

Segmentation and Analysis of 3D Cardiac Motion from Tagged MRI Images

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Abstract—This paper gives an overview of our framework for the automated segmentation and motion analysis of cardiac motion from MRI tagging lines. It consists of a series of novel methods which utilize theory from image processing, deformable models and finite elements. Our framework consists of several steps. In the first step we use Gabor Filter banks and deformable models for the automatic segmentation of tagging lines and cardiac boundaries. The extracted tagging lines and boundaries are then used as input to a volumetric deformable model for the heart's motion estimation analysis. In this step we first extract parameters that can determine the difference between a normal and a pathologic heart motion. Second, using an Expectation-Maximization methodology (EM) we are able to determine a given heart's stress-strain relationship and fiber orientation. Our hypothesis is that the 3D shape and motion analysis of the heart will allow the faster and timely diagnosis of heart disease compared to traditional 2D methods. We present a series of segmentation, shape, motion and tissue property analysis results.

Keywords—3D Heart motion analysis, deformable models, tagging line segmentation, tagged MRI images

I. INTRODUCTION

The leading cause of death in the Western World is heart disease and consequently the study of normal and pathological heart behavior has become the topic of rigorous research. In particular the study of the shape and motion of the heart is important because many heart diseases are thought to be strongly correlated to the shape and motion of the heart. Important examples of such heart diseases include ischemia and right ventricle (RV) hypertrophy.

The understanding of cardiac mechanics is crucial in clinical research for diagnosis and patient study. The imaging techniques, such as Magnetic Resonance Imaging (MRI), Ultrasound, CT, X-ray provide noninvasive methods to study internal organs *in vivo*. Typically 2-D slices are combined to generate a 3-D volumetric model. Furthermore the images taken over time make 4-D (3-D + time) analysis possible. Accurate and expedient interpretation of this data is difficult to achieve. These modalities provide a tremendous amount of data and when presented as 2D images typically require an expert anatomist to interpret. For our research, we use an imaging technique called SPAMM (SPAtial Modulation of Magnetization [10]). The advantage of the SPAMM technique over other imaging techniques,

such as Ultrasound and PET [18] is that a number of material points within the myocardium walls can be marked non-invasively and when tracked, provide the true 3D motion of the heart muscle over time. Our data typically consists of three sets of images. Two of these contain short axis views of the heart and one contains long axis views of the heart. We combine these sets to form 3D material points in the heart. Around 12-15 short-axis images are taken from apex to base area of the heart. The long-axis images are orthogonal to the short-axis images and about 9 long-axis images are taken rotating about an axis located roughly in the septum. The SPAMM method generates an MRI-visible tag pattern within the cardiac tissue that deforms with the tissue during the cardiac cycle *in vivo* and gives motion information of the myocardium normal to the stripes (as shown in figure 1).

In order to use this method clinically we need to develop automated analysis tools based on the SPAMM data. An automated analysis must address the following tasks:

- Automated Segmentation of tagging lines and heart boundaries
- Extraction of 3-D shape and motion information from the 2-D slices
- Generation of the anatomically correct 3D heart model
- Extraction of clinically relevant model parameters capable of determining normal and diseased heart motion
- Relation of the extracted motion parameters to specific diseases

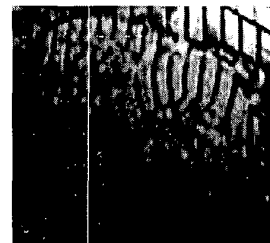


Figure 1. A tagged cardiac MRI

In this paper we will outline the major steps of our framework for the automated segmentation, shape and motion analysis of the heart. In particular, we have developed automated segmentation methods, deformable

model-based estimation and analysis of the heart's 3D shape and motion and estimation of the heart's stress-strain relationship [8,11,12,17,20,21,22,23].

II. METHODOLOGY AND RESULTS

A. Automated Segmentation of Tagged Images

The automated segmentation of tagged images consists of the automatic extraction of the tagged lines and of the heart's boundaries as we outline below.

We have developed a new method for the segmentation and extraction of tagging lines based on 2D Gabor filters [23]. Gabor filters have been widely used in image processing applications, such as texture segmentation [3, 4, 5] and edge detection [6]. A main advantage of Gabor filters due to their Gaussian envelopes is that they always achieve the minimum space-bandwidth product which is specified in the uncertainty principle [4]. This advantage helps Gabor filters to get full constraints in their spatial domains as well as in their frequency domain. However, a bandpass method like HARP [1] cannot achieve this. Gabor filters are wavelet-like local filters in the spatial domain, which makes it possible to design adaptive filters with respect to different spatial patterns of different local regions. We have designed a bank of Gabor filters with different frequencies, directions and shapes which are specified according to the tag line pattern in the input image. We then convolve each Gabor filter in the filter bank with the input image, and derive our results by seeking the optimum filter for those pixels whose output is greater than a certain threshold. Therefore our result is a combination of those outputs from several Gabor filters. Our Gabor filter-based algorithm is adaptive because we specify the frequencies of interest locally rather than using a mixture of arbitrary frequencies as in HARP [1,2].

Figure 2a shows three short-axis cardiac MRI images during systole. Figure 2b shows the segmentation results using our method. The directions, spacing, thickness, and shape of the resulting tag lines fit those in the input image quite well. Figure 2c shows the results of HARP. The myocardium contours are added manually for better readability. HARP's results are obtained by the method described in [2]. The Gabor filter bank method can achieve higher resolution, and is more robust for large local deformations.

Following the automated extraction of the tagged lines, we have developed [8] an automated method for the extraction of the heart's boundaries which include the epicardium, the Left- (LV) and the Right Ventricle's (RV) boundaries as shown in Figure 3. Our method consists of a sequence of image processing steps, followed by the computation of a force field in each image plane and then

the evolution of a deformable model in a physics based deformable framework until convergence is reached.

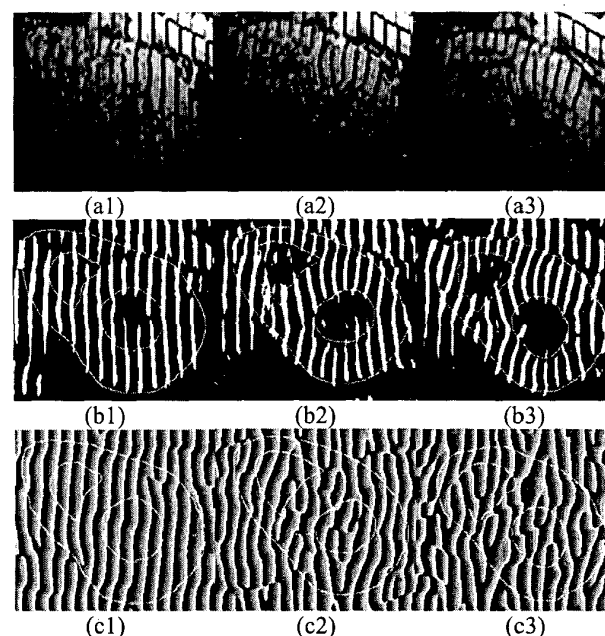


Figure 2. (a) Three tagged cardiac MR images in short axis. They are taken from a MRI sequence during systole. (b) The output results of our method. (c) HARP's result. The myocardium contours are drawn manually for better readability.

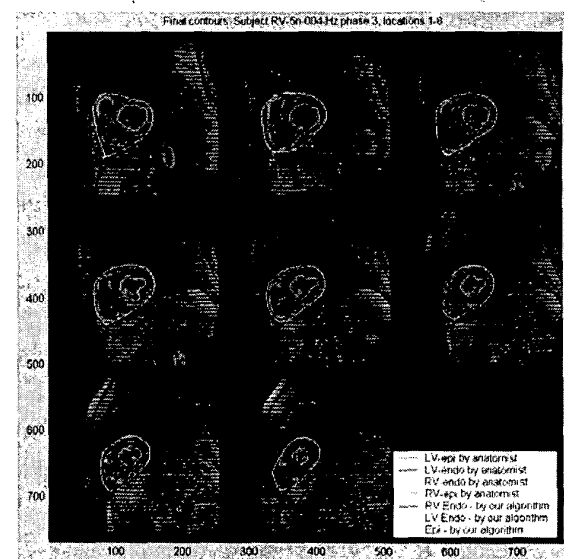


Figure 3. Sample results from the automated boundary detection algorithm for the LV and RV and inflow and outflow tracts of the RV

B. Cardiac Shape and Motion Analysis

Once we have estimated the heart's boundaries, we use our deformable model-based framework for the analysis of the heart's shape and motion [11,12,17]. We create dynamic models that deform based on Lagrangian dynamics due to forces computed from the boundary data-points. The model converges to the desired shape when the external forces go to zero and the residual motion is negligible.

The estimation process involves numerical integration of the dynamic equations of motion over time. The model deforms due to the data forces exerted on the model on each iteration. The deformation is computed based on the estimated model's shape parameters.

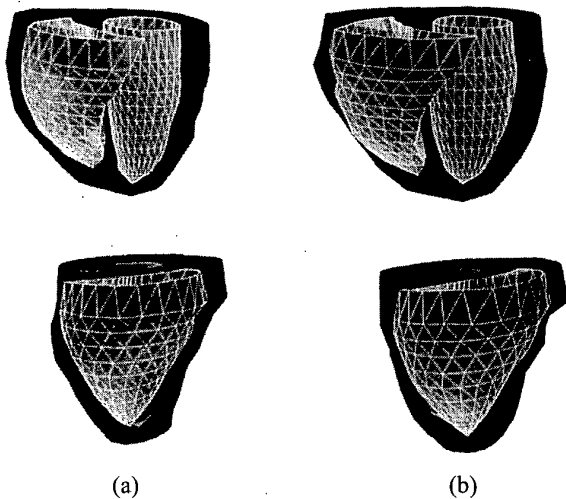


Figure 4. Normal and hypertrophic hearts at end-diastole. The RV endocardium of the RV hypertrophy patient is significantly larger than that of normal heart. (a) Normal Heart (b) RV Hypertrophy Heart

In simulating the heart cycle, our model deforms by computing the correct forces from the tagged data-points. Here the deformation of the model is governed by the theory of finite deformation elasticity implemented using finite elements. The meshes drawn in Figure 4 are the elements. The model deforms freely during systole due to SPAMM forces as shown in Figure 5.

C. Cardiac Stress-Strain Estimation Analysis

The above mentioned analysis of the heart's motion and associated strains is the first step in understanding the motion of the heart. The next step is the estimation of the stress-strain relationship and the computation of the associated forces that correspond to the estimated strains. This level of analysis promises to give us better insight into

how infarcts and other types of heart disease affect the amount of work done by the heart and the extent of the damage to the heart tissue.

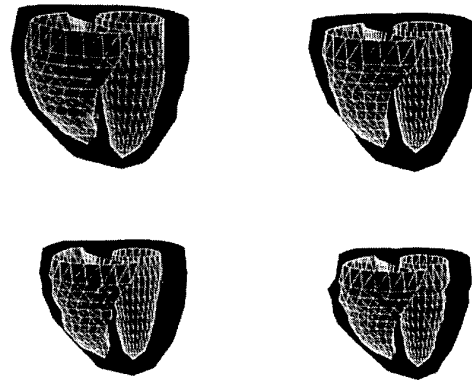


Figure 5. The heart model during systole (top left to bottom right).

We have developed a method for the estimation of the heart's stress-strain relationship [20,21,22] based on an Expectation-Maximization (EM) approach. Using as an initial guess published generic stress-strain curves, heart fiber orientations and estimated strains from patient data using our previously outlined method in section B., we can estimate the patient's specific stress-strain curve.

We have conducted several experiments estimating the bi-ventricular strain and stress distributions of normal volunteers and patients in one contraction cycle. In general, the ventricles become thicker radially, and shorter circumferentially and longitudinally when the heart contracts. Based on our results we can conclude that most radial stresses are positive while most circumferential and longitudinal stresses are negative.

Our findings show that a normal heart has a smoother distribution of strains and stresses compared to an abnormal heart in the free wall. In addition, normal hearts have larger strains than abnormal hearts although there is not much difference in stresses between normal and abnormal hearts. This implies that normal hearts deform more than abnormal hearts, but their stresses are similar because normal hearts have smaller Young's modulus.

III. CONCLUSION AND DISCUSSION

In this paper, we have outlined our framework for the automated segmentation, shape, motion and stress analysis

hearts from tagged MRI data. Based on our encouraging findings and results on a few patients we plan to further improve our analysis tools and conduct analysis experiments on large numbers of patients. Using our framework and the estimated motion analysis parameters, our goal is to establish statistically what is normal and diseased heart motion. Our hypothesis is that using the above framework we will be able to diagnose heart disease and its type earlier than the currently used approaches.

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REFERENCES

- [1] N. F. Osman, J. L. Prince, "Angle images for measuring heart motion from tagged MRI," *Proc. IEEE Int'l Conf. Image Proc.*, Chicago IL, Oct. 4--7, 1998.
- [2] N. F. Osman, J. L. Prince, "On the design of the bandpass filters in harmonic phase MRI," *Proc. IEEE Int'l Conf. Image Proc.*, Vancouver, Sept. 10-20, 2000.
- [3] D. Dunn, W. E. Higgins, J. Wakeley, "Texture segmentation using 2-D Gabor elementary functions," *IEEE Trans. Pattern Anal. and Machine Intell.*, 16, 130-149, 1994.
- [4] T. P. Weldon, W. E. Higgins, D. F. Dunn, "Efficient Gabor filter design for texture segmentation," *Pattern Recognition*, vol. 29, no. 12, pp. 2005-2016, Dec. 1996.
- [5] T. P. Weldon, W. E. Higgins, "An algorithm for designing multiple Gabor filters for segmenting multi-textured images," *Proc. IEEE Int'l Conf. Image Proc.*, Chicago IL, vol.3. pp. 333-337, Oct. 4-7, 1998.
- [6] R. Mehrotra, K. R. Namuduri, N. Ranganathan, "Gabor filter-based edge detection," *Pattern Recognition*, 25, 1479-1493, 1992.
- [7] J. Daugman, "Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters," *J. Opt. Soc. Am. A*, vol. 2, no. 7, pp. 1160-1169, July 1985.
- [8] A. Montillo, D. Metaxas, L. Axel, "Automated segmentation of the left and right ventricles in 4D cardiac SPAMM images," *MICCAI* (1) 2002: 620-633.
- [9] Y. Chen, A.A. Amini, "A MAP framework for tag line detection in SPAMM data using markov random fields on the B-spline solid," *Mathematical Methods in Biomedical Image Analysis*, 2001: 131-138.
- [10] Axel, L. and Dougherty, L. June 1989, MR imaging of motion with spatial modulation of magnetization, *Radiology*, Vol. 171, pp. 841-845
- [11] Haber, I. and Metaxas, D. and Axel, L. "Motion Analysis of the Right Ventricle From MRI Images" In *Medical Image Computing and Computer-Assisted Intervention - MICCAI*. Cambridge, MA, 1998, p177-188.
- [12] I. Haber, "Three-dimensional motion reconstruction and analysis of the right ventricle from planar tagged MRI", Univ. of Penn. PhD Thesis, 2000
- [13] M. A. Guttman, J. L. Prince, E. R. McVeigh, "Tag and contour detection in tagged MR images of the left ventricle", *IEEE transactions on Medical Imaging*, 13(1):74-88, 1994
- [14] J. Goutsias, S. Batman, "Ch 4: Morphological Methods for Biomedical Image Analysis", Editors M. Sonka, J Fitzpatrick, *Handbook of Medical Imaging*, Vol 2. Medical Imaging Processing and Analysis, pp 255-263, SPIE, 2000
- [15] Kerwin, W. and Osman, N. and Prince, J. "Ch 24: Image Processing and Analysis in Tagged Cardiac MRI", *Handbook of Medical Imaging: Processing and Analysis*, Editor-in-chief I. Bankman, 2000
- [16] Ozturk, C. and McVeigh E. "Four Dimensional B-spline Based Motion Analysis of Tagged Cardiac MR Images", *Proc. SPIE Medical Imaging 99*, San Diego, CA, Feb 1999.
- [17] Park, J. and Metaxas, D. and Axel, L. Analysis of left ventricle wall motion based on volumetric deformable models and MRI-SPAMM. *Medical Image Analysis* (1996) volume 1, number 1, pp. 53-81
- [18] X. Papademetris and A. J. Sinusas and D. P. Dione and J. S. Duncan, Estimation of 3D Left Ventricular Deformation from Echocardiography, *Medical Image Analysis*, 2001
- [19] Amini, A and Radeva, P. and Elayyadi, M. and Li, D., Measurement of 3D Motion of Myocardial Material Points from Explicit B-Surface Reconstruction of Tagged MRI Data, *MICCAI*, 1998, pp.110-118
- [20] Z. Hu, D. Metaxas, L. Axel. In-Vivo Strain and Stress Estimation of the Heart Left and Right Ventricles from MRI Images. To Appear in *Medical Image Analysis*, Sep. 2003.
- [21] Z. Hu, D. Metaxas, L. Axel. In-Vivo Strain and Stress Estimation of the Left Ventricle from MRI Images. In *Medical Image Computing and Computer-Assisted Intervention (MICCAI02)*, Tokyo, Japan, Sep. 2002.
- [22] Z. Hu, D. Metaxas, L. Axel. Left Ventricle Composite Material Model for Strain-Stress Analysis. To Appear in *International Symposium on Surgery Simulation and Soft Tissue Modeling*, Juan-Les-Pins, France, Jun. 2003.
- [23] Z. Qian, A. Montillo, D. Metaxas and Leon Axel. Segmenting Cardiac MRI Tagging Lines using Gabor Filter Banks. *Procs. 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Cancun, Mexico, September 17-22, 2003.