Toward True Myocardial Plannar Strain Using ZHARP: Experimental In-Vivo Validation

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Introduction: Quantitative strain maps can be used to identify and characterize healthy and diseased myocardial tissue. Strain maps are typically calculated from 2D cine images including tagging(1), displacement encoding(2), or velocity encoding(3). However, because of through-plane motion, the imaged slice is not necessarily the same slice that was motion-encoded, which may adversely affect strain computation. With slice-following tagging (SF-CSPAMM) (4), the same tissue of the myocardium is always examined; however, through-plane rotation can still be misinterpreted as a false strain. As a result, only the in-plane motion and apparent strain can be computed for conventional 2D imaging. The purpose of this research is to develop and test a method that provides a true planar strain map for a given imaged slice. The method takes the through-plane motion into consideration and corrects for the false strain component caused by through-plane rotation. Phantom and in-vivo results demonstrating the ability to remove the through-plane rotation effect from the strain maps are presented.

Methods: *Concept:* A method for true planar strain mapping has been developed using zHARP tagging MRI. ZHARP is a recently developed tagging MRI methodology, which images and automatically tracks the 3-D myocardial displacement of all points in an image plane (5). An R-wave triggered tagged cardiac slice starts as a flat plane. It then undergoes both in-plane and through-plane displacements and the slice becomes a shaped 3D surface. As shown in Fig.1, a through-plane rotation will be interpreted as in-plane compression if only x- and y-displacements were observed. With the acquisition of all of the 3-D displacement components, this misinterpretation of rotation is removed and a true planar strain map can be obtained by using a 3x3 displacement gradient tensor instead of a 2x2 tensor.
Theory: Given a 2D slice from the myocardium, the strain tensor at any material point is defined by $e = \frac{1}{2}\left[\nabla_{\underline{x}}\underline{u} + (\nabla_{\underline{x}}\underline{u})^T + (\nabla_{\underline{x}}\underline{u})^T \times (\nabla_{\underline{x}}\underline{u})\right]$ where $\underline{u}(\underline{x}) = \underline{u}(x, y, z) = [u_x \, u_y \, u_z]^T$. zHARP acquires u_z in addition to u_x and u_y in contrast to conventional tagging techniques.. The component u_z is used here to remove the false apparent strain due to through-plane rotation. This is done by adding u_z into the computation of the displacement gradient as follows

$$\underbrace{\nabla_{\underline{x}}\underline{u} = \begin{pmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_z}{\partial x} & \frac{\partial u_z}{\partial y} \end{pmatrix}}_{\text{with SF-CSPAMM}},$$

$$\underbrace{\nabla_{\underline{x}}\underline{u} = \begin{pmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} & 0 \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} & 0 \\ \frac{\partial u_z}{\partial x} & \frac{\partial u_z}{\partial y} & 0 \end{pmatrix}}_{\text{Using zHARP}}$$

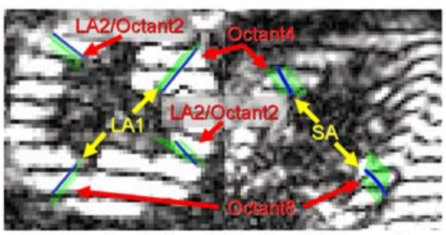


Fig3. SA slice (left) and LA slice (right) used in the study. Blue: The intersection lines. Green: The lines' displacements with time

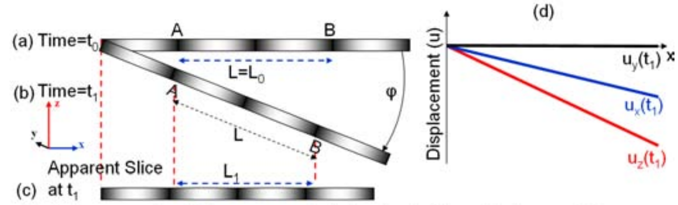


Fig.1 An example of false apparent strain due to through-plane rotation φ.
(a) Original slice plane location at t_0. The segment length (L) is always the same.
(b) True slice location at t_1.
(c) The imaged projection or the apparent slice. The imaged segment AB has a false length L_1. Apparent false strain= $(L_1-L_0)/L_0 = \cos(\varphi)-1$
(d) The components of the displacement vector (u) at t_1 . At t_0 u=0.

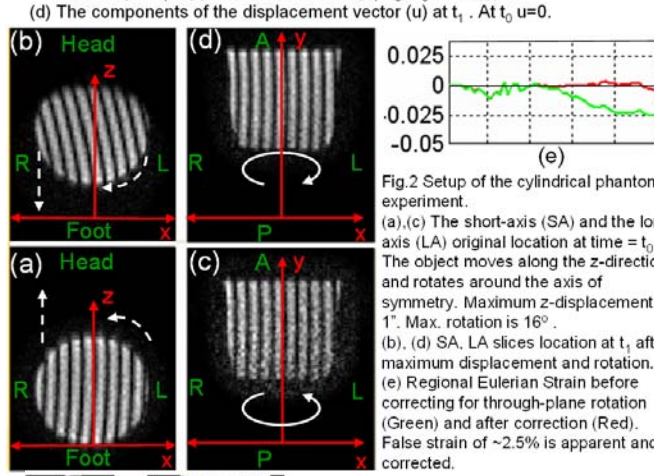
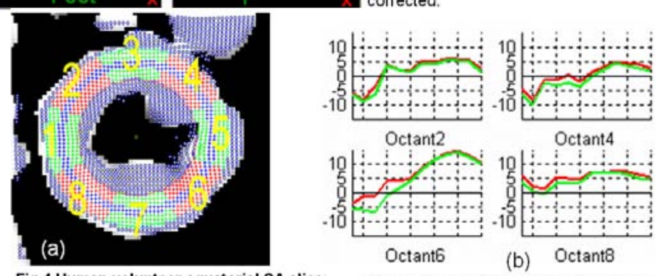


Fig.2 Setup of the cylindrical phantom experiment.
(a),(c) The short-axis (SA) and the long-axis (LA) original location at time = t_0 . The object moves along the z-direction and rotates around the axis of symmetry. Maximum z-displacement is 1". Max. rotation is 16° .
(b), (d) SA, LA slices location at t_1 after maximum displacement and rotation.
(e) Regional Eulerian Strain before correcting for through-plane rotation (Green) and after correction (Red). False strain of ~2.5% is apparent and is corrected.



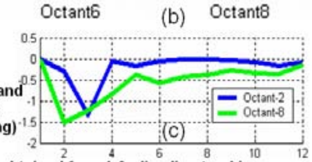


Fig.4 Human volunteer equatorial SA slice divided into 8-Segments: 1,2: Septal, 3,4: Interior, 5,6: Lateral, 7,8: Inferior.
(a) Err time-profile before correction (green) and after correction (red). Through-plane rotation adds false negative strain. True Err (stretching) is larger than the apparent Err.
(c) False strain due to through plane rotation obtained from LA slice line tracking

Implementation: The pulse sequence was implemented on a Philips 1.5T-Intera system. In brief, zHARP uses a small gradient in slice selection direction which is added to the refocusing gradient. This leads to an additional signal phase that is dependent on the distance of the slice from the isocenter. Image processing was performed off-line on a personal computer. The pulse sequence and the algorithm were tested first in a periodically moving rotating gel-phantom. Cine tagged images, were then obtained using a spiral imaging sequence (10ms acq. window, 20 spirals, Res.=256x256, FOV =320mm, slice thick.=8mm, tag spacing=8mm, TE=1.1ms, TR=30ms). The phantom was moving forward and backward in the direction parallel of the main magnetic field at a rate of 30rpm. Simultaneously, the phantom was rotating about its axis of symmetry as shown in Fig.2. Fig.2 shows some images acquired using this experimental setup. For in-vivo validation, a healthy 26 year old male subject was scanned with 15ms acq. window, 12 spirals, FOV =350mm, slice thickness=6mm, TE=4ms. Horizontally and vertically tagged zHARP cine images were obtained in a short axis (SA) and two long axis (LA) views. The intersection of the tags were then additionally tracked in 3D (Fig.3) using 3D-SF-HARP (6) for comparison. Through-plane rotations φ of the lines were computed, and the expected false strain was obtained from these images using the formula [$\varepsilon = \cos(\varphi)-1$].

Results: Fig.2(e) visualizes the regional strain profiles obtained from the phantom. Without removing the through-plane rotation effect, an erroneous compression of the tissue is detected (green line). Results show the effective removal of through-plane rotation effects using the new zHARP method (red line). Fig.4 shows the results obtained in a healthy adult subject. A short axis slice is shown and is divided into eight segments. A dense mesh of points was tracked. Results show radial strain (Err) before and after correction. Fig.4(c) shows the expected false strain in octants 2 and 8 obtained from tracking of the intersection lines at these regions. The strain profiles obtained using zHARP and the new displacement gradient are closer to the expected values.

Conclusions: A new planar strain mapping methodology was developed to resolve the strain ambiguity caused by through-plane rotation. With zHARP, the 3D quantification of myocardial motion is obtained for an arbitrary slice with no extra scanning time. By using these data and by expanding the displacement gradient into 3D, true planar strain can be computed for the imaged slice. When compared to conventional strain maps, a more accurate strain computation is observed.

References: 1)Axel: Rad'89, 2)Pelc: JMRI'95, 3)Aletras: JMR'99, 4) Fischer: MRM'94, 5)Abd-Elmoniem: IPMI'05, 6) Sampath: 1SMRM'04