Artifact-Free Stimulated-Echo Acquisition Mode (STEAM) Cardiac Images with Improved Signal-to-Noise Ratio (SNR)

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Introduction: Stimulated echo acquisition mode (STEAM) MRI is currently used in a wide range of applications because of its sensitivity to different imaging parameters and black blood property (nulled signal from blood), which is appealing for cardiac imaging. In addition, a technique has recently been proposed for acquiring STEAM images of the heart without the artifacts introduced by myocardial deformation during the cardiac cycle [1]. The technique is based on acquiring two sets of STEAM images with different demodulation frequencies, which when added together, result in artifact-free images. Basically, the signal loss in one image is compensated by a signal gain in the other image. However, the resulting cardiac STEAM images have poor signal-to-noise ratio (SNR). In this work, a new technique is proposed to improve SNR in the resulting images. The technique is composed of two parts: Firstly, the usually-used spoiled gradient (SPGR) pulse sequence is replaced with balanced steady-state free precession (SSFP) pulse sequence for the imaging part is STEAM, which results in substantial improvement in SNR. Certain modifications are implemented to apply the required demodulation frequencies while maintaining nulled gradient moments as required in SSFP. Secondly, the simple image addition technique proposed in [1] is not the optimal combination method from the SNR perspective, especially at the highly (or minimally) contracting regions since one of the two images is mainly noise at these regions. Thus, we propose an adaptive algorithm for the combination of the two modulated images, such that the images are weighted based on their relative SNR before summation. The proposed technique results in significant increase in SNR, as evidenced by the conducted phantom and *in vivo* experiments.

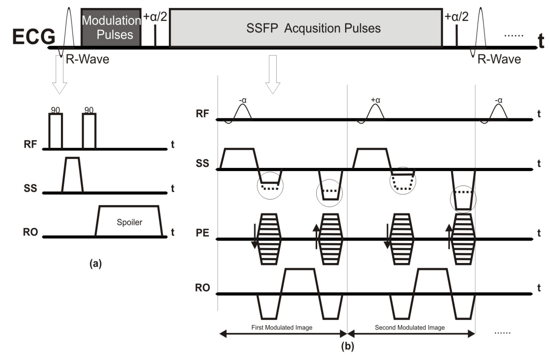

Figure 1: STEAM-SSFP pulse sequence diagram. (a) Modulation pulses, and (b) SSFP signal acquisition with the demodulation gradients. The dotted lines illustrate the original values for the gradients while the solid lines show the actual used values.

Methods: **Pulse Sequence:** A schematic diagram of the pulse sequence is shown in Fig. 1. The modulation pulses are applied at the beginning of each cardiac cycle. The magnetization vectors are brought into steady-state using half the first flip angle technique [2] before applying the train of the imaging radiofrequency (RF) pulses. The magnetization is stored into the longitudinal direction at the end of the cardiac cycle using half the last flip angle as described in [3]. The flip angles are ramped in a scheme similar to [**] to maintain constant signal intensity throughout the cardiac cycle. The gradient moments are nulled in all three gradient channels to achieve the balanced SSFP concept. In the slice-selection direction, the gradient added to achieve certain demodulation frequency is compensated for by the end of the repetition time (TR), such that the total gradient area is nulled within each TR.

Combination of the Two Modulated Images: To recover the signal loss caused by tissue deformation, the authors in [1] proposed the acquisition of two images $I_1(x, y, \omega_{\min})$ and $I_2(x, y, \omega_{\max})$ using two different demodulation frequencies $\omega_{\min}$ and $\omega_{\max}$, which are determined as described in [**]. The final STEAM image is then obtained by simply summing the two images. However, this simple addition ignores the fact that SNR is not equal in each two corresponding pixels in the two images. Thus, instead of direct summation, we perform a weighted average summation of each two corresponding pixels, where the weights are determined based on the relative SNR of each pixel, such that: $I = (I_1/(I_1+I_2))\times I_1 + (I_2/(I_1+I_2))\times I_2$.

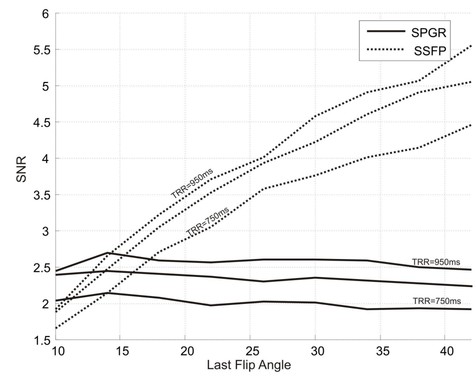

Figure 2: Phantom results show higher SNR gain with SSFP over SPGR for different simulated heart rates and last flip angle values.

Phantom Experiment: A gel phantom experiment was conducted to examine the SNR gain using the proposed technique. The phantom was scanned on a 3T Philips MRI scanner. The two sets of images were acquired using STEAM with SPGR and SSFP using the following imaging parameters: simulated cardiac gating with RR-intervals (TRR) = 750, 850, and 950 ms; matrix size = 256×256; FOV = 30×30 cm^2; slice thickness = 8 mm; number of heart phases = 20; TFE factor (the number of RF pulses per heart phase per cardiac cycle) = 6; TR = 3.3 ms; phase interval = 20 ms. Each two demodulated images are then combined using the proposed weighted summation technique to obtain the final STEAM image. 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 40° in 2° increments.

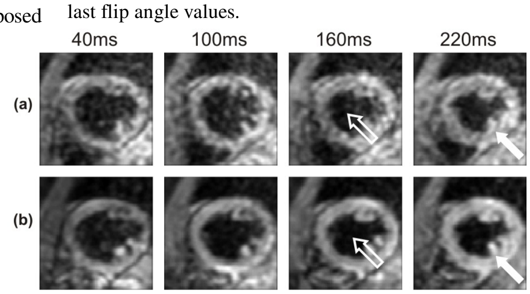

Figure 3: Short-axis (basal left ventricle) images showing longitudinal myocardial strain for different cardiac phases at two different last flip angles using: (a) SPGR, and (b) SSFP. For each image, the acquisition time, measured directly after the R wave, appears below its column.

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

Results: **Phantom Results:** Fig. 2 shows the measured SNR in the phantom study. While SNR reaches its maximum value at last flip angle of 15˚ in the case of SPGR, it shows a monotonic increase with the value of ***In Vivo* Results:** Fig. 3 shows short-axis STEAM images of the heart 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 in the SSFP images can be easily noticed in the enhanced signal intensity of the myocardial tissue (solid arrows) and also in the suppressed noise in the non-myocardial areas (the blood pool pointed to by the open arrows and the chest cavity pointed to by the dashed arrows). Fig. 4 shows the SNR gain between the SSFP and SPGR sets of *in vivo* images for different flip angles.

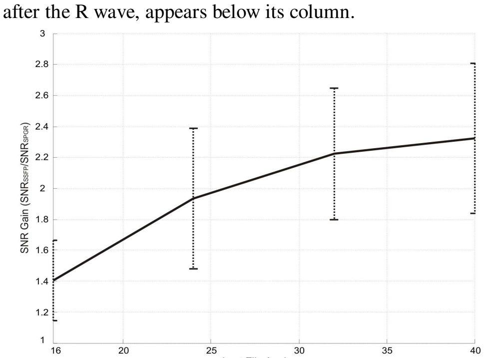

Figure 4: In-vivo results show SNR gain of SSFP over SPGR for different last flip angles.

Conclusion: The proposed technique significantly enhances SNR in cardiac STEAM imaging. The technique addresses two points: Firstly, the balanced SSFP pulse sequence is used for imaging, with considerable improvement in SNR. Secondly, the two STEAM images, acquired with different demodulation frequencies, are combined in a pixel-wise fashion, such that relative SNR is taken into consideration between corresponding pixels in the two images, which reduces the noise component in the resulting STEAM image. The SNR improvement would allow for better analysis of the resulting cardiac images, or could be used to increase

References: [1] Fahmy et al., MRM 55, 404-412.
[2] Scheffler et al, MRM 45, 1075-1080.
[3] Ibrahim et al., JMRI 24, 1159-1167.