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MR Imaging Using Stimulated Echoes (STEAM)[1]

The introduction of STEAM (stimulated echo acquisition mode) magnetic resonance (MR) sequences provides access to a variety of MR parameters. T1-weighted and calculated T1 proton MR images of the head of healthy volunteers and a patient with an astrocytoma are presented. MR examinations were performed with a 2.0-T whole-body system. The STEAM T1 method can be used to characterize multiexponential relaxation behavior, to evaluate T1 relaxation times, and to improve the T1 contrast within MR images. Both the measuring time and the spatial resolution are the same as for a conventional image.

Index terms: Brain, MR studies, 10.1299 • Magnetic resonance (MR), physics

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EARLY relaxation time studies of normal and pathologic tissues (1) have indicated the importance of spin-lattice relaxation times (T1) in medical applications of magnetic resonance (MR) imaging. T1-weighted MR images normally are obtained by inversion-recovery (IR) and/or saturation-recovery (SR) techniques. However, for calculation of T1 images at least two separate IR and/or SR experiments with different inversion and/or repetition times have to be performed.

Some of us recently have designed an MR imaging technique dubbed STEAM (stimulated echo acquisition mode) imaging, which is based on the acquisition of stimulated MR echoes (2–4). Although the intensity of a stimulated echo is only half that of a spin echo, an important feature of STEAM MR is the access to continuously variable T1 contrasts as well as to multipoint T1 imaging experiments. Thus, a complete series of images with different T1 weightings can be obtained without the need for increasing the measuring time. This is due to the fact that stimulated echoes directly depend on both T1 and T2 relaxation times. The influence of T1 and T2 can be varied independently by adjusting the length of two different intervals within the STEAM sequence. Here we present our results with STEAM T1 imaging in healthy volunteers and a patient with an astrocytoma.

METHODS

MR imaging was performed with a research system (Philips, Forschungslaboratorium, Hamburg) using a 1-m bore, 2.0-T (Oxford Magnet Technology, Oxford) superconducting magnet operating at a proton resonance frequency of 85 MHz. The experiments were based on STEAM imaging sequences previously described (2, 3). The echo time (TE) of the sequences was 25 msec. The repetition time (TR) was about 1.1 sec for multisection STEAM imaging and 2.3 sec for single-section multipoint STEAM T1 imaging. The corresponding measuring times were about 9 min and 19 min, respectively, for 256 × 256 pixel images with two excitations. Multiplanar imaging has been limited to eight contiguous sections owing to actual software limitations. The eight-point single-section T1 measurements suffer from the same restriction.

The basic radio frequency (RF) sequence for MR imaging using stimulated echoes (STE) (1) is

$$90° - TE/2 - 90° - TM$$

$$- 90° - TE/2 \text{ (STE)}.$$

In the multisection STEAM experiment the first pulse nonselectively excites transverse magnetizations of the entire volume. The second pulse realigns these phase-encoded magnetizations along the direction of the static field. During the middle interval (TM) their intensities decrease with T1. The third section-selective RF pulse "reads" the magnetizations of a certain plane by creating a stimulated echo. The remaining longitudinal magnetizations further decline with T1. For multisections the last period is repeated n times to measure n sections. Thereby, the individual sections acquire different T1 contrasts depending on the increase in TM. Strong T1 contrasts for all sections can be obtained by selecting a long initial TM interval.

Figure 1 shows a schematic diagram for multipoint T1 imaging. In the single-section version used here the first pulse is section-selective. The read pulses probe the actual longitudinal magnetization of the section at different times (i.e., increasing TM values). For this purpose they employ flip angles of less than 90°, which should excite equal amounts of magnetization. Thus, the resulting n stimulated echo signals represent only part of the entire "stored" longitudinal magnetization, with the echo heights decreasing according to the T1 relaxation curve. The whole imaging sequence results in n T1-weighted images (here, $n = 8$). Image artifacts owing to unwanted echoes resulting from the successive read pulses are not produced because of the dephasing action of the read gradient during the relaxation delays. Taking the series of T1-weighted

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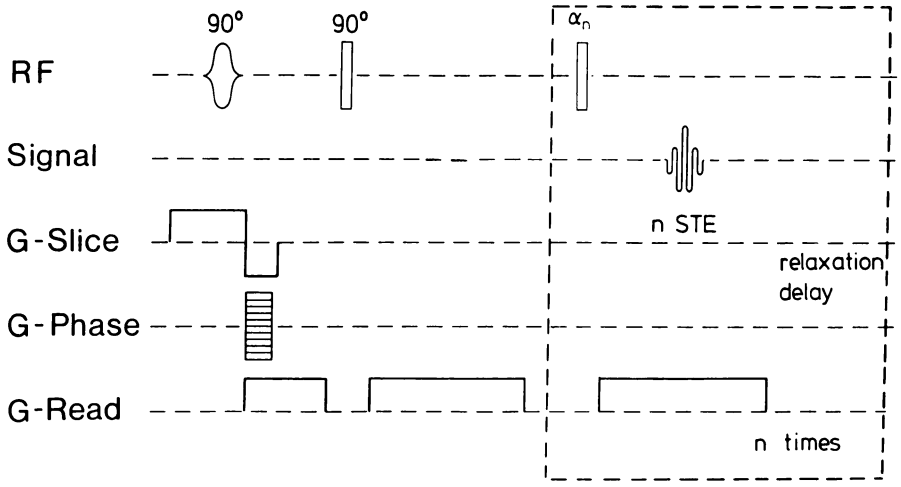


Figure 1. Schematic diagram of an RF and gradient-pulse sequence for single-section *n*-point STEAM T1 imaging. Frequency-selective pulses are represented by Gaussian-shaped pulses; nonselective pulses are represented by rectangles. The *n* read pulses have flip angles of less than 90°. They create *n* stimulated echoes (STE) with increasing T1 weighting.

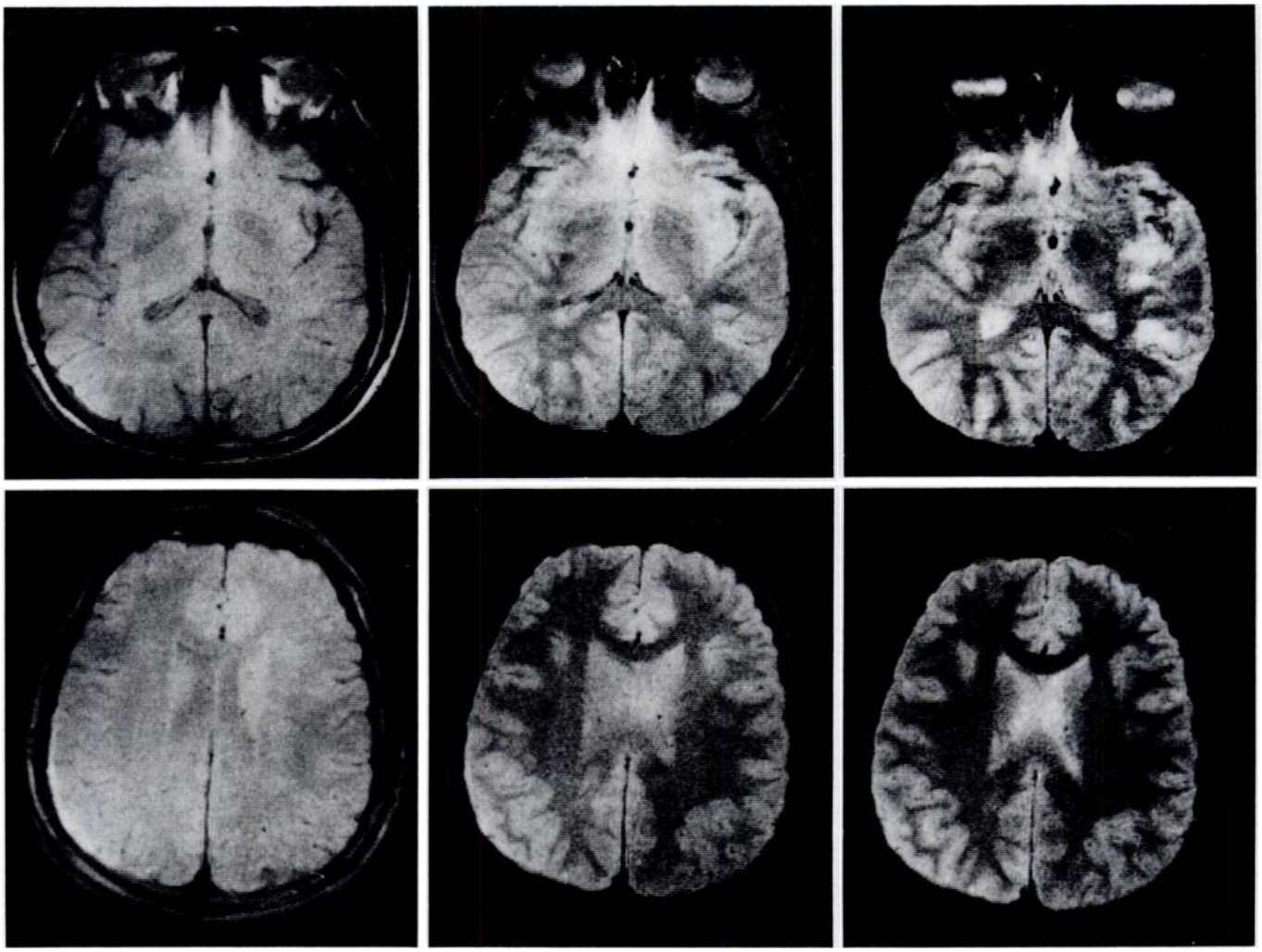


Figure 2. Transaxial multisection proton MR images of the head of a healthy volunteer demonstrate the accessible T1 contrast using STEAM imaging. The length of the interval TM increases from 60 msec (left) to 260 msec (middle) to 460 msec (right). The T1 contrast between the sections is slightly different because TM increases from section to section by about 30 msec. The repetition time was 1.1 sec, 1.3 sec, and 1.5 sec. The section thickness was 5 mm.

images, true T1 images are calculated by a linear least-squares fit to a monoexponential decay. In the present applications no multiexponential behavior has been detected. In cases where the flip angles of the read pulses do not increase according to the theoretical optimum (3), the computation has to deal with a manipulated relaxation curve. Here we have used eight 25° read pulses and corrected for the apparent relaxation due to the sampling. T1 values with correlation coefficients of less than 0.8 have not been included in the calculated images.

RESULTS

The T1 contrast accessible with STEAM MR is clearly demonstrated on multisection images of the human brain. Figure 2 shows three series of eight contiguous transaxial sections

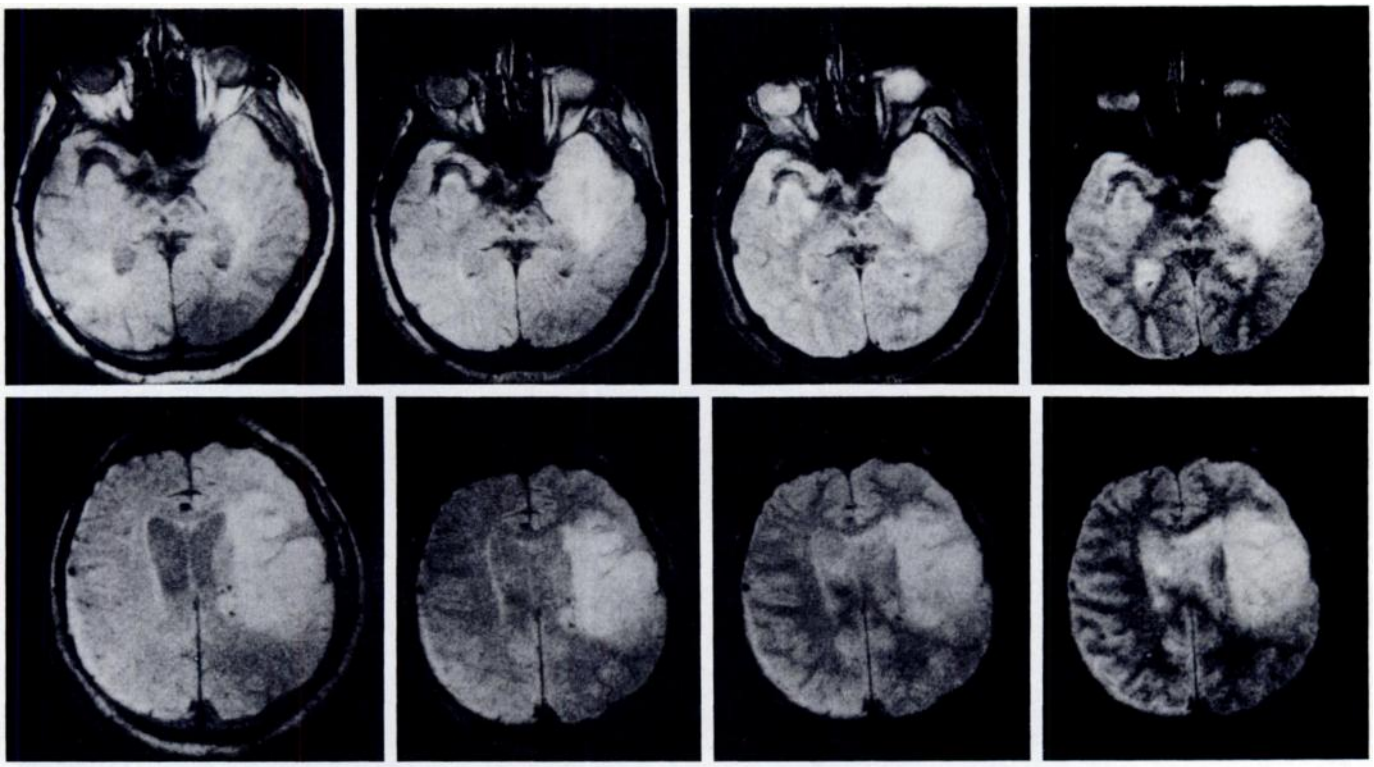
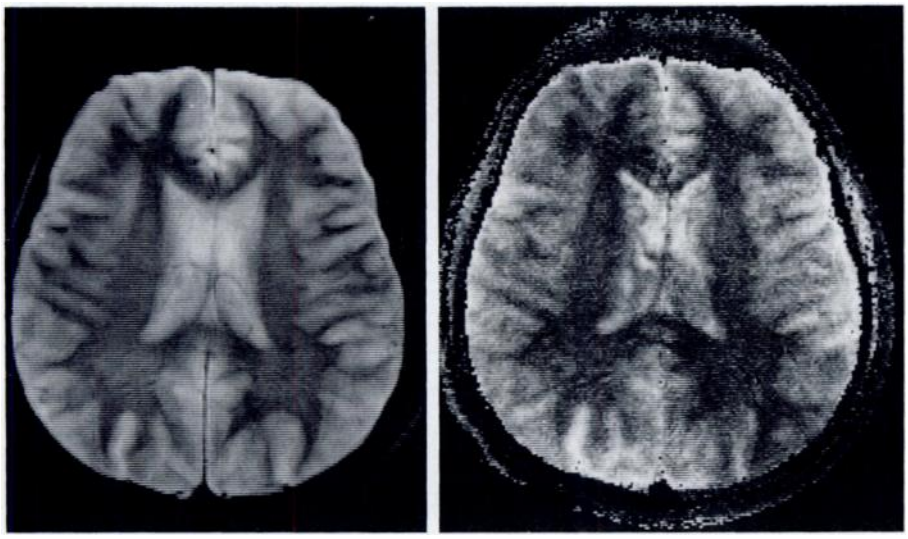


Figure 3. Transaxial multisection proton MR images of a patient with an astrocytoma. The length of the interval TM increases from 60 msec (left) to 260 msec (middle, left), to 460 msec (middle, right), to 860 msec (right). The repetition time was 0.9 sec, 1.1 sec, 1.3 sec, and 1.7 sec, respectively. The section thickness was 5 mm.



a. b.

Figure 5. **(a)** Summed T1-weighted image and **(b)** true T1 image calculated pixelwise from the data shown in Figure 4. The image covers a range of T1 values from 0 to 2.5 sec, with high intensities for long relaxation times.

through the head of a healthy volunteer, with initial TM values of 60 msec, 260 msec, and 460 msec. Obviously, the contrast between structures with high T1 values, such as gray matter and cerebrospinal fluid, and those with low T1 values, such as white matter, is strongly enhanced with increasing TM. Figure 3 shows transaxial sections of the brain of a patient with an astrocytoma in the right frontal lobe. The four series of images are recorded with initial TM values ranging from 60 msec to 860 msec. The lesion exhibits long T1 values, which lead to enhanced signal intensities in the late STEAM images. In contrast to late spin-echo images, these strongly T1-weighted images retain the T1 contrast of gray and white matter.

An important economic and scientific aspect of STEAM T1 experiments is the determination of T1 images within the measuring time of a conventional MR image. The images of the normal brain (See Figure 4 on following page) represent different T1 weightings of the same transaxial section obtained within a single experimental run using the sequence of Figure 1. Although the flip angle of the read pulses is only 25°, signal-to-noise is sufficient to calculate T1 values pixelwise without averaging. The resulting true T1 image and a summed image of all eight T1-weighted images are displayed in Figure 5. The T1 contrast and the signal-to-noise ratio of the summed image allow a delineation even of small anatomical structures such as vessels. Together with T1 data recently reported by some of us for muscle and bone marrow at 2.3 T (4), Figure 5 presents (to our knowledge) the first in vivo T1 values for the human brain at 2.0 T. The values are 0.73 sec ± 0.1 for white matter, 1.0 sec ± 0.15 for gray matter, and 1.8 sec ± 0.2 for cerebrospinal fluid. These values are in agreement with in vitro results (5).

CONCLUSION

This work presents the application of a technique for quantitative T1 MR imaging using a 2.0-T whole-body

MR system. For routine medical use, the STEAM T1 method offers the simultaneous recording of a large number of T1-weighted images of contiguous sections with arbitrary repetition times. Its major advantages are (*a*) the access to strong and continuously variable T1 contrasts and (*b*) a determination of accurate T1 values from multipoint T1 images without the need for increasing the measuring time. STEAM T1 imaging can improve the reliability of relaxation data from MR images. Clinical studies are needed to evaluate the relative merits of a calculated T1 image versus a T2 image in the detection and diagnosis of disease. ■

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References

1. Damadian R. Tumor detection by nuclear magnetic resonance. Science 1971; 171:1151–1153.
2. Frahm J, Merboldt KD, Hänicke W, Haase A. Stimulated echo imaging. J Magn Reson 1985; 64:81–93.
3. Haase A, Frahm J. NMR imaging of spin-lattice relaxation using stimulated echoes. J Magn Reson 1985; 65:481–490.
4. Matthaei D, Frahm J, Haase A, Merboldt KD. Hänicke W. Multi-purpose NMR imaging using stimulated echoes. Magn Reson Med 1986; 3:554–561.
5. Bottomley PA, Foster TH, Argersinger RE, Pfeifer LM. A review of normal tissue hydrogen NMR relaxation times and relaxation mechanisms from 1-100 MHz: dependence on tissue type, NMR frequency, temperature, species, excision, and age. Med Phys 1984; 11:425–448.

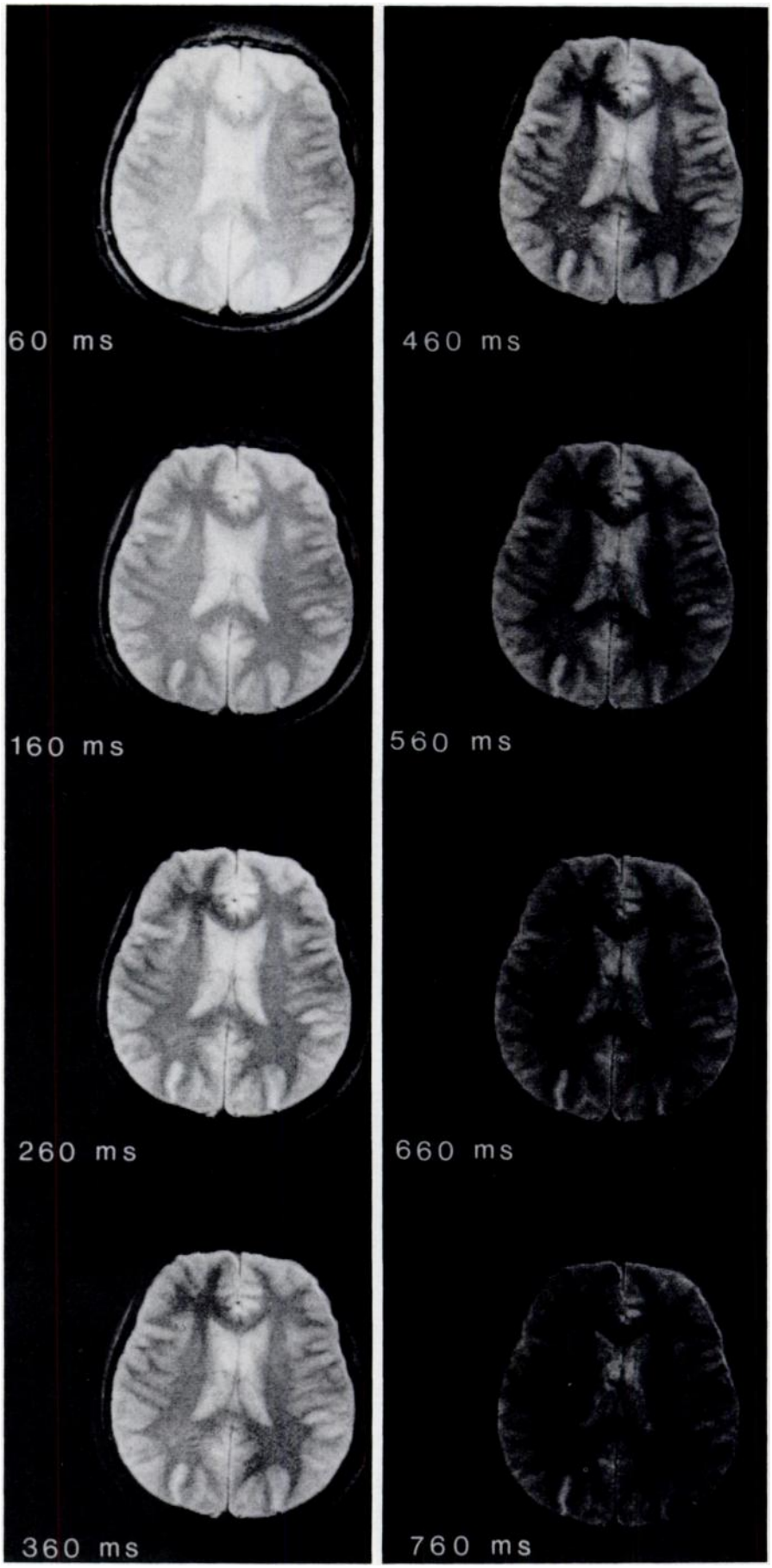

Figure 4. Transaxial single-section eight-point T1-weighted proton MR images of the head of a healthy volunteer. All images have been recorded simultaneously using the sequence shown in Figure 1 with $n = 8$, 25° read pulses, and relaxation delays corresponding to TM values increasing from 60 msec to 760 msec. The repetition time was 2.3 sec. The section thickness was 10 mm.