3-D dense cardiac strain reconstruction from tagged MR data set

H-H. Chang[1], J. M. Moura[1], Y. L. Wu[2], C. Ho[2]

[1]Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, United States, [2]Pittsburgh NMR Center for Biomedical Research, Carnegie Mellon University, Pittsburgh, PA, United States

Synopsis

This paper develops algorithms to reconstruct the 3-D cardiac motion through the cardiac cycle from tagged MR data sets. Developing the algorithms is a highly ill-posed problem because MRI provides only a sparse representation of the 3-D heart. We regularize the problem by combining the tagged MR data with a cardiac fibrous architecture for the heart into an energy minimization approach. We first describe the heart with a layered aggregate of oriented elastic fibers and the cardiac motion by a 3-D dense displacement field $\mathbf{U}$. We then use continuum mechanics to model the cardiac motion. This 3-D dense motion model is fit to the tagged MR data by minimizing an energy functional $E(\mathbf{U}, t)$ with respect to the displacement field $\mathbf{U}$.

Introduction

Cardiologists need diagnostic tools to monitor the 3-D strain map of the left ventricle. However, 3-D strain computation requires a good 3-D *dense* motion reconstruction of the left ventricle. Estimating the 3-D dense cardiac motion of *small animals* is challenging because the practical cardiac MR imaging usually takes a small number of slices to cover the heart. Such imaging leads to very sparse temporal and spatial representation of the heart. In addition, the abnormal rats can experience irregular or/and faster cardiac motions, so the problem is aggravated. To overcome these difficulties, we in each image start with estimating 2-D dense displacement field $\mathbf{U}^{2D}$ derived from the motions of tag lines [1], and then use a 3-D fibrous architecture to establish the spatial correspondences between all the myocardial pixels in MR images. Next, we adopt continuum mechanics to describe this fibrous architecture's motion. Finally, we use energy minimization to fit the motion model into MR images to derive the 3-D dense displacement field $\mathbf{U}$.

Methods

Data: Transplanted rats were studied by using heterotopic working heart and lung model [2]. Density-weighted spin-echo images were used to cover the 3-D volume of the heart at 10 time points through the cardiac cycle. Cardiac tagging was achieved by a modified DANTE sequence. All MRI scans were performed on a Bruker AVANCE DRX 4.7-T system. The matrix size is 256×256.

Modeling myocardial structure: Cardiology reveals that the heart consists of parallel layers of fibers from the endocardium to the epicardium. On each layer, the fibers roughly follow the same orientation η. The orientations η smoothly range from +60º at the endocardium to –60º at the epicardium. To capture this observation, we model the left ventricle as a thick, elastic cylinder, which consists of L (L=8 in our experiment) concentric cylindrical layers. On each layer, we model the myocardial fibers by helices [2]. This fibrous architecture is a dense representation of the left ventricle and also establishes the spatial correspondences between slices.

Modeling myocardial motion: We use linear elastic model in continuum mechanics to describe the motion of the fibrous architecture. We first treat each long fiber as a series of small rods. The coordinates of the ends of rods at time instant t are $\mathbf{a}_i(t)$, where i are the indices representing rods. The displacements $\mathbf{u}_i(t)$ of the ends of the rods between t and t+1 are $\mathbf{u}_i(t) = \mathbf{a}_i(t+1) - \mathbf{a}_i(t)$. In linear elastic model, the strain energy of rod i is $s_i(\mathbf{u}_i, t) = \mathbf{e}_i(\mathbf{u}_i, t)^T \mathbf{C} \mathbf{e}_i(\mathbf{u}_i, t)$, where $\mathbf{e}_i(\mathbf{u}_i, t)$ is the strain defined as $1/2(\nabla\mathbf{u}_i(t) + \nabla\mathbf{u}_i(t)^T)$, and the constant matrix $\mathbf{C}$ describes the material properties of the fibers. Thus, the strain energy $s_{\text{myo}}(\mathbf{U}, t)$ of the myocardium is $\sum_i s_i(\mathbf{u}_i, t)$, where $\mathbf{U}$ is the vectorization of all $\mathbf{u}_i$ and represents the 3-D dense cardiac motion.

Energy minimization: To fit the motion model to the MR images, we adopt a constrained energy minimization approach to derive $\mathbf{U}$. The energy functional is defined as

$E(\mathbf{U}) = \gamma_1 E_{\text{int}}(\mathbf{U}) + \gamma_2 E_{\text{ext}}(\mathbf{U}) + \gamma_3(\mathbf{g}(\mathbf{U}) - \mathbf{U}^{2D})$, where γ_i are the weightings, $E_{\text{int}}(\mathbf{U})$ is the strain energy of the heart derived from linear elastic model, $E_{\text{ext}}(\mathbf{U})$ is the mismatch errors of pixel intensities between two consecutive frames, and $(\mathbf{g}(\mathbf{U}) - \mathbf{U}^{2D})$ constrains the x and y components $\mathbf{g}(\mathbf{U})$ of 3-D dense displacement field in the imaged slices to be equal to $\mathbf{U}^{2D}$. Minimizing $E(\mathbf{U})$ with respect to $\mathbf{U}$ will give us the 3-D displacement field $\mathbf{U}$.

Results

Figure 1 shows the dense displacement field obtained from tag lines. Based on the 2-D dense displacement field, we can derive the 3-D dense displacement field layer by layer. Figure 2 shows the reconstructed epicardial motion of the nominal fibrous structure of the heart. The 3-D dense strain map derived from the 3-D dense displacement field is shown in Figure 3. From the result, we can clearly see the abnormal motion of the heart.

Conclusion

We develop a method to estimate the 3-D dense motion of the myocardium by considering biomechanics and MR data set under constrained energy minimization. Experiments demonstrate that our algorithm is able to reconstruct the realistic cardiac motion and obtain the 3-D strain map.

Acknowledgements

References

[1] H.-H. Chang, J. M. F. Moura, Y. L. Wu, K. Sato, and C. Ho, *2nd IEEE Int. Symp. Biomed. Imag.*, 2004.

[2] Y. L. Wu, K. Sato, H.-H. Chang, J. B. Williams, T. K. Hitchens, J. M. F. Moura, and C. Ho, "The two-pronged approach for non-invasive early detection of acute cardiac allograft rejection by MRI in a rodent transplantation model," *ISMRM*, 2004.
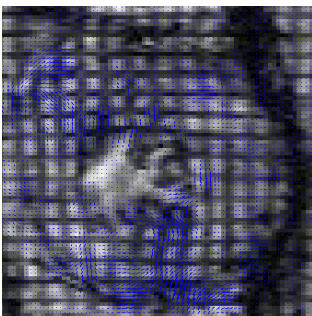
Figure 1: A 2-D dense displacement field derived from tag lines. The field reveals the 2-D cardiac motion.

Figure 2: The reconstructed 3-D dense displacement field of the epicardial fibrous surface based on the continuum mechanics.
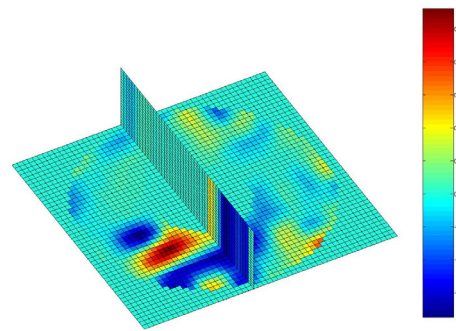

Figure 3: The 3-D dense strain map derived from the 3-D dense displacement field. From the result, we can clearly see the abnormal motion of the heart.