Direct Quantification of 3-D Myocardial Principal Strain Orientations: A new Insight into Heart Regional Function Abnormality

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Introduction

Three-dimensional (3-D) myocardial regional function quantification can be used to accurately identify and characterize healthy and diseased myocardial tissue. Due to the prolonged and clinically unfeasible examination time, regional function quantification has been limited to calculating radial, circumferential, and longitudinal strains. Maximum contraction vector $\vec{\varepsilon}_1$, and maximum stretching vector $\vec{\varepsilon}_2$ are the minimum and maximum principal strains of the strain tensor, respectively. Recently, the orientation of $\vec{\varepsilon}_1$ was shown to be highly correlated with viability[1]. In 3-D space, each principal strain $\vec{\varepsilon}_i$ has two unique orientations φ_i and θ_i, with respect to the radial and circumferential directions, respectively (Fig.1). However, the previously described technique was restricted to calculate the angle of $\vec{\varepsilon}_1$ at one time-point with respect to the circumferential direction θ_1 using MR tagged images of orthogonal slices and computationally intensive post-processing techniques. However, collecting images in orthogonal orientations and at multiple anatomical levels is very time consuming and susceptible to misregistration. The time-course of these orientations is also potentially useful in identifying abnormally functioning regions of the heart.

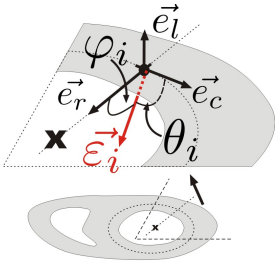

Fig.1 Principal strain angles

Recently, the zHARP imaging sequence was developed for direct 3-D motion characterization from a single imaged slice as well as for direct quantification and tracking of the 3-D strain tensor[2,3]. The present work extends this approach, presenting an algorithm for direct and complete characterization of 3-D principle strain *orientations* using data acquired with zHARP imaging protocol from SA slices without the need for LA data. Using this scheme, two or more SA slices are acquired and processed using zHARP and the 3-D strain tensor and principal strain angles are calculated. Initial in-vivo results show that 3-D principal strain angles calculated using this two-slice zHARP approach agrees with the previously reported values in the literature.

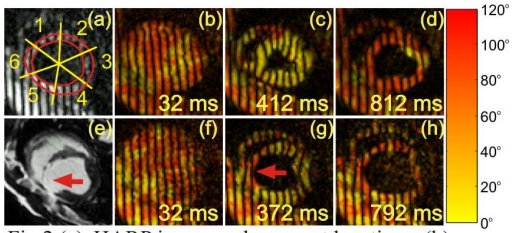

Fig.2 (a)zHARP image and segment locations. (b)-(c)θ_1 in a normal pig. (e)Delayed enhanced image and the infarcted region (red arrow). (f)-(h) θ_1 in the infarcted pig.

Theory zHARP is a slice-following tagging imaging sequence with a z-encoding frequency κ, applied during a slice-select gradient immediately before the readout [2]. An R-wave triggered tagged cardiac slice starts as a flat plane. It then undergoes 3-D displacements. The method yields both 3-D displacement vectors and 3-D strain tensor map E throughout the heart muscle at each pixel in adjacent slices without the need for interpolation.

In order to calculate 3-D principal strain orientations φ_i and θ_i, we first calculate the unit eigenvectors $\vec{x}_i$ and eigenvalues λ_i of E as the solutions of $\mathrm{E}\vec{x}_i = \lambda_i \vec{x}_i$, $\lambda_3 \geq \lambda_2 \geq \lambda_1$.

At every point, the principal strain vectors are defined by $\vec{\varepsilon}_1 = \lambda_1 \vec{x}_1$ and $\vec{\varepsilon}_2 = \lambda_3 \vec{x}_3$.

At every point, the two unit vectors $\vec{e}_r$ and $\vec{e}_c$ are created in the image plane toward the center-line of the left ventricle and orthogonal to it as shown in Fig.1.

The 3-D principal angles, which represent the direction of contraction and stretching are $\theta_i = \sin^{-1}\sin\cos^{-1}\left(\vec{e}_c \bullet \vec{\varepsilon}_i / |\vec{\varepsilon}_i|\right)$ and $\varphi_i = \sin^{-1}\sin\cos^{-1}\left(\vec{e}_r \bullet \vec{\varepsilon}_i / |\vec{\varepsilon}_i|\right)$, for i=1,2, respectively.

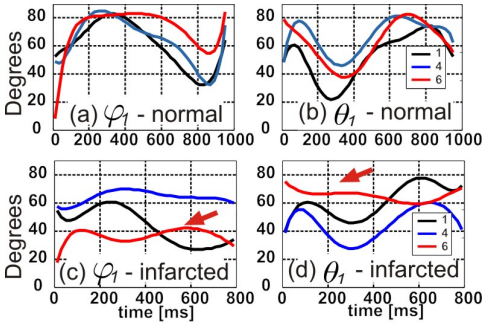

Fig.3 3-D principal angles φ_1 and θ_1 in normal and infarcted pig model in infarcted (red curve), peri-infarcted (black curve), and far (blue curve) zones.

Methods ***Imaging:*** The zHARP pulse sequence was implemented on a commercial Philips 3T-Achieva whole body system. Image processing was performed off-line on a personal computer. Gadolinium contrast and zHARP were performed on 6 pigs before and after myocardial infarction (MI) induced by left anterior descending coronary artery ligation. zHARP scans were done using VECG triggered spiral imaging with a 9 ms acq. window, 10 spiral readouts, FOV =300mm, slice thick.=8mm, TR=20 ms, tag spacing=7 mm, an 8 mm slice-gap and $\kappa = 2\pi/33$ rad/mm.

Analysis: The endo- and epicardial contours were segmented manually. Harmonic phases were calculated using zHARP processing[2]. The myocardium was then divided into 16 segments, which were categorized by contrast images into infarct, periinfarct and remote zones. The regional 3-D strain tensor and principal strain orientations were calculated over multiple cardiac phases using the algorithm above.

Results and Discussion: Fig.2 shows example images of the normal and infarcted datasets at different times after the R-wave of the ECG. The θ_1 map is shown overlaying the corresponding zHARP image. Note the uniform symmetric variations of θ_1 except in the infarcted zone (red arrows). More details about heart dynamics by watching the time course changes of θ_1 and φ_1 in infarct, peri-infarct, and far zones (Fig.3). As an example, in systole, contraction is almost downward $\varphi_1 \approx 90^o$ causing twisting in the circumferential-longitudinal direction ($\theta_1 \approx 40^o$). The direction of $\vec{\varepsilon}_1$ in the infracted zone (red arrow) weakly varies and mostly downward and radially.

Conclusion: A fast algorithm for calculating the time-course of 3-D principal strain orientations was proposed. Results from infarct swine model shows that strain orientations time-course can provide more information about heart dynamics, especially when combined with efficient 3-D motion imaging.

References:

1) B. P. Cupps, et. al., 2005;79:1338–43. 2) Abd-Elmoniem, et. al., *Mag. Res. in Med.*,2007, 92-102. 3) Abd-Elmoniem, et. al., *Inf. Proc. In Med. Imaging*, 2007, pp. 62-73.