

Sheet Tractography Provides a Multi-Dimensional Representation of Architecture in Normal and Infarcted Hearts

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Target Audience: Scientists interested in the use of diffusion MRI tractography to characterize myocardial architecture.

Purpose: Myofiber organization is characterized by a branching network of sheets, each consisting of 2-4 individual myofibers.¹ Diffusion Tensor MRI (DTI) studies have shown that the secondary and tertiary eigenvectors of the diffusion tensor (DT) correspond to the orientation and thickness, respectively, of the myolaminar sheets.¹ Myofiber tractography has traditionally relied on solely the primary eigenvector to determine fiber trajectory and to obtain fiber-wise statistics. Here, we extend tractography in the heart to include the trajectories of the secondary and tertiary eigenvectors, and use this to reconstruct ribbon-like tracts of myolaminar sheets in normal and infarcted hearts.

Methods: 15 hearts were studied *ex vivo*: human (n=5), sheep (n=5), and infarcted sheep (n=5). The hearts were fixed and imaged on a 3T clinical scanner (TRIO, Siemens). DTI was performed using a fat-suppressed single shot spin echo EPI (echo planar imaging) sequence, oriented along the short axis of the left ventricle (LV). Six diffusion encoding gradients were acquired with voxel-size = 2x2x2 mm³, TR/TE = 8430/96 ms, and a flip angle of 90 degrees. 50-70 slices (without gaps) were acquired in the short axis of the LV to cover the entire heart, with 24 averages per slice. Sheet tractography was performed by integrating the primary eigenvector using a 4th order Runge-Kutta method into solid sheets, oriented in addition by the secondary or tertiary eigenvectors and scaled by their eigenvalues. The sheet torsion angle (TA) represents the angle between adjacent sheet normal vectors. Figure 1A depicts the TA concept as the angle between the projection of the sheet normal of a given segment (*i.e.* \hat{e}_3) onto the plane defined by the complementary eigenvectors of the adjacent segment (*i.e.* \hat{e}_{2+1} , \hat{e}_{3+1}). The torsion represents the amount of local sheet twisting.

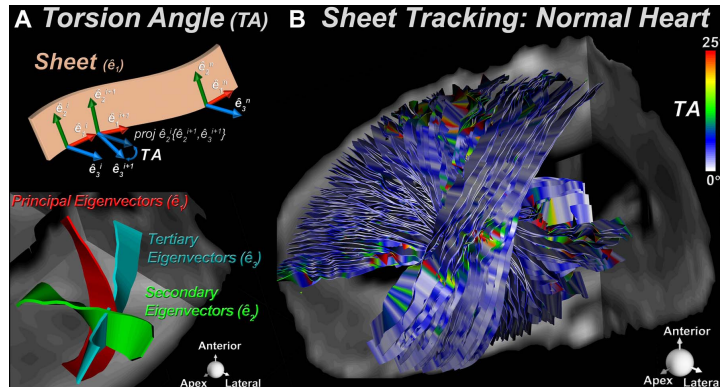


Figure 1. (A) Sheet tractography involves the integration of the primary eigenvector into ribbon-like sheets, rather than unscaled cylindrical streamlines. The orientation of the major axis of the sheet is defined by the primary eigenvector \hat{e}_1 . The orientation and scale of the minor axis of the sheet are defined by the secondary eigenvector and eigenvalue, respectively. The thickness of the sheet is defined by the tertiary eigenvalue. The orientation of the minor axis of the sheet changes between adjacent segments of the tract, defining the sheet torsion angle. (B) Sheet tractography in the lateral LV wall of a normal human heart. The tracts are oriented by their helix angle (\hat{e}_1) and color-coded by the sheet torsion angle along the tract.

Results: Figure 1A illustrates the sheet-tracking concept by sweeping a solid ribbon along the trajectory of \hat{e}_1 , assuming \hat{e}_3 as the sheet vector normal. Note that the tracking trajectory can take any of the directions defined by the eigenvectors \hat{e}_1 , \hat{e}_2 and \hat{e}_3 (shown in red, green and cyan). Figure 1B shows the distribution of myofiber sheets in the lateral LV wall of a human heart, color-coded by the sheet TA. The major axis of the ribbons follows the helix angle (\hat{e}_1) of the myofibers. The minor axis of the ribbons is defined by the sheet trajectory (\hat{e}_2), which is fairly radial. Sheet tractography in the remote zone (lateral wall) of a remodeled sheep heart with a large anteroseptal infarct is shown in Figure 2. Average TA was significantly ($p < 0.05$, Mann-Whitney test) reduced in the remote zone of the remodeled hearts compared to the identical location in normal hearts. The orientation of the sheets can also be seen to differ in normal (Figure 1B) and infarcted (Figure 2B) myocardium. The major axis of the sheets has undergone a rightward rotation due to a change in the helix angle (\hat{e}_1) in the remote zone.² The minor axis of the tract remains radial but the sheets are now more regular (reduced TA) and closely packed.

Discussion: Diffusion MRI tractography in the heart has traditionally involved integrating the streamlines defined by the primary eigenvector into unscaled cylinders. While of significant value, the structural information contained in the rest of the tensor is lost with this approach. In particular, no information on sheet architecture, which plays a central role in myocardial mechanics, is provided by cylindrical streamlines. Here, by scaling and aligning the minor axis of the streamlines by the secondary eigenvalue/vector, the tracts become ribbon-like sheets from which several parameters can be derived. The major axis of the sheet defines \hat{e}_1 (helix angle), the minor axis \hat{e}_2 (sheet angle) and the rotation of the sheets the torsion angle. We show that TA in the remote zone of remodeled/infarcted hearts is significantly reduced and may account for the contractile dysfunction in this zone.

Conclusion: Sheet tractography is a powerful extension to traditional fiber tractography as it fully reflects the complete eigensystem. The technique may provide valuable insights into the structure and function of the myocardium.

References: 1) Kung GL et al., JMRI 2011; 2) Mekkaoui C et al., JCMR 2012.

Figure 2. (A) The sheet torsion angle is significantly reduced in the remote zone (lateral wall) of remodeled hearts with large anteroseptal infarcts. (B) The tracts in the remote zone have undergone a rightward rotation and are more tightly packed than the sheet tracts in normal hearts.

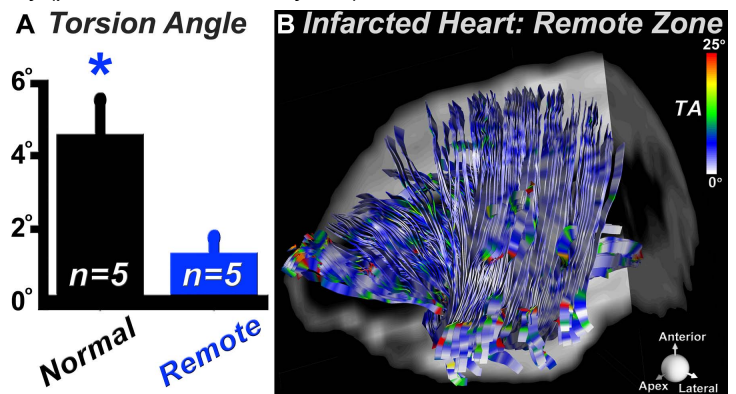


Figure 2. (A) The sheet torsion angle is significantly reduced in the remote zone (lateral wall) of remodeled hearts with large anteroseptal infarcts. (B) The tracts in the remote zone have undergone a rightward rotation and are more tightly packed than the sheet tracts in normal hearts.