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Evidence for the existence of a functional helical myocardial band

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Nasiraei-Moghaddam A, Gharib M. Evidence for the existence of a functional helical myocardial band. *Am J Physiol Heart Circ Physiol* 296: H127–H131, 2009. First published November 7, 2008; doi:10.1152/ajpheart.00581.2008.—Characterization of local and global contractile activities in the myocardium is essential for a better understanding of cardiac form and function. The spatial distribution of regions that contribute the most to cardiac function plays an important role in defining the pumping parameters of the myocardium like ejection fraction and dynamic aspects such as twisting and untwisting. In general, myocardium shortening, tangent to the wall, and ventricular wall thickening are important parameters that characterize the regional contribution within the myocardium to the global function of the heart. We have calculated these parameters using myocardium displacement fields, which were captured through the displacement-encoding with stimulated echoes (DENSE) MRI technique in three volunteers. High spatial resolution of the acquired data revealed transmural changes of thickening and tangential shortening with high fidelity in beating hearts. By filtering myocardium regions that showed a tangential shortening index of <0.23, we were able to identify the complete or a portion of a macrostructure composed of connected regions in the form of a helical bundle within the left ventricle mass. In this study, we present a representative case that shows the complete morphology of a helical myocardial band as well as two other cases that present ascending and descending portions of the helical myocardial band. Our observation of a helical functional band based on dynamics is in agreement with diffusion tensor MRI observations and gross dissection studies in the arrested heart.

left ventricle; mechanical strain; structure; function

A BETTER UNDERSTANDING OF the structure and function of the heart continues to challenge modern medicine and physiology (4, 7, 10). Despite the remarkable advances in the understanding of myocardial cell function and its complex molecular structure, the role of cardiac sarcomeres and myofibers in generating contractile forces in the normal heart baffles us at all levels (4). A better understanding of the spatial distribution of regions with elevated contractile dynamics within the myocardium mass would perhaps help to resolve this issue.

Our hypothesis is that if myofibers of the left ventricle form a gross macroscopic structure in the form of a band, as previously suggested by blunt dissection efforts (11, 12), its importance in the dynamics of the heart must be revealed in characterized regional and global function of the myocardium. Based on our hypothesis, such an anatomic structure should act like a physical pathway for the maximum transmission of systolic contractile force and should facilitate the spatial coordination of relaxation and diastolic recoil. In this study we sought to find such a structure directly based on its kinematical behavior in beating hearts. The effectiveness of this approach depends on the proper identification of the cardiac regions that exhibit higher contractile activity and the nature of their linkage and innerconnectivity. In this article, we implement an approach that enables us to map regions of intense and directional contractile activities within myocardium to examine the nature of gross morphology that would represent these regions. Our investigation suggests that a band in the form of an open figure eight characterizes the most intense contractile activities within the ventricular mass.

METHODS AND RESULTS

Displacement encoding with stimulated echoes MRI. Displacement-encoded imaging with stimulated echoes (DENSE), an advanced noninvasive MRI technique, provides high spatial resolution measurement of three-dimensional myocardial points tracking (Lagrangian displacement) over the entire cardiac cycle (1, 9). DENSE MRI from 10 healthy volunteers was acquired using a Siemens Trio 3T MR whole body scanner at the Caltech Imaging Center with an eight-channel cardiac array coil. Our HIPAA compliant study was approved by the Institutional Review Board, and informed consent was obtained from subjects. Seven out of 10 data sets were used for the optimization of the DENSE sequence parameters on the 3T MR machine, and the rest were used for this study.

For this article, we present three data sets from which one covers the entire left ventricle and two others miss its apical part due to technical difficulties in DENSE imaging. All three data sets comprise the displacement field from end diastole (right after QRS) to the end systole, when the myocardium contraction is at its maximum (14). The data set that covers the entire left ventricle consists of 10 short-axis (SA) images captured from the heart of a 36-yr-old male volunteer. The vector position of spatially designated muscle volume elements was mapped with a starting time at end diastole and time steps 70 ms apart. These positions were captured and registered relative to the positions of these elements at the end systole. The end systole time was determined through MRI cine images and for this subject was 380 ms after QRS complex. The imaging parameters are as follows: repetition time = 3.1 ms, mixing time = 250 ms, flip angle = 90°, in-plane displacement encoding strength = 6.25 mm/π, out-of-plane displacement encoding strength = 3.21 mm/π, number of averages = 3, number of phases = 3, in-plane resolution = 1.5 × 1.5 mm^2, slice thickness = 5 mm, and distance factor = 50%.

Using the DENSEView software, the three-dimensional displacement field was generated in a matrix format. Segmentation was then performed by masking all parts of the anatomy except for the myocardium. For this study, we have masked regions of the heart outside the left ventricle. Phase unwrapping was then performed on the segmented images by scanning the myocardium area while searching for sudden changes in the displacement magnitude. These phase wrappings were later unwrapped by adding or sub-

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tracting the displacement correction value, which corresponds to the 2π radiant changes in phase. This step was repeated separately for all three directions of displacement; Matlab 7.0.4 (MathWorks, Natick, MA) was used for the calculations.

In Fig. 1, we present 10 SA slices of the heart at end systole along with arrows that show the displacement during the contraction that spans from end diastole to end systole. The first depiction in this figure includes parts of the right ventricle to show the position and orientation of the muscle volume elements that we track. Other illustrations depict the displacement field with colors exploited to show the direction of vectors. Color coding was performed by using three components of each normalized vector as the color levels in the RGB color space; that is, the parallel vectors have the same color. The image on the right side of the first row shows these displacement vectors in one long-axis view. This image, in particular, reveals the superiority of the spatial resolution of DENSE data to MRI tagging. By having four to eight data points across the left ventricle wall, depending on the wall thickness, we are able to calculate the transmural changes of the thickening and shortening index across the wall through the method suggested by Moore et al. (8). Density and orientation of displacement vectors are better illustrated in the *middle* and *bottom rows* of Fig. 1, where the side view and corresponding top view of the displacement field were presented, respectively, for three of those slices. It should be noted that the direction of these vectors represents the displacement directions that resulted from the contraction of many myofibers. Therefore, vector directions are not necessarily aligned in the muscle fiber directions at each myocardium point.

Regional contraction analysis. The reduction of the left ventricle volume in systole, and therefore its pumping function, is mostly caused by wall thickening (7), which is the effect of tangential shortening of the myocardium. Therefore, these two dependent quantities can be used as the quantitative characteristics for the local contribution of the left ventricle myocardium to global heart function. The spatial distribution of regions that contribute the most to cardiac function acts as a functional macrostructure for the myocardium. The mere existence of such a distinct structure and the knowledge of its normal morphology will facilitate a more effective modeling of left ventricle function.

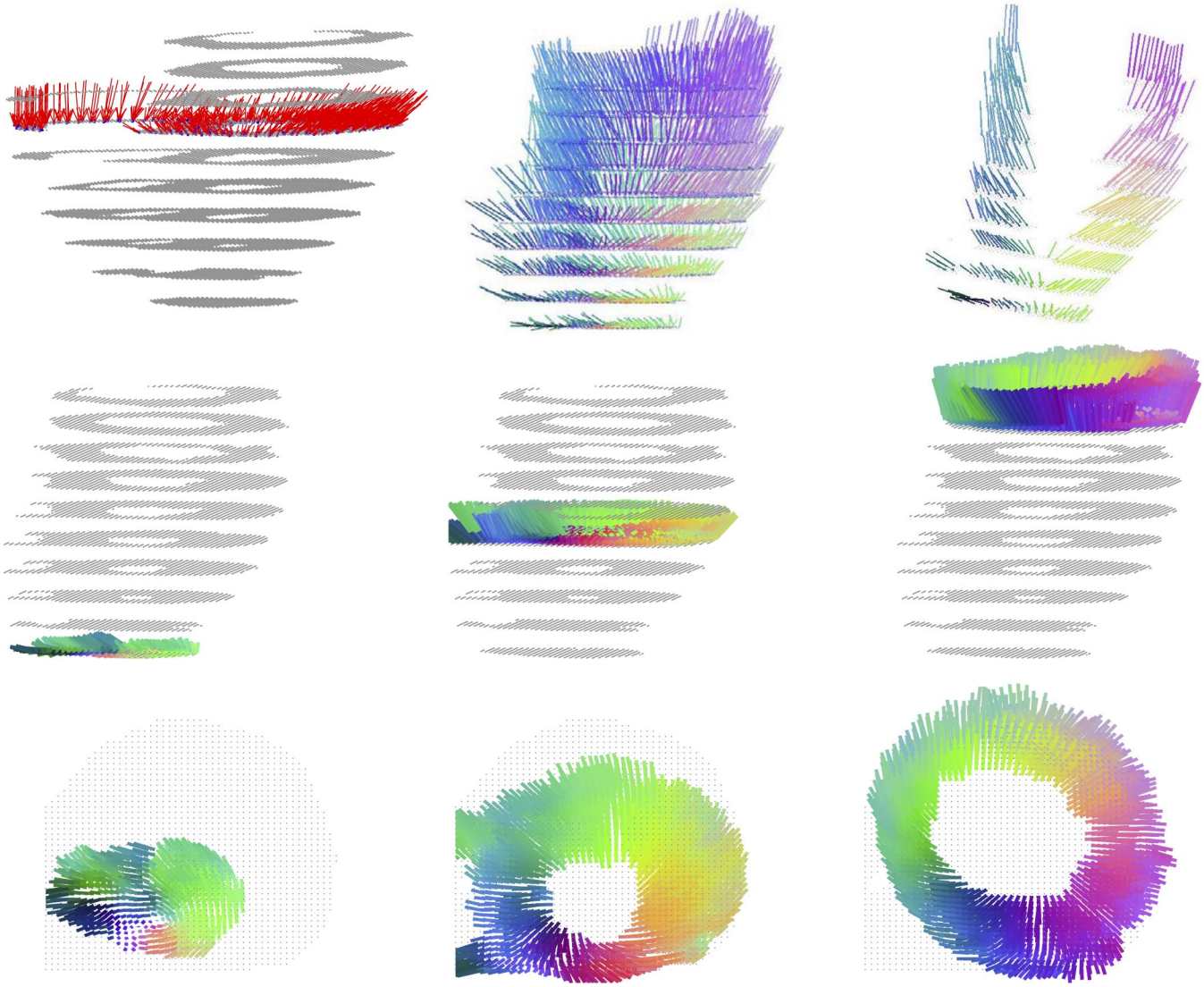

Fig. 1. *Top row*: in the left positions 10 short-axis slices are shown at the end systole. For 1 slice, the displacement field from end diastole to end systole was shown by red arrows. In the middle of the row, color-coded displacement field has been illustrated for all slices. Only 1 out of 5 vectors is shown. The same displacement field on a long-axis view was depicted at *right*. Image resolution is high enough to show 4 to 8 points across the left ventricle (LV) wall, depending on the wall thickness. *Middle row*: side view of the displacement field for 3 slices during the contraction that spans from end diastole to end systole. *Bottom row*: corresponding top view for the same slices. Color coding was performed to show the direction of vectors.

Moore et al. (8) have suggested a scalar quantity to measure the tangential shortening in a manner that is not sensitive to the deformations in the tangent plane. This quantity, known as the shortening index (SI), measures the change of the in-plane area based on the stretch tensor U, in the radial, longitudinal, and circumferential (RLC) coordinate system. With the consideration of the incompressibility of the myocardium, the local thickening of the wall (T) is also calculated by elements of U. Therefore, T and SI can be measured at any point inside the heart muscle using stretch tensor. These two dependent quantities have been used in this study as surrogates for regional contraction level.

With the use of high resolution displacement field of the myocardium, acquired by DENSE, maps of T and SI with high spatial resolution were calculated based on the maximum deformation of the left ventricle, i.e., from the end diastole to the end systole. The macrostructure of the left ventricle was subsequently sought by calculation and comparison of the isosurfaces of these quantities for their relatively higher absolute values. The isosurfaces were calculated for SI values above a certain threshold. Starting from low values near zero, we gradually increased the magnitude of the threshold and removed myocardium regions that were left out of the isosurface corresponding to the threshold. According to Moore et al. (8), the maximum mean SI magnitude in the left ventricle is -0.25 ± 0.05 in healthy hearts. Figure 2 shows the isosurface of left ventricle wall thickening and tangential shortening, corresponding to SI = -0.23, assembled from data shown in Fig. 1. In Fig. 2*A*, the isosurface is shown from the same view of Fig. 1 (anterior view). Fig. 2, *C* and *D*, also shows this structure from the right (septal) and superior views, respectively. It demonstrates that local wall thickening is not uniformly distributed through the wall, but rather, it is spatially distributed and oriented like a helical shape band. This band initiates from the posterior-basal region of the heart (denoted by the asterisk), continues through the left ventricle free wall, reaches the septum, loops around the apex, ascends, and ends to the superior-anterior section of the left ventricle. This pathway has been shown with a blue curve in this figure. The curve was obtained automatically through an algorithm that started from one point on the posterior-basal part of the myocardium and followed the band by measuring the mean of coordinates for points over the isosurface. Choosing the set of points that is used for this measurement at each step was guided by continuity requirements projected in the motion direction. These sequential directions are shown as little vectors in Fig. 2*B*. A more demonstrative view of this band can be seen from the supplemental movie (all supplemental material can be found with the online version of this article).

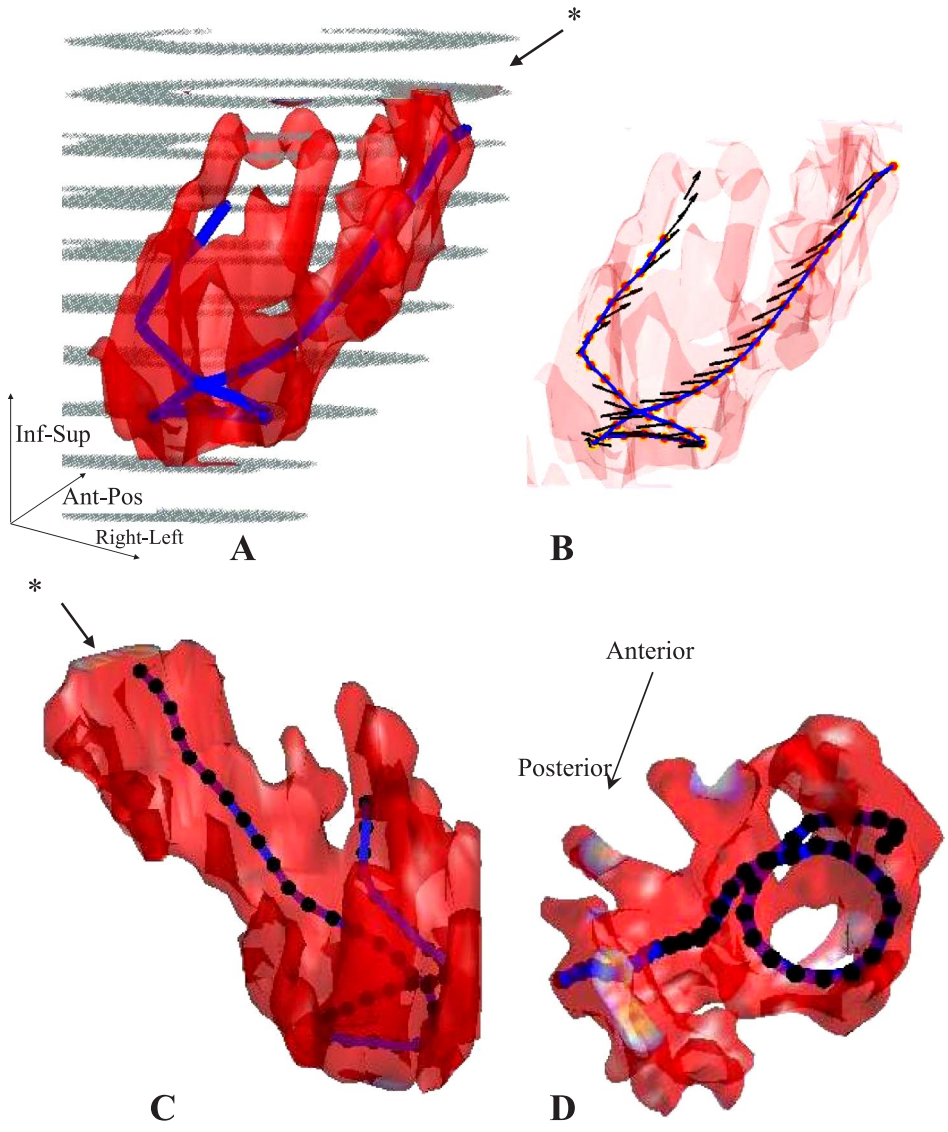

Fig. 2. Calculated isosurfaces of -0.23 shortening index (SI) for the human LV at the end systole from anterior (Ant; *A* and *B*), right (septal view; *C*), and superior (Sup; *D*) views. The blue curve, which approximates the midline of the isosurface volume, is superimposed to guide the reader on the orientation of muscle band. This curve was obtained automatically through an algorithm that follows the band through sequential steps. This algorithm uses continuity information projected in the motion direction in addition to the geometry of the rendered isosurface. *B* demonstrates the sequential directions as little vectors. *The band initiates from the posterior (Pos)-basal region of the heart. Inf, inferior.

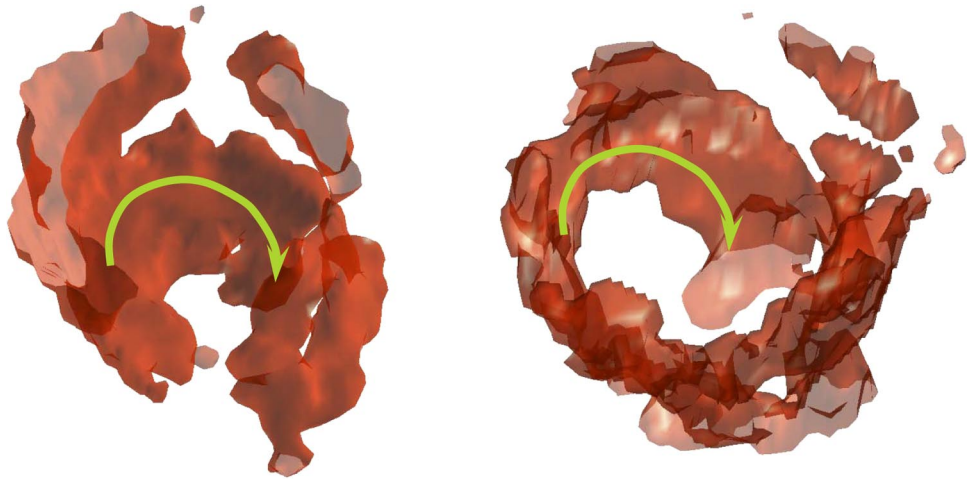

Fig. 3. Isosurfaces of tangential shortening (SI) for 2 other data sets. Although in those cases the apical loop was missing due to lack of data in that area, the helical band is retrieved wherever the displacement data were available. It verifies the reproducibility of the method especially in determining the ascending and descending parts of the band.

Figure 3 shows the band wherever the displacement data were available for two other data sets. Although in those cases the apical loop was missing due to the lack of data in that region, ascending and descending parts of the band are evident and similar to the case of Fig. 2, confirming the reproducibility of the band for those regions.

DISCUSSION

Previous attempts to study the spatial distribution of the myofibers through blunt dissection (12) have suggested the existence of a helical myofiber arrangement interlaced with connective tissues within the ventricular mass. Recent imaging studies on the structure of the myocardium using diffusion tensor MRI (DTMRI) have produced evidence in support of the above mentioned conjecture. For example, works at University of Virginia and Johns Hopkins have clearly depicted a continuous bundle of muscle fibers in the helical form within the elaborate connective tissue matrix of the left ventricular mass (Fig. 4) (5). It is important to note that in the DTMRI technique, the static structure of myofibers is mapped by following the diffusive direction of water molecules along these fibers in arrested hearts. Therefore, crucial dynamic information such as strain field must be obtained by other means. In this respect, it would not have been possible to confirm the functional role of such an intriguing structure in the cardiac function and dynamics. For this reason, these observations and other efforts to model cardiac dynamics based on the existence of a helical myofiber band have faced severe criticism due to the lack of evidence in support of the dynamical significance and functional role of a helical myofiber band within the chamber wall (6). Our observation through DENSE imaging shows strong resemblance to the cardiac muscle fibers obtained by DTMRI as well as to the conjectures that originated from blunt dissection studies (5, 12). The main distinction is in the approaches used to identify and characterize the band. Unlike DTMRI and dissection techniques, we employed a dynamical characteristic approach to reach a similar morphological conclusion.

When the function and the morphology of the most active region of the myocardium are linked, one can notice the ability of the heart to twist during the systole and untwist during diastole (2, 3). From a macromechanical point of view, such twisting dynamics cannot be produced without the presence of a helically oriented and dynamically preferential muscle morphology within the myocardium mass. It is natural to conclude that transmission of forces along such a helical pathway would generate global resultant motion of the chamber wall in the form of twisting and untwisting action, which has been observed and could not be fully explained by the prevailing localized, fiber structure models of the left ventricle (2).

CONCLUSION

In this article we presented an image-based approach for patient-specific modeling of the left ventricle. In this approach, the relation of the form and function of the left ventricle (myocardium) has been studied through investigating the spatial distribution of its regional function. We showed that regions with a higher degree of functionality appear to form a macrostructure in the form of a helical band (open figure 8). This observation is in agreement with previous findings that

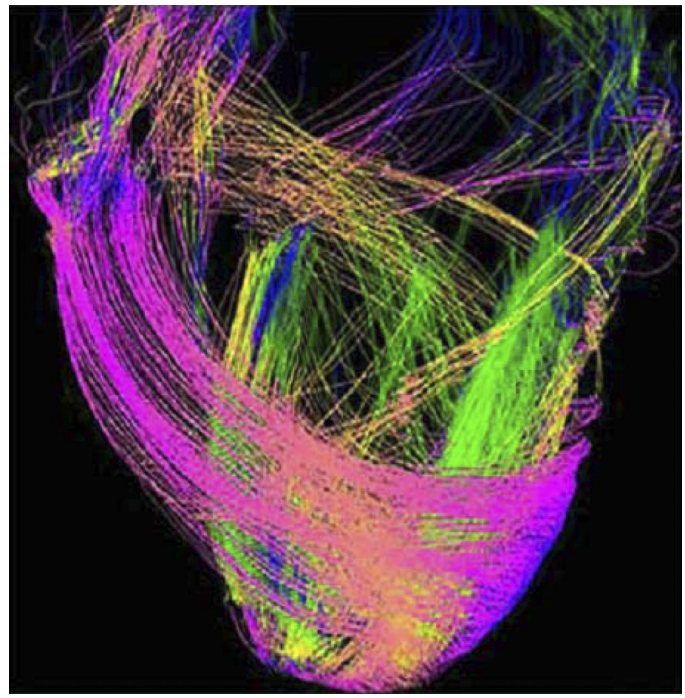

Fig. 4. Muscle fibers in the LV through diffusion tensor MRI (DTMRI), provided to us by P. Helm. It shows how fibers have 2 dominant orientations.

suggest an asymmetric orientation of fibers in the left ventricle (13).

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GRANTS

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