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REGISTRATION-ENHANCED RECONSTRUCTION OF DENSE-MRI TISSUE DISPLACEMENT FIELDS

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INTRODUCTION

Displacement fields are important to analyze deformation, which is associated with functional and material tissue properties often used as indicators of health. Because of its soft tissue sensitivity and robust contrast, magnetic resonance imaging (MRI) has been employed to measure displacement within biological systems via tagging [1], displacement encoding with stimulated echoes (DENSE) [2], or post-imaging registration such as Hyperelastic Warping [3]. Although both DENSE and Hyperelastic Warping are capable of producing 3D displacement fields at the pixel level, which is desirable in modeling small animal cardiac mechanics, they each have its limitations. The objective of this research is to detail a new method of combining these two techniques, along with numerical verification and demonstration in the rat's heart.

THEORY

In DENSE, motion is encoded in the phase of the MRI signal. The displacement vector in spatial coordinates $\vec{r}$, $\vec{u}(\vec{r})$, is proportional to the phase angle ϕ of complex images sensitized in each direction of motion (say x, y and z), or $u_i(\vec{r}) = c_i\phi_i(\vec{r})$, for $i \in \{x, y, z\}$, where c_i is a constant [2]. When displacement results in a phase angle outside $[-\pi, \pi]$ it is cyclically wrapped (Figure 1, gray line). Encoding constants may be adjusted during acquisition, but their values affect image resolution and quality [4], making some phase warping inevitable in practice. Methods for phase unwrapping exist, but they either require more acquisitions, or produce relative phase maps that need a known reference displacement $\vec{u}_{ref}$ [5-6] (see also Fig. 1). Reference approximation (at least 3 per slice) requires some prior knowledge of the vector field, and/or the user's judgment, which can be potential sources of systematic error.

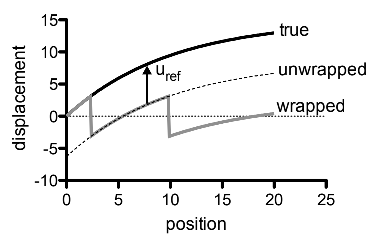

Figure 1: Effects of phase wrapping on a displacement profile. The true displacement as a function of position (solid black line) is cyclically wrapped (gray line) after encoding. The relative displacement after unwrapping (dashed line) needs a known reference u_{ref} to be restored.

In Hyperelastic Warping, the displacement field in material coordinates $\vec{R}$, $\vec{u}(\vec{R})$, is found by registering magnitude images before and after deformation, known as template S and target T, respectively. The deformation map $\vec{\varphi}(\vec{R}) = \vec{r} = \vec{R} + \vec{u}(\vec{R})$, which minimizes the intensity difference energy $U = \frac{\lambda}{2}\left(T(\vec{R}) - S(\vec{R}, \vec{\varphi})\right)^2$ and the strain energy W over a discrete domain, is found by the Finite Element (FE) approach [3]. The material-dependent strain energy from continuum mechanics W, provides regularization and physically relevant constrains, whereas U depends on the registration of the images, and a penalty parameter λ. Registration forces arise form the material model, and the first variation of U. Areas where the intensity gradients are large will produce image-driven results, otherwise the solution will depend on the material model. If the material model is unknown, more error is expected in the absence of image contrast. Also, if motion does not cause intensity changes, e.g. rotation about a symmetry axis, no registration forces (and hence no displacement) will be produced.

Using Hyperelastic Warping across temporally contiguous DENSE magnitude images it is possible to extract displacement references $\vec{u}_{ref}$ to frame unwrapped phase images. Registration is posed such that the deformation map $\vec{\varphi}$ is defined in spatial coordinates. Without material parameters, a Hyperelastic material with arbitrary constants is set, and the FE domain is discretized so that nodes coincide with pixels forming hexahedral elements eliminating the burden of manual meshing. The variable λ is tuned to maximize registration, and produce an approximated displacement field $\vec{u}_w(\vec{r})$. The DENSE motion-encoded images are unwrapped with the minima of the phase quality maps as references, which are found automatically, and ensure unwrapping smoothness, not displacement accuracy. A displacement field $\vec{u}_u(\vec{r})$ is found with the unwrapped phases. The final field of displacements is iteratively found varying candidate reference values in $\vec{u}_d(\vec{r}) = \vec{u}_u(\vec{r}) + \vec{u}_{ref}$ according to

$$\int_B \vec{u}_d(\vec{r}) \cdot \nabla S(\vec{r}, \vec{\varphi}) dB = \int_B \vec{u}_w(\vec{r}) \cdot \nabla S(\vec{r}, \vec{\varphi}) dB. \qquad (1)$$

Where $\nabla S(\vec{r}, \vec{\varphi})$ is the intensity gradient of the registered image with respect to the spatial coordinates, and B is the image domain.

METHODS

Numerical phantoms consisting of template and target magnitude images for Hyperelastic Warping (Fig. 2), and wrapped DENSE phase images were produced by deforming slices of a hollow spheroid with a displacement field consisting of radial shrinking of 30% of the radius, and 10^o rotation about the out-of-plane axis (Fig. 2, right). Phase wrapping was set to occur on displacements of more than 2 pixels.

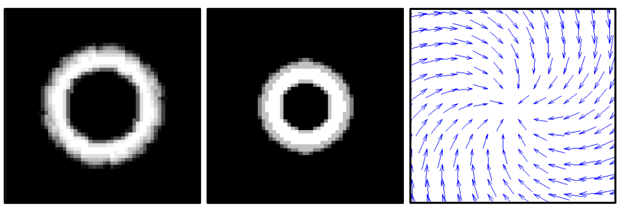

Figure 2. Phantom images: True vector field (right)-one in four vectors are show for clarity. Reference image (left) Deformed image (center)

For experimental demonstration, cardiac DENSE MRI (short axis, multislice *black blood* CINE acquisition, TR = 15.0ms, TE = 2.0ms, 7 frames, FOV 40 × 40mm, 96 × 96 matrix) was performed on an isoflurane-anesthetized rat in a Bruker Biospec 7T scanner. Hyperelastic Warping was run in NIKE3D [3,7] with parameters including linearly increasing penalty λ from 0 to 0.03 for phantom, and to 0.2 in the rat images, blurring mask varying from 5 to 1 pixels, and a Mooney-Riving material model with constants C_1 =8, C_2 =4, ν=0.3. DENSE phase images were processed according to [8], but the "guided path following" method [5] was used for unwrapping. True reference displacements $\vec{u}_{ref}$ are known in the phantom images, which allow comparison with the solution with the new method. For demonstration in the rat heart, displacement fields with references found manually and iteratively are compared.

RESULTS

Figure 3 shows deformation fields from Hyperplasic Warping (left), DENSE with initial references (center), and DENSE with references found by the iterative method (right). Hyperelastic warping is effective in registering the images and minimizing the intensity difference. However, because there is little local contrast with respect to the rotation, only radial displacements are resolved. The vector field with initial references is dominated by systematic error. Using the presented iterative approach, the references were calculated within 3%, and the field is comparable to the true motion (Fig. 2).

A representative slice of motion from diastole to systole in the rat is shown in Figure 4, which also shows vector fields via manually found DENSE references (top center), Hyperelastic Warping (top right), and by the new approach (bottom left).

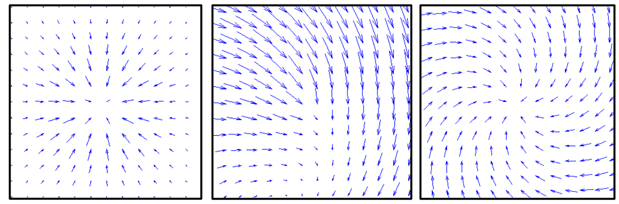

Figure 3. Displacement fields measured with Hyperelastic Warping (left), DENSE with no phase reference correction (center), and DENSE with registration-based phase correction (left)—the best match to the true field.

Spending some time generating references manually yields a reasonable solution, but in some areas the displacement is incoherent with the deformation of the heart. Using the new approach, the displacement map is more consistent with the displacement of the heart; a slight rotation is also observed, which does not appear when using Hyperelastic Warping alone. A 3D field is shown last.

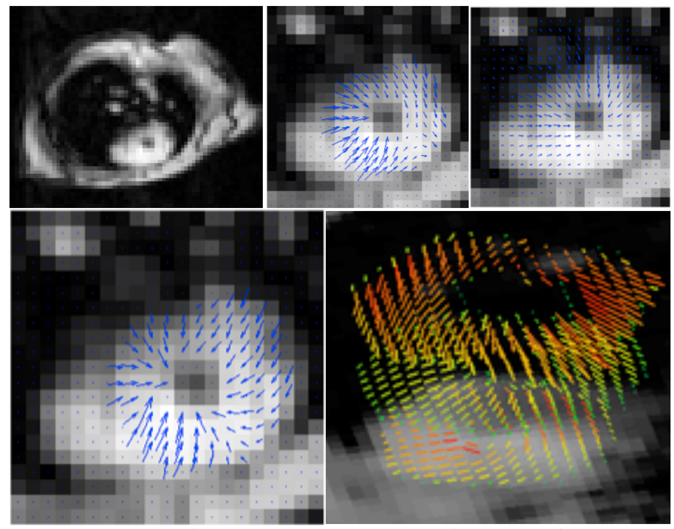

Figure 4. Images of the rat heart: (clockwise from top left) anatomical location of selected slices, DENSE with manual references, Hyperelastic Warping field, rendition of multislice acquisition encoded in 3D, Registration-enhanced DENSE field.

DISCUSSION

Equation 1 is a projection of the displacement fields onto the image intensity gradient, so it is possible extract references from areas where the warping solution depends on the images and not material parameters. The projection constitutes physically valid components of displacement used as objective approximations to the references. This approach can compensate for bulk motion potentially missed by DENSE alone because of phase wrapping. The combined approach is a relatively simple and robust method to produce high-resolution vector fields with large deformations.

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