High resolution imaging of trabecular bone structure using Wideband SSFP

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Introduction: Balanced steady state free precession sequences (SSFP) are used in many clinical areas because of their high signal to noise ratio (SNR) efficiency [1]. MRI of trabecular bone micro-architecture for diagnosis of osteoporosis and osteoarthritis is one such application [2]. However, SSFP sequences are highly sensitive to off-resonance, experiencing signal nulls at intervals of 1/TR [1]. In trabecular bone imaging where the TR is in the order of ~10-14 ms, a multiple phase-cycled SSFP (m-SSFP) has to be employed to avoid banding artifacts at 3 T and higher field strengths [1,3]. But this increases scan time by at least a factor of 2. In contrast, wideband SSFP (w-SSFP), a recently proposed technique, uses alternating TR to widen the passband with a lower scan time penalty (~20-70%) [4]. In this work, we will investigate the potential of w-SSFP as a faster alternative to m-SSFP for the trabecular bone MRI application.

Method: Signal responses to w-SSFP, conventional SSFP and m-SSFP were simulated in MATLAB [5,6] and average signal over the passband and signal efficiencies were calculated. A key design parameter for w-SSFP is $\boldsymbol{a}$, the short TR (TR_s) to long TR ratio which is decided as a trade-off between SNR and the passband width [4]. To choose an optimal value of $\boldsymbol{a}$ for this application, a simplified model of trabecular bone and marrow was used to simulate local susceptibility variations and the typical range of off-resonance (~60-80 Hz) [2]. Based on the required minimum passband width, value of $\boldsymbol{a}$=0.45 was adopted. After obtaining informed consent, a normal volunteer's knee was imaged on a 3T scanner (Signa HDx, GE Healthcare, Waukesha, WI) using an eight channel knee array with TR=11.6 ms, TE= 5 ms, flip = 55°, 16 cm field-of-view, 2 mm slice thickness, 512x384x32 acquisition matrix and a scan time of 2:20/3:27/4:47 mins for SSFP/w-SSFP/m-SSFP sequences respectively. In addition to banding artifacts, the other concern when imaging trabecular bone with SSFP is the signal phase cancellation within voxels that are occupied partly by bone and partly by bone marrow, manifested as artifactual broadening of bone micro-structures in the image. The resulting images were, therefore, compared on the basis of bone structural metrics [7] as well as SNR efficiency. SNR efficiency was measured as SNR divided by $\sqrt{scantime}$

Results: Based on simulations, mean SNR efficiency of w-SSFP was predicted to be 82% of m-SSFP with 2 phase-cycles. Using the off-resonance distribution generated by the bone model, bone images were simulated for the conventional SSFP, w-SSFP and m-SSFP sequences (Figure 1). In the simulated images, the red pixels indicate higher signal corresponding to marrow, the blue pixels indicate lower signal corresponding to bone while intermediate colors signify intermediate signal intensities corresponding to partial occupancy of bone and marrow. The bone structures were fused in the SSFP image due to artifactual broadening but depicted more accurately in the w-SSFP and m-SSFP images as shown in Figure 1. This observation also held true for images of the bone structure obtained with the MR experiment, shown in Figure 2. Relative SNR efficiency of the w-SSFP sequence was measured as 89% of the m-SSFP sequence, while scan time savings with the w-SSFP was 38.7% compared to m-SSFP. Two bone structural metrics, bone fraction (BF) and trabecular bone structural thickness (TbTh) were measured from the images [7]. BF measures were .37, .34 and .31 and TbTh measures were .47, .42 and .42 mm for conventional SSFP, w-SSFP and m-SSFP respectively.

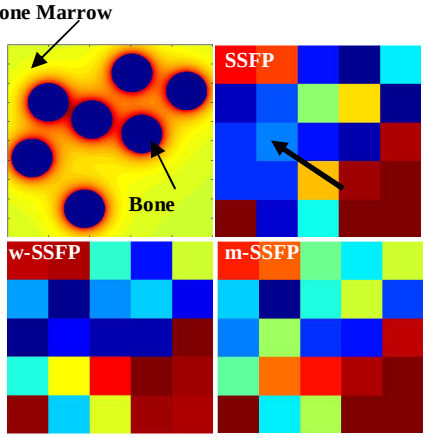

Figure1 *shows simulated magnetic inhomogeneity gradients (ΔB_0) at bone and bone marrow interfaces and simulated bone images using SSFP, w-SSFP and m-SSFP sequences. In the simulated images, the red pixels indicate higher signal corresponding to marrow while the blue pixels indicate low signal corresponding to bone. The bone structures are broadened and fused in the SSFP image but depicted more accurately in w-SSFP and m-SSFP images.*

Discussion: Initial results shows good potential for the w-SSFP sequence as a faster alternative to m-SSFP for imaging of trabecular bone micro-architecture. Relative signal efficiency of w-SSFP compared to m-SSFP was slightly underestimated in the simulation studies, possibly due to the assumption of uniform distribution of off-resonances. Bone thickness measurement was highly overestimated from the SSFP image, while measurements from w-SSFP and m-SSFP were in good agreement. Slight intensity variations were observed in w-SSFP images, possibly due to the small signal dip on-resonance. In future studies, suitable frequency offsets will be investigated to overcome this problem.

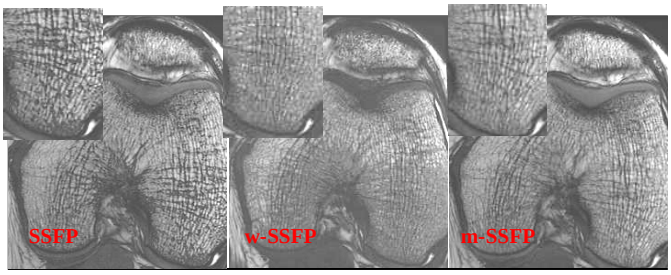

Figure 2 *shows representative images of bone structure at the knee images with SSFP, w-SSFP and m-SSFP sequences. Artifactual broadening of bone structures is seen in the SSFP image, but not in w-SSFP and m-SSFP images (zoomed inset).*

Reference: [1] Zur et al 1988 MRM 6:175-93 [2] Banerjee et al 2004 JMRI 21:818-25 [3] Bangerter et al 2004 MRM 51: 1038-47 [4] Nayak et al. 2007 MRM 58:931-938 [5] Hargreaves et al 2001 MRM 46:149-58 [6] Leupold et al 2006 MRM 55:557-65 [7] Newitt et al 2002 Osteoporosis Intl 13:278-87