Optimal Combination of Phase Cycling and Gradient Spoiling in DENSE Displacement Mapping

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Introduction

Displacement encoding with stimulated-echo (DENSE)(1) is an extension of phase-contrast imaging in which two opposite gradient pulses induce phase shifts proportional to spin movement between them. To image displacement over long durations, a stimulated-echo (STEAM) sequence puts the X component of the transverse magnetization back to the Z-axis after the first gradient pulse, and returns it to the transverse plane at a later time for the second gradient pulse and data acquisition. This causes a SPAMM tagging like modulation of Mz which is a combination of 3 parts, the stimulated echo (I_0), the anti-echo (I_2) and the DC part (I_1) that arises from T_1 relaxation during the lapsed time. Indeed an independently developed technique HARP (2) was based on tagged imaging and reached a similar solution. The difference between DENSE and HARP is that the former centers the k-space data acquisition on the stimulated echo I_0 and suppresses the other two parts to prevent interference, the latter uses k-space masking and filtering to separate the echoes.

$I(\theta) = I_0 e^{i\theta} + I_1 e^{iKz \cdot z} + I_2 e^{i2Kz \cdot z} e^{-i\theta} + I_n$,
I_n is noise independent of θ.

3-point phase cycling:
$\theta = 2m\pi/3,\ m=0,1,2.$
First Fourier peak $I'^2_0 = I_0^2 + I_n^2/3$,
SNR^2/unit time = I_0^2/I_n^2.

2-point phase cycling:
$\theta = 2m\pi/2,\ m=0,1.$
$I'^2_0 = I_0^2 + (I_2 e^{i2kz\, z})^2 + I_n^2/2$,

Figure 1

There are two ways to separate or selectively suppress the echoes. The first is gradient spoiling, which is most effective with encoding gradient Kz in the through-slice direction as it is the thickest dimension of the pixel. Kz is refocused for I_0, but not for I_1 and I_2 and so spoils the latter two echoes. The second approach is phase-cycling(3-5), where a phase θ is put on the first 90^0 RF pulse which results in different phase multiplication factors in the three echoes (Fig. 1). If the net signal I(θ) is Fourier transformed relative to θ, there will be three Fourier peaks at frequencies (-1, 0, 1) which correspond to the three echoes. A minimum of three images of $\theta = m*2\pi/3$ (m=0, 1, 2) are needed to fully resolve the echoes. Noise and artifacts uncorrelated with θ contribute an extra noise term of the same amplitude to all three echoes.

Methods and Results

To find the optimal combination of gradient spoiling and phase cycling we measured SNR^2 per unit time for 3-point and 2-point phase cycling. In 2-point phase cycling the echoes cannot be fully resolved, so we choose to separate I_1 from the sum of I_0 and I_2 and then rely on gradient spoiling to suppress I_2. The expressions for signal and noise are given in Fig.1. In a cine data set SNR varies with time for several reasons: Kz causes intravoxel dephasing and signal drop in I_0 which is dependent on the time-varying through-slice strain; I_1 is dependent on T_1 recovery; all echoes are affected by multiple stimulated echoes in the RF pulse train in a heartbeat. We therefore looked at end-systole when through-slice strain peaks, and the last phase of the cine sequence.

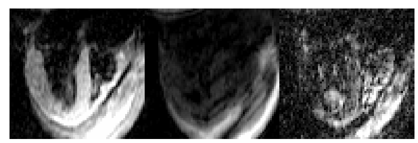
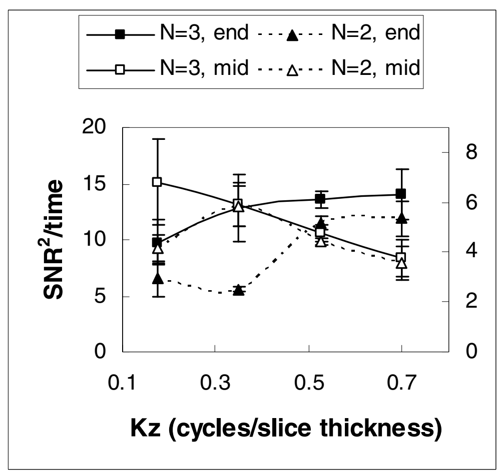


Fig.2 I_0, I_1 and I_2 images.

In four volunteers (M, age 30 – 41) long axis 4-chamber view images were acquired on a 1.5T scanner (Sonata, Siemens). In 18 heartbeats 9 cine data sets are acquired, including the displacement encoding sets of (Y, Z), (-Y, Z) and (X, Z), and 3-phase cycling for each set. A segmented EPI readout was used with 6-echoes per RF excitation and 4 RF pulses per cardiac phase. The temporal and spatial resolutions were 31 ms and 2.0x3.7 mm^2, matrix size 48x128. The second RF pulse of STEAM preparation was selective in the phase-encode direction to limit FOV. 20 phases were acquired with ramped RF flip angle to equalize the signal amplitude. The X and Y encoding strengths were 0.05 cycle/mm. Four Kz values from 0.175 to 0.7 cycles/slice thickness were used. The three echoes were fully separated (Fig. 2). The lateral wall segment had the lowest signal level and was investigated. The noise I_n was measured in the I_2 image in a void area aligned with the lateral wall in the phase-encode direction. SNR^2/unit time for all measurements are plotted in Fig. 3.



Taking into account both time points, the optimal combination is a 3-point phase cycling with a through slice encoding gradient of 0.35 cycle/slice thickness.

References

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