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zHARP: 3-D cardiac motion tracking from Short-Axis acquisitions

Introduction: MRI is a powerful tool for the quantification of myocardial regional function in health and disease. Displacement encoding (1) and phase contrast (PC) (2) techniques require the acquisition of two or more datasets for the computation of the three-dimensional (3-D) displacement or velocity information, thus requiring long acquisition times and concomitant sensitivity to misregistration. HARP is a fast automatic algorithm for computing in-plane myocardial displacement and strain from tagged MRI datasets (3). To measure 3-D motion, it is customary to acquire tagged MR images on perpendicular planes. In this work, a pulse sequence that encodes both in-plane and through-plane motion without affecting the acquisition speed is presented. An automatic algorithm called zHARP, which directly tracks the 3-D displacements of every point within the image plane through the entire image sequence, is also presented. Experimental results include a phantom validation with a comparison to phase contrast imaging and an in vivo cardiac tagged MRI study of a normal human volunteer results demonstrating that the simultaneous extraction of in-plane and trough-plane displacement from CSPAMM tagged images is feasible..

Theory and Methods: The proposed technique, zHARP, is similar to the standard slice-following CSPAMM (SF-CSPAMM) (4), except that during the imaging sequence, a small *z*-encoding gradient is applied immediately before the readout and again with opposite polarity to the second orthogonal CSPAMM acquisition. This gradient adds a *z*-position dependent phase, φ_z , to every material point in the acquired slice. This additional phase is linearly related to the distance of the point from the iso-center. Unfortunately, susceptibility and general field inhomogeneities lead to an additional and artifactual phase accumulation. This erroneous phase is identical in both the horizontally and vertically tagged images, however, which can be exploited to separately compute the in-plane and through-plane displacements. The two datasets are represented as the spin density $\rho(x,y)$ modulated by the tagging in the *x*- and *y*-directions:

$$\rho(x,y)e^{j(\varphi_E+\varphi_z)}\cos(\omega_x x+\varphi_x)=\rho(x,y)\frac{e^{j(\varphi_E+\varphi_z+\varphi_x+\omega_x x)}+e^{j(\varphi_E+\varphi_z-\varphi_x-\omega_x x)}}{2},$$

$$\rho(x,y)e^{j(\varphi_E-\varphi_z)}\cos(\omega_y y+\varphi_y)=\rho(x,y)\frac{e^{j(\varphi_E-\varphi_z+\varphi_y+\omega_y y)}+e^{j(\varphi_E-\varphi_z-\varphi_y-\omega_y y)}}{2},$$

$$\varphi_A=\varphi_E+\varphi_z+\varphi_x+\omega_x x\ ,\quad \varphi_B=\varphi_E+\varphi_z-\varphi_x-\omega_x x\ ,$$

$$\phi_C=\varphi_E-\varphi_z+\varphi_y+\omega_y y\ ,\quad \phi_D=\varphi_E-\varphi_z-\varphi_y-\omega_y y\ ,$$

where, ω_x is the tagging frequency, φ_x , and φ_y are the harmonic phase (HARP) maps and φ_E is the phase due to inhomogeneity.

The algorithm runs on the two orthogonally tagged datasets. First, k-space data are processed using HARP, upon extracting both the positive and negative harmonic peaks. Second, the phases ϕ_A, ϕ_B, ϕ_C, and ϕ_D are computed by inverting a system of independent linear equations in the four unknowns φ_z, φ_x, φ_y, and φ_E, yielding an inhomogeneity-free 3-D displacement map on the acquired slice. Third, material points are tracked in 3-D. Given an arbitrary material point $p(x_t,y_t,z_t,t=0)$, a tracking procedure is introduced to track the in-plane motion using HARP on the φ_x and φ_y maps, from which the z-position can be extracted using the φ_z map.

Experiment: The pulse sequence was implemented on a Philips 3T-Intera system. Image processing was performed off-line on a personal computer. Three experiments were conducted. The pulse sequence and the algorithm were first tested on a water-filled-bottle phantom moving sinusoidally (1" peak-to-peak) in parallel to the main magnetic field (z-direction) at a rate of 52 cpm. Fourteen axial-plane cardiac phases were acquired during the first 466 ms of each cycle. In this setup, only zHARP though-plane displacement occurred. For comparison, the phantom was also imaged using a conventional PC method and a z-displacement map was obtained thereafter by integration (Figure 1). As a reference standard, z-displacement was also computed using a cross correlation method (CC) applied to long-axis (LA) tagged dataset (Figure 1b). Figure 2 compares the mean displacement value and the standard deviation obtained from PC, zHARP, and CC. Relative RMS error between PC and CC was 10.7% and between zHARP and CC was only 4.0%. In the second experiment the phantom and the imaged slice were tilted by 43° about the anterior-posterior axis while the phantom was moving along the B_o field direction. Since the bottle was tilted, only x- and z-direction motion occurred with |x-displacement|=tan(43)*|z-displacement| (Figure 3). Figure 4 shows the preliminary results obtained in a healthy adult subject. A dense mesh of points was tracked. Results show in-plane twisting of the mesh and color-encoded z-displacement. Note that the systolic and mid-diastolic (t=183 and 645) through-plane position are similar as expected. Figure5 shows the though-plane displacement profile of selected tracked points.

Discussion and Conclusion: The zHARP methodology supports direct 3D quantification of myocardial motion. In zHARP, an extra signal phase representing the position in the 3rd dimension is added to each material point. In contrast to the PC method, where tracking errors accumulate while tracking, zHARP shows a consistent tracking performance throughout the time of tag persistence. ZHARP data acquisition requires no extra time over conventional CSPAMM acquisition and has the ability to track any point in the image plane.

References: 1.)Pelc:JMRI'95, 2.)Aletras:JMR'99, 3.)Osman:TMI'00, 4.)Fischer:MRM'94

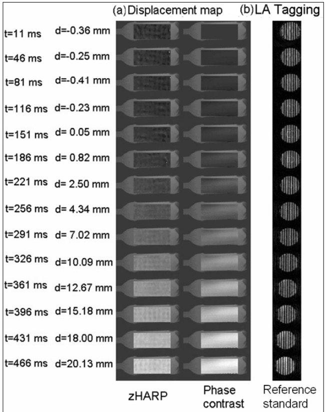

Figure 1 Displacement maps through the 14 CINE images. t: time, d: displacement.
(a) left :Using zHARP and right : using phase contrast.
(b) Reference standard dataset; tagged long axis slices that used for displacement calculations using cross correlation.

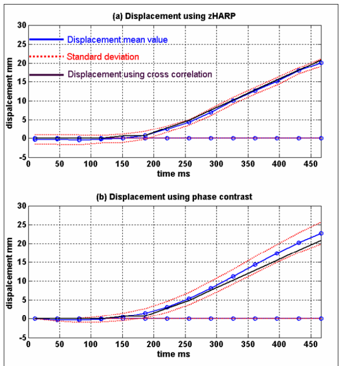

Figure 2 The displacement profile in the first 460ms of the cycle. (a) Using zHARP. (b) Using phase contrast (PC). Notice the increasing standard deviation and the drift of the PC values from the cross correlation values.

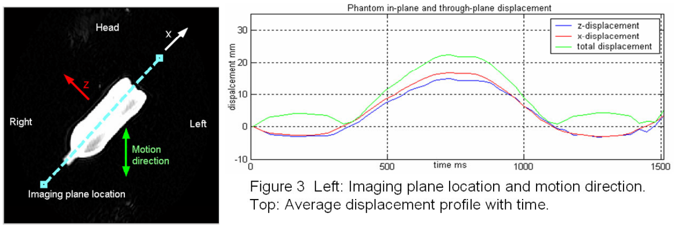

Figure 3 Left: Imaging plane location and motion direction. Top: Average displacement profile with time.

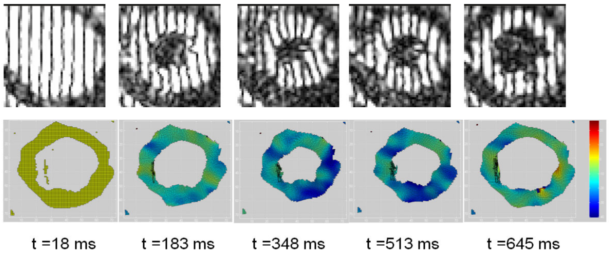

Figure 4 Top: Sample frames at different cardiac phases. Bottom: Tracked mesh points. Mesh deformation represents in-plane displacement and mesh color represents through-plane position.

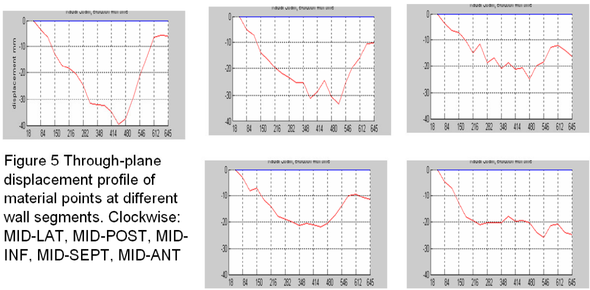

Figure 5 Through-plane displacement profile of material points at different wall segments. Clockwise: MID-LAT, MID-POST, MID-INF, MID-SEPT, MID-ANT