

Reconstruction of the Architecture of Ventricular Myocardial Fibers in Ex Vivo Human Hearts

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ABSTRACT

Background: The 3-dimensional arrangement of the ventricular mass has been controversial. The aim of the present study was to investigate the macroarchitecture of ventricular myocardial fibers and to analyze whether it is consistent with the helical ventricular myocardial band (HVMB) hypothesis.

Methods: Eight excised human hearts were scanned by diffusion tensor magnetic resonance imaging (DT-MRI). Fiber tracking was then used with the DT-MRI data to reconstruct and visualize the positions of the myocardial fibers to reveal the architecture of ventricular myocardial fibers.

Results: The left ventricular myocardial fibers were found to consist of 2 crossed populations that were approximately normal from the epicardium to the endocardium in the tangent plane. The myocardial fibers in the middle of the myocardium had a smooth, linear angular rotation. The ventricular myocardial fibers maintained complete continuity and specific orientations that corresponded to the HVMB structure.

Conclusions: The architecture of the ventricular myocardial fibers in the human heart conforms to the HVMB structural hypothesis.

INTRODUCTION

The architecture of the ventricular myocardial fibers is the structural basis for the normal systolic and diastolic functions of the left ventricle. Because of limitations in the means of study, the 3-dimensional arrangement of the ventricular myocardial fibers has remained controversial and unclear [Gilbert 2007]. Some structural models and hypotheses have been proposed, including the nested pretzel [Jouk 2000], 3-layered ventricle [Anderson 2005], and simple laminar structure [LeGrice 1995] models. These models have

evaluated the ventricular fiber architecture from different perspectives and have helped us to increase our understanding of myocardial fiber structure. Many physiological and pathologic phenomena still cannot be explained with these models, however, and the models are incompatible with each other in some respects.

Torrent-Guasp et al proposed the theory of the helical ventricular myocardial band (HVMB), a structural and functional hypothesis that the ventricle consists of a single band of muscle [Torrent-Guasp 2001, 2004, 2005]. The HVMB hypothesis has gained broad favor in the medical community, particularly among cardiac surgeons.

At present, the evidence supporting HVMB hypothesis has come either from traditional dissection approaches or via a functional perspective, but objective morphologic evidence that directly reveals the architecture of ventricular myocardial fibers has been scarce. In addition, most investigators have used animal hearts as the objects of study.

In recent years, diffusion tensor magnetic resonance imaging (DT-MRI) has emerged as a powerful tool for rapid and noninvasive measurement of myocardial fiber structure at high spatial resolution. The approach gathers abundant data for statistical analysis, avoiding the bias inherent in the traditional dissection method. DT-MRI is a 3-dimensional imaging technology that can disclose the entire structure of heart fibers. DT-MRI reflects detailed tissue architecture through the acquisition of anisotropic information about the diffusion of protons of water molecules in tissue. This technology allows myocardial fibers to be reconstructed and visualized. Substantial research has confirmed that the primary eigenvector of the diffusion tensor is aligned locally with the long axis of cardiac fibers [Hsu 1998; Scollan 1998]. The orientation of myocardial fibers measured by DT-MRI represents the general direction of sarcomere segments, myofibrils, and heart muscle cells. Accordingly, this technique can reveal the orientation of myocardial fiber populations and further clarify the macroarchitecture of ventricular myocardial fibers.

Our previous preliminary investigation found that the structure of ventricular myocardial fibers corresponded to the HVMB in the pig heart as well [Gao 2006, 2009]. In the present study, we used DT-MRI scanning to further study the architecture of myocardial fibers in ex vivo human hearts.

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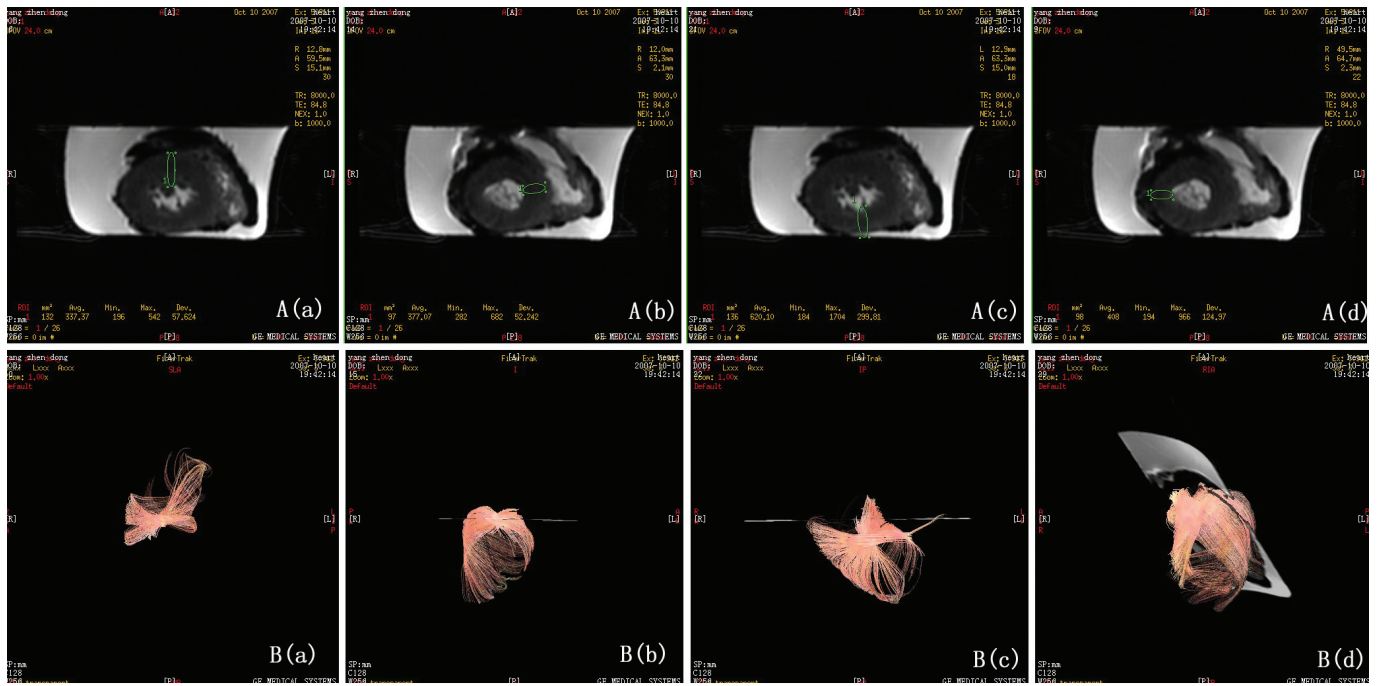


Figure 1. Reconstruction of the myocardial fiber in different regions of the left ventricle. A, The areas of fiber tracking (green ellipses) in the anterior (a), septum (b), posterior (c), and free (d) walls of the middle left ventricle (ventricular basal view). B, Corresponding images of fiber reconstruction (a-d). The myocardial fibers in the left ventricle show a crossed distribution.

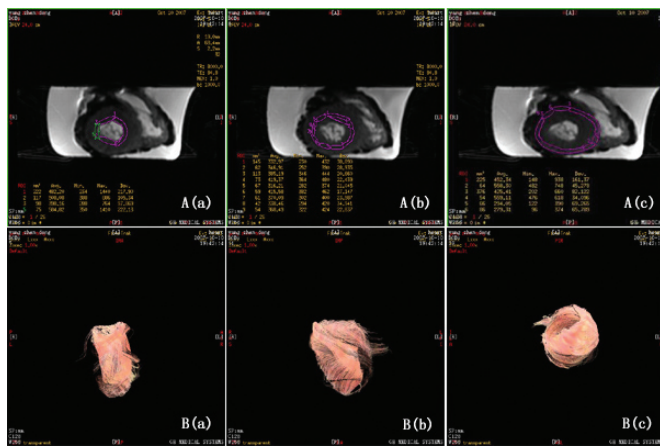


Figure 2. Reconstruction of the myocardial fibers in different sections of the left ventricle. A, The areas of fiber tracking (red ellipses) in the subendocardium (a), midwall (b), and subepicardium (c) of the middle left ventricle (ventricular basal view). B, Corresponding images of the fiber reconstruction (a-c).

MATERIALS AND METHODS

Eight human hearts were excised at autopsy in the Pathology Department of the PLA General Hospital. All autopsied patients had no heart diseases. The intact hearts were placed in a plastic container filled with water, and residual inner air was removed to eliminate unwanted susceptibility artifacts. The samples were scanned immediately with an MRI scanner;

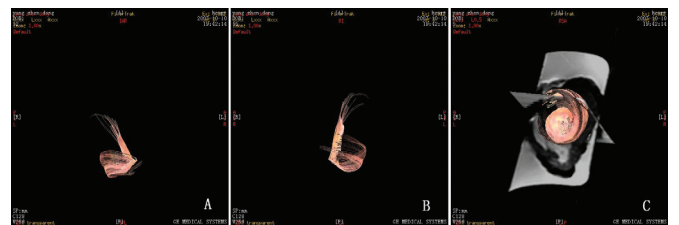


Figure 3. Reconstruction of the fiber bundle in the apex of the left ventricle. A, The myocardial fibers appear to turn near the apex (anterior view). B, Posterior view. C, Counterclockwise outward rotation of the myocardial fibers near the apex (apical view).

the myocardial fibers were then reconstructed and visualized via fiber tracking with Function Tool software (GE Advantage Workstation for Windows; GE Healthcare, Piscataway, NJ, USA) designed for the scanner to show the architecture of ventricular myocardial fibers. The mean (\pm SD) interval between patient death and scan was 18.6 ± 5.2 hours.

Images were acquired with an 8-element phased-array coil on a 3.0T GE CV/i MRI Scanner (GE Medical Systems, Piscataway, NJ, USA; provided by the Magnetic Resonance Imaging Center, PLA General Hospital). Data acquisition was performed with an SE-EPI (spin-echo echo planar imaging) sequence. Values for other parameters were as follows: slice thickness, 3 mm; b value, 1000 s/mm²; TR (repetition time), 2000 milliseconds; TE (echo time), 86.4 milliseconds; FOV (field of view), 14 cm \times 14 cm; data set, 128 \times 128 array; 2 scans; and continuous imaging.

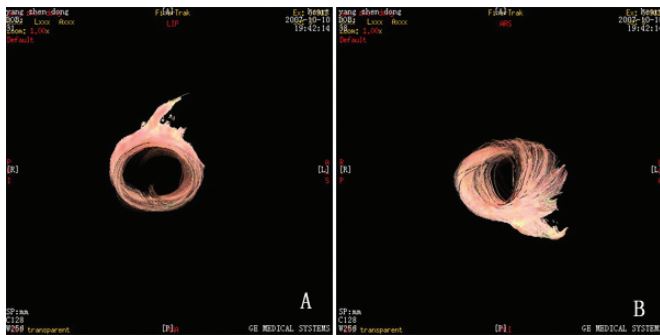


Figure 4. Reconstruction of the myocardial fibers in the posterior ventricular wall and interventricular septum. A, Interventricular septum and right ventricular fibers collect at the posterior left ventricular wall (apical view). B, Oblique basal view.

RESULTS

Reconstruction of Myocardial Fibers in Different Regions of the Left Ventricle

The fibers of the anterior, septum, posterior, and free left ventricular walls were reconstructed for visualizing myocardial fibers in these regions (Figure 1). Two intersecting fiber populations of approximately normal orientations in the tangent plane could be seen in the left ventricular wall from the epicardium to the endocardium (Figure 1B). The myocardial fibers in the middle myocardium showed a smooth, linear angular rotation and gradual transition between the epicardium and the endocardium (Figure 1B).

Reconstruction of Myocardial Fibers in Different Sections (Layers) of the Left Ventricle

The myocardial fibers of the subendocardium, midwall, and subepicardium of the left ventricle were reconstructed to show the orientations of myocardial fibers in these sections (Figure 2). The myocardial fiber orientations in different sections of the left ventricle were obviously distinct. The orientations of subendocardial fibers were close to the longitudinal axis of the left ventricle, the midwall fibers paralleled the circumferential axis of the left ventricle, and the orientations of subepicardial fibers were oblique (Figure 2B).

Reconstruction of the Fiber Bundle in the Apex of the Left Ventricle

The myocardial fiber bundles in the subendocardium of the left ventricle went down along the longitudinal axis of the left ventricle, rotated outward, and then turned up near the apex (Figures 3A and 3B). In the apical view, the myocardial fiber pathways displayed a counterclockwise rotation (Figure 3C).

Reconstruction of the Myocardial Fibers in the Posterior Ventricular Wall and the Interventricular Septum

The myocardial fibers from both the interventricular septum and the right ventricle joined the fibers of the posterior wall of the left ventricle. The myocardial fibers of the posterior left ventricular wall in the outer third continued

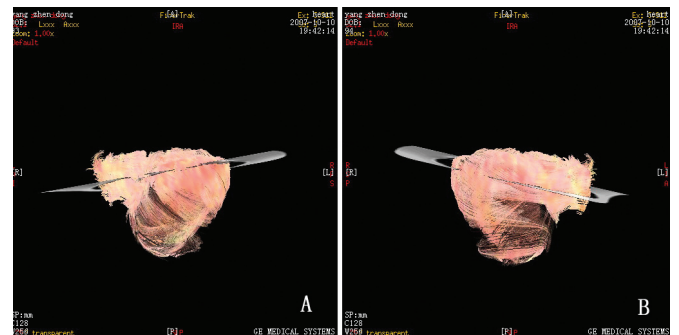


Figure 5. Reconstruction of the myocardial fibers of the 2 ventricles. A, The subepicardial myocardial fibers of the left ventricle displays an oblique direction (anterior view). B, The myocardial fibers of the right ventricle proceed to the posterior left ventricular wall in a circumferential direction (posterior view).

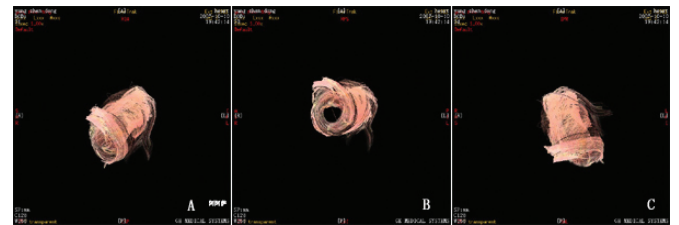


Figure 6. Reconstruction of the myocardial fibers of the left ventricle. A, The subendocardial fibers intersect the subepicardial fibers at the tangent plane after they rotate one circle (anterior view). B, The myocardial fibers of the left ventricle proceed from the subepicardium to the subendocardium, passing the midwall and returning to the subepicardium (apical view). C, Right lateral view.

into the right ventricle as the right ventricular fibers, whereas the myocardial fibers of the inner two thirds came from the interventricular septum (Figure 4).

Reconstruction of the Myocardial Fibers of the Whole Ventricle

The myocardial fibers of the right ventricle went in the circumferential direction, then passed the interventricular septum, and continued to the subepicardial fiber of the posterior left ventricular wall (Figure 5). The subepicardial fibers intruded gradually, passed the midwall, and then transformed into the subendocardial fibers (Figure 6). The subendocardial fibers went downward to the apex, rotated outward, and turned upward near the apex. Thus, the subendocardial fibers returned to the subepicardium after they had rotated a complete circle and intersected with each other at the tangent plane. In other words, 2 crossed fiber populations of approximately normal orientations in the left ventricular wall in fact maintained continuity at the apex (Figure 6).

DISCUSSION

Torrent-Guasp et al hypothesized that the ventricles are a single band of muscle that is coiled into 2 loops with insertions at the pulmonary trunk and aorta; each of the 2 loops

divides into 2 segments [Torrent-Guaspa 2001, 2004, 2005]. Buckberg et al [2006a, 2006b] used a variety of imaging methods in acquiring abundant evidence to support the HVMB hypothesis.

Our 8 excised human hearts were scanned by DT-MRI, and the myocardial fibers were reconstructed and visualized through fiber tracking. These heart samples all had the following architectural features:

1. The myocardial fibers of the left ventricular wall appeared to be arranged as 2 orderly fiber populations from the subepicardium to the subendocardium. Two fiber populations maintained approximately normal intersection at the tangent plane. The myocardial fibers in the middle myocardium had a smooth, linear angular rotation, and they functioned as the transition between the epicardium and the endocardium.
2. The ventricular myocardial fibers maintained specific orientations and continuity. The ventricular myocardial fibers had a definite helical pathway from the right ventricle to the left ventricle and from the epicardium to the endocardium, as described above in the section, "Reconstruction of the Myocardial Fibers of the Whole Ventricle." The ventricular myocardial fiber populations maintained continuity in the entire course, and the 2 crossed fiber populations of the left ventricular wall consisted of a single continuous fiber population that rotated and twisted at the apex.

To prove the HVMB hypothesis, we must answer several critical questions. The first question is: Does the left ventricular wall divide into fiber populations of different orientations? In our study, our reconstruction of the fibers clearly confirmed that 2 crossed fiber populations existed in the left ventricular wall. The study of Geerts et al demonstrated a similar fiber structure in goat hearts [Geerts 2002]. Helm et al also found 2 dominant fiber angles in the canine ventricular wall [Helm 2005]. Additional reports have supported the concept that 2 approximately perpendicular fiber families exist in the left ventricular wall [Dokos 2002; Ashikaga 2004; Harrington 2005]. We assume that fiber populations with a coherent orientation can perform their actions independently as functional subunits in the ventricular wall. The second question is: Do the myocardial fiber populations continue as a whole? In the past, it was difficult to observe the intact structure of ventricular myocardial fibers with traditional histologic approaches. The 3-dimensional imaging system of the DT-MRI approach provides us with the means to visualize the arrangement of ventricular myocardial fibers and their intact course. Reconstructions of the myocardial fibers by DT-MRI of course do not reflect individual myocytes or myofibrils, but they do provide general information on the gross pathways and distributions of the myocardial fibers. Figures 3 and 6 show that 2 crossed fiber populations in the left ventricular wall maintain continuity at the apex. Figures 4 and 5 show that the myocardial fiber populations of the right ventricle and left ventricle maintain continuity in the posterior ventricular wall. According to our findings from these imaging-based reconstructions, we conclude that the intact course of the populations of ventricular myocardial fibers consists of a continuous and helical

structure. The third question is: Are the directions in which the myocardial fibers run consistent with those of the HVMB? According to the structural hypothesis of the HVMB, the double-helical structure of ventricular populations of myocardial fibers run from the right ventricle to the left ventricle, from the left ventricular epicardium to the endocardium, and back to the epicardium again. Our study has found that the courses of ventricular myocardial fibers described above are consistent with those of the HVMB hypothesis. Rohmer et al [2007] observed similar myocardial fiber pathways in the left ventricle of the human heart.

The limitations of our study were that the reconstruction of fibers was inevitably random; however, this randomness did not affect the gross fiber pathways. In addition, we reconstructed the myocardial fibers in specific areas and sections of the ventricle only in part and could not show all ventricular myocardial fibers at one time.

In conclusion, through reconstructing and visualizing the ventricular myocardial fibers in the human hearts by fiber tracking, we have confirmed that the architecture of ventricular myocardial fibers conforms to the structure of the HVMB. Further studies are indicated.

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