Novel Atlas of Fiber Directions Built From Ex Vivo DT images of Porcine Hearts

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Introduction: Cardiac MR image-based predictive models integrating statistical atlases of heart anatomy and fiber orientations can aid in better diagnosis of cardiovascular disease, a major cause of death worldwide. Such atlases have been built from diffusion tensor (DT) images of various species: rat, dog, and human heart[1,2,3], and can be used in anisotropic models for personalized computational electro-mechanical simulations when the fiber directions from DTI are not available. Here, we propose a framework for constructing a statistical fiber atlas from high resolution *ex vivo* DT images of porcine hearts, by first computing an average geometry and then obtaining directional information of diffusion tensors linked to the reference frame of the transformed subjects (i.e., hearts).

Methods: A diagram of the workflow is presented in Figure 1. First, the diffusion-weighted (DW) MRI studies were performed on a dedicated 1.5T GE Signa Excite scanner using a small database of N=8 explanted healthy pig hearts, with approval from our institute. In the current study, we used the following MR parameters: TE=35 ms, TR=700 ms, ETL=2, b=0 for the unweighted MR images, and b=500 s/mm^2 when the seven diffusion gradients were applied, respectively[4]. Image resolution was ~0.5x0.5x1.6 mm.

The geometries of the 3D anatomical volumes T_i $(i = 1, \dots, N)$ were first normalized to generate a mean cardiac volume. This was done through an iterative groupwise registration scheme. At every groupwise iteration, all the subjects were registered to the current reference volume via multilevel nonparametric registration[5]. The resulting transformations from the pairwise registration step were used to update the reference geometry I^n_{mean}.

The diffusion tensors associated with each subject were subsequently transformed using the transformations aligning the subjects to the average geometry; this was done to project the tensors onto a common reference frame, which would ultimately enable us to extract tensor statistics for the population. We used a Finite Strain reorientation method to transform the tensors. Given a deformation field y, the rotation component of the local affine transformation given by $A = I + \nabla y$ was used to reorient the tensor at every voxel. It was obtained by solving for R in the polar decomposition of A: $A = RU$, while the reoriented tensor $A(D)$ was given by $A(D) = RDR^T$. Finally, we used the Log-Euclidean metric to calculate the average diffusion tensor field $\overline{D}_{log}(X)$: $\overline{D}_{log}(X) = \exp\left[\frac{1}{N}\sum_{i=1}^{N} log\big(D_i(X)\big)\right]$, where $D_i(X)$ refers to the reoriented tensor of the i^{th} subject.

Results and Discussion: The groupwise registration algorithm took only 8 iterations until it converged to the stable average geometry shown in Fig 2(a). The error evolution of the groupwise algorithm (measured in terms of change in average intensity values between consecutive reference geometries) is shown in Fig 2(b).
In Figure 3, we present the average tensor field and the results of the Finite Strain reorientation method. Note that the geometric features and the local orientation of the diffusion tensor fields were preserved. This makes Finite Strain an ideal method for inter-subject DT-MRI registration[3].

The average cardiac fiber architecture is shown in Figure 4 in three views: anterior (A), posterior (P), and lateral (L). Fiber tractography was performed on the average DT field using MedInria (http://med.inria.fr) to find the end-to-end pathway of the principal direction of diffusion given by the first eigenvector of the diffusion tensors.

Conclusions and Future Work: We successfully created the first cardiac fiber atlas for porcine hearts. In addition, we laid the foundation of a framework for building a statistical cardiac atlas by computing an average cardiac geometry from a small database without the need for selecting landmarks, transforming the diffusion tensors of the subjects, and obtaining the associated average diffusion tensor field and cardiac fiber architecture. The next step will be to compute tensor statistics to better understand the underlying fiber and laminar sheet structure, and to use the fiber atlas for electro-mechanical simulations to predict cardiac function.

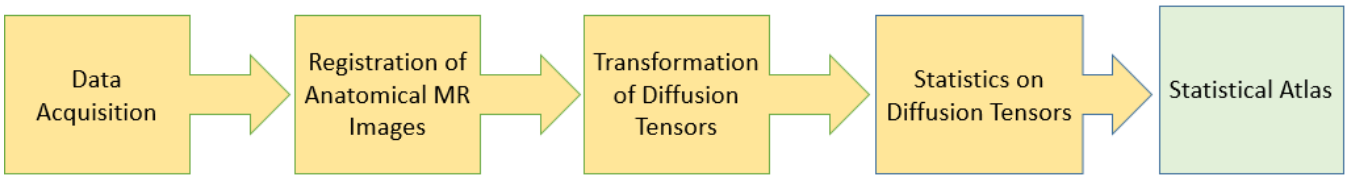

Figure 1. **Workflow diagram for building a statistical porcine cardiac atlas.** DW images were acquired, and then an average cardiac geometry was constructed through groupwise registration. The diffusion tensors for each heart were reoriented and averaged to compute a cardiac fiber atlas.

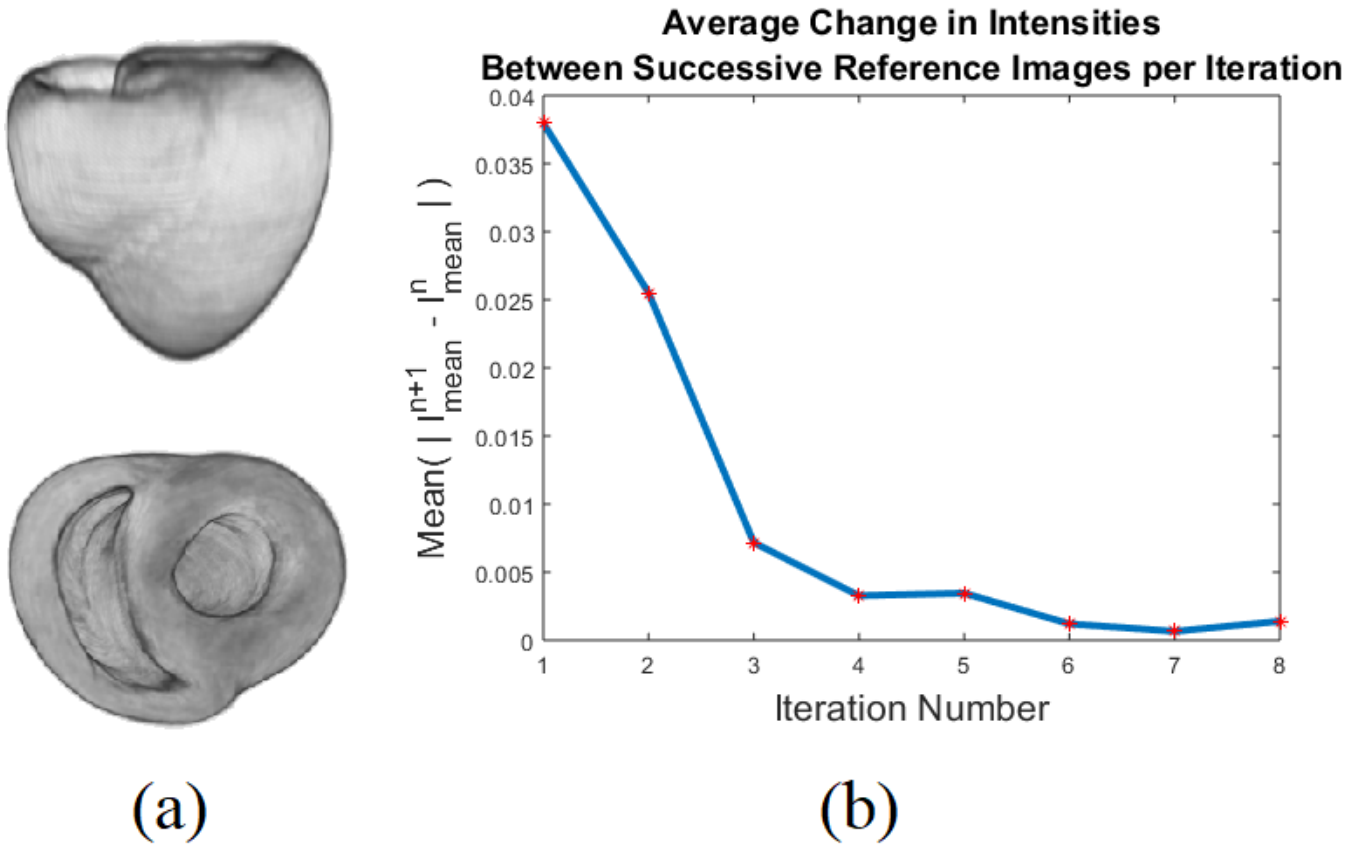

Figure 2. Results of the groupwise registration. (a) 3D and axial views of the computed average geometry, (b) the rate of convergence of the groupwise scheme was measured in terms of the average change in intensity

values between successive reference volumes. The groupwise registration algorithm terminates when either the maximum number of iterations (n = 10) is reached, or when there is no significant improvement in the average change in intensity values, i.e., when $\frac{mean(|\, I_{mean}^{n+1} - I_{mean}^{n}\,|)}{mean(|\, I_{mean}^{n} - I_{mean}^{n-1}\,|)} > 0.05$.

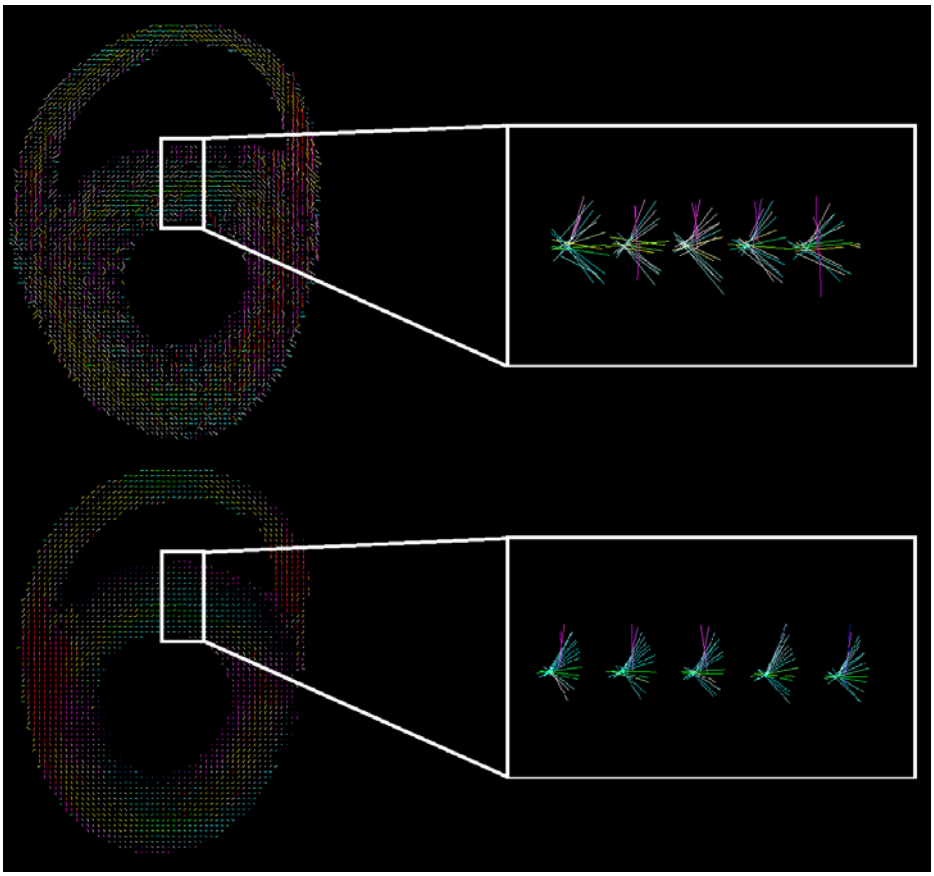

Figure 3. Tensor Reorientation and Averaging. (Top) The original tensors of one of the subjects and (Bottom) the average DT field. The local orientation of the tensors were preserved by the Finite Strain reorientation method. The tensors are red when the primary eigenvector is oriented along the direction of the x-coordinates, green along the direction of the y-coordinates, and blue along the direction of the z-coordinates.

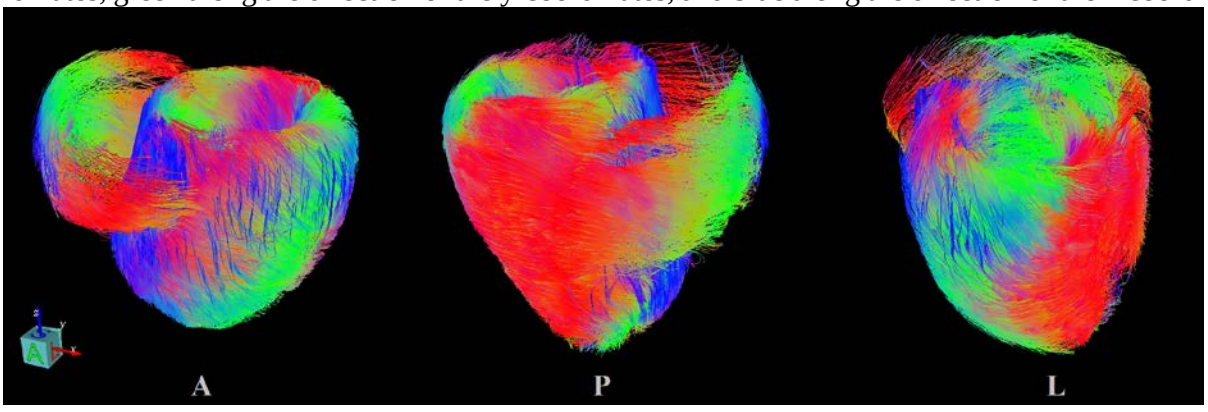

Figure 4. Fiber Tractography. Cardiac fiber atlas obtained by tracking the end-to-end pathway of the principal direction of diffusion at every voxel. As indicated by the cube in the bottom left, the fibers are red when the primary eigenvector is oriented along the direction of the x-coordinates, green along

the direction of the y-coordinates, and blue along the direction of the z-coordinates.

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