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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**Abbreviations:**

CPMG = Carr-Purcell-Meiboom-Gill

GRASE = gradient echo and spin echo

MBEST = modulus-blipped-echo-planar single-pulse technique

NSA = number of signal averages

RARE = rapid acquisition with relaxation enhancement

SAR = standard absorption rate

S/N = signal-to-noise ratio

TE = echo time

TR = repetition time

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2 RSNA, 1991
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 successive 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.

**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 (\(N_{echoes}\)), 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 \(N_{echoes} \times N_{GR}\). 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 \(T\), eliminating image distortions and loss of S/N. Small field-inhomogeneity errors evolve within each group of \(N_{echoes}\) echoes during the relatively short time between each gradient-recalled echo and the center of the 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 \(N_{echoes}\) 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 \(N_{echoes}\) 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 \(N_{echoes}\) 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 \(T = ([TR \times (N_i \times NSA)]/[N_{echoes} \times N_{GR}]) + TR\), where \(N_i\) = 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 \(N_i = 192, N_{echoes} = 3\), and

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**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 (\(\pi_1, \pi_2, \ldots\)) 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 center 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 (\(N_{echoes}\)) are shown.
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 $N_M = 3$ and $N_E = 8$, there is a total of 24 signals per 90° excitation to give exactly 192 phase-encoded signals in eight excitations. The $192 \times 256$ k-space data set acquired in this way is symmetrically zero-filled to $256 \times 256$ before two-dimensional Fourier-transform image reconstruction. A standard multislice 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 ($NSA = \frac{1}{2}$) 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 $NSA = \frac{1}{2}$ 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 lumbar 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
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 GRASE 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\textsubscript{RF}) equal 5 msec; the net time of the initial phase-encoding pulse and final phasing pulse (T\textsubscript{EP}) equals 4 msec; a 4-msec echo readout period plus gradient rise times (T\textsubscript{GR}) equals 5.2 msec. Average time per echo = [T\textsubscript{RF} + (N\textsubscript{sa} × T\textsubscript{GR})]/ N\textsubscript{sa}.

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

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.

Intermediate 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 refocusing certainly appears to directly reduce the efficiency of GRASE imaging. These additional refocusing, 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.
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 $512 \times 512$ 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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References


