Quantification of Left Ventricular Torsion by Off-Resonance Insensitive CSPAMM (ORI-CSPAMM)

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Introduction: Alterations in left ventricular (LV) torsion are important in many pathophysiologic scenarios including myocardial infarction [1], dilated cardiomyopathy [2], mitral regurgitation [3], diastolic dysfunction [4] and aging [5]. LV torsion is a measure of the rotation of the apex relative to the base of the heart. Employing a previously developed and validated method, Fourier Analysis of STimulated echoes (FAST), which measures object rotation directly in Fourier space, we performed quantitative analysis of LV torsion in five (N=5) healthy volunteers. For this study a new pulse sequence was developed, Off-Resonance Insensitive CSPAMM (ORI-CSPAMM), which modified the original 1-1 SPAMM tagging preparation of CSPAMM [6] by adding a 180° RF refocusing pulse in the middle of the motion encoding gradient, which refocuses off-resonance accumulated during the motion encoding gradient. Qualitative analysis of the effects of refocusing is presented. Furthermore, key differences in LV torsion between ORI-CSPAMM, CSPAMM, and SPAMM for torsion values derived from the FAST method [7] are shown.

Methods: A spoiled gradient echo pulse sequence was modified to support 1-1 SPAMM line tags, 1-1 variable flip angle (FA) CSPAMM [8], and 1-1 variable flip angle ORI-CSPAMM, and used to acquire short-axis images in healthy volunteers at the base and apex with the following parameters: 360-300x300-280mm FOV, 5-6mm slice thickness, 192x144 acquisition matrix, 501 Hz/pixel receiver bandwidth, TE/TR=3.5-3.7/4.7-6.5ms, 10 mm tag spacing, 7-8 k_y-lines per segment, 3/4 partial Fourier imaging, 14-16 cardiac phases, 15° FA and two averages for SPAMM imaging, and 21° FA for CSPAMM. *Torsion Estimates* – Estimates of LV rotation at basal and apical slice levels for all frames were obtained from the rotation of the stimulated echo and stimulated anti-echo in Fourier Space using the FAST method. The FAST method utilizes nulling of the FID with a circular mask. However, for CSPAMM the FID was largely suppressed due to the subtraction of the two phase cycled experiments, thus FID nulling was not necessary for the CSPAMM or ORI-CSPAMM studies. *Statistical Analysis* – For each healthy volunteer, torsion was calculated on a frame-by-frame basis for each method. Bland-Altman analysis was used to compare SPAMM to ORI-CSPAMM and CSPAMM to ORI-CSPAMM (Figure 2). The SPAMM and ORI-CSPAMM Bland-Altman analysis only used torsion data obtained during the first 500ms (duration of trackable tag persistence). The mean difference between the methods (SPAMM and ORI-CSPAMM; CSPAMM and ORI-CSPAMM) and the 95% confidence intervals (CI) were calculated and reported. The mean and standard deviation of peak systolic torsion for all healthy volunteers were calculated and reported.

Results: The effects of refocusing are especially apparent in epicardial fat (Figure 1) where the myocardial and fat signal is plotted as a function of pixel number for the different sequences. In ORI-CSPAMM the myocardium and fat tagging patterns are the least out-of-phase (0.4 pixels) compared to CSPAMM (4.4 pixels) and SPAMM (0.9 pixels). CSPAMM is the most susceptible to the chemical shift effects. CSPAMM fat tags are shifted by an additional ~3 pixels, compared to SPAMM, due to subtraction of the complementary tagged data sets, which have twice the tag spacing (four times tag thickness) compared to SPAMM. There was excellent agreement between LV torsion derived from CSPAMM and ORI-CSPAMM with a bias (CSPAMM - ORI-CSPAMM) of -1.5° and 95% CIs of (-4.0°, 0.9°). There was also excellent agreement between LV torsion derived from SPAMM and ORI-CSPAMM with a bias (SPAMM - ORI-CSPAMM) of -1.1° and 95% CIs of (-4.0°, 1.7°). The mean peak systolic torsion for all healthy volunteers was 8.9°±2.1° for ORI-CSPAMM, 7.0°±2.2° for CSPAMM, and 7.4°±2.2° for SPAMM, Figure 3.

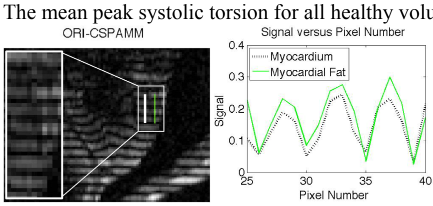
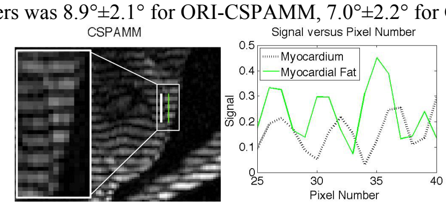
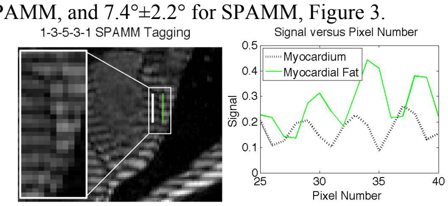


Figure 1. A. ORI-CSPAMM chemical shift effect



B. CSPAMM chemical shift effect



C.1-3-5-3-1 SPAMM chemical shift effect

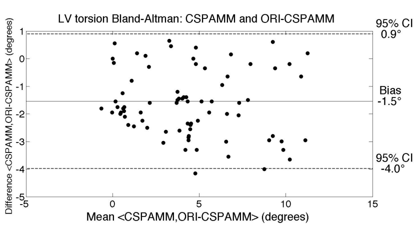
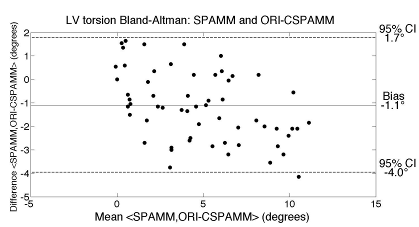


Figure 2. A. Bland-Altman of CSPAMM vs. ORI-CSPAMM



B. Bland-Altman of SPAMM vs. ORI-CSPAMM

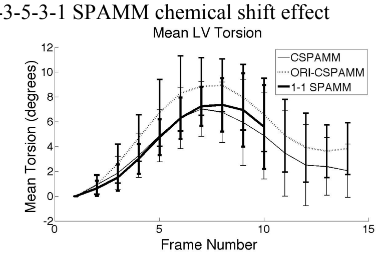


Figure 3. Mean LV Torsion

Discussion: Figure 1 illustrates the effect of the refocusing pulse in epicardial fat near the anterior interventricular sulcus. The consequences of chemical shift were not visible in epicardial fat for the ORI-CSPAMM case, however the spatial displacement of the tags due to chemical shift was visible in the CSPAMM and SPAMM tagged images. The effects of ORI-CSPAMM refocusing significantly improve the large chemical shift of CSPAMM. Chemical shift still also arises during the readout interval, but this is challenging to mitigate without significantly increasing SAR. The Bland-Altman analysis between CSPAMM and ORI-CSPAMM and between 1-1 SPAMM and ORI-CSPAMM both show excellent agreement. The differences between CSPAMM and ORI-CSPAMM may be due to off-resonance effects within the myocardium, due to veinous dephasing within epicardial voxels in the vicinity of the great cardiac vein, middle cardiac vein, and posterior vein of the LV [9], or more generally by intra-myocardial venous blood. The differences between SPAMM and ORI-CSPAMM may be due to the inherent differences in the Fourier space data between the two tagging techniques combined with the refocusing effects. CSPAMM tagged images are generated from a difference between two sets of 1-1 SPAMM tagging data, thereby largely nulling the FID. In Fourier space, the stimulated echo and anti-echo persist longer and with a greater intensity when using a ramped imaging flip angle as in the cases of CSPAMM and ORI-CSPAMM. Furthermore, as a result of the different imaging flip angles, tag contrast is higher in the ORI-CSPAMM and CSPAMM images. In addition, the intensity of the tags fade in SPAMM images as a function of T_1, however due to the ramped imaging flip angle and the difference of the two data sets, the contrast of the ORI-CSPAMM tags remain relatively constant with time. The implications of these differences between the two tagging techniques are not well understood with regard to the FAST method used for calculation of slice rotation, but may contribute to higher estimates of LV torsion with ORI-CSPAMM. Future improvements to the CSPAMM tagging sequences [10] may improve the ability to quantify LV untwisting during diastole.

Conclusion: ORI-CSPAMM refocuses off-resonances that occur during the tagging encoding gradient without increasing scan time. ORI-CSPAMM produces mean peak LV torsion values in good agreement with the literature and our previous results, minimizes the effects of off-resonance during motion encoding, and permits the FAST analysis of LV torsion during systole and diastole. This technique may be especially useful for accurately assessing torsion in patients with fatty infiltration of the LV and/or RV (ARVD [11], lipomas [12], fatty heart [13], or post-ischemic fibrofatty infiltration).

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