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Estimating cardiac fiber orientations in pig hearts using registered ultrasound and MR image volumes

James D. Dormer [1], Yuguang Meng [2], Xiaodong Zhang [2],
Rong Jiang [3], Mary B. Wagner [3], Baowei Fei [1,4 *]

[1] *Department of Radiology and Imaging Sciences, Emory University, Atlanta, GA*
[2] *Yerkes National Primate Research Center, Emory University, Atlanta, GA*
[3] *Department of Pediatrics, Emory University, Atlanta, GA*
[4] *Department of Biomedical Engineering, Emory University and Georgia Institute of Technology, Atlanta, GA*
**E-mail: bfei@emory.edu; web: http://feilab.org*

ABSTRACT

Heart fiber mechanics can be important predictors in current and future cardiac function. Accurate knowledge of these mechanics could enable cardiologists to provide a diagnosis before conditions progress. Magnetic resonance diffusion tensor imaging (MR-DTI) has been used to determine cardiac fiber orientations. Ultrasound is capable of providing anatomical information in real time, enabling a physician to quickly adjust parameters to optimize image scans. If known fiber orientations from a template heart measured using DTI can be accurately deformed onto a cardiac ultrasound volume, fiber orientations could be estimated for the patient without the need for a costly MR scan while still providing cardiologists valuable information about the heart mechanics. In this study, we apply the method to pig hearts, which are a close representation of human heart anatomy. Experiments from pig hearts show that the registration method achieved an average Dice similarity coefficient (DSC) of 0.819 ± 0.050 between the ultrasound and deformed MR volumes and that the proposed ultrasound-based method is able to estimate the cardiac fiber orientation in pig hearts.

Keywords: Magnetic resonance diffusion tensor imaging (MR-DTI), ultrasound imaging, cardiac fiber orientation, image registration, deformable registration, heart disease, cardiac fiber imaging.

1. INTRODUCTION

Cardiac modeling provides important information about heart structures. In turn, knowledge of heart structure can lead to predictions about future heart complications [1]. Fig. 1 shows how this fiber structure is arranged in a porcine heart. Structural data can be acquired with a range of imaging modalities, including computed tomography (CT), magnetic resonance imaging (MRI), and echocardiography. MR diffusion tensor imaging (DTI) has been used to determine cardiac fiber orientations [2-5]. Computed tomography and ultrasound (US) can provide anatomical information but lack the ability to identify individual fibers. Of these two, US has advantages in that no ionizing radiation is used during image acquisition and allows physicians to adjust parameters in real time to view cardiac anatomy. This makes the modality well-suited for routine cardiac examinations. In order to determine fiber orientations for these hearts, we deform a MR-DTI volume from a template heart onto an US volume. Previous work by our group has explored cardiac fiber estimations in rat hearts [6, 7]. In this work, we apply the same process to *ex vivo* pig hearts, which are similar to human hearts in size and structure.

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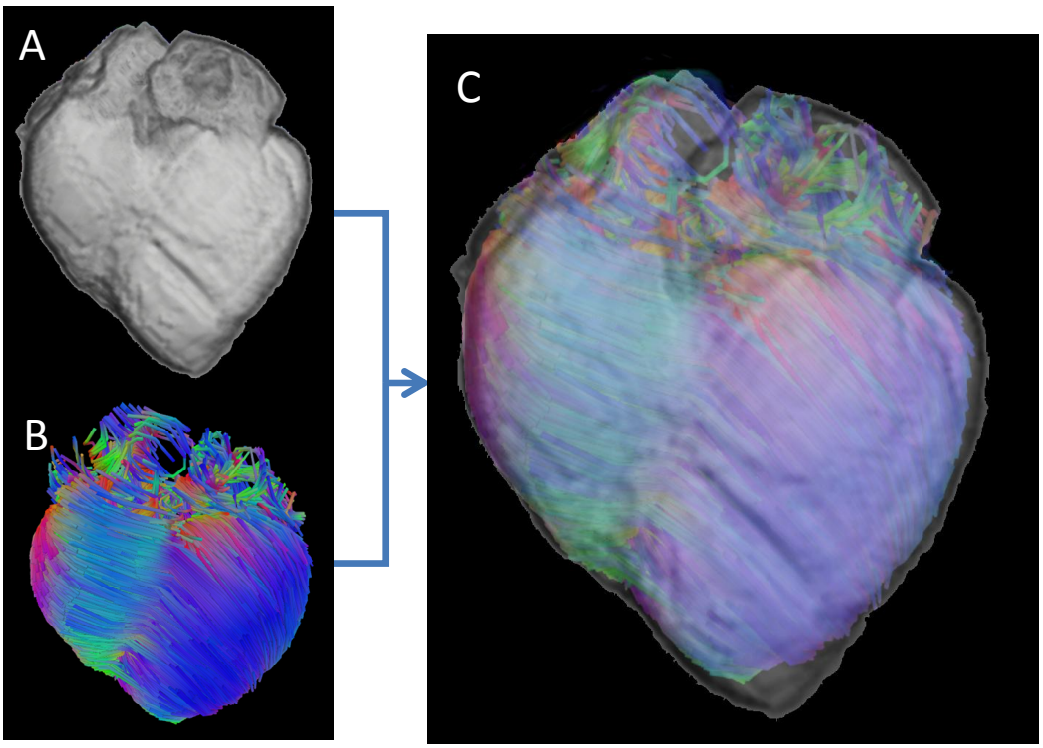

Fig. 1. (A) Three-dimensional (3D) T1-weighted MR image of a pig heart. (B) 3D fibers extracted from MR-DTI. (C) Fibers superimposed onto the T1 MR images.

2. METHODS

The procedure was composed of five steps (Fig. 2). First, ultrasound and MR images of fixed pig hearts are collected. These volumes are processed and loaded into the registration routine. After volume registration, the fiber orientations for the heart imaged using ultrasound are estimated. Finally, the results are evaluated for accuracy. Each of these steps will be explored in greater detail below.

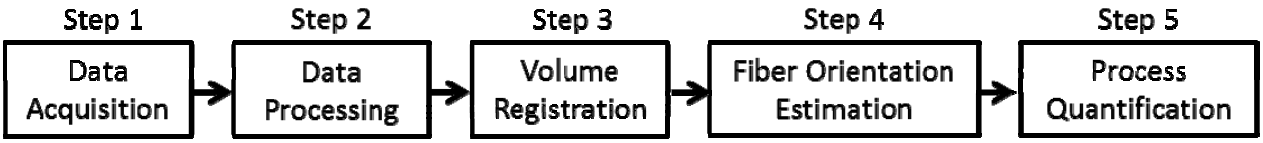

Fig. 2. The five main steps used in the procedure. Ultrasound and MRI data is first collected and processed (Steps 1 and 2). The volumes then undergo deformable registration (Step 3). Fiber orientations are estimated for the ultrasound volume (Step 4) and the process is evaluated for accuracy (Step 5).

2.1 Data acquisition

Four healthy pig hearts were obtained and washed with PBS to remove blood from the heart chambers. Two hearts were in the diastolic phase (Hearts 1 and 4) and two were in the systolic phase (Hearts 2 and 3). Each heart was placed into neutral buffered 10% formalin for fixation. After fixation, each heart was thoroughly rinsed with PBS to remove any formalin residue and embedded into a 2% agar gel phantom and chilled for 24 hours before imaging.

The heart phantoms were imaged on a 7 T Bruker Biospec system (Bruker Corp, MA), with an isotropic resolution of 1 mm for T1-weighted MR images and 1.5 mm for 30 directions for diffusion weighted images. Ultrasound volumes were formed from a series of short axis slices taken using a BK Flex Focus 400 ultrasound system (Analogic Corp., MA). Ultrasound slices were acquired with a 0.2 mm step size.

2.2 Data processing

Ultrasound slices were loaded into MATLAB (MATLAB 2016a, The MathWorks, Inc., Natick, MA) and converted into a 3D volume for each heart. This volume was imported into Analyze (AnalyzeDirect, Inc., Overland Park, KS) and resampled into a volume with a 1.5 mm isotropic resolution. MR-DTI data were loaded into DTI Studio ([8]) and averaged to calculate the eigenvalues.

In Analyze, binary mask images were created from the T1-weighted MRI for each heart. In addition to the masks, an affine transform matrix (translation, rotation, and scaling) was found by manually aligning template hearts (T1 MRI) to target hearts (ultrasound). These transformations were later applied to the template hearts in MATLAB before the deformable registration process.

2.3 Volume registration

The volume registration workflow is shown in Fig. 3. The binary masks created during the data processing step were applied to the corresponding ultrasound and T1 MR volumes, after which underwent an affine registration using the matrix determined previously. Next, the LogDemons [9, 10] intensity-based deformable registration algorithm was used to warp the template T1 MR volume to the US target volume. This also produced a deformation field which would be used later.

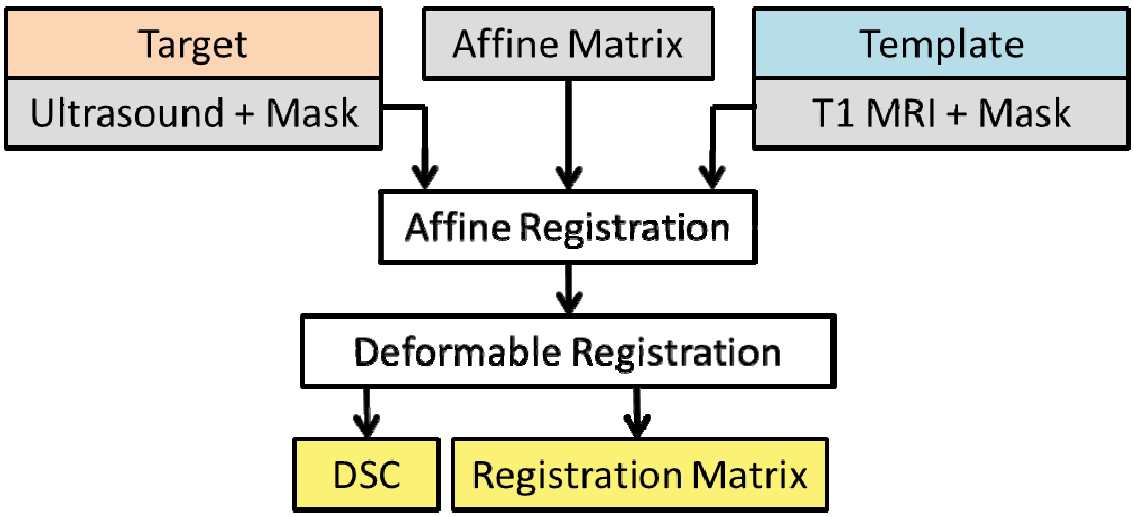

Fig. 3. Workflow for the registration of ultrasound and T1-weighted MRI volumes. A Dice similarity coefficient (DSC) measurement and a deformed registration matrix are produced in the processes. Gray boxes indicate user input, white boxes code procedures, and yellow boxes output.

2.4 Fiber orientations

Fiber orientations were estimated using the preservation of principle direction, which uses the largest eigenvector of a prolate structure as the fiber orientation [11]. In a similar manner to the volume registration described in the

previous step, binary mask images from the T1 MRI are applied to the target (gold standard) and template DTI volumes. The same affine registration matrix was then used on the template DTI volume, after which the deformable registration matrix from the LogDemons algorithm in Step 3 was used to produce a final deformably-registered volume. The complete fiber estimation workflow is shown in Fig. 4.

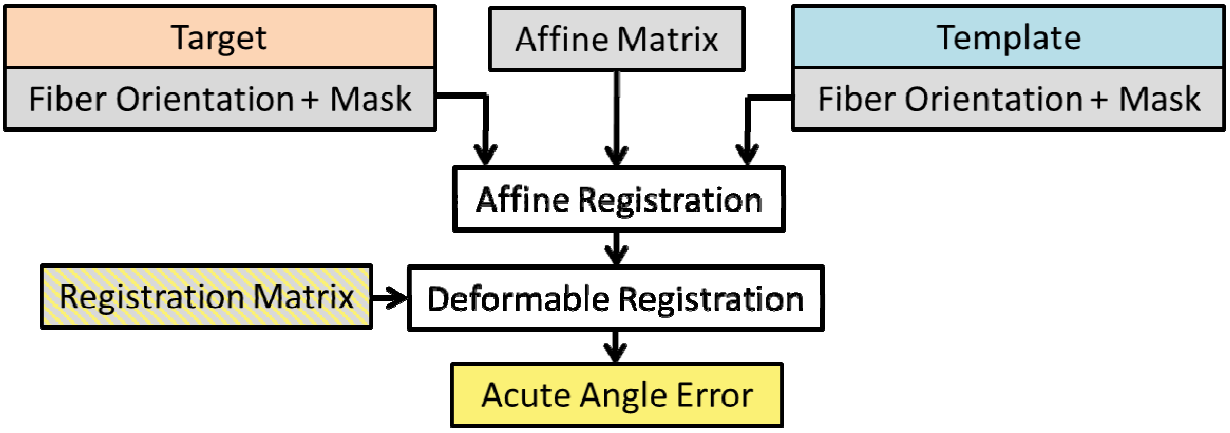

Fig. 4. Workflow for estimating fiber orientations of an ultrasound volume using template MR-DTI data. The deformed registration matrix produced in the volume registration processes is used to deform the fiber orientations. Gray boxes indicate user input, white boxes code procedures, yellow boxes output, and striped boxes input from automatically-generated output.

2.5 Quantification

The Dice similarity coefficient (DSC) was employed to describe the degree of overlap between volumes after registration [12, 13]. The acute angle error (AAE) was used to quantify the accuracy of the fiber orientation estimation, as described in previous works [7, 11, 14].

3. RESULTS

The method was applied to 4 pig hearts with maximum diameters of less than 10 cm and in two different cardiac phases (systolic and diastolic). Experiments from the pig hearts show that the registration method achieved an average Dice similarity coefficient (DSC) of 0.819 ± 0.050 between the ultrasound and deformed MR volumes. Fig. 5 shows an example of the deformation applied. The unaligned volumes (Fig. 5A) first underwent a manual affine transformation (Fig. 5B), followed by the deformable registration (Fig. 5C).

Fiber orientations were also estimated between each heart. Between the diastolic hearts (1 and 4), the average acute angle error (AAE) was 19.96° with a standard deviation of 1.23°. For the systolic hearts, the average AAE was 29.92° with a standard deviation of 1.00°. When comparing the systolic to diastolic hearts and vice versa, the AAE was found to be 25.91° with a standard deviation of 5.08°. The fiber orientation estimation errors were partially due to the segmentation and registration errors, which can be further improved in future studies. The AAE and DSC values are shown in Table I.

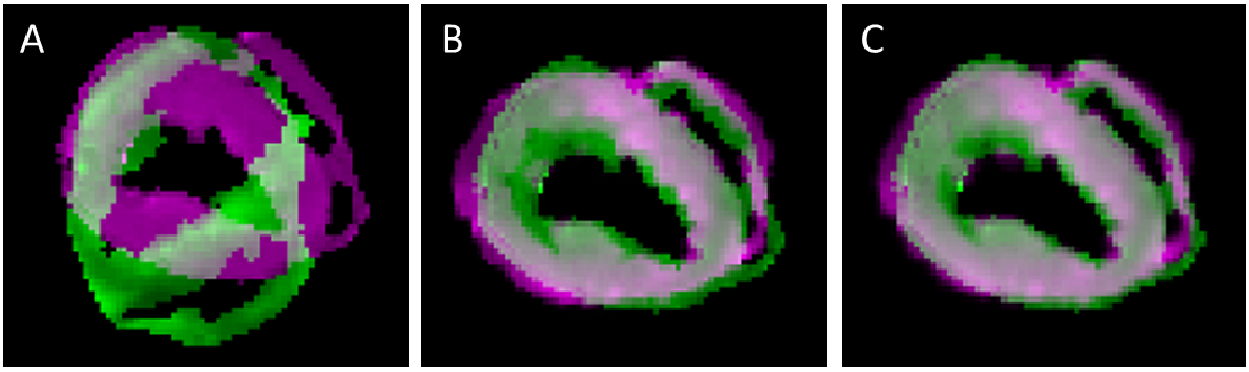

Fig. 5. Representative example of the registration procedure between a template heart (green) and a target heart (magenta). **A**: Starting volumes. **B**: Volumes after affine registration. **C**: Volumes after affine and deformable registration.

Table I: Dice similarity coefficients for the registration of pig hearts and acute angle errors for the estimated fiber orientations.

Template	*Target*	*DSC*	*AAE (degrees)*
Pig 1	Pig 2	79.7%	25.92
Pig 1	Pig 3	83.4%	19.89
Pig 1	Pig 4	79.9%	18.73
Pig 2	Pig 1	82.0%	33.65
Pig 2	Pig 3	86.9%	28.92
Pig 2	Pig 4	82.3%	29.77
Pig 3	Pig 1	83.1%	28.24
Pig 3	Pig 2	85.3%	30.92
Pig 3	Pig 4	86.1%	29.87
Pig 4	Pig 1	87.9%	21.19
Pig 4	Pig 2	71.1%	21.34
Pig 4	Pig 3	74.7%	18.61

4. CONCLUSIONS

We estimated cardiac fiber orientations from ultrasound volumes of pig hearts. This work demonstrated the feasibility of the ultrasound-based fiber estimation method in large animal hearts that more closely resemble the anatomy of human hearts than the rat hearts. Future work will further improve the accuracy of the registration and orientation estimation, with the described procedure eventually being applied to human cardiac tissue.

ACKNOWLEDGEMENTS

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