Fully Balanced Steady State 3D-Spin-Echo (bSSSE) Imaging at 3 Tesla

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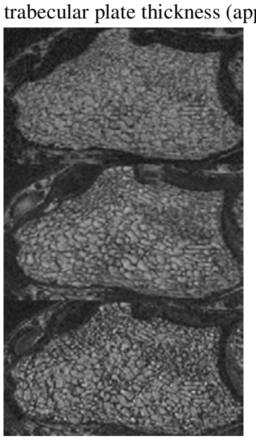
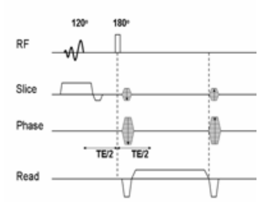
Introduction

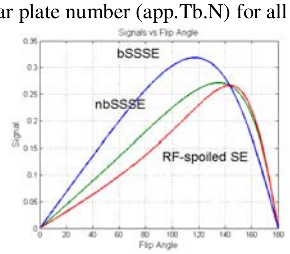
3D spin-echo (SE) imaging has limited use because of the prohibitive imaging time and thus low signal to noise (SNR) efficiency. Several variations of fast 3D-SE imaging has been previously presented (1,2). In this work we introduced a new fully balanced steady state 3D-spin-echo (bSSSE) sequence with all applied gradients fully rewound. We demonstrated that its SNR efficiency outperforms that of non-balanced SSSE (nbSSSE) sequences. SE based sequences are less prone to off-resonance artifacts arising from magnetic field inhomogeneities compared to gradient-echo (GE) based sequences which makes them suitable for imaging inhomogeneous tissue environment with high differences in susceptibility. To assess its performance we applied the sequence to in-vivo imaging of trabecular microstructure (Figure 1).

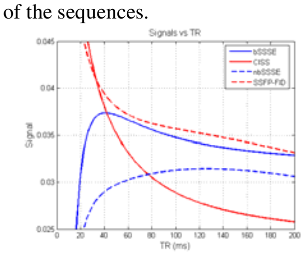
Material and Methods

We have implemented a 3D bSSSE pulse sequence on a 3 Tesla Signa system (General Electric, Milwaukee, WI) featuring a minimum-phase Shinnar-Le Roux excitation pulse and fully rewound gradients (Figure 2). In order to avoid a disruption of the steady-state magnetization, all phase-encodings and the readout prephasing are performed after the refocusing pulse. Artifacts due to imperfections of the 180 refocusing pulse were eliminated by phase cycling the pulse and placing crushers on either side. In order to further shorten TE, crushers were combined with slice-rephaser and slice-encoding gradients. Additionally, nbSSSE sequence similar to (1) was implemented with phase-encodings placed after the inversion pulse. Both sequences were optimized for trabecular bone imaging according to simulations of Bloch equation. TR was set to 80 ms in both cases and the flip angle to 120° (bSSSE) and 140° (nbSSSE) in order to maximize SNR (Figure 3). A readout bandwidth (BW) of ±8 kHz was used and a fractional echo (TE = 10ms) was acquired. For the GE sequences, a commonly used standard SSFP which acquires the Free Induction Decay signal (FID) immediately after the RF pulse (SSFP-FID), and a bSSFP sequence (a.k.a FIESTA, True FISP, Balanced FFE) with multiple acquisitions based on constructive interference in the steady state applying maximum intensity projection (CISS) was used. For the 3D CISS sequence, the readout BW was adjusted to ±32 kHz in order to minimize TR in the limits of gradient heating and RF power deposition. A flip angle of 60°, TR=14 ms and TE=2.9 ms (in-phase) were adopted as optimal parameters according to conducted simulations. Number of excitations (NEX) and number of slices (≥ 32) were adapted for all sequences in order to keep the imaging time below 7 minutes for all wrist scans (Figure 1) for 3 volunteers. After image acquisition, previously described methods were used to compute the apparent trabecular structural parameters such as apparent bone-volume over total-volume fraction (app.BV/TV), apparent trabecular plate separation (app.Tb.Sp), apparent trabecular plate thickness (app.Tb.Th) and apparent trabecular plate number (app.Tb.N) for all of the sequences.









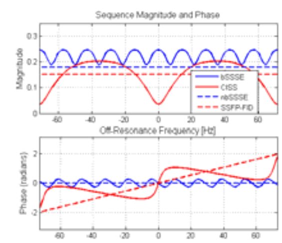


Figure 1: Images of the wrist acquired by using bSSSE (top), CISS (middle) and SSFP-FID (bottom)
Figure 2: Pulse sequence diagram for bSSSE. All gradients are rewound and a partial fourier acquisition is performed
Figure 3: Signal behavior versus flip angle. Both discussed SE sequences are compared to a fully rf-spoiled version of the same type
Fiugre 4: The sensitivity to off-resonance frequencies is shown. Note, that there is only one acquisition depicted for CISS with zero phase cycling. Furthermore, the amplitude plateau for bSSSE is maximal around 0 Hz off-resonance due to the inversion pulse
Figure 5: SNR efficiency calculated as square root of TR. It is shown that bSSSE has higher SNR efficiency compared to nbSSSE. The SNR efficiency for GE sequences drops with increasing TR

Results

MR images of the wrist using bSSSE, CISS and SSFP-FID are shown in Figure 1. Mean SNR from 3 volunteer scans was higher for bSSSE (13.4) than for nbSSSE (12.9) as expected from theory. SNR efficiency (Figure 4) was numerically calculated using the optimized scanning parameters and assuming one NEX per sequence. SNR efficiency was found to be 0.035 (bSSSE), 0.031 (nbSSSE), 0.058 (CISS) and 0.050 (SSFP-FID). The phase of bSSSE is not opposed to the primary echo as it is for CISS and therefore no alternating excitation pulse is required (Figure 5). The resulting transverse magnetization of bSSSE and CISS depend on the distribution of off-resonance frequencies in the voxel. There is also a modulation of the amplitude as a function of off-resonances visible for the bSSSE with a period of ± 1/(TR-TE) since the residual transverse magnetization is dephasing during that time . However, these modulations are small and the phases of the spins remain in a range of ± 0.2 rad, thus no cancellation occurs and no bandings were visible in the images. The app.TbTh was found to be smaller for all 3 volunteers using bSSSE compared to nbSSSE. The app.TbTh of both gradient-echo sequences was significantly higher (>18 %). The same is true for app.BV/TV which is significantly higher using GE sequences compared to the here applied SE sequences and slightly higher for bSSSE compared to nbSSSE.

Discussion

In this study we have introduced a new fully balanced SSSE sequence and compared with non-balanced sequences used in previous publications (1,2). We found that bSSSE reveals highest SNR compared to other SSSE sequences (Figure 3). The flip angle could be reduced for higher SNR and thus allowing shorter TR due to less SAR limitations. Both spin-echo sequences performed similar in terms of depiction of the trabecular structure (structural parameters). However, the trabecular thickness was smaller for bSSSE. This is due to the higher SNR and thus higher contrast between bone and marrow. In conclusion we think that bSSSE is the sequence of choice for trabecular bone measurements at 3 T.

References

1. Ma J, Wehrli FW, Song HK. Fast 3D large-angle spin-echo imaging (3D FLASE). Magn Reson Med 1996;35(6):903-910.
2. Vasilic B, Song HK, Wehrli FW. Coherence-induced artifacts in large-flip-angle steady-state spin-echo imaging. Magn Reson Med 2004;52(2):346-353.

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