Three-dimensional Principal Strain Patterns in Acute Myocardial Infarction

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INTRODUCTION: Comprehensive characterization of myocardial viability continues to be of diagnostic interest to clinicians. Magnetic resonance (MR) tagging is considered the gold standard imaging tool for noninvasive assessment of functional viability in the form of mechanical strain tensors [1]. Principal strain orientations, which correspond to directions of maximal deformations (stretching, contraction, and elongation), can potentially provide a sensitive metric of functional viability. Recent reports have shown principal strain directions to change with ischemic injury [2]. However, these investigations were limited to the direction of maximal contraction, due to large effect of noise in calculation of other principal strain orientations. Prolonged examinations and the need for imaging orthogonal slices, susceptibility to misregistration and large amount of inaccuracy in calculation of angles, hindered the assessment of the clinical value of three-dimensional (3D) principal strain orientations and the adoption of this information in clinical practice. In this work, we developed an accelerated algorithm using zHARP tagging [3] and a generalized vector convolution to robustly measure 3D principal strain orientations and investigate their potential clinical value in the assessment of viability. Preliminary in-vivo results in a closed-chest porcine model of myocardial infarction (MI) confirm the potential of principal strain orientations to characterize abnormal function.

THEORY: zHARP, a slice-following tagging imaging technique, provides 3D motion tracking of the imaged short-axis slice with application of additional z-gradient in the slice-select direction. By forming rectilinear mesh of points on a stack of equally separated images, 3D Eulerian strain tensor is calculated for each spatial point. Eigensystem decomposition of the strain tensor yields three eigenvalues and three corresponding eigenvectors, representing the magnitude and the orientation of principal strains, respectively. Regional principal strain orientations are quantified by finding a similarity to a pattern in the neighborhood of each point in the vector field. Similarity in vector space is defined as the convolution between vector field and the pattern. The convolution provides an approximation to the cosine of the angle between the direction of individual vectors in the field and the direction of the pattern. Since the scalar vector components are not independent, scalar convolution of individual strain vector components does not describe the vector as a whole and disrupts angle information. Direct vector convolution [4] is the generalized inner product of vectors defined as $(V * f)(x) = \iiint \langle V(x'), f(x-x') \rangle dx'$ where x is a position in the 3D space, V is the normalized strain vector field and filter f is the pattern. The convolution consists of three scalar 3D convolutions. To make regional classification, filters are multiplied by a rotational symmetric weighting function to be spatially limited. Furthermore, since the convolution is interpreted as the cosine between the filter and the structure, the filters must be normalized and fulfill $\iiint \langle f(x), f(x) \rangle dx = 1$. For illustration, a filter and a vector field with parallel flow at 45° with Gaussian noise (SNR~15dB) are simulated (Figs. 1a and b). For each vector in the field, the angle with vertical axis is computed directly (Fig 1c) and compared with the results from vector convolution (Fig 1d). Clearly, the spatial convolution offers a better estimation of the angle.

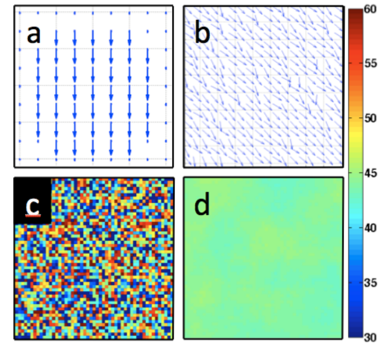

Figure 1 (a) Filter (b) Input vector field (c) Angle of vector field with vertical axis. (d) Results from convolution of (b) and (a).

METHODS: Left anterior descending coronary artery was occluded in six pigs to induce MI. Animals were imaged 36±9 days after infarction on a 3.0T Achieva MR scanner (Philips Medical Systems, Best, NL). Late gadolinium enhanced (LGE), and zHARP images were acquired at multiple short axis slices covering the left ventricle. Imaging parameters were the following: LGE: repetition time (TR) 4.6 ms, echo time 2.2 ms, flip angle 15°, field-of-view (FOV) 320x300 mm^2, slice thickness 3mm. zHARP: TR 20ms, echo time 2.5ms, flip angle 15°, FOV 320x320 mm^2, slice thickness 8 mm, temporal resolution 20ms, and tag spacing 7mm. FWHM technique [5] was used on LGE images to locate healthy (H), MI and peri-MI (PMI) regions. 3D principal strain vectors were calculated from zHARP images. Three separate vector fields were formed by the eigenvectors and each was convolved with three filters with orthogonal parallel flow at every spatial position. The three resulting angles were then rotated in the local coordinate system, on the basis of the orientation of the overlying reconstructed epicardial surface. Epicardial outward normal vector is considered as radial direction (R). Circumferential direction (C) lies in short-axis plane and is the cross product of long-axis with R. Longitudinal direction lies in longitudinal plane and is the cross product of R and C. The strain vectors are reconstructed based on the new angles with R, C, and L orientations.

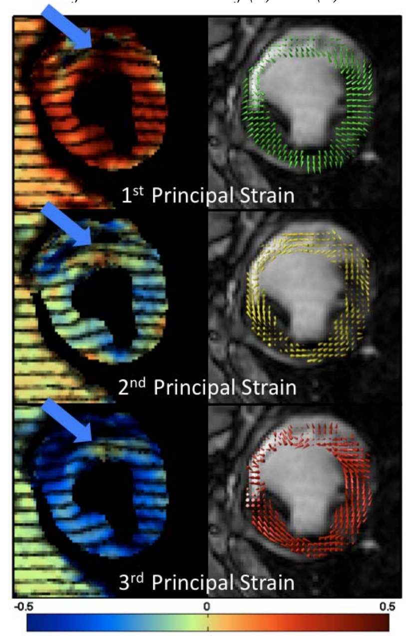

Figure 2 (left) Systolic principal strain value overlaid on zHARP image. (right) 3D strain vectors projected on the 2D short-axis plane, overlaid on LGE image.

RESULTS and DISCUSSION: Principal strain vectors were calculated in all the animals. At every pixel, the angles of the vectors with respect to radial (θ_R), circumferential (θ_C), and longitudinal (θ_L) directions were computed. Fig. 2. shows an example of the end-systolic principal strain values and projection of resulting strain vectors from vector convolution in one animal. In the hyper-enhanced region representing the unhealthy tissue, vectors do not have the same organized pattern as in the healthy region. Fig. 3 shows mean±std of the angles for the end-systolic principal strains and results of unpaired unequal variance t-test in all animals. All three angles in the first principal strain are significantly different in MI region vs. PMI and H region. In the PMI region, θ_R and θ_C are different from H region. The second principal strain shows difference of θ_R and θ_L in all three regions. Lastly, the third principal strain shows difference of θ_R and θ_C in MI vs. PMI and H region. However, none of the angles of this strain vector show difference in PMI vs. H region.

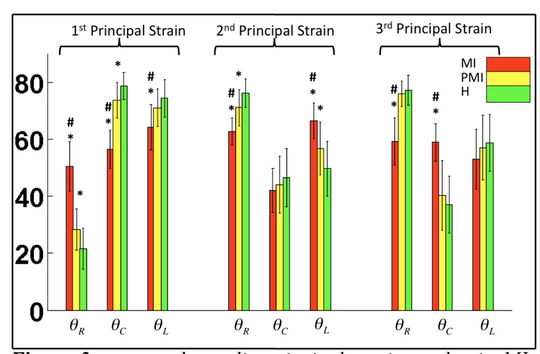

*Figure 3 mean end-systolic principal strain angles in MI, PMI, and H regions. Error bar shows standard deviation. *p<0.05 vs. healthy; #p<0.05 vs. PMI.*

CONCLUSION: A reliable method of measuring 3D principal strain angles was proposed which enabled for the first time to investigate the comprehensive effect of infarction on the orientation of all principal strains. The consistency of the angles in normal myocardium, combined with the results in the dysfunctional tissue, suggest that principal strain orientations can be useful in assessment of myocardial viability.

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