a flip angle of 30° with TR = 300 and TE = 16.

The recent development of fast MR imaging [1] has opened the door to new clinical applications. Because of the intrinsically complex behavior of signal intensity as a function of TR, TE, and pulse angle, agreement about the clinically most useful sequence parameters has not yet been reached. Finding optimal values for flip angle is a complex task, since the optimal angle depends on T1, T2, N(H) of the tissues, and TR and TE parameters [2]. We evaluated the FLASH (fast low-angle shot) gradient-refocusing imaging technique for gray and white matter differentiation.

Materials and Methods

Two sets of measurements with various parameters were obtained in normal volunteers (Table 1). The mean of the intensities of the two sets of measurements was used to obtain the contrast between gray and white matter plotted in Figures 1–6. The same data were used to illustrate the behavior of intensities for particular sets of parameters (Figs. 7–11). In Fig. 9, the results of an additional test are shown (FLASH = 10°; TR = 50, 100, 300, and 500; TE = 35) to illustrate the behavior of intensities for heavily T2-weighted FLASH sequences. The para- or supraventricular slice was chosen for optimization of the boundary between the gray and white matter.

All images were acquired on a 1.5-T Magnetom scanner with a matrix of 256 × 256, a slice thickness of 8 mm, and four acquisitions. The sequences were optimized as far as gradient values are concerned, but no special effort was made to optimize sampling times. The contrast-to-noise ratio between the gray and white matter (calculated by equation 1) was plotted as a function of increasing TR for various TEs (Figs. 1–6)

$$\frac{C}{N} = \frac{\mathrm{IWM} - \mathrm{IGM}}{1/2\ (\mathrm{SDWM} + \mathrm{SDGM})} \tag{1}$$

where IWM and IGM are intensity of the white and gray matter, and SDWM and SDGM are standard deviation of white and gray matter (the mean value of these standard deviations provides a measure for the noise). A positive contrast value means that the white matter is more intense than the gray matter (as in T1 weighting). Our evaluation did not include a study of slice profiles and their correlation with experimental parameters. Owing to the limitation to one RF pulse of limited duration, slice profiles may be expected to be somewhat poor, a

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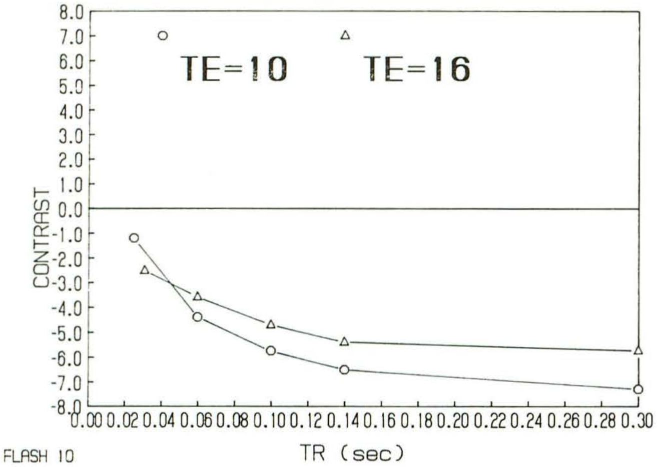

Fig. 1.—Contrast between gray and white matter by FLASH = 10° for different TEs as a function of TR.

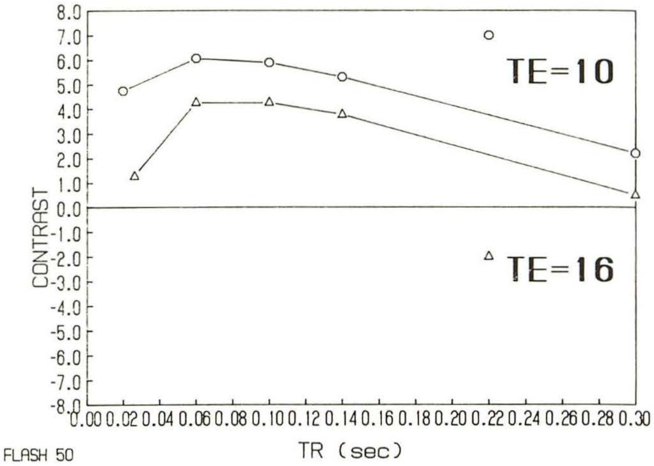

Fig. 3.—Contrast between gray and white matter by FLASH = 50° for different TEs as a function of TR.

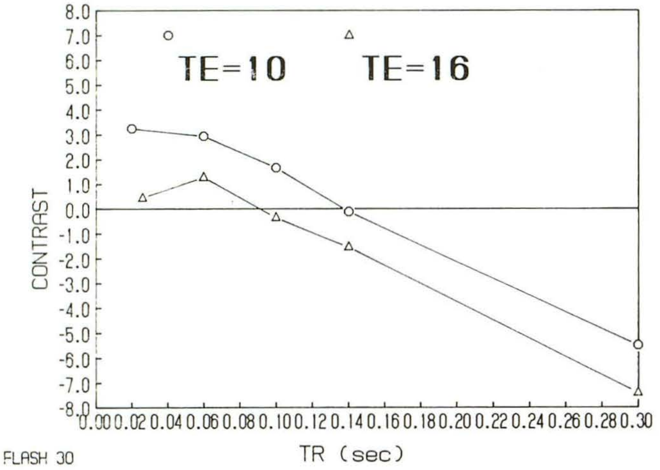

Fig. 2.—Contrast between gray and white matter by FLASH = 30° for different TEs as a function of TR.

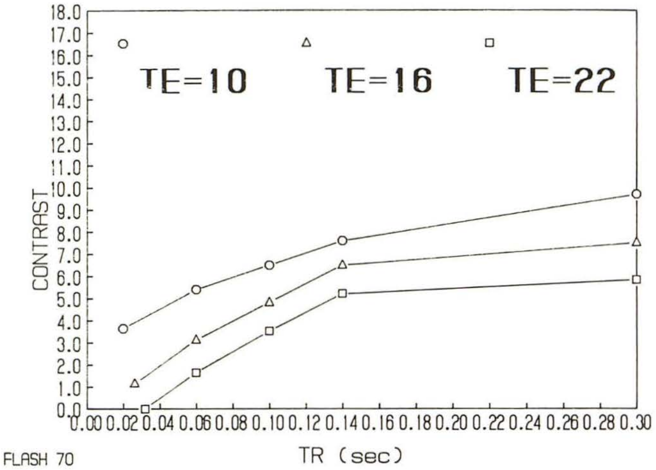

Fig. 4.—Contrast between gray and white matter by FLASH = 70° for different TEs as a function of TR.

TABLE 1: Parameters Used for FLASH Imaging

Flip Angle (degrees)	TR (msec)	TE (msec)
10	20	10
30	60	16
50	100	22[a]
70	140	(35)[b]
90	280	–
120	–	–

[a] It was technically impossible to test for flip angles of 10°, 30°, and 50°, because the signal intensity was too low.

[b] Tested only for FLASH = 10°, TR = 50, 100, 300, 500.

problem that can be alleviated by using adequate slice gaps (100% or more). Visual evaluations was made by two independent neuroradiologists.

Results

For nearly all sets of parameters, FLASH images behave like T1-weighted SE images (the white matter is more intense than gray matter) (Fig. 12). Only for small flip angles (10°) is T2 weighting—or, more exactly, a proton-density aspect—achieved (the gray matter is more intense than white matter, the CSF being relatively isointense with gray matter) (Figs. 1 and 13).

For a flip angle of 30°, the proton-density aspect is only obtained by using long TRs (Fig. 2). This behavior is in good agreement with theoretical predictions, because, effectively, a proton-density weighting is achieved with small flip angles (flip angle <25°) [3]. T2-weighted images can be produced as quickly as T1-weighted SE images by using a small pulse angle, a long TE [3], and also a longer TR. Because of the reversal of intensities at intermediate TRs, only very short TR (20 msec) and long TR (300 msec) give clinically useful gray-white matter contrast for the flip angle of 30°.

For a flip angle of 50° (Fig. 3), the best contrast was achieved for a short TE of 10 msec and a TR between 60 and 100 msec. A longer TR leads to decreased contrast. It is also for this flip angle that the highest gray-white matter contrast was achieved by using the very short TR of 20 msec.

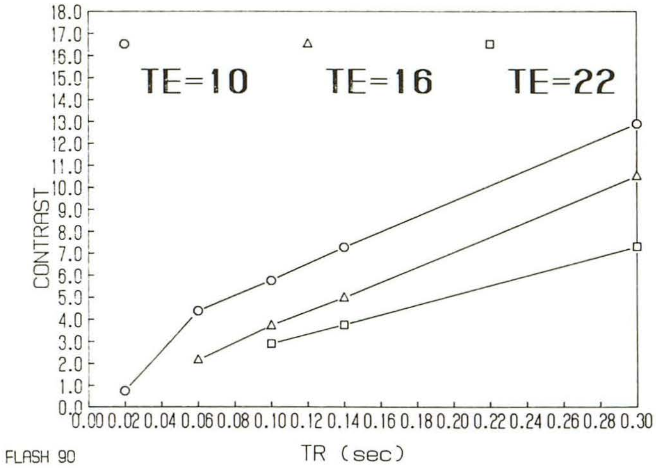

Fig. 5.—Contrast between gray and white matter by FLASH = 90° for different TEs as a function of TR.

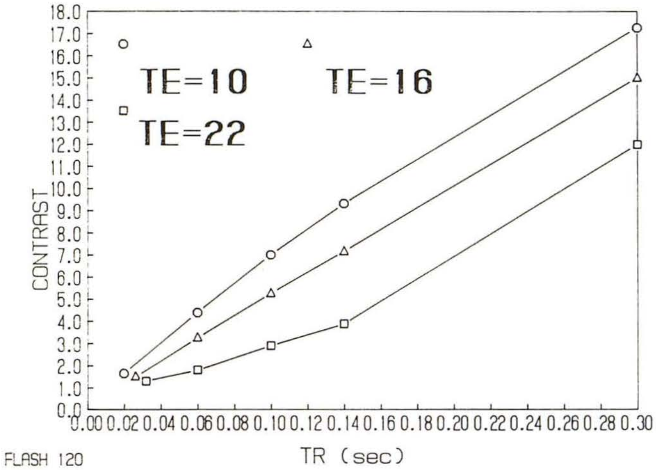

Fig. 6.—Contrast between gray and white matter by FLASH = 120° for different TEs as a function of TR.

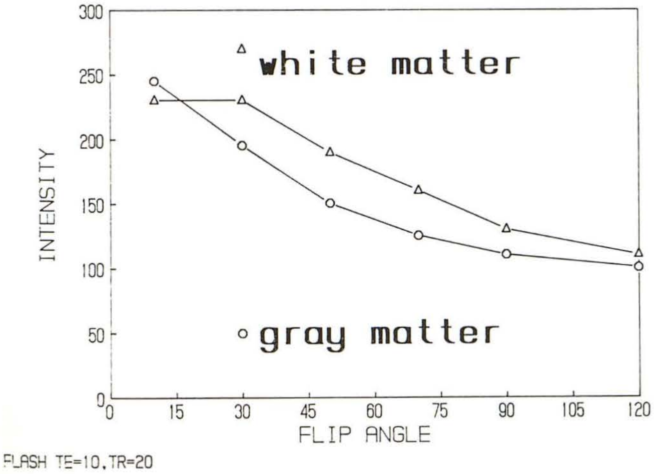

Fig. 7.—Signal intensity of the gray and white matter by FLASH for TR = 20, TE = 10 as a function of flip angle.

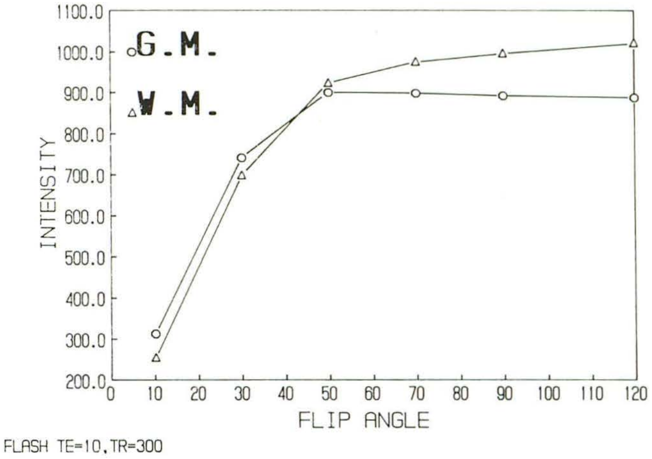

Fig. 8.—Signal intensity of the gray and white matter by FLASH for TR = 300, TE = 10 as a function of flip angle.

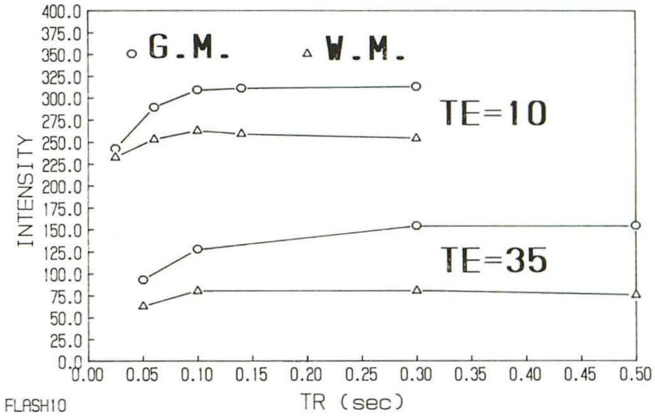

Fig. 9.—Signal intensity of the gray and white matter by FLASH = 10° for different TEs as a function of TR.

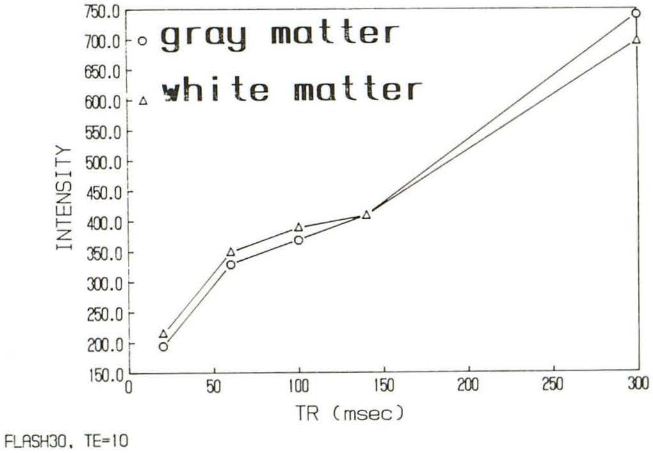

Fig. 10.—Signal intensity of the gray and white matter by FLASH = 30° for TE = 10 as a function of TR.

For larger flip angles (70°, 90°, 120°) (Figs. 4–6), behavior was similar: contrast increased with longer TR, larger flip angle, and shorter TE.

Discussion

The very high signal from CSF, as described with the GRASS technique [4], is not present with FLASH. The use of a spoiler is responsible for this behavior (the residual transverse magnetization is not converted into longitudinal magnetization).

The behavior of the signal intensity of white and gray matter for short TR and TE as a function of the flip angle (Fig. 7) is similar to GRASS [4]: proton-density-weighted effect for a very small flip angle (between 10 and 15°) and T1-weighting effect from 30° onward. For long TR (300) (Fig. 8), the proton-density effect is obtained up to a flip angle of 30–40° (in GRASS up to 15–20°) [4]. The best contrast is achieved with a flip angle of 10°, but the signal-to-noise ratio becomes critical for longer TEs (16–35 msec) (Fig. 9). The contrast for FLASH = 10 with TR = 300 and TE = 10 is equivalent to FLASH = 30 with TR = 300 and TE = 16, the latter giving much higher signal than FLASH = 10. The behavior of gray-white matter contrast with a small flip angle of 30° and a short TE of 10, as a function of TR, is different from GRASS [4]: the T1 effect is present for very short TR, and the proton-density effect only appears with longer TRs (from 140 msec) (Figs. 2 and 10).

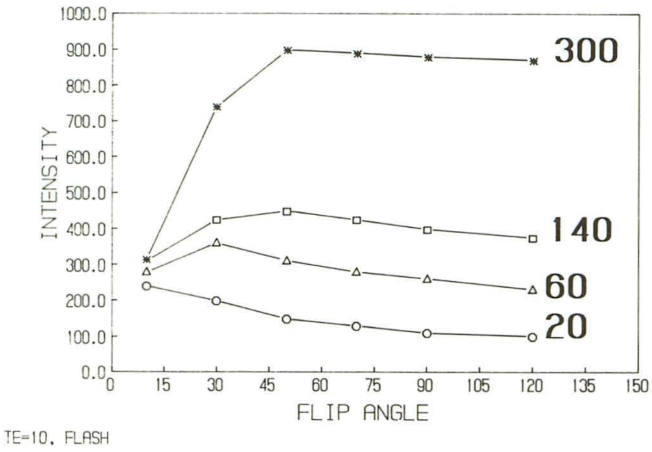

Fig. 11.—Signal intensity of the gray matter as a function of flip angle and TR (TE=10).

This behavior is important in clinical use because with the longer TR of 300, the number of available slices is increased. Furthermore, the signal intensity is higher, yielding a good signal-to-noise ratio.

About 70% of the gray-white matter contrast of the T1-weighted SE sequence (600/15/2) was achieved with flip angles of 70° and 90° with TR of 140 (TE = 10), and with a flip angle of 120° with TR = 100 and onward. One-hundred percent of the gray-white matter contrast of the T1-weighted SE sequence was achieved with flip angles of 90° and 120° with a TR of 300 (TE = 10) and onward. For all values of flip angle and TR, the longer TE has the effect of increasing proton-density weighting, but always with a lowering of signal intensity and therefore of signal-to-noise ratio (eventually clinically useful for proton-density-weighted FLASH = 30° with TR = 300 and TE = 16).

Three clinical situations can be considered in fast gradient-refocusing imaging of the brain: (1) very fast imaging with unavoidable loss of signal intensity but with minimal loss of contrast (e.g., in dynamic MR after contrast injection) [5]; (2) imaging faster than T1-weighted SE but without loss of signal intensity and contrast resolution (e.g., to improve the effectiveness of the examination per unit time); and (3) imaging faster than proton-density-weighted SE with limited loss of contrast (to replace long TR, short TE SE).

The intensity of the signal for very short TR is strongest for small flip angles (Fig. 7). For longer TRs, the behavior is more complex. Initially, the intensity of the signal increases (up to 40°) and then decreases with greater flip angles (Fig. 11). Furthermore, for a given flip angle, the signal intensity is always stronger for longer TRs. This is important if we wish

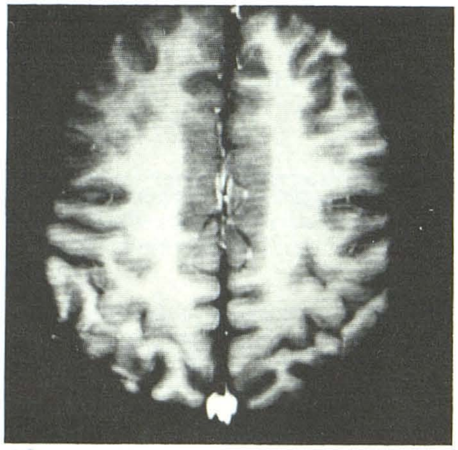

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Fig. 12.—Axial, supraventricular slice with FLASH = 120° (300/10/4). The white-gray matter contrast and signal intensity are comparable with classical T1-weighted spin echo. Note the very high signal from flowing blood.

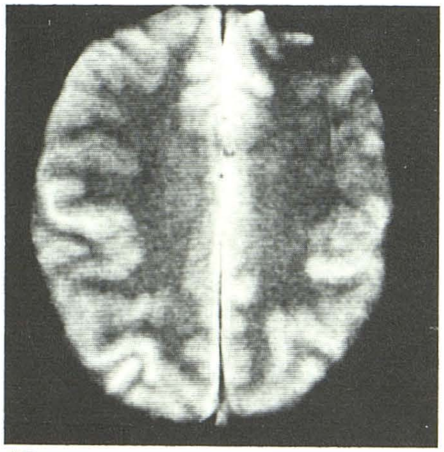

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Fig. 13.—Axial, supraventricular slice with FLASH = 10° (300/10/4). The contrast behavior is comparable to proton-density spin echo.

to perform very fast imaging with short TR. In this case, in order to keep the signal-to-noise ratio at a reasonable level, we have to choose small flip angles and short TE (e.g., angle = 30°, TR = 20, and TE = 10). If we consider the contrast between the gray and white matter for TR = 20 or 60, the best results are achieved with the flip angle of 50°.

For TR = 300, the signal intensity is comparable to T1-weighted SE for flip angles equal to or greater than 50°. The contrast resolution is equivalent to SE for flip angles of 70° and 90° with TR = 300 and for a flip angle of 120° with TR = 150. We are currently evaluating the value of FLASH for the second application (replacement of T1-weighted SE by faster FLASH). The initial findings confirm the previous results. All pathologic images visualized on conventional T1-weighted SE images can be visualized with FLASH = 70°, using TR = 140, TE = 10, and four acquisitions (the time gain is 50%). In some cases (namely, multiple sclerosis plaques and hematoma) (Figs. 14 and 15), the value of FLASH was superior to SE (probably because of the cumulative effect of T1- and T2-dependence of FLASH). Nevertheless, the quality of FLASH can be seriously lowered by susceptibility artifacts, especially at the air-bone boundary (typically at the level of the sella turcica). To overcome this problem, the use of a TE that is as short as possible (e.g., 6) should attenuate these artifacts.

The same contrast level (with proton-density effect) is achieved by FLASH = 30° with TR = 300 and TE = 16, and by FLASH = 10° with TR = 300 and TE = 10. Because the signal intensity for FLASH = 30° with TR = 300 and TE = 16 is three times larger than that obtained for FLASH = 10° with TR = 300 and TE = 10, the former parameters will be more useful for this indication.

The possibility of replacing SE with long TR, short TE by FLASH = 30° with TR = 300 and TE = 16 remains to be evaluated. Our initial experience suggests that this sequence will not be sufficiently sensitive to replace long TR, short TE SE.

In summary, the results of this study concern gray-white matter differentiation and were achieved on 1.5-T system.

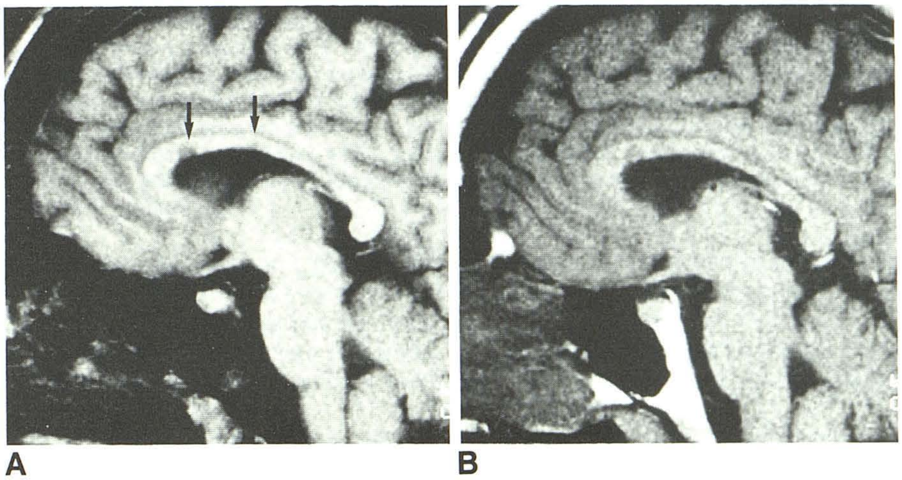

Fig. 14.—*A*, Sagittal slice with FLASH = 70° (150/10/4). Very good visualization of multiple sclerosis plaques in corpus callosum (*arrows*).

B, Identical slice as in *A*, except with SE (600/15/2). The multiple sclerosis plaques are difficult to distinguish.

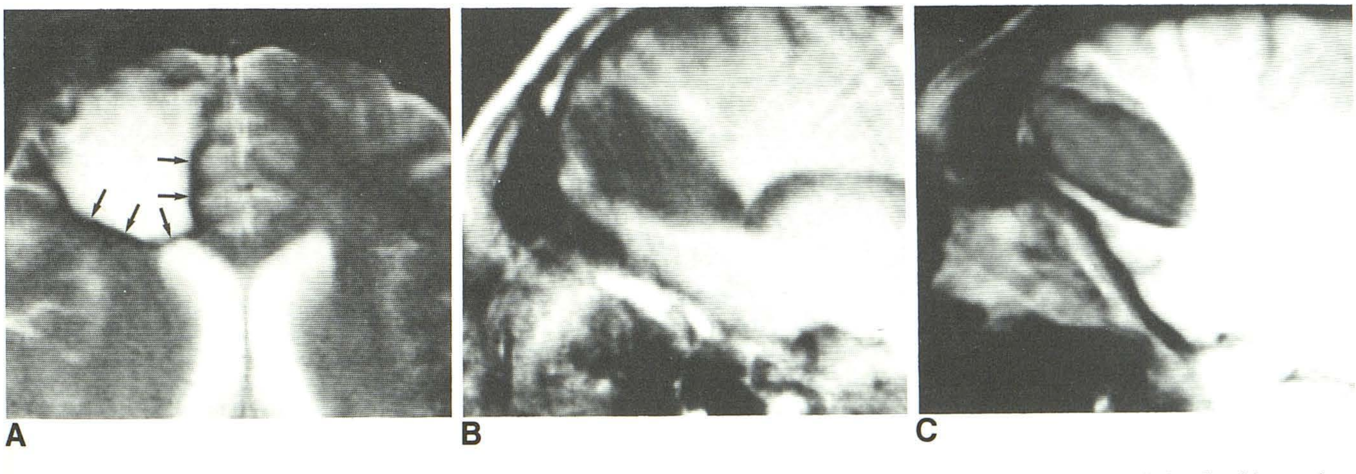

Fig. 15.—*A*, Axial T2-weighted SE image of old frontal hematoma. The typical low signal from residual hemosiderin layer is well visualized (*arrows*).

B, Sagittal T1-weighted SE (600/15/2) of same patient. The hemosiderin deposits are not visible.

C, Identical slice as in *B*, except with FLASH = 70° (150/10/4). The hemosiderin layer is well seen as a low-intensity band.

The FLASH gradient-echo sequence from Siemens is essentially a T1-dependent sequence. If we aim at very fast imaging and T1 weighting (e.g., TR = 20), the following parameters have to be used: flip angle of 30° with TR = 20 and TE = 10 if the signal-to-noise ratio is important; and flip angle of 50° with TR = 20 and TE = 10 if the contrast between the white and gray matter is the most important factor.

If we want to replace T1-weighted SE by a faster FLASH sequence, the following parameters have to be used: flip angle of 70–120°, TR of 150 or 300, and TE as short as possible (e.g., 10 msec).

The possibility of replacing the proton-density-weighted SE by proton-density-weighted FLASH (flip angle = 30°, TR = 300, TE = 16) has to be evaluated by clinical studies [6].

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