Statistical Atlas of the Human Left Ventricular Fibre Architecture using In-Vivo DT-MRI

Nicolas Toussaint[1], Christian Stoeck[2], Sebastian Kozerke[2], Maxime Sermesant[3], and Tobias Schaeffter[1]
[1]*Imaging Sciences, King's College London, London, London, United Kingdom,* [2]*Biomedical Engineering, ETH, Zurich, Switzerland,* [3]*asclepios research project, INRIA, Sophia Antipolis, France*

Introduction: The study of myocardial fibre architecture is crucial for the understanding of cardiac morphology and mechanics. Up-to-date myocardial structure has been investigated mostly in ex-vivo hearts [1][2] using microscopy or magnetic resonance Diffusion Tensor Imaging (DTI). A recent study showed fibre variability on a set of ex-vivo human hearts [3]. However such detailed studies in the beating human heart are still challenging due to the magnitude and complexity of cardiac motion. We propose a statistical atlas of the left ventricular fibre architecture reconstructed from in-vivo DT Images acquired in healthy volunteers. In this study 4 to 5 short axis slices were acquired on 5 healthy human subjects during systolic contraction. A statistical atlas of this population was computed and physiological parameters such as helix and laminar sheet angles were derived from it. Results indicate a strong correlation of the helix angle with the transmural depth and reveal the distribution of the laminar sheet angle.

Material and Methods: (I) Acquisition: Cardiac DTI was performed in 5 volunteers (2 males, 3 females) on a 1.5T clinical MR scanner (Philips, The Netherlands) equipped with a gradient system with maximal strength of 80mT/m and a slew of 100mT/m/ms per channel. A 32 channel cardiac coil array was used. The imaging protocol consisted of a B0 map for image based shimming, a trigger delay scout sequence for estimation of optimal trigger during systolic contraction [4], the actual DTI acquisition and a single breath hold 3D T2 contrast enhanced whole heart acquisition. All sequences were ECG-triggered, and DWIs were acquired during free breathing using a respiratory navigator, with a gating window of 5mm, placed on the right hemidiaphragm. DTI acquisition was planned in short axis view of the heart and 4-5 slices were placed manually along the long axis of the LV. Imaging was performed using a diffusion weighted spin echo sequence with single shot echo planar imaging readout (Fig. 1). Imaging parameters were as follows: TE/TR 59ms/2R-R intervals, FOV: 230×102mm^2, in-plane resolution 2×2mm^2, slice thickness: 8mm. The echo time was shortened by the use of a rectangular FOV (local-look), applying the excitation pulse in phase encoding direction and the refocusing pulse in slice encoding direction [5]. Furthermore a partial Fourier coefficient of 0.63 was used and the echo pulse duration was shortened applying the variable rate selective excitation algorithm [6]. Diffusion encoding was achieved by two bipolar gradients [7] applied in 18 directions creating a b-value of 500s/mm^2. Ten single averages were acquired for each diffusion encoding direction and residual breathing offsets were corrected for by in-plane image registration during post processing, resulting in 10 averages per direction. The total scan time was 10 to 15mn per DTI slice.

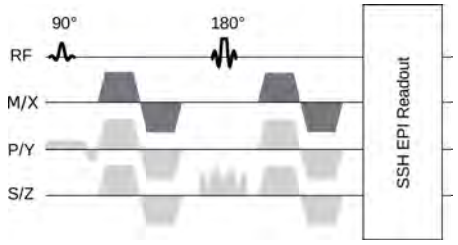
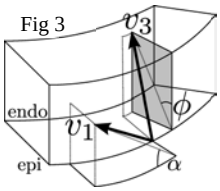


Fig 1: Diffusion weighted spin echo pulse sequence with single-shot EPI readout. Diffusion encoding is established by a pair of velocity compensating bipolar gradients. For local look imaging the excitation pulse is applied in phase encoding direction, while the echo pulse remains in slice encoding direction. The echo pulse duration is shortened using VERSE.



(II) Atlas construction: The elaboration of the statistical atlas was here based on a concept introduced in [8]. For each of the volunteers, the manually segmented LV anatomy is mapped to a common truncated ellipsoid using non-linear bijective registration (see Fig. 2). The LV was truncated at an angle of 100 deg. (10 deg. above its largest cross-section). The plane (ξ_1=0) was matched with the intersection between anterior wall and RV for all subjects. For each acquired position in the volunteer's LV, a corresponding point and tensor in curvilinear coordinate (Prolate Spheroidal) was assigned in the ellipsoid. Repeating this operation for N volunteers allowed us to gather data in the ellipsoid frame. This accumulation can be seen as a single global scattered dataset. We then estimate a dense tensor field over the entire LV that formed a statistical atlas, using Prolate Spheroidal curvilinear interpolation [8]. Two physiologically meaningful quantities are derived from the averaged DTI atlas: the helix angle α and the sheet angle Φ. They are respectively the angle between the fibre direction and the transmural plane, and the angle between the local laminar sheet and the epicardial wall. They can both be derived using 1st and 3rd eigenvectors of the tensor, as shown in Fig. 3.

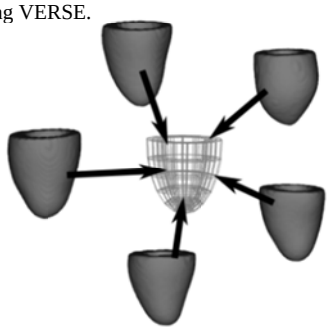
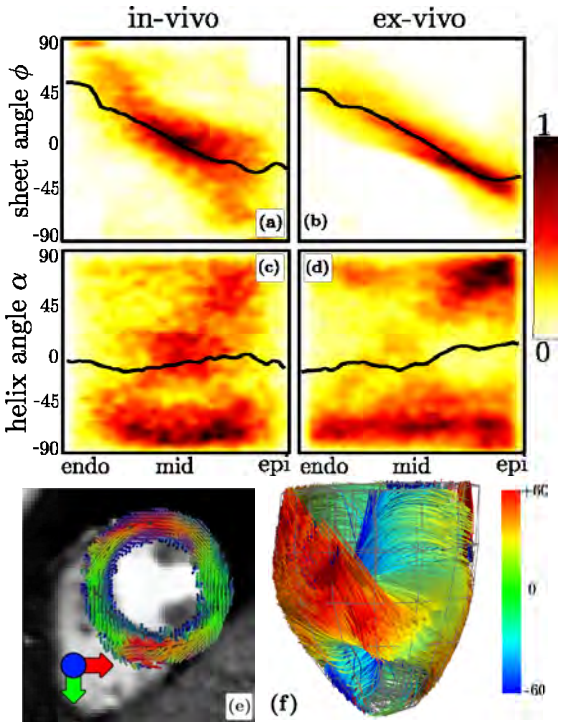


Fig 2: Schematic of the atlas construction: anatomical LVs are mapped to a common ellipsoid coordinate frame.



Results: In Fig. 4(e) we show DTI short axis slice as acquired in one of the 5 volunteers. The tensors are shown as first eigenvectors and are color-coded with their directions. Additionally to the visible circumferentiality of the vectors, we observe vectors parallel to the long axis (colored in blue) at the LV and RV endocardial boundaries, i.e. at the connection with papillary muscles. Fig 4(a,b,c,d) gathers joint histograms of the helix (a,b) and sheet (c,d) angles across the transmural distance. The first column (a,c) corresponds to the in-vivo atlas distributions. In the second column (b,d), for comparison, the same histograms have been computed using the CCBM ex-vivo human DTI dataset [9]. The range of the helix angle variation is found to be from +50 deg. at endocardium to -45 deg. at epicardium in both ex-vivo and in-vivo graphs. The sheet angle is found less correlated to the transmural depth in both cases. In Fig. 4(f) we show the fibre tractography from the statistical atlas.

Conclusions and Discussions: This study presents an acquisition and reconstruction method to build a statistical atlas of the human LV fibre architecture in-vivo. The method was successfully applied to a population of 5 healthy volunteers. Resulting in-vivo atlas fibre distribution of the helix angle is in strong agreement with the ex-vivo dataset. The double helix structure is clearly visible on the in-vivo atlas fibre reconstruction. As also found in similar ex-vivo studies [10], the laminar sheet angle distribution is only weakly correlated to the transmural depth, suggesting that a more local (zone by zone) description is necessary to describe the laminar sheets. However, in-vivo joint histogram appears to depict a structure that is coherent with what is seen in ex-vivo dataset. This methodology and those results may lead to larger scale studies and patient applications.

References: [1] Anderson et al. Clin. Anat. 2009. [2] Peyrat et al. TMI 2007. [3] Lombaert et al. FIMH 2011 [4] Stoeck et al ISMRM 2010. [5] Gamper et al. MRM 2007. [6] Hargreaves et al. MRM 2004. [7] Dou et al. MRM 2003. [8] Toussaint et. al. MICCAI 2010. [9] http://www.ccbm.jhu.edu/research/DTMRIDS.php. [10] Lombaert et al. MICCAI 2011.

Fig 4: (a,b,c,d) Joint histograms of the helix and sheet angle across transmural depth for the in-vivo atlas (left) and an ex-vivo dataset (right). (e) An acquired in-vivo DTI slice. (f) Fibre structure reconstruction from the atlas.