Maintaining the CPMG Conditions with Slice Accelerated Parallel Imaging in 2D Fast Spin Echo

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Introduction

Parallel imaging in the slice encoding direction is used with 3D pulse sequences to allow high acceleration while maintaining reasonable geometry factors via 2D acceleration. For T2-weighted imaging, 3D spin echo acquisition has relatively long scan time and consequently 2D spin echo pulse sequences are frequently favored. Slice acceleration can be used with 2D acquisition (1) and can be applied to 2D Fast Spin Echo (FSE). One advantage of using 2D acquisition is the lack of slab wrap artifacts from slice acceleration (2), allowing slice coverage smaller than the object. Slice acceleration with 2D pulse sequences is accomplished by exciting multiple slices simultaneously using cosine modulation of the RF pulses. For FSE, care must be taken to maintain the CPMG conditions. The cosine modulation imparts additional phase shifts that can disrupt the CMPG conditions unless properly compensated, resulting in unacceptable ghosting artifacts.

Methods

One of the CPMG conditions requires that the excitation and refocusing pulses have a $\pi/2$ relative phase shift, i.e. the excited magnetization must be aligned with the refocusing pulse, to prevent signal loss and ghosting artifacts. To excite two slices on equal and opposite sides of isocenter, each RF pulse is multiplied by a factor $2\cos 2\pi\Delta f\,(t-T_\Delta)$ where $\Delta f=(\gamma/2\pi)G_z\Delta z$, G_z is the slice selection gradient, and $\pm\Delta z$ is the spatial offset of each slice. Since the cosine function is typically applied in software, its time origin T_Δ can be chosen arbitrarily. To a good approximation, the transverse magnetization is effectively created at a time T_I prior to the end of the pulse (isodelay time). The magnetization in the two excited slices receives an additional phase shift $\pm 2\pi\Delta f\,(T_\Delta - T_I)$ relative to the unmodulated case, where the sign depends on which side of isocenter the slice is located. For most pulse sequences, the relative phase of the magnetization is unimportant, however for FSE, the additional phase shift can violate the CPMG conditions. CPMG phase alignment is accomplished in many implementations by applying a small phase correction to the RF pulses. The correction is sometimes calibrated from a single echo train without phase encoding. Phase correction is not completely effective for cosine modulation because each simultaneously excited slice requires a different phase shift. By choosing $T_\Delta = T_I$ for each RF pulse, the cosine modulation does not cause any extra phase shifts. For refocusing pulses, which are typically symmetric, T_I is located at the center of the pulse. Excitation pulses may not have T_I located at the center of the pulse, for example when a minimum phase pulse is used. If the group of excited slices is not centered at isocenter, an additional modulation $e^{i2\pi f_c(t-T_c)}$ is applied to the RF pulse where $f_c=(\gamma/2\pi)G_z z_c$, z_c is the average location of the slices, and T_c is a start time that may differ from T_I. Each slice then experiences an additional phase shift $2\pi f_c(T_c - T_I)$. If T_c is under software control it can be chosen to equal T_I, eliminating the phase shift. Alternatively, since the phase shift is the same for all slices in the group, it can be removed by a phase correction.

The software of a 1.5T commercial scanner (GE Healthcare, Waukesha, WI) was modified to implement slice acceleration using cosine modulation of the RF pulses in a 2D FSE pulse sequence. The reconstruction software was modified to implement SENSE (3) in the slice direction as well as the normal phase encoding direction. Phantoms and volunteers were scanned using an 8-channel head coil (MRI Devices, Gainesville, FL) with a T2-weighted protocol (TE/TR = 102/5000, bandwidth 25 kHz, 24 cm field of view, 5 mm slice, skip 0, 20 slices, 256 x 256, scan time 2:10 without acceleration). The excitation pulse duration was 4 msec with T_I = 1.52 msec. Increased SAR caused by simultaneously exciting multiple slices was mitigated by stretching the refocusing pulses. The refocusing pulses were symmetric with duration 4.72 msec with cosine modulation and 3.2 msec without. A phase correction was applied that removed the $2\pi f_c(T_c - T_I)$ phase shift for each group of simultaneously excited slices. Acceleration factors up to four in each direction were tested using sagittal and coronal planes.

Results

Figure 1 shows an unaccelerated sagittal volunteer image. Figure 2 shows R=2 with 1D acceleration in the slice direction. For this case, T_Δ was set to the center of each RF pulse, giving $T_\Delta - T_I$ = 2 – 1.52 = 0.48 msec for the excitation pulses and $T_\Delta - T_I$ = 0 for the refocusing pulses. The frequency separation of the aliased slices was $2\Delta f$ = 7680.15 Hz, giving an additional phase shift of $\pm 1.84\pi$ after the excitation pulses, which results in severe ghosting. Figure 3 shows R = 3 with 2D acceleration split between 2-fold in the slice direction and 1.5-fold in the phase direction, but with $T_\Delta = T_I$ for all pulses. Minimal ghosting is present. Other acceleration factors show similar results.

Conclusions

Slice accelerated parallel imaging is a useful technique for T2-weighted 2D FSE scans. The CPMG conditions must be maintained in order to ensure optimal image quality. For cosine modulated RF pulses, this requires that the center of the cosine modulation correspond to the isodelay point of the RF pulse.

References

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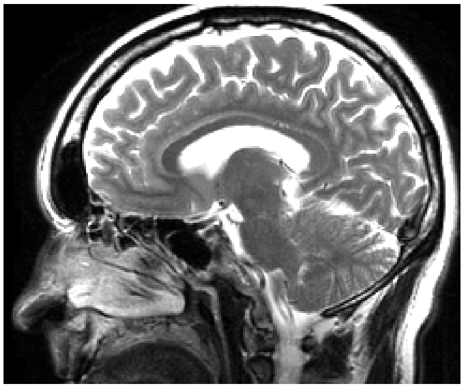

Fig. 1. Unaccelerated scan.

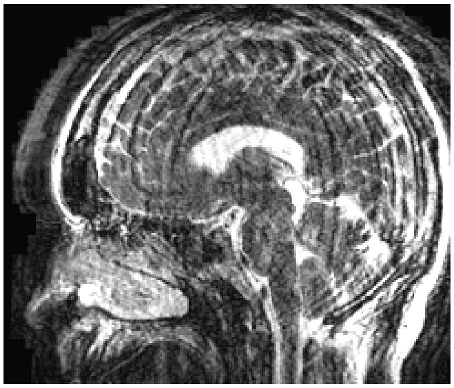

Fig. 2. 2-fold slice acceleration, T_Δ at center of RF pulses

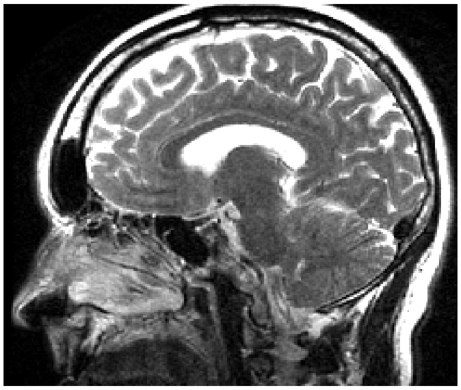

Fig. 3. 3-fold acceleration, 2-fold in slice, 1.5-fold in phase, $T_\Delta = T_I$