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GRASE (Gradient- and Spin-Echo) MR Imaging: A New Fast Clinical Imaging Technique[1]

A novel technique of magnetic resonance (MR) imaging, which combines gradient-echo and spin-echo (GRASE) technique, accomplishes T2-weighted multisection imaging in drastically reduced imaging time, currently 24 times faster than spin-echo imaging. The GRASE technique maintains contrast mechanisms, high spatial resolution, and image quality of spin-echo imaging and is compatible with clinical whole-body MR systems without modification of gradient hardware. Image acquisition time is 18 seconds for 11 multisection body images (2,000/80 [repetition time msec/echo time msec]) and 36 seconds for 22 brain images (4,000/104). With a combination of multiple Hahn spin echoes and short gradient-echo trains, the GRASE technique overcomes several potential problems of echo-planar imaging, including large chemical shift, image distortions, and signal loss from field inhomogeneity. Advantages of GRASE over the RARE (rapid acquisition with relaxation enhancement) technique include faster acquisition times and lower deposition of radio-frequency power in the body. Breath holding during 18-second GRASE imaging of the upper abdomen eliminates respiratory-motion artifacts in T2-weighted images. A major improvement in T2-weighted abdominal imaging is suggested.

Index terms: Abdomen, MR studies, 70.1214 • Brain, MR studies, 13.1214 • Magnetic resonance (MR), comparative studies • Magnetic resonance (MR), echo planar • Magnetic resonance (MR), rapid imaging • Magnetic resonance (MR), technology

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While magnetic resonance (MR) imaging has improved rapidly over the last decade, it is remarkable that multisection two-dimensional Fourier-transform spin-echo imaging (1) with T2 weighting has remained a standard of reference for routine clinical MR imaging studies of the body and head. Since the earliest studies in 1982, there has been a progressive reduction in image acquisition time. Improvements in MR-imager hardware and pulse-sequence design have permitted faster imaging times by reducing the number of signals averaged (NSA) used to raise the signal-to-noise ratio (S/N) in images. Conjugate synthesis of data (half Fourier or NSA = ½) yields nearly another factor-of-two reduction in imaging time by taking advantage of a natural symmetry in the k-space data to halve the number of phase-encoded signals (2,3). For clinical imaging, it is significant that the conjugate synthesis method produces tissue contrast, chemical shift, and spatial resolution identical to that of spin-echo imaging with one excitation. Whereas the conjugate synthesis method produces an expected 35%–41% reduction in image S/N, this S/N is acceptable for many T2-weighted examinations.

An alternative approach for fast T2-weighted imaging is the rapid acquisition with relaxation enhancement (RARE) technique (4). The hybrid RARE technique, also called fast spin-echo imaging, reduces imaging time by performing phase encoding both in trains of multiple spin echoes and during multiple cycles (repetition times [TRs]) of signal excitation. While there is a reduction in the number of image sections and in S/N, the hybrid RARE technique currently has a four- to 16-fold reduction in imaging time from that of spin-echo imaging with one excitation and has tissue contrast similar to that of the spin-echo technique. In hybrid RARE imaging, the rapid application of a large number of 180° radio-frequency (RF) pulses produces considerably higher deposition of RF energy in the human body at the standard absorption rate (SAR). Although SAR increases with shorter time intervals between RF pulses, the speed of RARE imaging is ultimately limited by the time requirements of section-selective 180° RF pulses during which signal cannot be acquired.

In echo-planar imaging (5), signals are produced by rapid switching of gradient polarity in place of the slower selective 180° RF pulses. In this way, echo-planar imaging and its modern variants, modulus-blipped echo-planar single-pulse technique (MBEST) (6) and Instascan (Advanced NMR, Woburn, Mass) (7), both involving use of a single 180° RF pulse, can produce an image in less than 100 msec. At high magnetic field strengths, methods of echo-planar imaging produce a large amount of chemical shift on the phase axis of images, typically 10–15-pixel misregistration between water and fat. This problem can be circumvented by using fat-suppression methods. These single-shot images, however, have lower spatial resolution and S/N than spin-echo images. This can be improved by using multiple excitation

Abbreviations: CPMG = Carr-Purcell-Meiboom-Gill, GRASE = gradient echo and spin echo, MBEST = modulus-blipped echo-planar single-pulse technique, NSA = number of signals averaged, RARE = rapid acquisition with relaxation enhancement, RF = radio frequency, SAR = standard absorption rate, S/N = signal-to-noise ratio, TE = echo time, TR = repetition time.

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cycles (multiple TRs) that lengthen imaging times. Other stringent requirements of echo-planar imaging include static magnetic fields with good homogeneity (better than 0.3 ppm for head imaging with a 1.5-T system) to avoid signal loss and image distortions resulting from inhomogeneity-induced phase errors. All echo-planar imaging variants require strong magnetic gradients with fast rise times, which to date has limited their application to a handful of research centers. It is significant that the subsecond imaging time of echo-planar techniques eliminates artifacts caused by both respiratory and cardiac motion.

In this article, a novel technique of MR imaging, which combines gradient echo and spin echo (GRASE) techniques, enables T2-weighted abdominal imaging in less than 18 seconds. This is sufficiently fast to permit breath holding during image acquisitions to eliminate respiratory-motion artifacts, currently not possible in clinical T2-weighted spin-echo studies of the abdomen performed with acquisition times of 4–8 minutes.

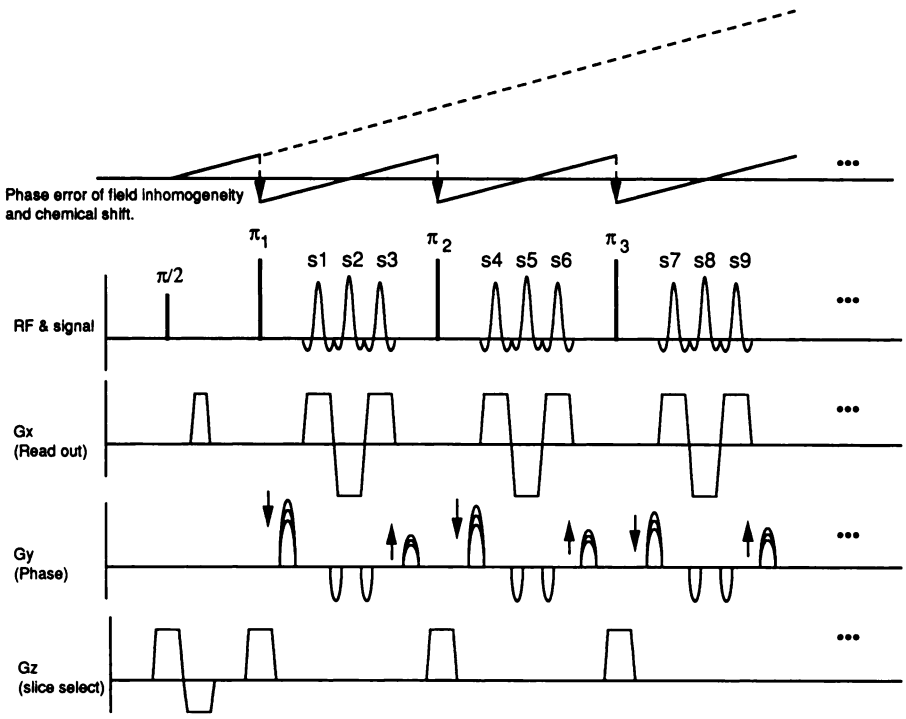


Figure 1. Pulse-sequence diagram of the GRASE technique. An echo train is formed with the Carr-Purcell-Meiboom-Gill (CPMG) sequence with selective 180° RF pulses (π_1, π_2, . . .) and multiple signal readout gradient (Gx) reversals. With the multiple 180° pulses, phase errors due to field inhomogeneity and chemical shift are greatly reduced in magnitude and are periodically reproduced throughout the echo train. In echo-planar imaging, with the absence of 180° pulses there would be a large accumulation of phase errors and chemical shift (dashed line). The 24 echoes are phase-encoded differently by the gradient pulses in the phase-encoded direction (Gy). In each excitation cycle (TR), the strength of certain Gy pulses are changed (down-directed arrows) to offset the phase position in k space, while the pairs of negative Gy pulses maintain constant large jumps in the k-space trajectories. (The k-space location of signals [*s1–s9*] is shown in Fig 2.) By using refocusing pulses (up-directed arrows), the net accumulated Gy phase shift is returned to zero before each 180° RF pulse. Here, three readout gradient reversals (N_{GR} = 3) are shown, and only three of the eight RF refocused spin-echo periods (N_{SE}) are shown.

MATERIALS AND METHODS

GRASE Technique

The technique of combining gradient echoes with spin echoes is shown in the pulse-sequence diagram (Fig 1). A train, or number of RF refocused spin echoes (N_{SE}), is produced by using the CPMG spin-echo sequence. Centered about each spin echo, a number of gradient-recalled echoes (N_{GR}) are produced by switching the polarity of the readout gradient. The speed advantage over standard spin-echo imaging is proportional to the total number of echoes per 90° excitation and equals $N_{GR} \times N_{SE}$. The effective echo time of the image is the time at which the origin of k space (zero order phase encode) is sampled, near the middle of the echo train.

In GRASE imaging, the use of 180° RF pulses to nutate or reverse the position of spins leads to the nulling of field inhomogeneity errors at the Hahn spin-echo time (8), eliminating image distortions and loss of S/N. Small field-inhomogeneity errors evolve within each group of N_{GR} echoes during the relatively short time between each gradient-recalled echo and the center of their respective spin echo. In a similar way, the modern echo-planar imaging techniques, MBEST (6) and Instascan (7), involve use of a single 180° RF pulse, but with greater field-inhomogeneity error, proportional to half the time of the gradient-echo train typically composed of 64–128 signals.

Common to both GRASE and echo-planar imaging, chemical shift is greater on the phase axis of the image than on the read (frequency) axis as a result of frequency sensitivity through the echo train. In GRASE imaging, the chemical shift is proportional to the time interval of the short echo train with N_{GR} echoes, whereas in echo-planar imaging, the chemical shift is proportional to the longer time of the gradient-echo train composed of 64–128 echoes.

The GRASE pulse sequence is more complicated than a simple combination of spin echo with gradient echo, since the relatively small field-inhomogeneity phase errors recur identically in each group of N_{GR} echoes between successive 180° RF pulses, as shown in Figure 1. If phase encoding is continuously incremented along the total echo train, as in echo-planar imaging or the RARE technique, there would be modulation of chemical shift and T2* on the phase axis of k space. After Fourier-transform image reconstruction, these modulations would result in severe ghosting artifacts in the image.

This problem is eliminated with use of a discontinuous phase-encoding order during the echo train. As more fully described elsewhere (9), phase encoding sweeps through three large increments of k space during each group of N_{GR} echoes. Holding these large phase increments constant, small phase increments are imposed during each 180°–180° interval along the total echo train. Subsequent computer reordering or interleaving of the signals in k space (Fig 2) effectively removes the periodicity of field inhomogeneity errors on the phase axis.

In this way, GRASE phase encoding order is significantly different from that of RARE and echo-planar imaging, which continuously increase their phase-encoding steps as a function of time in the echo train (Fig 2). Similar to the hybrid RARE technique, multiple excitations are performed with small incremental phase shifts to fill in additional areas of k space. Multiple sections are imaged during each TR cycle of GRASE echo-train excitation.

The acquisition time (T) of the GRASE technique can be directly expressed as $T = [TR \times (N_L \times NSA)/(N_{GR} \times N_{SE})] + TR$, where N_L = number of acquired phase-encoded image lines. The additional TR is required to establish steady-state magnetization. This initial excitation also produces a template of echoes without phase encoding, which can be used for T2* magnitude normalization and gradient-echo timing corrections in the phase-encoded echoes. In the presented imaging experiments in which N_L = 192, N_{GR} = 3, and

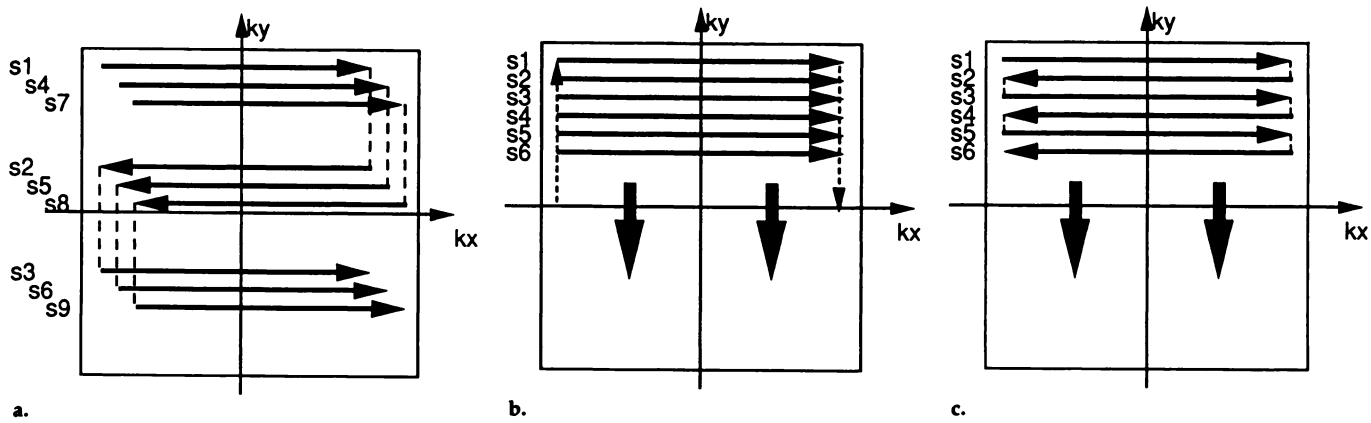


Figure 2. The k-space trajectory of **(a)** the GRASE technique, **(b)** RARE technique, and **(c)** echo-planar imaging techniques, including MBEST and Instascan. Numbers on the left side in **a–c** correspond to the time order of the signal in the echo train. The phase-encoded signals (horizontal arrows) reverse their direction from right to left during the negative-polarity readout gradients (Fig 1). In the GRASE technique **(a)**, the trajectory of the first group of three signals scans over nearly the entirety of k space, with identical trajectories for subsequent groups of signals except for a slightly displaced starting position between each group. In RARE imaging **(b)** and echo-planar imaging **(c)**, the k-space trajectories are continuously displaced on the phase axis sequentially in time (thick arrows), unlike GRASE imaging. Multiple excitation cycles fill in k space by interleaving signals in both GRASE and hybrid RARE imaging. *ky* = phase axis, *kx* = frequency axis.

N_{SE} = 8, the total data acquisition time is (9 × TR × NSA).

Methods

Experiments were performed with a 1.5-T MR system (Signa; GE Medical Systems, Milwaukee) using maximal gradient strength of 1 G/cm (10 mT/m). The readout periods were 2 msec or 4 msec with 0.6 msec gradient ramp times for a respective 18- or 24-msec interval between each pair of 180° RF pulses. Free-induction-decay spoiler pulses were used on the read-gradient axis and are not shown in Figure 1. The effective echo time (TE) is the time at which the origin of the k space is sampled: 80 or 104 msec.

With N_{GR} = 3 and N_{SE} = 8, there is a total of 24 signals per 90° excitation to give exactly 192 phase-encoded signals in eight excitations. The 192 × 256 k-space data set acquired in this way is symmetrically zero-filled to 256 × 256 before two-dimensional Fourier-transform image reconstruction. A standard multisection excitation scheme (1) was performed by using selective RF excitations with frequency offsets.

Head and body images of the same healthy volunteer were obtained. Also, two patients with a known radiologic and clinical diagnosis of multiple sclerosis underwent imaging with the GRASE technique at the time of their routine T2-weighted spin-echo studies.

RESULTS

To compare tissue contrast, brain images were obtained with the GRASE, spin-echo, and RARE techniques, each with similar pulse sequences: 2,500/100–104 (TR msec/TE msec). For this comparison, the S/N was intentionally set to be nearly equal by using conjugate synthesis (NSA = ½) for spin-echo and NSA = 2 for the GRASE and RARE techniques (Fig 3). In all three images, the phase axis is horizontal. The contrast among gray matter, white matter, and cerebrospinal fluid is similar in these images. The signal intensity of skin in the RARE image (Fig 3c) is noticeably more intense than that in either the GRASE or spin-echo image due to a higher signal of lipid in the RARE image. Greater flow artifact is present across the central region of the spin-echo image (Fig 3b).

Quantitative measurements of tissue signal intensity (pixel intensity) obtained from the comparative head study involving the spin-echo, RARE, and GRASE techniques are provided in the Table. Comparison of tissue contrast is somewhat affected by the different TE values. To obtain similar S/N in images, acquisitions of GRASE and RARE images involved use of NSA = 2 and a signal readout period of 4 msec, whereas acquisition of spin-echo images involved use of NSA = ½ and a signal readout period of 8 msec. Although estimates of image S/N, calculated from the ratio of tissue signal intensity to air signal intensity, are similar among the three techniques, the accuracy of measurement is affected and limited by variability in tissue structure.

Images of the abdomen (Fig 4) were obtained in 18 seconds, during a single breath hold. Therefore, respiratory motion artifact is totally absent. The renal arteries branching from the abdominal aorta are well demonstrated without respiratory motion artifact. The contours of the liver, spleen, and kidney are sharply defined. Chemical shift on the phase axis (horizontal) is 1.6 pixels and on the frequency axis (vertical) is 0.8 pixel.

Typical long-TR head studies (Figs 5, 6) obtained with a pulse sequence of 4,000/104 and NSA = 2, require a 72-second imaging time; those obtained with NSA = 1 require a 36-second imaging time. Comparison of the image quality and S/N can be made at similar brain levels in these NSA = 1 and NSA = 2 studies. The image quality is sufficient to demonstrate many small radial arteries in the neocortex. By using the GRASE technique with NSA = 1, a multiple sclerosis plaque is readily demonstrated in the right frontal white matter (Fig 6b) of a patient with multiple sclerosis. Direct comparison by a neuroradiologist of the number of multiple sclerosis plaques in T2-weighted spin-echo images with that in GRASE images at the same levels demonstrated an equal number of plaques in the two patients studied.

Sagittal GRASE images of the lumbosacral spine (Fig 7) demonstrated the myelographic effect of cerebrospinal fluid with a TR of 3 seconds. Degenerative disk disease was noted in the lumbar spine.

DISCUSSION

The development of computed tomographic (CT) technology for abdominal imaging, not unlike that of MR imaging, required a large leap in image acquisition speed to move from the early head imaging times of 3–5 minutes to the present imaging times of 1–3 seconds. CT body imaging is now of great clinical utility, while the problems of respiratory motion have not been overcome in routine clinical MR imaging. To date, respiratory motion

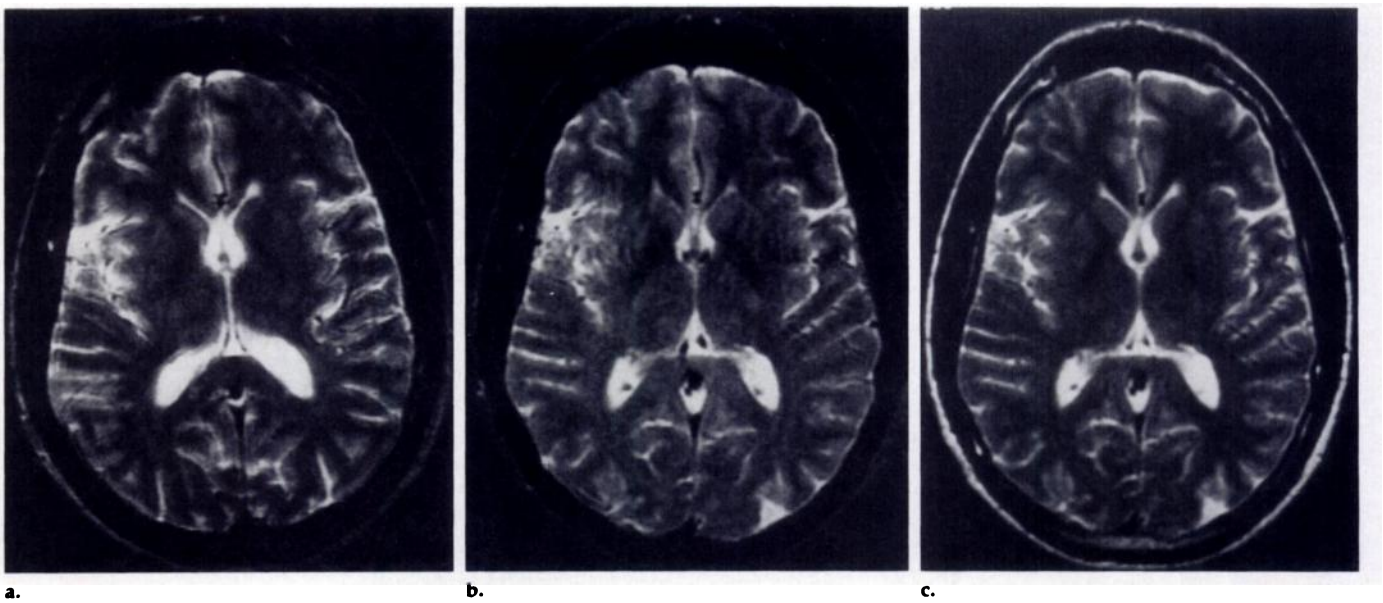


Figure 3. Comparison of tissue contrast in **(a)** GRASE, **(b)** spin-echo, and **(c)** RARE MR images of the brain. The three multisection images were acquired with a TR of 2.5 seconds and a section thickness of 5 mm. **(a)** The GRASE image was obtained with NSA = 2 and an image time of 45 seconds for 13 sections. **(b)** The spin-echo image was obtained with conjugate synthesis (NSA = ½) and an image time of 4.6 minutes for 25 sections of both proton-density and T2-weighted images. **(c)** The hybrid RARE image was obtained with NSA = 2 and an image time of 64 seconds for 13 sections. RARE and spin-echo images were acquired with a TE of 100 msec, while the GRASE TE differed slightly (104 msec) due to sequence timing differences.

artifacts have significantly limited T2-weighted spin-echo imaging, which otherwise has great sensitivity to abdominal pathologic conditions. To eliminate respiratory artifact, GRASE imaging times of 18 seconds permit comfortable breath holding for a large portion of the patient population.

Due to the discontinuous phase-encoding method of GRASE imaging, Hahn spin echoes cover the entire central third portion of k space where the highest signal energy occurs (8). For this reason, the tissue contrast of GRASE, in theory and practice, is indistinguishable from that of spin-echo imaging, determined predominantly by these central gradient echoes that in fact are spin echoes. Given their similar contrast mechanism, GRASE and spin-echo imaging demonstrate multiple sclerosis plaques equally well, unlike low-flip-angle gradient-echo imaging, which is suboptimal for detection of some pathologic conditions.

As demonstrated in the head studies (Fig 3, Table), tissue contrast in GRASE images is essentially the same as that in spin-echo images obtained with similar TRs and TEs. The abdominal tissues (Fig 4), including liver, spleen, kidney, muscle, and fat have the expected spin-echo T2-weighted contrast. While breath holding effectively eliminates much of the motion-related artifact, some residual artifact remains because of pulsations in the liver and adjacent structures. Pulse sequence modifications to reduce cardiac pulsation effects and other related artifacts are currently being investigated (10).

The primary determinant of S/N in GRASE, RARE, and spin-echo imaging is signal bandwidth (S/N is proportional to the square root of signal read time). While the GRASE technique more efficiently uses the T2 relaxation period to refocus or "pump out" more signals per acquisition time, this factor does not directly cause S/N loss unless shorter read periods with larger signal bandwidths are used. Conjugate synthesis spin-echo imaging, not having the time constraint of many signal read periods in each excitation, permitted twice as long a read period as the GRASE and RARE techniques in these experiments, compensating for its intrinsic 35%–41% S/N loss. The demonstrated image quality in head and body studies obtained with the GRASE technique with NSA = 1 is suitable for routine clinical imaging.

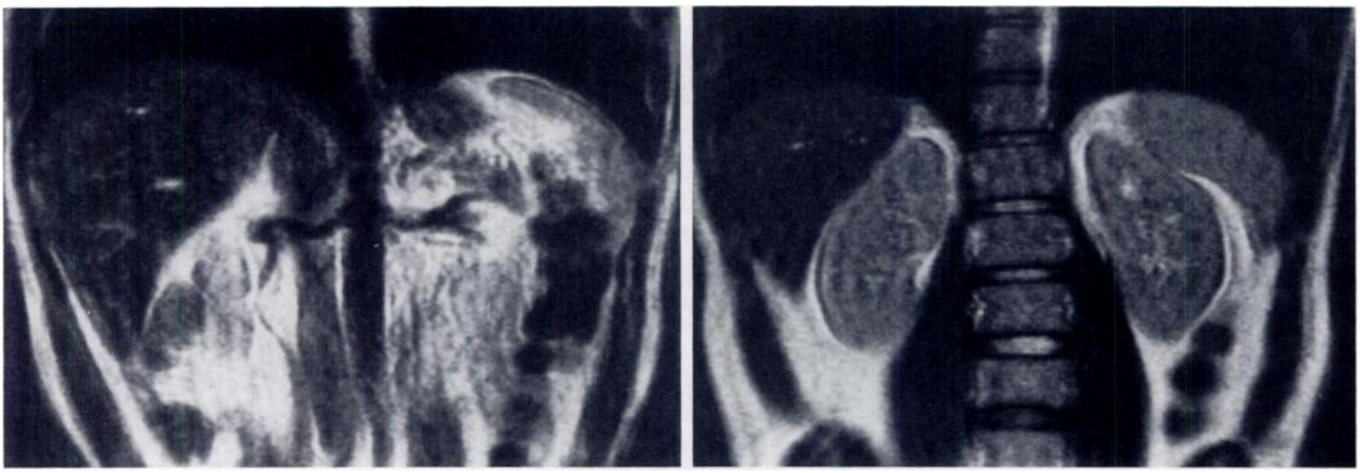
It is significant that GRASE imaging involves use of about a third the number of 180° RF pulses per multisection acquisition that are used in a similar RARE acquisition, which has a higher SAR. The speed advantage of the GRASE over the RARE technique can be given in a simple expression for the average time of each phase-encoded signal. The average time of a phase-encoded echo can be directly calculated by using exemplary time values; the selective 180° RF refocusings and surrounding free-induction-decay spoiler gradients (T_{RF}) equal 5 msec; the net time of the initial phase-encoding pulse and final rephasing pulse (T_{PE}) equals 4 msec; a 4-msec echo readout period plus gradient rise times (T_{RO}) equals 5.2 msec. Average time per echo = $[T_{RF} + T_{PE} + (N_{GR} \times T_{RO})]/N_{GR}$.

For RARE imaging with $N_{GR} = 1$, the average time per signal is (5 + 4 + 5.2)/1, or 14.2 msec. For GRASE imaging with $N_{GR} = 3$, the average time per echo is [5 + 4 + (3 × 5.2)]/3, or 8.2 msec. For GRASE imaging with $N_{GR} = 7$, the average time per echo is 6.5 msec. Although the efficiency of GRASE imaging is currently in-

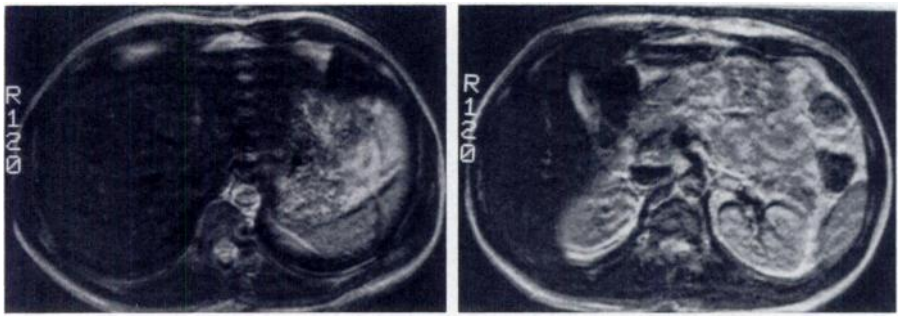
Image Signal Intensities Obtained in Head and Body MR Studies

Location and MR Imaging Technique	Region-of-Interest Measurements of Signal Intensity					
	Gray Matter	White Matter	Cerebrospinal Fluid	Scalp	Air	
Head						
GRASE	212 ± 12	176 ± 11	413 ± 8	125 ± 20	8.8 ± 4.6	
Spin-echo	200 ± 17	162 ± 12	454 ± 13	123 ± 19	8.5 ± 6.0	
RARE	205 ± 12	170 ± 6	436 ± 14	271 ± 96	7.9 ± 9.0	
	Spleen	Kidney	Liver	Muscle	Fat	Air
Body						
GRASE	128 ± 11	121 ± 15	112 ± 11	43 ± 13	223 ± 13	12.0 ± 7.0

Note.—Values are mean ± 1 standard deviation. Measurements were obtained from the head and body studies shown in Figures 3 and 4b.

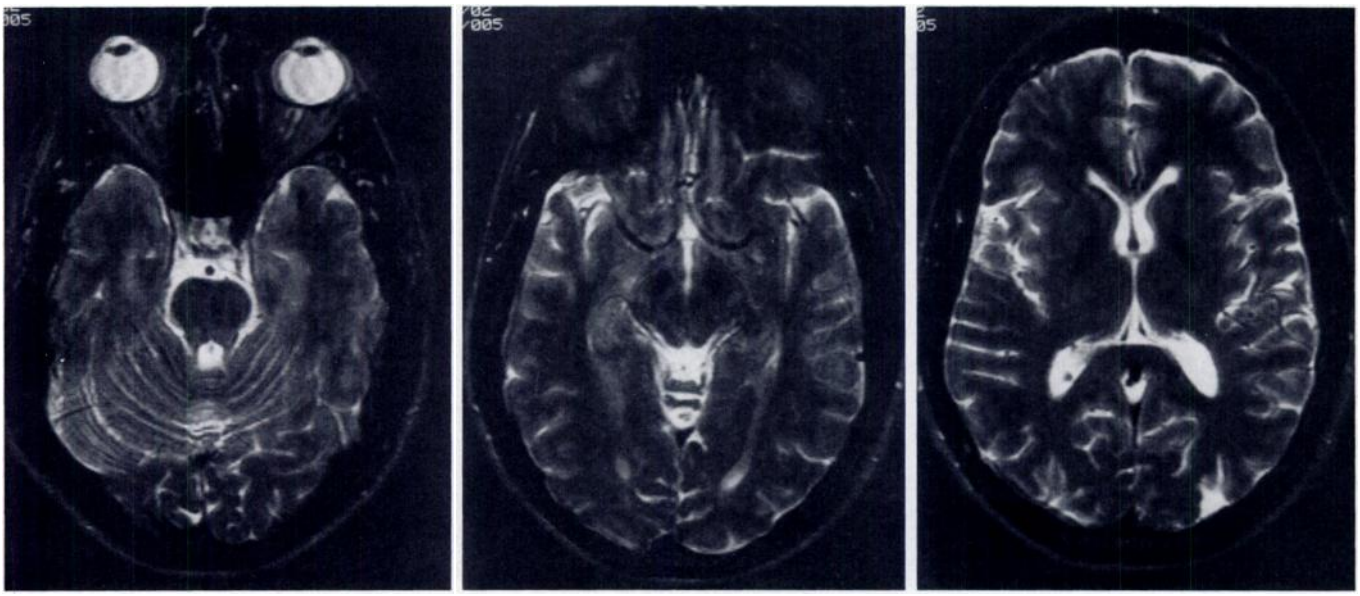


a. b.



c. d.

Figure 4. Abdominal MR images. **(a, b)** Coronal studies of the upper abdomen obtained during single breath holds. The total image time was 18 seconds for 11 multisection images, pulse sequence was 2,000/80, section thickness was 10 mm, and field of view was 38 cm. **(c, d)** Axial images obtained with parameters identical to those of the coronal images except for a TE of 90 msec.



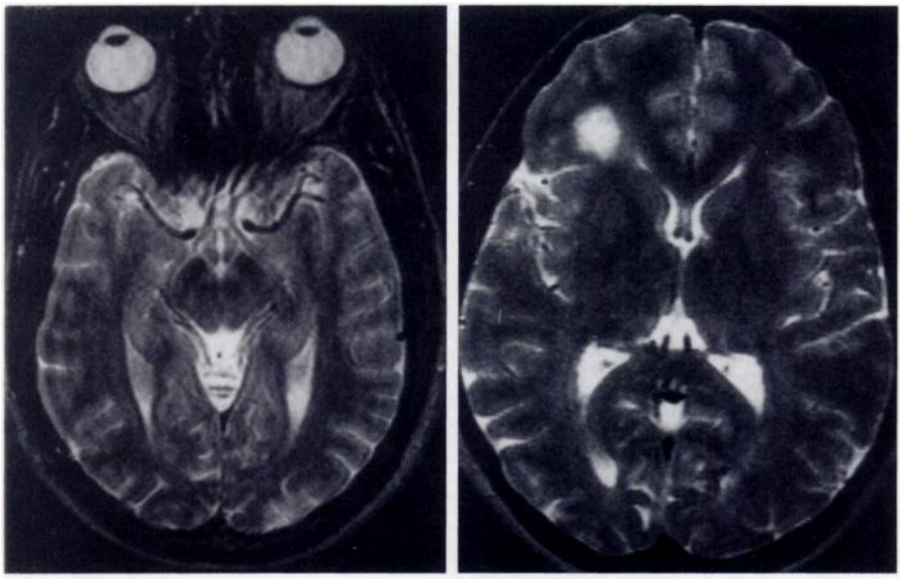
a. b. c.

Figure 5. **(a–c)** GRASE MR images obtained in the head of a healthy volunteer with NSA = 2. Imaging time was 72 seconds, pulse sequence was 4,000/104, field of view was 24 cm, and section thickness was 5 mm.

termediate between echo-planar and RARE imaging, application of the GRASE technique with an imaging system with high performance gradients (fast rise times and strong maximal gradient) will further increase the efficiency of GRASE imaging, making it closer to that of echo-planar imaging. The RARE technique cannot benefit nearly as much from high performance gradients because of the absence of gradient refocusing, its large time overhead in 180° RF pulses, and SAR limitations.

At first glance, in comparing GRASE with MBEST and Instascan, the additional time cost of the multiple 180° RF refocusings certainly appears to directly reduce the efficiency of GRASE imaging. These additional refocusings, however, permit signal acquisition to occur much earlier than in these echo-planar techniques, which necessarily have a much longer 90°–180° time interval when no signals can be acquired. This advantage of GRASE imaging may largely offset the efficiency differences between these techniques for T2-weighted imaging.

It is important to realize that GRASE imaging is a variant of spin-echo imaging that involves use of the CPMG sequence



a. b.

Figure 6. GRASE MR images obtained in the head with NSA = 1, image time of 36 seconds, and pulse sequence of 4,000/104. **(a)** Image obtained in healthy volunteer and **(b)** image obtained in a patient with multiple sclerosis. The image quality and S/N can be compared with those of brain images obtained with NSA = 2 in Figure 5, which were otherwise acquired with identical image parameters.

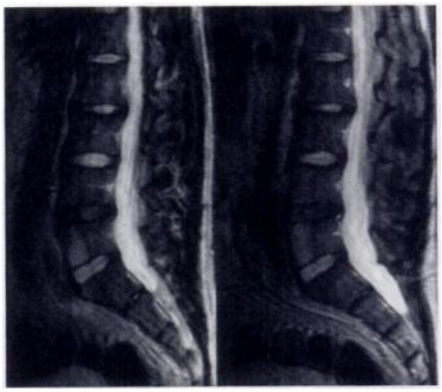


Figure 7. Sagittal GRASE images of the spine obtained with a TR of 3 seconds, NSA = 2, and section thickness of 5 mm. Image time was 56 seconds. Note the myelographic effect of cerebrospinal fluid. Degenerative disk disease is demonstrated at multiple disk levels, with more severe central disk bulging at the L2-3 level and loss of signal intensity in the L4-5 disk.

to produce spin-echo contrast. GRASE imaging lies on a continuum between RARE imaging, which involves use of multiple spin echoes, and single-shot echo-planar imaging, which involves use of multiple gradient echoes. In GRASE imaging, a small amount of chemical shift is accepted with the decrease in imaging time and SAR afforded by the use of gradient echoes.

Several obvious modifications of GRASE imaging are possible: division of the echo train into two identically phase-encoded data sets for simultaneous proton-density and T2-weighted (double-echo) imaging; use of different TEs and TRs for desired image contrast; extension to multislab three-dimensional volume imaging; and use of 512 × 512 high-resolution imaging in clinically acceptable imaging times. Methods of performing diffusion and flow imaging with the CPMG sequence have been described (11). Another possible application of GRASE imaging in systems with low magnetic field strength could be to perform imaging with NSA = 4 or 8 to increase image S/N in clinically acceptable imaging times.

In summary, multisection GRASE imaging is similar to long-TR spin-echo imaging in terms of image fidelity, contrast, and spatial resolution with a 24-fold reduction in image acquisition time. The time advantage of GRASE over spin-echo imaging is accomplished by more efficiently using the T2 decay period. A penalty of fewer image sections in the current implementation of the GRASE technique can be optimized with tradeoffs in T2 weighting and imaging time. Combination of the GRASE technique with high-performance gradient systems should produce further large reductions in imaging time while maintaining image quality and spatial resolution. The ability to implement the GRASE technique without the need to change gradient hardware, however, is a significant advantage of this new high-speed imaging technique. ■

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