Cardiac Laminae Structure Dynamics from In-vivo Diffusion Tensor Imaging

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Introduction: The laminar sheet organization of the heart has been observed in many ex-vivo studies [1-2]. These studies have shown that cardiac myocytes are grouped in layers of approximately 4 cells thickness [3] separated by cleavage (sheet) planes, that can be observed using high resolution imaging [4]. The laminae arrangement is believed to strongly determine the tissue shearing that allows the muscle contraction [2]. In this work we demonstrate that in-vivo DTI is capable of detecting discrepancies between diastolic and systolic laminae organization that agrees with previously reported histological studies.

Material and Methods: Imaging was performed on 10 healthy volunteers in a 1.5T Philips Achieva clinical MRI using a 32 channel receive array and a gradient system with a maximum gradient strength of 40mT/m and a slew rate of 200mT/m/ms per channel. Diffusion data were acquired using a STEAM acquisition [5] with a single shot EPI readout module [6], at 2mm in-plane resolution and with a slice thickness of 8mm. Five slices were acquired both in diastolic and systolic phases for each of the 10 volunteers. The minimum achievable TE was used for all acquisitions (20 ms). Diffusion encoding was performed along 10 directions with a b-value of 500s/mm^2 and 9 averages per direction. The average scan time was 7 min. per slice. A B0 map was acquired covering the LV in order to perform image based shimming. Two single breath-hold 3D whole-heart acquisitions were performed covering the entire LV during the systolic and diastolic rest periods. Tensors were estimated by solving a linear system of equations based on the log of the diffusion weighted images. The third eigenvector v3 of the tensors was extracted. The orientation of this vector is believed to be perpendicular to the underlying laminae plane [7]. To test the hypothesis that v3 contains information, the transverse anisotropy TA (ratio between second and third eigenvalues) was extracted at each voxel. Its distribution in each phase was compared against the one computed from randomly distributed second and third eigenvalues. Tensor information from the 10 volunteers was transformed to a Prolate Spheroidal frame for each phase using a conformal mapping described in [8]. The sheet angle (angle between the third eigenvector and the myocardial wall) was then extracted at each voxel. For visualization purposes only, full LV tensor approximation was performed [8] using data from the 10 volunteers. The laminae plane was tracked from seed points using an advection-diffusion tracking algorithm as described in [9].

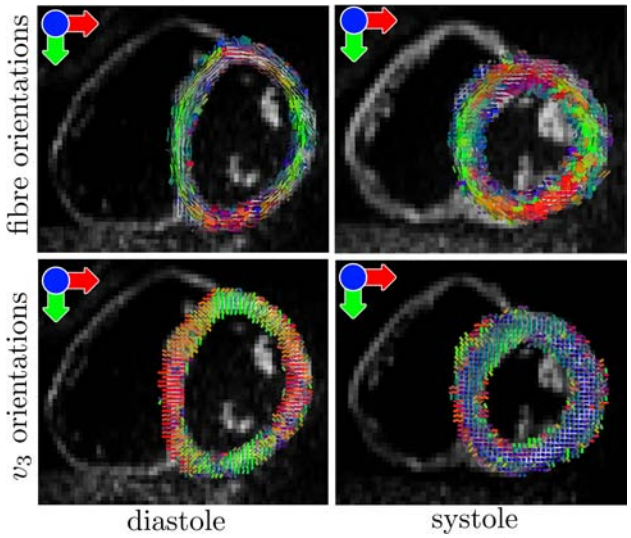

Figure 1: top: *Color-coded DTI slices in diastole (left) and systole (right). The circumferential fibre orientations are observed.* ***Bottom:*** *Corresponding third eigenvector maps, where a change of sheet orientation is visible between phases.*

Results: Tensor slices in diastole and systole are presented in **Figure 1** (top). The tensors are color-coded with the direction of their principal eigenvector. Maps of the underlying third eigenvector v3 are shown in **Figure 1** (bottom). The vectors are color-coded with their directions. Normalized histograms of the helix, transverse and sheet angles in diastole and systole are presented in **Figure 2** (a,b,c). Normalized histograms of the diastolic and systolic TA are presented in **Figure 2** (d) and compared to the histogram of TA computed from randomly distributed second and third eigenvalues (10000 samples). **Figure 3** illustrates the laminae plane tractography results from the approximated dense tensor fields in diastole and systole.

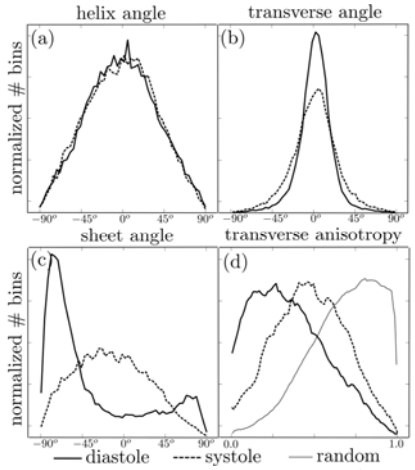

Figure 2: *Normalized Histograms (from 10 volunteers) of the helix* ***(a)****, transverse* ***(b)*** *and sheet* ***(c)*** *angle in diastole (plain line) and systole (dash line).* ***(d):*** *Histogram of transverse anisotropy TA in both phases compared with the one of randomly distributed eigenvalues (thin line).*

Discussion: Previous studies [1-3] on the laminae organization and dynamics suggest that the sheet planes are changing orientation during the cardiac cycle. Specifically, [1] reports sheets parallel to the wall when the wall is the thinnest and going toward parallel to the short axis when the wall thickens (Fig. 2 in [1]). As illustrated in **Figure 1** (bottom), our findings confirm this histological report by suggesting that laminae are organized parallel to the myocardial wall in diastole and that, during contraction and wall thickening, the laminae spread to a more complex organization ("chevron pattern", as observed in [2]) where the sheet planes tend to become parallel to the short axis plane in the mid-wall area (**Figure 2-3**). Furthermore, TA distributions in **Figure 2**(d) confirm the assumption that the information given by the third eigenvector is significant (p-value<0.001). The graphs also indicate a change of distribution between phases, suggesting that the tensors are more planar in diastole than in systole. This characteristic may be explained by fibre cell shortening and diameter increase during contraction, thereby allowing more diffusion perpendicular to the fibre direction. Additionally, **Figure 1** (top) and **Figure 2** (a,b) suggest that, as opposed to the sheet orientation, the fibre orientation does not change significantly between phase.

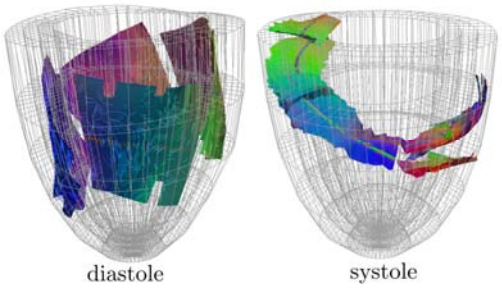

Figure 3: Laminae plane tractography results in diastole **(left)** and systole **(right)**.

In conclusion, this work represents to our knowledge the first report on laminae structure dynamics depicted from in-vivo DT-MRI.

References: [1] Spotnitz, J. Mol. Cell. Card., 1974 [2] Costa, Am. J. Phys. Heart. Circ., 1999 [3] Legrice, Am. J. Phys. Heart. Circ., 1995 [4] Kohler, MRM, 2003 [5] Tseng, MRM 1999 [6] Stoeck, ISMRM, 2011 [7] Kung, MRM 2011 [8] Toussaint, MICCAI, 2010 [9] Rohmer, Inv. Radiol. 2007.