Robust prescan calibration for multiple spin echo sequences at high field: Application to FSE and balanced SSFP

C. V. Bowen[1], J. S. Gati[1], R. S. Menon[1]

[1]Imaging Research Laboratories, Robarts Research Institute, London, Ontario, Canada

Introduction

In recent years, the use of high field MR scanners for human body imaging has grown rapidly owing to the improved SNR and susceptibility contrast achievable. However, associated with these benefits, there exist additional challenges resulting from increased difficulty in producing adequate RF homogeneity (B_1) and shim quality (B_o) [1]. These problems manifest artifacts most sensitively within the family of multiple spin echo (MSE) sequences, where signal from multiple refocusing pathways must coherently combine to prevent destructive signal interference [2,3].

Two clinically significant MSE sequences, fast spin echo (FSE) and balanced steady state free precession (b-SSFP), are investigated in this work using a 4T Varian whole body scanner. We developed a readout projection based pre-scan technique that automatically adjusts the read and slice gradient balance to ensure coherent signal formation. This technique utilizes the banding artifacts that form through deliberate adjustment of the readout gradient balance from the nominal value in order to calculate calibration parameters. Subsequent image acquisition using the results of this pre-scan permits the formation of coherent echo images, robust under challenging imaging conditions such as oblique imaging and in regions of highly inhomogeneous B_o field. The robustness of this approach is demonstrated for FSE and b-SSFP images obtained from the knees of human volunteers. We believe the use of this pre-scan calibration technique for the alignment of signal pools in MSE sequences is critical at high field, and will facilitate the implementation of high quality clinically significant sequences such as FSE and b-SSFP.

Theory

The generation of artifact-free images for the family of multiple spin-echo (MSE) sequences relies upon a precise phase relationship between the transverse magnetization and the refocusing pulse B_1 vectors [2]. For FSE, non-zero gradient area is applied over the refocusing intervals and so the required phase condition is $\Delta\phi = 0$ where $\Delta\phi = \phi_2 - \phi_1 = \gamma[(A_{x2}-2A_{x1})\,x + (A_{z2} - 2A_{z1})z]$ where ϕ_1 and ϕ_2 are the phase accrued over the 90-180 interval and refocusing intervals, respectively. x and z are the read and slice positions, and A_x and A_z are the gradient area applied over the subscripted intervals in each respective direction. Phase encode balance for each interval is zero for FSE. Failure to meet this condition produces a modulation in late effective-echo FSE images that varies sinusoidally with $\Delta\phi$ [2]. A similar condition is required for b-SSFP, however, in this case zero gradient area is required over each TR interval. Failure to achieve this condition results in a more complex modulation with respect to the phase error over the TR interval, with a broader passband and a narrower stopband [3]. Nonetheless, unbalanced readout gradients result in a periodic banding profile in the readout direction, and so both FSE and b-SSFP are amenable to the same readout profile based pre-scan calibration technique described below.

Prescan Methods

All experiments were performed on a 4T Varian/Siemens whole body scanner using FSE and b-SSFP sequences developed in house. Phantom studies involved an 11 cm diameter Ni-doped water sphere and a 27 cm diameter quadrature birdcage coil. Phantom acquisitions had the following imaging parameters for FSE (14 cm fov, 256x256, 5 mm slice, 15 ms echo spacing, 8 echoes, 3000/60 ms TR/TE). Normal human volunteers were scanned for knee imaging studies, using an 18 cm quadrature birdcage coil with the following acquisition parameters for FSE (16 cm fov, 512x512, 2 mm slice, 15 ms echo spacing, 8 echoes, 3000/60 ms TR/TE) and b-SSFP (16 cm fov, 512x512, 2 mm slice, 13/6.5 ms TR/TE).

Fig. 1 shows read profiles obtained from a phantom using the 4th echo of FSE where the readout pre-winder lobe has been deliberately scaled from the nominal value by the indicated fractions (f_x). The prominent feature is a sinusoidal banding of the signal intensity in the readout direction in accordance with theory [2]. The spatial frequency of modulation is extracted from the peak location of the first harmonic in the 1D Fourier transform profiles (arrow in Fig. 2). Fig. 3 shows the band frequency, extracted according to the approach described in Fig. 2, as a function of f_x for two slices from a phantom. Excellent linearity is present for all slices. The optimal f_x value to produce no spatial banding in the frequency encode direction ($f_x^{(opt)}$) is obtained from extrapolation of the linear fits to zero band frequency (arrow in Fig. 3). Fig. 4 shows the *phase* of the FT profiles at the first harmonic peak location (Fig. 2), extrapolated to the $f_x^{(opt)}$ value calculated in Fig. 3. Physically this phase, ϕ_o, corresponds to the relative angle between the two interfering signal pools at gradient isocenter (x=0). Plotting this band phase, ϕ_o, versus slice position (Fig. 4) and fitting to a linear regression produces the final two required calibration parameters (P_{sl} and P_o corresponding to the slope and intercept). This slice dependent phase correction is applied to the phase of RF pulses during subsequent image acquisition. Together, these three correction factors ($f_x^{(opt)}$, P_{sl} and P_o) are employed for the subsequent acquisition of images. Acquisition of 10 f_x-varied prescan profiles requires 10 TR periods with approximately 4s for automated processing.

Figure 1: FSE Read Profiles

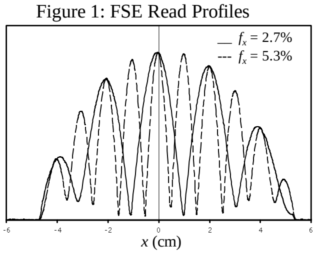


Figure 2: FSE Profile Banding Freq

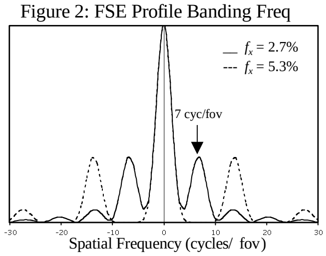


Figure 3: $f_x^{(opt)}$ calculation

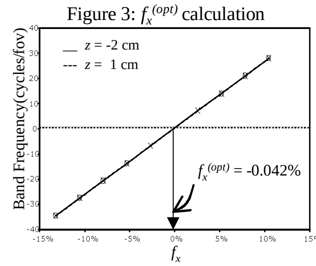
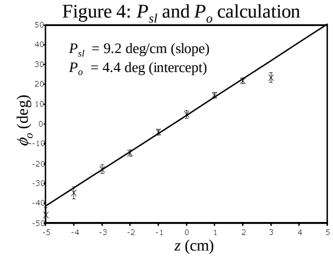


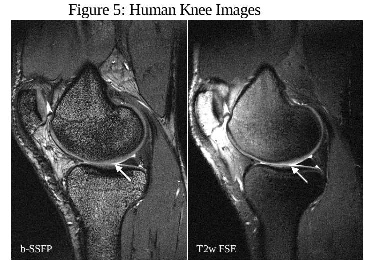
Figure 4: P_{sl} and P_o calculation



Results and Discussion

Fig 5. shows matched sagital knee images from a volunteer using b-SSFP and 4th effective echo FSE. Excellent contrast between cartilage and synovial fluid is apparent (arrow) indicating a lack of image blur and good alignment of all signal coherence pathways. Images acquired using nominal calibration settings demonstrate dark banding artifacts across the image (not shown). Although small, failure to consider the calibration values given in Figs. 3-4 results in signal modulation greater than 30% across the image volume, assuming sinusoidal variation, with larger compensation typical for higher res scans. The calibration technique is very robust even within complex *in vivo* images, like the knee, since the banding patterns far dominate any intrinsic modulation in typical images. We employ this prescan technique daily within our lab and have observed robust behavior in multiple anatomic locations for all oblique imaging, surface coil and 3D scans. We believe the application of this prescan technique will greatly compensate for many of the technical challenges present at higher field and permit the implementation of many MSE sequences, including FSE and b-SSFP demonstrated within this work.

Figure 5: Human Knee Images



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