The Heart Surgery Forum #2008-1118
12 (2), 2009 [Epub April 2009]
doi: 10.1532/HSF98.20081118

Online address: http://cardenjennings.metapress.com

Investigation on the Structure of Ventricular Mass Using Magnetic Resonance Diffusion Tensor Imaging

Dr. Gao

Changqing Gao, MD,[1] Weihua Ye, MD,[1] Libing Li, MD,[1] Tao Zhang, MD,[1] Chonglei Ren, MD,[1] Liuquan Cheng, MD,[2] Junlan Yan[1]

Departments of [1]Cardiovascular Surgery and [2]Radiology, PLA General Hospital, PLA Institute of Cardiac Surgery, Beijing, China

ABSTRACT

Objective: The 3-dimensional arrangement of the ventricular mass remains controversial. In this study, we used magnetic resonance diffusion tensor imaging (MRDTI) in an attempt to determine whether the ventricular mass is arranged in the form of a helical ventricular myocardial band (HVMB) and what the geometrical features of the HVMB are in postmortem pig hearts.

Materials and Methods: Ten pig hearts were harvested from the slaughterhouse, and their whole-body MR images were obtained. The data were obtained via DTI by single-shot echo planar imaging and sensitivity encoding. The pig hearts were scanned with single-shot echo planar imaging and sensitivity-encoding scans (TE/TRZ78.5/10000 ms) with diffusion-sensitized gradients (b = 800 s/mm^2) along 6 directions. Color-coded imaging and fiber-tracking techniques were used to investigate the arrangement of the fibers of ventricular mass on a GE Healthcare Advantage Workstation (Microsoft Windows).

Results: Color-coded images showed that the ventricular wall in each section was uniformly divided into 3 layers (subendocardial, middle, and subepicardial) in all samples. Fiber tracking showed that the subendocardial layer ran obliquely from base to apex, turned a circle, and transformed into the middle layer at the apex, and then ran obliquely upward. The ventricular mass was arranged in the form of double-helical coils. The crossing angle between subendocardial layer and middle layer was nearly vertical.

Conclusion: Results of our investigation with MRDTI support the theory of Torrent-Guasp et al that the ventricular mass is arranged in the form of an HVMB.

INTRODUCTION

It is well known that heart failure is becoming an increasingly serious health problem, owing to the increasing age of the population and the increased survival of patients who have heart failure. Unfortunately, few strategies have been found to be effective in treating heart failure because our understanding of the heart's structure and function is still limited, both microscopically and macroscopically. The helical ventricular myocardial band (HVMB) described by Torrent-Guasp et al [2005] provides important and firm ground for further understanding the relationship between heart structure and function. Torrent-Guasp et al presumed that heart failure due to ischemia, or nonischemia, might produce architectural distortion and create a more spherical ventricular shape, which creates a more transverse angle configuration of the apical loop fiber. This distortion may be responsible for the decreased pumping function of the failing heart [Buckberg 2001, 2003].

Nevertheless, the theory of Torrent-Guasp et al has faced challenges [Anderson 2002; Lunkenheimer 2004; Anderson 2005; Schmid 2005; Lunkenheimer 2006; Anderson 2007; Dorri 2007]. Anatomic investigations have provided some support, but the architecture of the ventricular myocardial mass remains controversial [LeGrice 1995; Lunkenheimer 1997a, 1997b; Schmid 2005; Lunkenheimer 2006; Anderson 2007; Dorri 2007]. When the HVMB was unfolded with anatomic techniques and the 3-dimensional structure was turned into a 2-dimensional band, it was difficult to obtain comprehensive 3-dimensional visualization of the entire ventricular mass. To further determine whether the ventricular mass was arranged in the form of an HVMB and to establish the geometrical features of an HVMB, we studied pig hearts with magnetic resonance diffusion tensor imaging (MRDTI). Pig hearts are a good model for studying fiber orientation, and it is easy to get them [Schmid 2005]. Cadaver hearts were used in another of our studies, which will be published soon.

MATERIALS AND METHODS

We harvested 10 pig hearts from a slaughterhouse and removed the subepicardial fat, coronary vessels, atria, and papillary muscles of the atrioventricular valves so as to minimize artifacts of magnetic resonance imaging (MRI). We then placed the hearts in a plastic box filled with 2% agarose gel (w/v), which contained 0.5% copper sulfate (w/v) to enhance the signal contrast between the myocardium and the gel. We

Received September 30, 2008; received in revised form November 27, 2008; accepted January 14, 2009.

Correspondence: Changqing Gao, Department of Cardiovascular Surgery, PLA General Hospital, PLA Institute of Cardiac Surgery, 28 Fuxing Rd, 100853 Beijing, China; 86-10-88626988; fax: 86-10-88626988 (e-mail: gaochq301@yahoo.com).

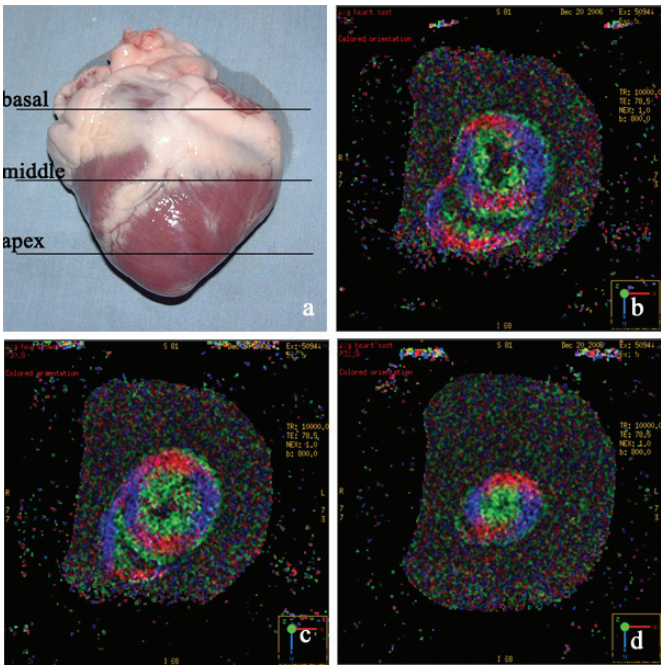

Figure 1. Color-coded magnetic resonance diffusion tensor imaging of a cross section of a normal heart. A, Different scan levels on short-axis slices. Color-coded images were produced at the basal (B), middle (C), and apical levels (D). The green, red, and blue colors indicate a main diffusion in the superoinferior, right-left, and through-plane directions, respectively. The ventricular wall was uniformly divided into 3 layers in each section. In the subendocardial, middle, and subepicardial layers, the prominent orientations of the myocardial fibers were longitudinal, circular, and oblique, respectively.

slowly filled the left ventricular cavity and then the right cavity with the gel. Finally, we embedded the entire heart in the gel. We paid attention to avoiding the inclusion of air bubbles within the ventricular contour. The images of the hearts were obtained when the agarose solution gelled, as described by Schmid et al [2005].

The images of the fixed hearts were obtained with the 3T Excite HD (GE Healthcare, Piscataway, NJ, USA) via 8-channel head coils. The data were obtained from diffusion-weighted spin-echo measurements with 2 different protocols for DTI, namely single-shot echo planar imaging and the parallel-imaging technique with sensitivity encoding [Jaermann 2004; Schmid 2005]. The former was used to scan the entire heart, with enhanced in-plane resolution and decreased geometric distortions. The latter was applied to improve the quality of the images. The 10 whole hearts were scanned with single shot echo planar imaging and sensitivity encoding (TE/TRZ78.5/10000 ms) with diffusion-sensitized gradients (b = 800 s/mm^2) along 6 directions. With sensitivity encoding reconstruction, each slice matrix consisted of 128 × 128 voxels with a nominal resolution of 1.1 × 1.1 × 3 mm^3.

MRDTI Analysis

We processed the diffusion tensor images of the hearts with the 3T Excite HD. The independent elements of the diffusion tensor were obtained on a pixel-by-pixel basis by singular-value decomposition. We then determined the principal eigenvalues and eigenvectors and created color-coded vector maps. Each individual vector was associated with the first principal eigenvector and corresponded to the main diffusion orientation, which reflected the orientation of the myocardial fibers.

The orientation of the vector was then color-coded by a coordinate system that assigned one of 3 colors to each of the 3 orthogonal axes. A total of 25 continuous short-axis slices were taken from the basal to middle and apical levels of the ventricular mass (Figure 1A). The green, red, and blue colors indicated a main diffusion in the superoinferior, right-left, and through-plane directions, respectively. Then, the predominant pathways of diffusion were shown in different colors on cross sections. Additionally, using the fiber-tracking technique on a GE Advantage Windows Workstation (GE Healthcare), we tracked the arrangement of the fibers of the ventricular mass in different regions of interest. These regions involved specified sites in the subendocardial and middle layers of the ventricular wall on different levels (Figures 2A, 3A, and 4A). The angles of prominent orientation of the myocardial fibers were measured.

After MRI scanning, the 10 samples were then boiled for 1.5 hours. The hearts were dissected with the methods described by Buckberg et al [Buckberg 2001; Gao 2006], and the ventricular myocardial band was observed.

Data were presented as morphologic pictures. The angles of the myocardial fibers were reported as the mean ± SD. To demonstrate whether the ventricular mass was arranged in the form of an HVMB as described by Torrent-Guasp et al, we evaluated the 3-dimensional features of the ventricular mass.

RESULTS

MRDTI of the Left Ventricle

Color-coded images of the cross sections showed that the ventricular wall in each section was regularly divided into 3 distinct layers (subendocardial, middle, and subepicardial layer). The thickness of the subendocardial layer was similar to that of the middle layer, but the subepicardial layer was far thinner than the former. In the subendocardial, middle, and subepicardial layers, the prominent orientations of the myocardial fibers were longitudinal, circular, and oblique, respectively (Figures 1B-1D).

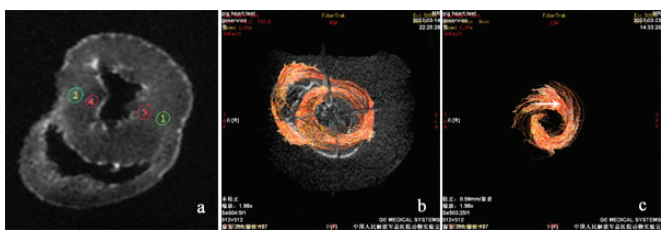

Figure 2. Magnetic resonance diffusion tensor imaging of fiber tracking at the base of the left ventricle (above). A, Four main regions of interest (green circles 1 and 2 at middle layers; red circles 3 and 4 at subendocardial layers). B, The fibers of the middle layer ran circle-wise. C, The fibers of the subendocardial layer (arrow) helically descended from base to apex.

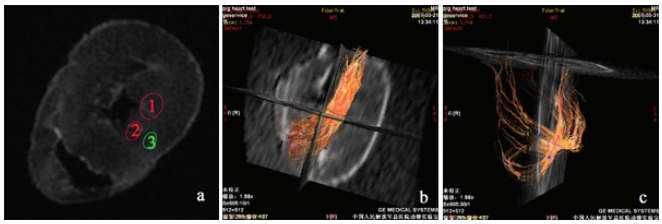

Figure 3. Magnetic resonance diffusion tensor imaging of fiber tracking at the middle of the left ventricle of a normal heart. A, Three main regions of interest (red circle 1 at subendocardial layers). B, The prominent orientation of the fibers of the subendocardial layer of the anterior wall was oblique at a larger gradient (B, from front). C, When the fibers of the subendocardial and middle layers were tracked simultaneously (red circle 2 at subendocardial layers and green circle 3 at middle layer), the crossing of the fibers in the 2 layers of the anterior wall was revealed (right anterior oblique position).

Fiber Tracking of the Left Ventricle

Basal portion. The middle layer constituted the main body of the base. The fibers of the middle layer ran circlewise (Figure 2B), and the fibers of the subendocardial layer helically descended from the base to the apex (Figure 2C).

Middle portion of the left ventricle. The prominent orientation of the fibers of the subendocardial layer was oblique, and the gradient was very large (Figure 3B). The prominent orientation of the fibers of the middle layer was also oblique, but the gradient was smaller. When we tracked the fibers of the subendocardial and middle layers simultaneously (Figure 3A), we found that the fibers of the 2 layers crossed at a mean angle of 89.04° ± 2.67° (Figure 3C) in the anterior wall.

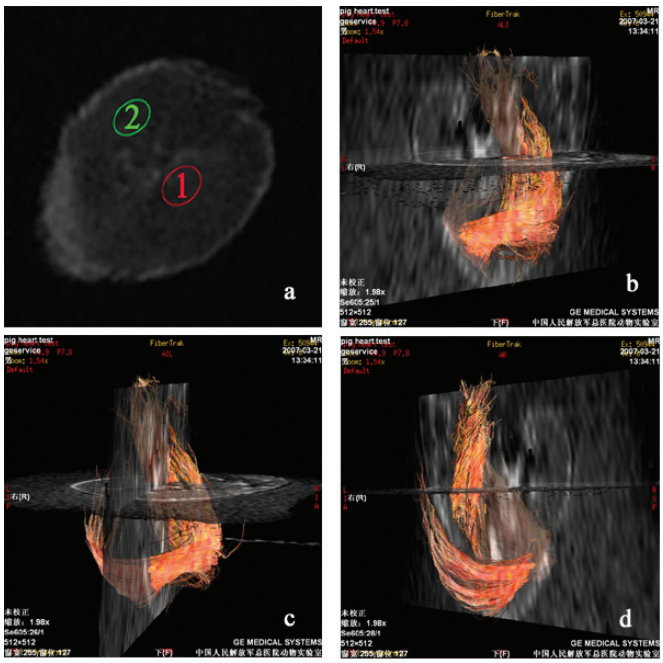

Figure 4. Magnetic resonance diffusion tensor imaging of fiber tracking at the apex of the left ventricle of a normal heart. A, Two main regions of interest (red circle 1 in the subendocardial layer of the anterior wall and green circle 2 at middle layer of the posterior wall) were tracked simultaneously. The structure of the ventricular mass was shown with different views when the images were rotated clockwise in anterior-posterior positions to 90° (B), 150° (C), and 170° (D). A double-helical coil structure was revealed.

Apical portion. The prominent orientations of the fibers of the subendocardial and middle layers remained oblique. Notably, the subendocardial fibers descended spirally, took a circular turn, and then ascended upward into the middle layer (Figures 4B-4D). A double-helical coil structure was revealed. In fact, MRDTI fiber tracking at the apex displayed a view of the structure of the ventricular mass because the fiber tracking was able to restructure the form of the regions of interest and the image of the parts connecting these regions. We did not trace the subepicardial layer at different levels, because it was very thin and would not affect our results.

Anatomy of the Ventricular Myocardial Band

Ten samples were dissected with the methods previously described. The ventricular myocardial band was observed. The dissection using Buckberg's technique agreed with the virtual dissection done by MRDTI.

DISCUSSION

The inseparability of form and function is the primary law in nature. In living beings, the specific function of an organ parallels its unique form. To fully understand the essence and magnitude of natural harmony between form and function in the heart requires us to expand our intellectual scope from the molecular to the organ level [Noble 2002; Brand 2003]. The heart is well known to serve as a pump for ejection and suction of blood and that the macroscopic motor function is an essential characteristic of the heart. Accordingly, it is logical and a prerequisite to place emphasis on the structure of the heart's ventricular mass. The HVMB theory of Torrent-Guasp et al explains the macroscopic structure of myocardial fibers within the ventricular mass. In this architecture, sequential activation and contraction beginning in fibers near the pulmonary artery and spreading toward the aortic end of

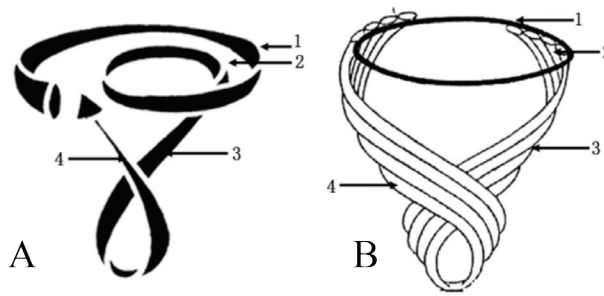

Figure 5. Diagrams show contrast illustrations of the magnetic resonance diffusion tensor imaging (MRDTI) data and the helical ventricular myocardial band (HVMB) hypothesis. A, Observed MRDTI data. At the basal portion, the middle layer of cardiac fibers is circular (1), and the subendocardial layer runs obliquely downward (2). At the middle portion, the subendocardial layer runs obliquely downward (3). At the apical portion, the subendocardial layer turns a circle and transforms into the middle layer, which runs obliquely upward (4). B, Illustration of the HVMB hypothesis, by comparison. Shown are the basal loop (1, 2), the descending segment (3), and the ascending segment (4). The results of the MRDTI study confirm the HVMB hypothesis.

the band might explain the patterns of ejection and suction needed for ventricular output and filling. This theory reasonably integrates cardiac pump function with the 3-dimensional arrangement of the ventricular mass [Torrent-Guasp 2001; Buckberg 2004].

Since 2005, we have dissected more than 250 hearts of different animal species with the techniques described by Buckberg and our new technique [Gao 2006; Zhang 2006; Ye 2007]. We believe that the theory of a myocardial ventricular band has important clinical implications in understanding the relationship between structure and function of the heart and heart failure.

However, the theory of Torrent-Guasp et al [Anderson 2002; Lunkenheimer 2004; Schmid 2005; Anderson 2005; Lunkenheimer 2006; Anderson 2007; Dorri 2007] about the HVMB has been controversial. Although several sources in the literature [Lunkenheimer 1984; Scollan 1998; Saber 2004] have documented data supporting the theory, Lunkenheimer's findings do not [Buckberg 2004]. He claimed that there was no unique cleavage plane that could be followed during the blunt unwinding of the structure and that the cleavage planes were not natural but arbitrary constructs [Lunkenheimer 1997b]. There has been insufficient anatomic evidence for the presence of an HVMB thus far [Anderson 2007]. The flaws inherent in anatomic dissection of a ventricular myocardial band are often a focus of disagreement. Because of its inherent destructiveness, anatomic dissection could never give a comprehensive 3-dimensional view of the myocardial architecture. Fortunately, MRDTI overcomes this limitation of anatomic procedures and offers a noninvasive and precise technique for assessing the structure of the ventricular mass. Schmid et al [2005] were the first to assess the orientation of the fibers with MRDTI. Their findings, however, negated the theory of Torrent-Guasp et al.

On the contrary, the findings of our study support the theory of Torrent-Guasp et al. According to our analysis of the cardiac structure of the ventricular mass with MRDTI (Figure 5), the cardiac structure of the ventricular mass coincides with that of the hypothesis of an HVMB. In color-coded images, the ventricular wall in each section is laminated into 3 sheets, ie, subendocardial, middle, and subepicardial layers. This finding proves that the heart muscle's 3-dimensionally netted structure actually consists of a secondary form that potentially is the basic structure of the ventricular mass.

In 1956, Lev and Simkins [1956] even described the ventricular wall as 3 different fascicles. LeGrice et al [1995] reported that the cardiac muscle fibers were arranged into distinct myocardial laminae separated from adjacent laminae by an extracellular collagen network. In their studies, these investigators revealed the histologic nature of the lamination, in which the myocytes were tightly coupled within the same lamina but sparsely coupled between adjacent laminae. In our study, we observed that in the subendocardial, middle, and subepicardial layers, the prominent orientations of fibers were longitudinal, circular, and oblique, respectively. Integrating color-coded images with fiber tracking, we found that the subendocardial layer ran obliquely from base to apex, took a circular turn, ascended upward into the middle layer at the apex, and then ran obliquely upward. It was evident that the ventricular mass was arranged in the form of double-helical coils. When we studied the MRDTI results for pig hearts in light of the hypothesis of an HVMB, we easily found that the MRDTI results conformed to this model (Figure 5). It is rational to define the subendocardial layer and the middle layer in MRDTI as the descending segment and the ascending segment, respectively, from the theory of Torrent-Guasp et al. Circular fibers at the base observed in the MRDTI analysis directly confirmed the presence of a basal loop.

Our findings were different from those of Schmid et al [2005]. We assume that they mainly adopted color-coded images in their study and so failed to find 3-dimensional double-helical coils. Using fiber tracking, Schmid et al obtained a more global view rather than the reconstruction of the structure of the ventricular mass. It is necessary to perform 3-dimensional fiber tracking in different regions at different levels, as described for our study. A global view merely gives an overlapped picture of a collection of fibers. According to the findings of Schmid et al, the overall arrangement of the heart is a complex 3-dimensional mesh. Intriguingly, Schmid et al did track the fibers at the base of the heart, and the fashion of basal fibers in his study was identical with that in our study.

In our study, we did find the presence of double-helical coils, a finding supported by our previous studies [Zhang 2006], although we did not find a successive and complete ventricular band in MRDTI that included the beginning and end, as is seen in skeletal muscles.

To obtain the 3-dimensional structure of myocardial fibers, it is necessary to track the arrangement of the fibers of the ventricular mass in the different regions of interest. These regions involved different sites in subendocardial, middle, and subepicardial layers of the ventricular wall on the basal, middle, and apical levels. We believe that tracking the arrangement of the fibers of the ventricular mass in different regions of interest might produce different findings.

CONCLUSIONS

The findings of our study support the theory that the ventricular mass is arranged in the form of an HVMB, as described by Torrent-Guasp et al and that MRDTI can be used as a noninvasive and precise technique to assess the structure of the ventricular mass.

ACKNOWLEDGMENT

This study was funded by the General Hospital of the PLA.

REFERENCES

Anderson RH. 2002. Spatial orientation of the ventricular muscle band. J Thorac Cardiovasc Surg 124:1053.

Anderson RH, Ho SY, Redmann K, Sanchez-Quintana D, Lunkenheimer PP. 2005. The anatomical arrangement of the myocardial cells making up the ventricular mass. Eur J Cardiothorac Surg 28:517-25.

Anderson RH, Sanchez-Quintana D, Redmann K, Lunkenheimer PP. 2007. How are the myocytes aggregated so as to make up the ventricular mass? Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu 76-86.

Brand T. 2003. Heart development: molecular insights into cardiac specification and early morphogenesis. Dev Biol 258:1-19.

Buckberg GD. 2003. Congestive heart failure: treat the disease, not the symptom—return to normalcy. J Thorac Cardiovasc Surg 125:S41-9.

Buckberg GD, Coghlan HC, Torrent-Guasp F. 2001. The structure and function of the helical heart and its buttress wrapping. V. Anatomic and physiologic considerations in the healthy and failing heart. Semin Thorac Cardiovasc Surg 13:358-85.

Buckberg GD, Weisfeldt ML, Ballester M, Beyar R, Burkhoff D, Coghlan HC. 2004. Left ventricular form and function: scientific priorities and strategic planning for development of new views of disease. Circulation 110:e333-6.

Dorri F, Niederer PF, Redmann K, Lunkenheimer PP, Cryer CW, Anderson RH. 2007. An analysis of the spatial arrangement of the myocardial aggregates making up the wall of the left ventricle. Eur J Cardiothorac Surg 31:430-7.

Gao CQ, Zhang T, Li LB. 2006. Empirical study of the anatomic structure of ventricular myocardial band. Chin J Thorac Cardiovasc Surg 22:410-2.

Jaermann T, Crelier G, Pruessmann KP, et al. 2004. SENSE-DTI at 3 T. Magn Reson Med 51:230-6.

LeGrice IJ, Smaill BH, Chai LZ, Edgar SG, Gavin JB, Hunter PJ. 1995. Laminar structure of the heart: ventricular myocyte arrangement and connective tissue architecture in the dog. Am J Physiol 269(pt 2):H571-82.

Lev M, Simkins CS. 1956. Architecture of the human ventricular myocardium; technic for study using a modification of the Mall-MacCallum method. Lab Invest 5:396-409.

Lunkenheimer PP, Müller RP, Konermann CHR, Lunkenheimer A, Köhler F. 1984. Architecture of the myocardium in computed tomography. Invest Radiol 19:271-8.

Lunkenheimer PP, Redmann K, Dietl KH, et al. 1997. The heart's fibre alignment assessed by comparing two digitizing systems. Methodological investigation into the inclination angle towards wall thickness. Technol Health Care 5:65-77.

Lunkenheimer PP, Redmann K, Florek J, et al. 2004. The forces generated within the musculature of the left ventricular wall. Heart 90:200-7.

Lunkenheimer PP, Redmann K, Kling N, et al. 2006. Three-dimensional architecture of the left ventricular myocardium. Anat Rec A Discov Mol Cell Evol Biol 288:565-78.

Lunkenheimer PP, Redmann K, Scheld H, Dietl KH. 1997. The heart muscle's putative "secondary structure." Functional implications of a band-like anisotropy. Technol Health Care 5:53-64.

Noble D. 2002. Modeling the heart—from genes to cells to the whole organ. Science 295:1678-82.

Saber NR, Gharib M, Wen H, Buckberg GD, Ross BD. 2004. Interpreting myocardial morphology and function from DENSE MRI data based on fluid mechanics concepts. J Cardiovasc Magn Res 6:365-6.

Schmid P, Jaermann T, Boesiger P, et al. 2005. Ventricular myocardial visualized in postmortem swine hearts using magnetic resonance diffusion tensor imaging. Eur J Cardiothorac Surg 27:468-74.

Scollan DF, Holmes A, Winslow R, Forder J. 1998. Histological validation of myocardial microstructure obtained from diffusion tensor magnetic resonance imaging. Am J Physiol 275:H2308-18.

Torrent-Guasp F, Ballester M, Buckberg GD, et al. 2001. Spatial orientation of the ventricular muscle band: physiologic contribution and surgical implications. J Thorac Cardiovasc Surg 122:389-92.

Torrent-Guasp F, Kocica MJ, Corno AF. 2005. Towards new understanding of the heart structure and function. Eur J Cardiothorac Surg 27:191-201.

Ye WH, Gao CQ, Li LB, Liu Zy, Ren CL. 2007. New method applied to dissection of myocardial band. Chin J Chin Thorac Cardiovasc Surg 14:122-5.

Zhang T, Gao CQ, Li LB. 2006. A study of spatial orientation of ventricular myocardial band. Chin J Thorac Cardiovasc Surg 22:413-4.