Improving SNR in DENSE MRI by Combining Stimulated Echoes

D. Kim[1], F. H. Epstein[2], W. D. Gilson[2], L. Axel[1]

[1]Radiology, New York University, New York, NY, United States, [2]Radiology, University of Virginia, Charlottesville, VA, United States

Introduction: Displacement-encoding with stimulated echoes (DENSE)[1] and harmonic phase imaging (HARP)[2] are quantitative MRI techniques for assessing intramyocardial function without the need for explicit tag detection. However, DENSE and HARP produce relatively low signal-to-noise ratio (SNR) because of the 50% signal loss inherent to stimulated echoes or bandpass filtering only one of the acquired echoes, respectively. The purpose of this study was to develop a technique for increasing the SNR in DENSE MRI. This technique is based on the SNR advantage of extracting two sub-sampled phase images with uncorrelated noise from a complex complementary spatial modulation of magnetization (CSPAMM) image and combining them during image reconstruction. We refer to this technique as SNR-enhanced DENSE (se-DENSE) MRI.

Methods: Figure 1 shows the magnitude, phase, and k-space images of a complex CSPAMM data set (Fig. 1A-C) and two extracted DENSE data sets (Fig. 1D-I). In order to extract two DENSE images from a complex CSPAMM image, the two stimulated echoes must be encoded in k-space at k_x = -0.25 cycles/pixel and k_x = 0.25 cyclex/pixel (Fig. 1C). Here we show that dividing the complex CSPAMM raw data at k_x = 0 (Fig. 1C) yields two DENSE image sets (Fig. 1D-I). Due to k-space symmetry, the two conjugate echoes in Fig. 1F,I shift and rotate through the cardiac cycle in opposite directions with respect to the origin of k-space. As a result, the two phase images (Fig. 1E,H) have the same magnitude but opposite polarity of phase. While the two raw data sets cannot be combined conventionally, the two phase images can be combined after appropriately changing the sign of the phase as needed. In se-DENSE there are two practical limitations associated with the receiver bandwidth and displacement encoding strength (k_e). In order to achieve equivalent spatial and temporal resolution and scan time as cine DENSE [3] that acquires just one of the echoes, se-DENSE must over-sample the readout points by a factor of two at the cost of increasing the receiver bandwidth. An optimial value of k_e for cine DENSE was determined to be 0.28 cycles/pixel as previously described [3]. The magnitude of k_e must be 0.25 cycles/pixel in se-DENSE. Accounting for over-sampling, cine DENSE and se-DENSE phase encode 0.28 and 0.50 cycles per unit distance, respecticely. Hence, se-DENSE is more prone to signal loss due to motion-induced intravoxel dephasing. All imaging was performed on a 1.5T scanner (Sonata, Siemens). Short-axis imaging was performed in 6 volunteers (3 slices) using se-DENSE, cine DENSE, and myocardial tagging sequences. Imaging parameters for se-DENSE included: field of view = 340 x 340 mm^2, acquisition matrix = 192 x 60, slice thickness = 8 mm, TR = 13.4 ms, flip angle = 15°, bandwidth = 1370 Hz/pixel, echo train length = 10, phase-encoding lines per cardiac phase per cardiac cycle = 30, and temporal resolution = 40.2 ms. Displacement was encoded in the frequency-encoding direction with 90° RF pulses and a gradient pulse that achieved k_e = 0.14 cycles/mm. Displacement was also encoded in the orthogonal direction by swapping the frequency-encoding and phase-encoding axes. Cine DENSE used the same imaging parameters except matrix = 96 x 60, bandwidth = 1240 Hz/pixel and k_e = 0.08 cycles/mm. For both DENSE techniques, phase reference and 2D displacement-encoded images were sequentially acquired in a single breathhold of 19 cardiac cycles. Pertinent parameters for the myocardial tagging sequence included: spatial resolution of 1.4 x 1.7 mm^2, breath-hold duration = 17 cardiac cycles, tag spacing = 7 mm, and temporal resolution = 40.2 ms. The se-DENSE and cine DENSE data were reconstructed and analyzed off-line using Matlab (Mathworks). The CSPAMM raw data matrix of 192 x 60 was parsed at k_x = 0 (Fig. 1C) into two 96 x 60 matrices as shown in Fig. 1F,I. After background phase correction, phase image sets were sign-adjusted (Fig. 1E,H) and averaged. The resulting phase image was then used to compute displacement and strain as previously described [3]. For each of two encoding directions, the composite magnitude images were constructed as the sum of two sub-sampled magnitude images (Fig. 1D,G). The SNR was measured from magnitude images over multiple cardiac phases. Relative SNR was calculated as the ratio of $SNR_{se\text{-}DENSE}$ and SNR_{DENSE}. Accounting for the difference in bandwidth and ignoring the effects of k_e, the theoretical value of relative SNR was computed as 1.34. The FindTags program was used to perform tag analysis [4]. Circumferential strain (E_{cc}) was computed over multiple cardiac phases. The correlation and agreement between se-DENSE and myocardial tagging were assessed by performing linear regression and Bland-Altman analyses on E_{cc} measurements.

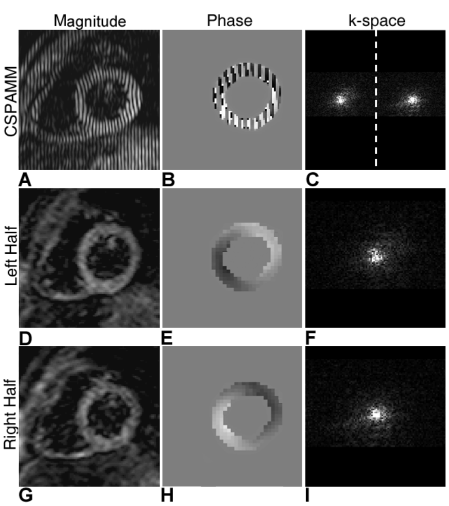

Figure 1. The magnitude, phase, and the corresponding k-space images of complex CSPAMM data (A-C) and two extracted DENSE data sets (D-I).

Results: In Fig.2, a magnitude image, a vector displacement map, and a E_{cc} map of a basal slice at end systole are shown. se-DENSE produced significantly higher SNR than cine DENSE throughout the cardiac cycle, from early systole (47.7 ± 2.6 vs. 35.4 ± 4.4; $p < 0.01$) to late diastole (11.9 ± 1.2 vs. 8.6 ± 1.3; $p < 0.01$). Relative SNR was on the order of the theoretical value of 1.34 at early systole and late diastole and showed a uniphasic response with a minimum value of 1.15 at end systole. Given that se-DENSE used a higher value of k_e than cine DENSE, this uniphasic response as a function of cardiac phase is consistent with previously reported motion-induced signal loss in cardiac STEAM techniques [5]. For pooled data of 180 points, there was a strong correlation between E_{cc} measured by se-DENSE and that by myocardial tagging (slope = 0.95, intercept = -0.02, and R = 0.92). According to the Bland-Altman analysis, 98% of the two E_{cc} measurements were within the 95% limits of agreement, with a systematic difference of –0.02, and showed no apparent trend.

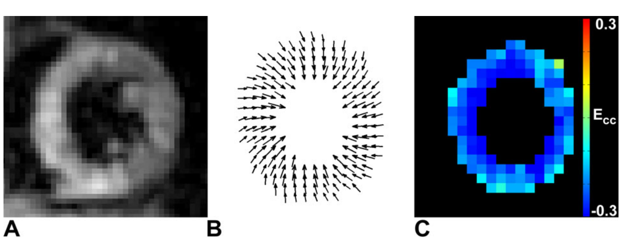

Figure 2. (A) A magnitude image, (B) a vector displacement map, (C) and a E_{cc} map of a basal slice.

Discussion: A new technique was developed to increase the SNR in DENSE MRI. This technique can also be applied to improve the SNR in HARP image processing. Future work may include imaging at higher field strengths and with dedicated cardiac coils for further improvements.

References

1 Aletras, A.H., *et al.* MRM, 46, 523-534, 2001
2 Osman, N.F., *et al.* MRM, 42, 1048-1060, 1999
3 Kim, D., *et al*. Radiology (in press)
4. Guttman, M.A., *et al.* IEEE TMI, 13, 74-88, 1994
5. Fischer, S.E, *et al.* MRM, 34, 80-91, 1995