Heart-within-heart Dynamic Systems Implicit in Myocardial Fiber Architecture Revealed by Diffusion Tensor Tractography

K-L. Liu[1], H-Y. Yu[2], V. J. Wedeen[3], and W-Y. I. Tseng[1,4]

[1]Center for Optoelectronic Biomedicine, National Taiwan University, Taipei, Taiwan, [2]Departments of Surgery, National Taiwan University Hospital, Taiwan,

[3]Department of Radiology, MGH Martinos Center for Biomedical Imaging, Harvard Medical School, Charlestown, Massachusetts, United States, [4]Department of Medical Imaging, National Taiwan University Hospital, Taiwan

Introduction

It is long known that the myocardial architecture has its functional significance. However, up to now there are no models that can fully explain the relationship between myocardial fiber structure and the mechanism of cardiac motion. Using blunt dissection, Torrent-Guasp modeled the myocardial structure as a single rope structure with figure-of-eight configuration [1]. Based on quantitative histology, Streeter modeled the myocardial structure as a 3D syncytium, composed of spiraling fibers continuously changing their orientations from outer wall to inner wall of the left ventricle (LV) [2]. These two models view the myocardial architecture from different perspectives and each model explains in part the cardiac motion. In this study, we proposed using diffusion tensor imaging (DTI) and fiber tracking technique to perform virtual dissection of the myocardial fiber architecture. The aim is to twofold, to reproduce myocardial structures presented in the previous two models, and to explain the cardiac motion based on the new perspective of fiber architecture derived from the virtual dissection.

Methods

DTI acquisition and image reconstruction. A rabbit heart in vitro was scanned on a 7-Telsla Bruker MRI system using a pulsed gradient echo planar imaging (EPI) sequence. The diffusion-sensitive gradients were applied in six different directions, {2/3, 1/3, 2/3}, {2/3, -1/3, 2/3}, {1/3, 2/3, 2/3}, {-1/3, 2/3, 2/3}, {2/3, 2/3, 1/3}, {2/3, 2/3, -1/3}, with the diffusion sensitivity b = 1000 s/mm^2. A total of 28 slices were obtained encompassing both right and left ventricles with the spatial resolution = 500 × 500 × 1000 μm, field of view = 3 × 3 cm, TR/TE = 7000 ms / 26.2 ms, and the number of excitations = 36. Image interpolation in z direction was performed to attain isotropic resolution of 500 × 500 × 500 μm. Based on the diffusion-weighted images, the diffusion tensor was reconstructed at each pixel, and the first eigenvector of the diffusion tensor was then determined to be the local fiber direction [3, 4].

Segmentation of ventricles. In this study, the ventricles were divided into five segments, the right ventricle (RV), the papillary muscles (PM), the LV from the apex to the roots of the papillary muscles (Apex), the LV from the roots to the tips of the papillary muscles (Mid), and the LV from the tips of the papillary muscles to the most basal level of the LV (Base). These five segments were used as regions of interest (ROIs) in tractography in order to select particular fiber tracts that pass through a particular ROI.

Tractography of myocardial fibers. After reconstructing the local fiber directions, fiber tractography was reconstructed based on the Euler's method [5] using in house developed tracking algorithm [6]. The tractography of the whole heart was first obtained by placing the seeds in both ventricles. By applying the intersection or complement of ROIs and by considering all possible combinations, virtual dissection of fiber architecture was performed.

Results and Discussion

The color map of the helix angle on each short axis slice reproduced the same fiber orientations as described by Streeter [2]; the myocardial fibers gradually change their helix angles from the subendocardium to the subepicardium (Fig. 1). On the other hand, our tractography findings partially supported the myocardial structure proposed by Torrent-Guasp. We observed that the main myocardial fibers can be classified into two systems (Fig. 2a and 2d). The first system was constituted of the longitudinal fibers of the LV inner wall including PM as well as the inner part of circumferential fibers in Apex and Base (Fig. 2a). The second system was composed of mid wall and outer wall circumferential fibers connecting the LV and RV (Fig. 2d). The fibers of the first system can be further separated into two subsystems. The first subsystem comprised of the spiral fibers at Apex and Base (Fig 2b), contributing to the LV torsion. The second subsystem consisted of longitudinal fibers in the subendocardium of the LV, responsible for the shortening along the LV long axis (Fig. 2b and 2c). In addition, this structure is implicit in the mechanism of the LV torsion: apical and basal segments rotate in the opposite directions and the middle segment rotates minimally [7]. From the virtual dissection, the fibers of the papillary muscles and their relationships with the LV can be appreciated (Fig. 2c). The roots of the papillary muscles inserted to the LV inner wall and merged into the circumferential fibers in a bandage-like pattern. The fibers of the second system consisted of circumferential fibers with the pitch much smaller than the circumferential fibers of the first system (Fig. 2d). These fibers passed from the RV, entered the anterior RV insertion to the interventricular septum, and merged into the circumferential fibers in the middle and outer walls of the LV. These circumferential fibers wrapped the first system in a bandage-like pattern, which were considered to dominate radial contraction of the LV wall. Symbolically, the LV can be viewed as a "heart-within-heart" system, the first system and the second system being the inner heart and the outer heart, respectively.

Conclusions

In this study, a systematic fiber tracking method was proposed to virtually dissect the fiber architecture of the LV. We found that the LV myocardial fibers can be classified into two systems; the inner heart system corresponds to the motion of torsion and longitudinal shortening and the outer heart system corresponds to radial contraction of the LV wall. Our findings might shed insight to the ventricular mechanics and could be valuable to the development of novel intervention of heart failure.

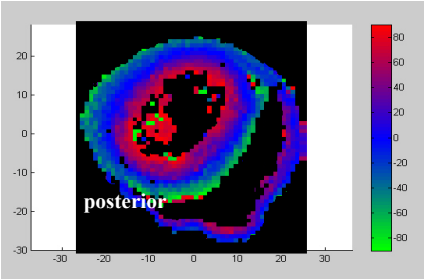

Fig 1. Color mapping of helix angle on a short axis slice of a rabbit heart with the scale of helix angle = 90° for the red and -90° for the green.

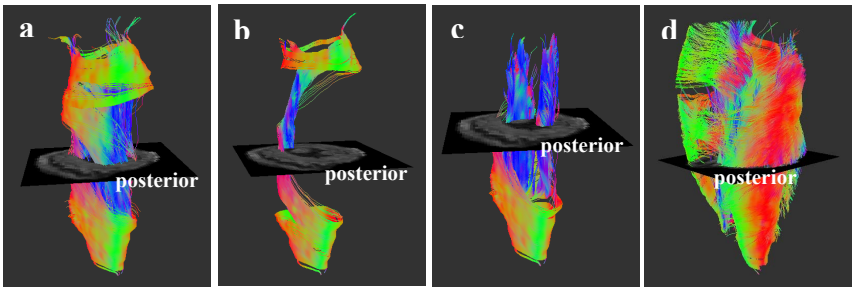

Fig 2. Myocardial fiber architecture of the ventricle, (a) the inner wall fiber structure of LV connecting fibers form Apex to Base, (b) partial fiber of non-PM system of LV, (c) papillary muscles fiber system of LV, (d) fibers connecting RV and LV.

References

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