Strain-Encoded (SENC) MR Imaging with Improved Signal-to-Noise Ratio Using Balanced Steady-State Free Precession

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Introduction: Strain encoding (SENC) is a new MRI technique for directly measuring regional strain in the heart [1]. SENC is based on applying parallel planes of saturated magnetization (tag planes), which lie parallel to, and inside, the imaging plane. Upon tissue contraction or stretching in the through-plane direction, i.e., the direction orthogonal to the imaging plane, the tagging planes move closer together or further apart, respectively, which affects the tagging frequency in the through-plane direction. Current implementations of SENC use the spoiled gradient echo (SPGR) pulse sequence, which is not the optimal sequence to achieve high signal-to-noise ratio (SNR). However, coherent steady-state pulse sequences, like balanced steady-state free precession (SSFP), offers much higher SNR compared to non-coherent sequences, like SPGR. In this work, a new technique (SENC-SSFP) is proposed for imaging and quantifying myocardial through-plane strain by combining SENC with balanced SSFP and implementing the necessary modifications to the pulse sequence. Numerical simulations of the Bloch equation are conducted to compare the resulting SNR in both SSFP and SPGR sequences, and to optimize the imaging parameters. The SENC-SSFP sequence is tested on phantom and *in vivo* experiments. The results show significant improvement (~ 100%) in SNR compared to conventional SENC imaging with SPGR.

Methods: **Pulse Sequence:** A schematic diagram of the SENC-SSFP pulse sequence is shown in Fig. 1. The demodulation gradients used in SENC are compensated for, such that the net gradient moments is nulled in each repetition time (TR) period in order to satisfy the requirements for balanced SSFP. The magnetization vectors are stored and restored before and after, respectively, tagging preparation in order to preserve the steady-state scheme as described in [2]. The imaging flip angles are ramped as described in [3] to maintain constant signal intensity through the cardiac cycle.

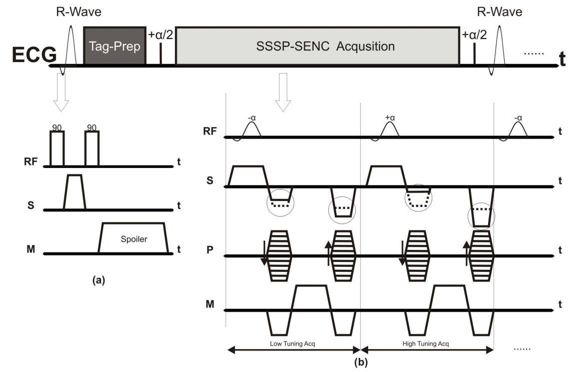

Figure 1: SENC-SSFP pulse sequence diagram. (a) Tag preparation, and (b) SSFP signal acquisition with the SENC tunings. The dotted lines illustrate the original values for the gradients while the solid lines show the actual used values for achieving the SENC tunings.

Numerical Simulation: Numerical simulations of the Bloch Eq. were conducted to examine the effect of the RR-interval (TRR) on the resulting SNR, and to determine the last flip angle that would result in the highest SNR throughout the cardiac cycle.

Phantom Experiment: A phantom experiment was conducted to verify the numerical simulations. The phantom was scanned on a 3T Philips MRI scanner. Images were acquired using SENC with SPGR and SSFP using the following imaging parameters: simulated cardiac gating with TRR = 750, 850, and 950 ms; scan matrix = 256×256; FOV = 30×30 cm^2; and slice thickness = 8 mm. During acquisition, 20 heart phases were acquired using multi-shot acquisition with TFE factor (number of RF pulses per heart phase) = 6; and TR = 3.3 ms, which yielded phase interval of 20 ms. To examine the effect of changing the last flip angle on the achieved SNR, cine loops were acquired with last flip angle ranging from 10° to 42° in 2° increments. SENC-related parameters were: tagging frequency = 3.8 mm; low-tuning (LT) frequency = 0.25 mm^{-1}; and high-tuning (HT) frequency = 0.38 mm^{-1}. This enabled measuring strain values from +5 % to -30 % (see [1] for more details), where the positive and negative signs represent stretching and contraction, respectively.

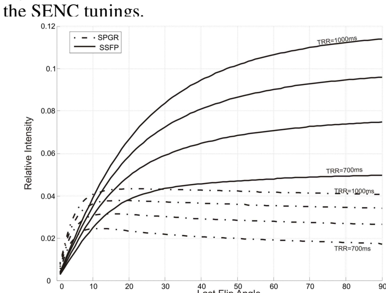

Figure 2: Simulation results for the signal intensity in both SPGR and SSFP sequences for different last flip angle and TRR values.

***In Vivo* Experiments:** Five normal volunteers were scanned using the SPGR and SSFP sequences on the same scanner and the same parameters in the phantom experiment. The last flip angle ranged from 10° to 40° for both SPGR and SSFP.

Results: **Numerical Simulation Results:** Fig. 2 shows the results from the numerical simulations. It shows the signal intensity (relative to the initial magnitude of the tagged vector) as a function of the last flip angle for different TRRs. While SNR reaches its maximum value at last flip angle of 15˚ in the case of SPGR, it shows a monotonic increase with the last flip angle in the case of SSFP.

Phantom & *In Vivo* Results: Fig. 3 shows the measured SNR values in the phantom study, which are consistent with the results from the numerical simulations. Fig. 4 shows short-axis SENC images of longitudinal myocardial strains at successive time points in the cardiac cycle. The figure shows images acquired with SPGR and SSFP pulse sequences for different last flip angles. The SNR gain can be easily noticed in the myocardial tissue (solid arrows) and also in the non-myocardial areas (the blood pool pointed to by the open arrows and the chest cavity pointed to by the dashed arrows). The noise is largely suppressed in the SSFP images. Fig. 5 shows the ratio between the SNR values achieved with SSFP and SPGR at different last flip angles. The figure shows that the SNR gain with SSFP was more than 100% over that with SPGR for last flip angles more than 25˚.

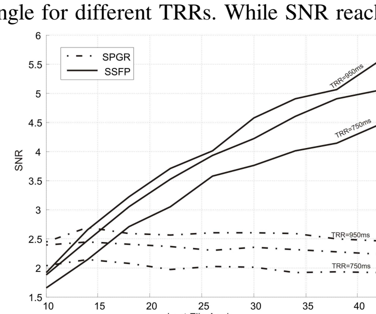

Figure 3: Phantom results show higher SNR gain with SSFP over SPGR for different simulated heart rates and last flip angle values.

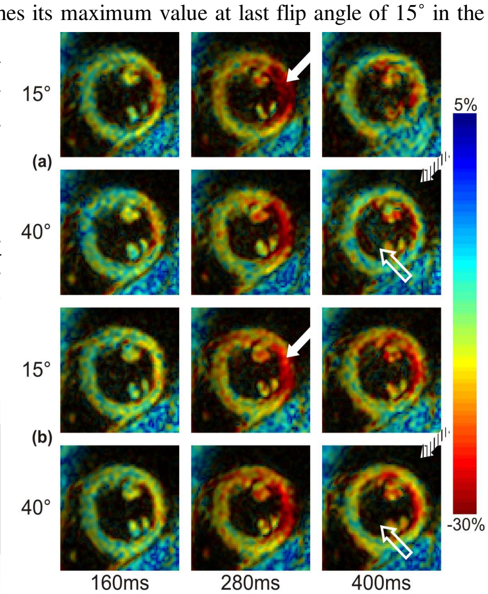

Figure 4: Short-axis (basal left ventricle) images showing longitudinal myocardial strain for different cardiac phases at two different last flip angles using: (a) SPGR, and (b) SSFP. For each image, the acquisition time, measured directly after the R wave, appears below its column, and the last flip angle appears to the left of its row.

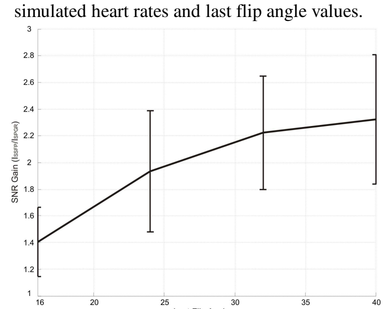

Figure 5: In-vivo results show SNR gain of SSFP over SPGR for different last flip angles.

Conclusion: A new technique (SENC-SSFP) is proposed for measuring regional myocardial strain with high SNR. The technique combines SENC imaging with SSFP pulse sequence, which results in significant increase (~100%) in SNR, compared to conventional SENC imaging. The achieved high SNR would improve myocardial strain quantification, which in turn would result in better analysis of myocardial regional function.

References: [1] Osman et al., MRM 46, 324-334.
[2] Scheffler et al, MRM 45, 1075-1080.
[3] Ibrahim et al., JMRI 24, 1159-1167.