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MR imaging: some applications of GRASE

The goal is increased speed with good signal-to-noise ratio, coverage and resolution.

To improve the speed of MRI scanning while maintaining good signal-to-noise ratio, coverage and resolution is the goal after which everyone strives. Some methods, such as fast field echo (or gradient echo) try to achieve an improvement in scan time over conventional spin echo by reducing the amount of time it takes to excite the tissue and prepare it for readout. Other methods employ techniques to read out the signal more quickly. This article is about one such technique.

Theory

The spin echo sequence is perhaps the most basic pulse sequence used in magnetic resonance imaging. While a slice selective gradient is applied, an RF signal is transmitted to excite, or tip, the protons in that slice from their longitudinal alignment (typically 90°). At some time (τ) later, a refocusing 180° RF pulse is transmitted, causing the spin echo to occur at time 2τ, which is also known as the echo time (TE). This echo (along with many more like it) is sampled to create an image. Spatial encoding is, of course, achieved by frequency encoding one direction during the readout of the echo and, for the other direction, by preparing the spins prior to readout with a phase-encoding gradient. A simplified diagram of this spin echo sequence in shown in Figure 1. In conventional spin echo imaging, this process is repeated for each slice as many times as there are lines in *k*-space (the domain in which the image data is sampled prior to Fourier transfer).

Fast Imaging Methods

In the previous simple example, only one line of *k*-space data (i.e. one phase-encoding step or *profile*) is acquired per excitation. This classic implementation allows for a long readout time per profile and, hence, a narrow bandwidth, giving a high signal-to-noise ratio (SNR). In many situations, however, it is desirable to have a faster imaging method. In general, faster scanning can be achieved by either spending less time per profile (which leads to a lower SNR) or by acquiring fewer profiles (which means less spatial resolution and/or a lower SNR). An alternative is to sample more than profile per excitation, and many methods have been developed for this purpose. Two primary examples of these techniques are echo-planar imaging (EPI) and turbo spin echo (TSE) imaging.

TSE

Expanding on the spin echo sample described above, the same technique used to generate the refocused spin echo can be applied to create multiple echoes. By applying multiple refocusing RF pulses (typically 180°) after the first echo, additional spin echoes can be generated. An example of this turbo spin echo technique was described by Van Vaals et al. [1]. A simplified diagram of the sequence is shown in Figure 2. Between each successive echo, the phase-encoding gradients can be used to prepare the spins for a different line in *k*-space. Thus, multiple lines in *k*-space can be filled per excitation (repetition). For a TSE sequence with an echo train length, or turbo factor, of three (i.e. three echoes per repetition), a *k*-space matrix can be filled in one-third the time of conventional spin echo. In the extreme case, known as single-shot TSE, the entire *k*-space matrix can be filled with a single excitation and a train of as many echoes as there are lines in *k*-space.

TSE offers a decrease in scan time proportional to the turbo factor.

In single slice (2D) imaging, the TSE technique offers a decrease in scan time that is directly proportional to the turbo factor. In practice, though, with interleaved multiple slice (M2D) imaging, where dead time in the TR of one slice is used to acquire other slices, the actual decrease in scan time is more moderate.

SE-EPI

Another method of decreasing scan time is through echo planar imaging. In EPI, just as in

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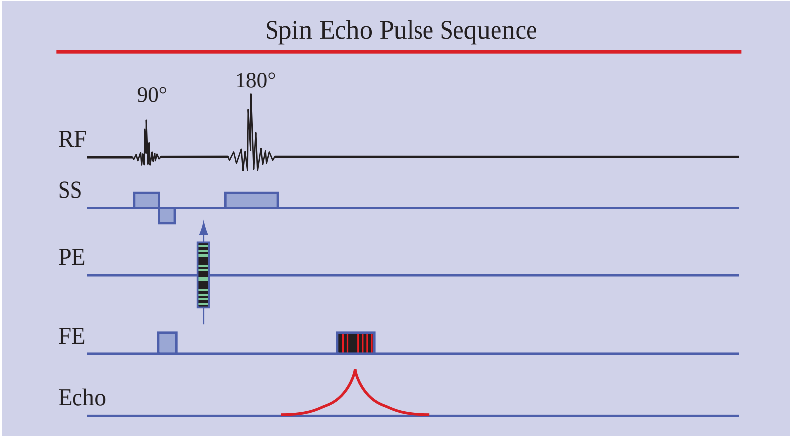


Fig. 1

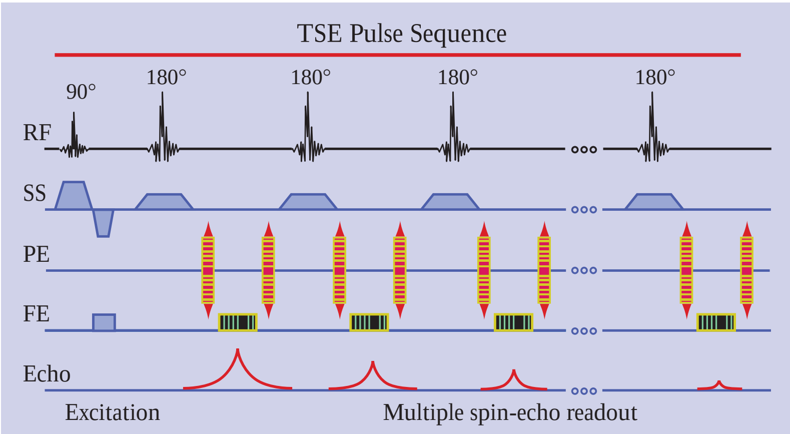


Fig. 2

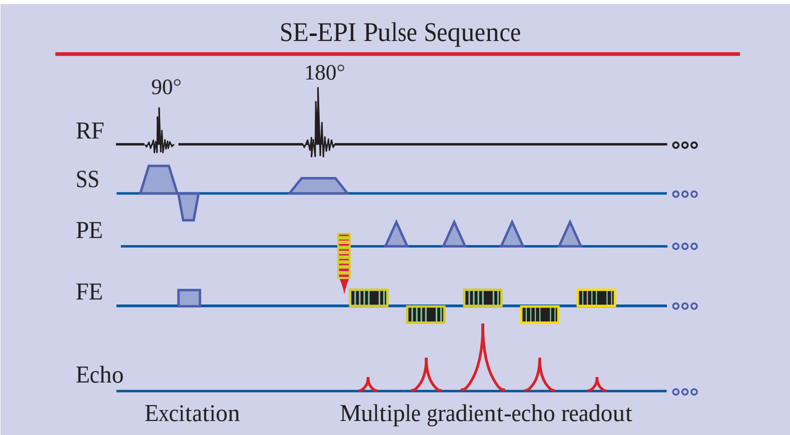
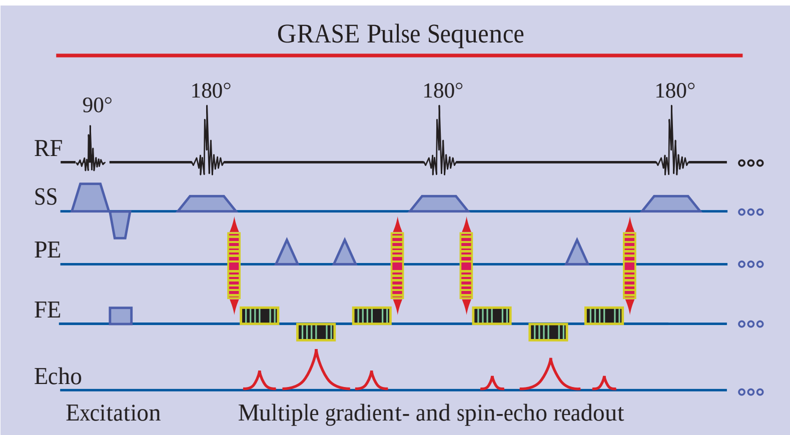


Fig. 3

Fig. 4



TSE, multiple lines of *k*-space are acquired through a multiple-echo readout train. However, instead of using multiple refocusing RF pulses, the multiple echoes are generated with alternating gradients (Fig. 3). The general effect is to use quick phase encode gradients to 'blip' from one line of *k*-space to the next between successive readout gradients which are alternating in sign. The EPI factor, similar to the TSE turbo factor, is the number of echoes (and phase-encoding *k*-space lines) acquired per repetition. Single shot EPI fills all the sampled *k*-space in one imaging repetition. Multi-shot EPI uses an EPI factor that is less than the number of phase-encoding *k*-space lines to be acquired. The number of shots in a multishot EPI scan is the total number of phase-encoding *k*-space lines divided by the number of lines acquired per shot. A scan with 255 phase-encoding steps can be acquired in 51 shots if the EPI factor is 5.

This accelerated method of traversing *k*-space can be much quicker than TSE since the extra time required for each refocusing 180° RF pulse is not needed. Thus, the same number of echoes can be packed into a shorter amount of time. However, in EPI sequences, since the multiple echoes are refocused by gradients and not 180° pulses, as compared to TSE there is more effect

Fig. 1. A simplified pulse sequence diagram for a conventional spin echo sequence. The 90° pulse initially excites the protons and the 180° pulse refocuses the protons to form the spin echo that is sampled. (RF= radio frequency, SS = slice select gradient, PE = phase encode gradient, FE = frequency encode or readout gradient).

Fig. 2. A simplified pulse sequence diagram for a turbo spin echo pulse sequence. Expanding on the conventional spin echo technique, this technique adds multiple slice selective refocusing 180° pulses to create multiple spin echos for a given excitation. Each echo is used to fill a different phase-encoding line in k-space. Each echo in the readout train is progressively weaker, as defined by the T2 decay envelope.

Fig. 3. A simplified pulse sequence diagram for spin-echo-based echo planar imaging. In this technique, many gradient recalled echoes are created for each RF excitation. Between each of the gradient echoes, the phase-encoding gradients 'blip' to the next line of k-space to be filled.

Fig. 4. A simplified pulse sequence diagram for a GRASE (gradient and spin echo) pulse sequence. This technique is the combination of TSE, where multiple 180° pulses refocus many spin echoes. But for each spin echo (the middle of each group), there are additional gradient recalled echoes. In this example, the EPI factor is three. Each successive spin echo is progressively weaker, as defined by T2 decay. The strength of the gradient recalled echoes surrounding the spin echo is defined by the T2 decay envelope.*

of T2* decay (e.g. magnetic susceptibility heterogeneity) and other artifacts (e.g. chemical shift) due to the lack of refocusing.

GRASE: the combination

Combining the TSE and EPI methods, GRASE (gradient and spin echo) imaging uses a train of refocusing 180° RF pulses, but for each spin echo of the readout, there are additional gradient recalled echoes [2, 3]. Figure 4 shows the beginning of a GRASE sequence in which the EPI factor is three; that is, there are three EPI-style echoes acquired within each TSE segment of the readout train. In GRASE, the EPI factor indicates the gain in speed (or the number of phase-encoding *k*-space lines) over the corresponding TSE sequence. For single slice imaging, the gain in time as compared to conventional spin echo is the TSE turbo factor times the EPI factor. For example, if a TSE sequence with a turbo factor of three reduces scan time to roughly 1/3, then a GRASE sequence with TSE turbo factor of three and EPI factor of three would reduce scan time to roughly (1/3 x 1/3) or 1/9.

Pros and cons

With all MRI scan techniques that decrease the scan time, the trade-off is typically in image resolution and/or signal-to-noise ratio (SNR). This is true with GRASE. Some image blurring and drop in SNR occur due to the longer multiple-echo readout and modulations in signal intensity across *k*-space due to signal decay. Separately, both TSE and EPI experience these effects in subtly different ways. For example, in EPI techniques, the strength of the successive gradient echoes can decay rapidly due to T2* effects, causing the later echoes to have a significantly reduced SNR as compared to the earlier echoes. However, in GRASE, the 180° RF pulses help to refocus intermittently the echoes to a maximum within the decay envelope. This refocusing also helps to reduce the artifacts related to magnetic susceptibility heterogeneity that are so common in EPI imaging. But, in the case of fixed metallic hardware for example, GRASE will clearly have related artifacts that would be less obvious in similar TSE scans [3, 4, 5].

GRASE combines the TSE and EPI methods.

Intermittent refocusing helps to reduce artifacts.

Figure 5 shows images from a patient with Sturge-Weber syndrome, with the typical calcifications and concomitant iron deposition. The gradient echo (FFE) image (Fig. 5 c) shows marked signal loss due to the local inhomogeneity in magnetic susceptibility caused by the presence of iron. The effect is less pronounced in the TSE image (Fig. 5 a). The GRASE image (Fig. 5 b) is somewhere in between, as it shares qualities of both the TSE and the gradient echo (FFE) images. An SE-EPI image would have even more magnetic susceptibility induced signal loss than the FFE image.

In GRASE, the combination of spin echoes and gradient echoes at differing times leads to modulation in measured signal strength over the multiple-echo readout time, and thus imposes signal modulations over *k*-space. Typically, the stronger spin echoes are used to fill the centre of *k*-space

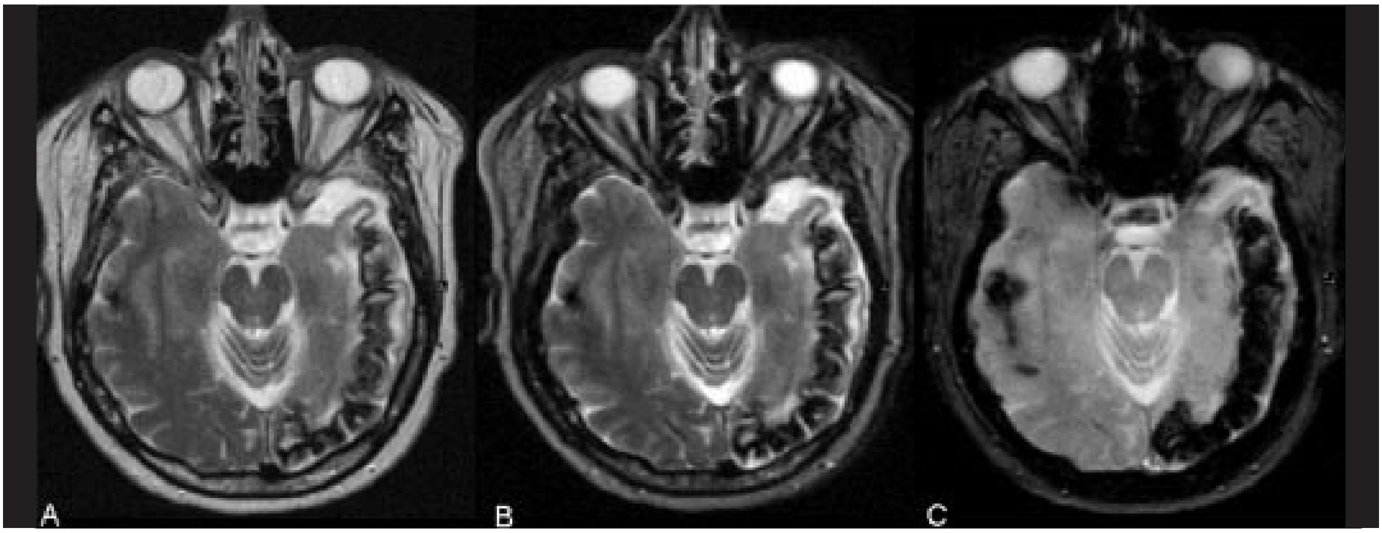
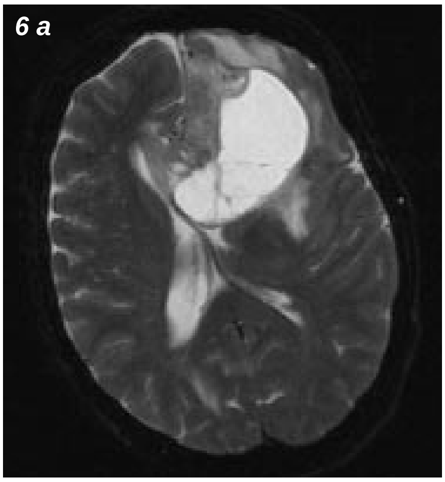
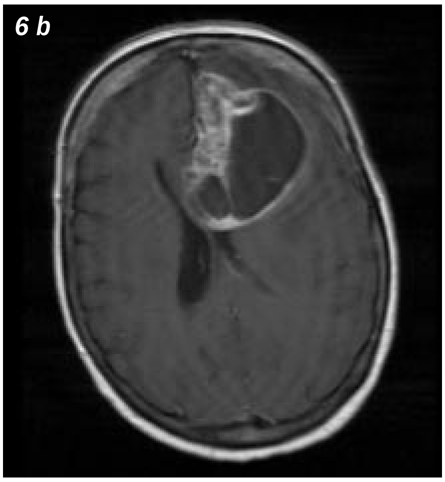


Fig. 5. Sturge-Weber syndrome. The images show the typical calcifications with concomitant iron deposition.
Fig. 5 a. TSE acquisition. The image is relatively unaffected by the presence of iron.
Fig. 5 b. GRASE acquisition. The image is affected by the iron, but the effect is less than in the FFE image.
Fig. 5 c. FFE acquisition. There is marked signal loss due to the presence of iron.





Larger speed-up factors can be achieved with fewer artifacts.

GRASE can have improved spatial resolution when compared with single shot EPI.

Image quality is similar to TSE, acquired in one-third of the time.

and the weaker gradient echoes are used in the periphery. This distribution tends to emphasize overall SNR with an image similar to TSE, at the expense of some fine detail as compared to a TSE scan with similar turbo factor. However, some authors have demonstrated that single shot GRASE can have improved spatial resolution when compared with single shot EPI [6].

In summary, with small speed increments in TSE turbo factor and EPI factor that combine synergistically, GRASE can achieve larger speed-up factors without paying as much in the way of artifacts such as those associated with large factors in either EPI or TSE techniques alone. The refocusing 180° pulses, as in TSE, help to reduce T2* related artifacts and signal loss. One can also use EPI's sensitivity to susceptibility heterogeneity to alter the sensitivity of the GRASE scans. EPI gives a greater effective acceleration factor in less time due to its gradient recalled nature. GRASE has more to gain in terms of echo packing than does TSE, as gradient technology improves with increased amplitudes and faster slew rates. As imaging speed increases, it can, as always, be exchanged for increased spatial resolution. Thus, GRASE is promising in high-resolution applications with fewer limitations of RF power deposition. However, since GRASE is a hybrid of TSE and EPI, it inherits benefits and limitations from both, as well as unique properties resulting from the mix. As new technology and techniques are developed to manipulate these relationships, GRASE will continue to mature as a flexible imaging method.

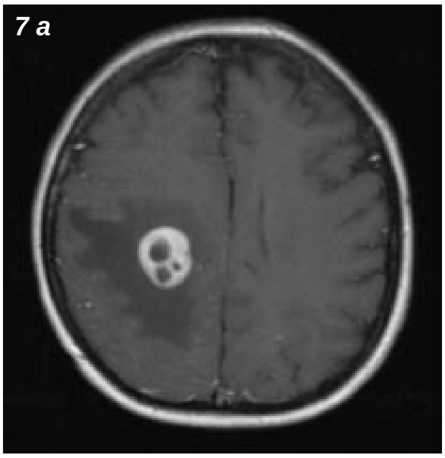
Applications

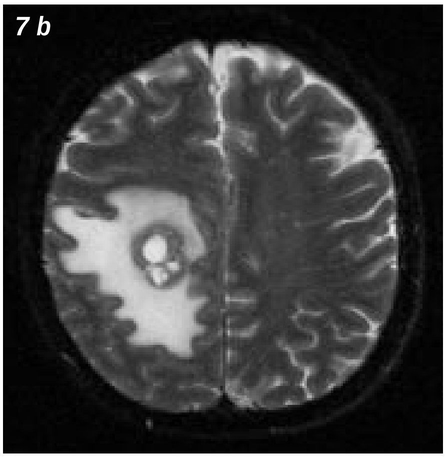
T2-weighted GRASE scan instead of T2-TSE

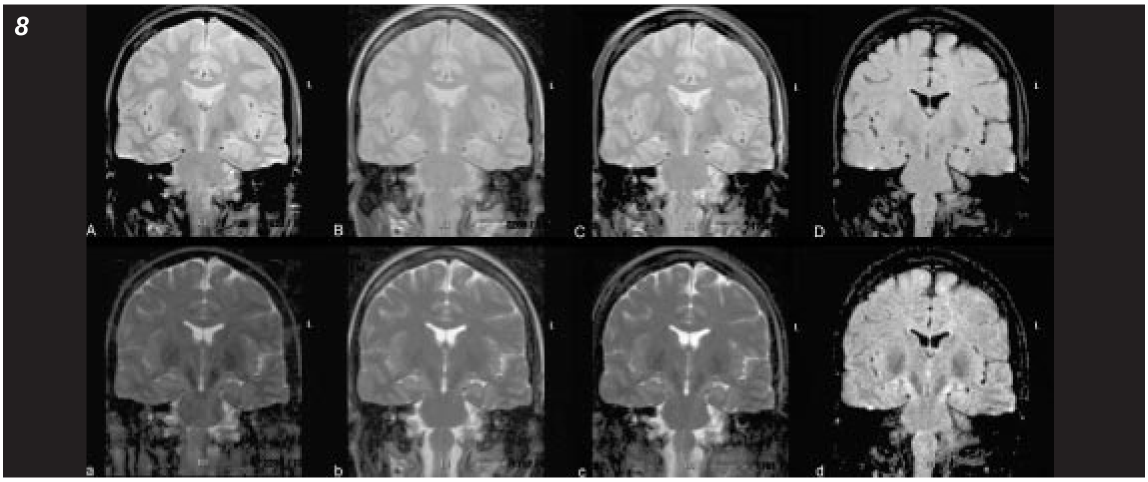
As a clinical alternative to conventional spin echo or T2-TSE imaging, T2-weighted GRASE can be used. Where conventional T2-weighted spin echo imaging is now considered too costly in time or risk of patient motion, TSE has replaced it. T2-weighted GRASE imaging offers an alternative that is of similar image quality, but acquired in one third of the time or less. Rockwell et al. [5] have shown that such a T2-weighted GRASE sequence (TR 5503 ms, $TE_{eff.}$ 110 ms, turbo factor 8, EPI factor 3, scan time 77s) is better than TSE at detecting hyper-intense lesions in the brain. Moreover, due to the

Fig. 6. Butterfly glioma. / Fig. 6 a. T2-weighted GRASE acquisition with SPIR. EPI/TSE factors 3/5, scan time 4:54, 512 matrix. / Fig. 6 b. T1-weighted conventional SE acquisition. TE 15, TR 783, scan time 5:39, 256 matrix. / Fig. 6 c. IRTSE FLAIR acquisition. TE 150, TR 6000, TI 2000, TSE factor 15, scan time 4:00, 256 matrix.

Fig. 7. Metastatic lesion with surrounding oedema. / Fig. 7 a. T1-weighted conventional SE image. TE 15, TR 783, scan time 5:39, 256 matrix. / Fig. 7 b. GRASE acquisition with SPIR. EPI/TSE factors 3/5, TE 110, TR 3500, scan time 4:54, 512 matrix.







GRASE is more sensitive to both hyper-intense and hypo-intense lesions.

susceptibility sensitivity, this technique is more sensitive to haemorrhagic or calcified lesions which show up conspicuously as hypo-intense areas [5]. Unfortunately, in the case of ferromagnetic hardware (e.g. dental hardware) the local artifacts can be severe.

Figures 6 and 7 show T2-weighted GRASE images of clinical cases. Figure 6 shows a typical glioblastoma multiforme with both cystic and solid components. Figure 7 shows a metastatic lesion with heterogeneous core and surrounding oedema.

Dual echo

Just as in conventional or turbo spin echo, dual echoes can be acquired with the GRASE technique. Dual echo GRASE offers a proton density weighted scan in addition to the T2-weighted scan. This method can also be used to calculate T2 relaxation times. Melhem et al. [7] compared dual echo techniques for the measurement of T2 values in the hippocampus (ultimately for qualitative assessment and staging of mesial temporal sclerosis, which is the pathology most commonly underlying complex seizures). These authors used a dual echo GRASE sequence (TR 3000 ms, $TE_{1\ eff.}$ 50 ms, $TE_{2\ eff.}$ 140 ms, turbo factor 6, EPI factor 3, scan time 2 min 54 s) to measure T2 values.

The most precise and repeatable scan in this comparison for measuring T2 values in small structures in the brain was a GRASE sequence with an added CSF-nulling technique (FLAIR). This dual echo FLAIR-GRASE technique (TR 5000 ms, TI 1790 ms, $TE_{1\ eff.}$ 60 ms, $TE_{2\ eff.}$ 151 ms, turbo factor 6, EPI factor 3, scan time 4 min 50 s) provides time-efficient scanning with whole brain coverage. By suppressing signal from cerebrospinal fluid, partial volume contribution from the CSF was minimized, and precision, test-retest and interoperator consistency of the T2 measurements were improved.

The CSF nulling of FLAIR-GRASE imaging has also been shown to be useful in detecting brain lesions with gadolinium enhancement [8]. Figure 8 shows a collection of dual-echo images with no visible abnormalities. Dual-echo images of the same region are acquired with conventional spin echo, TSE, GRASE and FLAIR-GRASE.

GRASE with CSF nulling is the most precise and repeatable scan for small structures in the brain.

Fig. 8. Dual-echo techniques can be used to calculate T2 maps. The images are arranged with the first echo in the top row (capital letters) and the second echo in the bottom row (lower case letters). A, a: conventional spin echo; B, b: TSE; C, c: GRASE; D, d: GRASE with FLAIR.

Fig. 9. Bone bruise in the mid-lateral femoral chondyle, typical of a rotational torque injury secondary to an anterior cruciate ligament tear. / Fig. 9 a. Proton density weighted TSE acquisition. TSE factor 6, TE 14, TR 2392, scan time 2:28. / Fig. 9 b. GRASE image with fat suppression and SPIR. EPI/TSE factors 3/3, TE 60, TR 3300, scan time 2:21. The bruise is well shown.

GRASE is useful in imaging joints and soft tissue, and in black blood angiography.

Other applications

While it has perhaps found its greatest utility in the somewhat standard neurological applications described above, GRASE imaging has also been applied in other areas. For example, some researchers have even developed a CSF-suppressed, single-shot diffusion weighted MRI scan based on a GRASE readout technique [9].

Outside the head, people have found GRASE to be useful in joint imaging [10]. It is good in detecting partial tears of ligaments and tendons. Furthermore, it is better than T2-TSE in the visualization and conspicuity of soft-tissue lesions and bone marrow abnormalities, including bone marrow oedema [11]. Figure 9 shows two images from a patient with a torn anterior cruciate ligament. The GRASE image shows the resulting bone bruise on the mid-lateral femoral chondyle.

Others have applied GRASE to angiography, specifically 'black-blood' angiography [12]. This technique takes advantage of the signal loss due to the inherent spin dephasing of flowing blood. Turbo spin echo sequences are useful in exaggerating this effect, but GRASE can do the same in less time and, because of the fewer 180° pulses, with deposition of less RF power to the patient. These authors [12] have also shown that, in multi-chunk 3D MRA with GRASE, using fewer slice-selective 180° pulses (which are known to have slice profile distortions) helps to improve the overall slice profile homogeneity, which is more evident in orthogonal maximum intensity projections.

Conclusion

In conclusion, GRASE is the synergistic union of turbo spin echo and echo planar imaging readout techniques. This union offers a powerful technique that is fast, combines the strengths (and weaknesses) of both techniques, and delivers less RF energy to the patient than TSE. The method can be combined with other standard techniques such as fluid attenuation, fat suppression and dual echo scanning. Multiple combination of these tools with GRASE can be used in applications from everyday clinical examinations such as routine head and joint scans to the more academic applications such as relaxation time measurements and single shot diffusion imaging with CSF attenuation.

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