AUTOMATED CONTOUR TRACKING FOR MYOCARDIAL ELASTOGRAPHY IN VIVO

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ABSTRACT

Using a high-resolution (30 MHz) ultrasound system (Vevo 770, VisualSonics Inc.) and a retrospective ECG-gating technique, an extremely high frame-rate (up to 8 kHz) was previously shown achievable for full-view (12-mm × 12-mm) myocardial elastography. In-vivo experiments were performed in anesthetized normal and infarcted mice. In this paper, myocardial contour was manually initialized in the first frame of the ciné-loop and automatically tracked over the entire cardiac cycle, which correctly determined the region of interest (ROI) for better interpretation. The end-systolic cumulative displacement and strain showed that motion and deformation in the infarcted myocardium were significantly reduced, and that the infarcted region underwent thinning, rather than thickening, during systole. In conclusion, high frame rate, full-view myocardial elastography with automated contour tracking could provide regional strain information of the left ventricle throughout an entire cardiac cycle, and characterize normal as well as detect abnormal myocardial function, such as an infarction.

***Index Terms*—** Contour, Elastography, Left ventricle, Myocardial strain, Tracking

1. INTRODUCTION

Cardiovascular diseases currently rank as the No. 1 killer in the United States. Early detection of abnormalities is the key in treating cardiovascular disease efficiently and reducing this enormous death toll. The noninvasive estimation of regional myocardial function thus plays a crucial role in clinical cardiology. Myocardial elastography has been proposed as a novel imaging method of the localized myocardial function for detection of a localized abnormal region resulting from ischemia or infarction, with the advantages of high resolution and high precision [1].

Mouse models are becoming increasingly popular in cardiovascular research, because mice are widely available and it is now easy to construct mouse models through genetic and pharmacologic manipulation. However, the small size (< 8-mm × 6-mm) of mouse hearts and rapid heart rate (400 to 600 bpm) demand an imaging modality with both high temporal and spatial resolution. Using a high frame rate (8 kHz) data acquisition system based on a high-frequency (30 MHz) Vevo 770 system (VisualSonics Inc., Toronto, ON, Canada) and the retrospective ECG-gating technique, we implemented a myocardial elastography system for the murine left ventricle (LV) at simultaneously very high temporal and spatial resolution [2, 3]. Preliminary statistical results from nine normal and seven infarcted mice indicated the capability of myocardial elastography in differentiating infarcted from normal myocardia [2, 3].

However, the displacements and strains in the surrounding tissues such as the lung, as well as the noise in the blood cavity, may influence the interpretation of the results. Only displacements and strains in the myocardium, or region of interest (ROI), should be shown for better visualization and interpretation. Therefore, in this paper, a myocardial contour was manually initialized to delineate the myocardial, i.e., epi- and endocardial borders in the first frame and then the entire contour was automatically tracked throughout the entire cardiac cycle using the information of the displacement estimation in the regions where the contour was initialized.

2. 2. METHODS

2.1 Data acquisition and processing

The same system [2, 3] was used for RF data acquisition. Nine wild-type mice were anesthetized. A 30-MHz ultrasound probe (Vevo 770, VisualSonics Inc., Toronto, ON, Canada) was placed on the mouse chest in the parasternal position to obtain a longitudinal (long-axis) view of the LV of the heart. The field of view is 12 mm × 12 mm. RF signals of the ultrasound scanner and the associated ECG were synchronously acquired at 160 MS/s. The acquired RF signals were gated between two consecutive R-waves of the ECG to reconstruct the full-view RF image sequence of the entire LV for a complete heart cycle at the extremely high frame rate of 8 kHz. In the myocardial infarction (MI) model, an MI was induced through permanent ligation of the left anterior descending (LAD) coronary artery. Two mice died due to the surgical complications while the remaining seven mice (MI mice) were scanned one day after the operation to avoid repeated anesthesia procedures over the course of one day.

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The incremental axial displacements of the myocardium were estimated off-line using the RF speckle tracking technique based on the normalized cross-correlation function. The increment axial strains were calculated from the spatial gradient of axial displacement field. Using the incremental displacements at the LV wall over one cardiac cycle, the preset points were tracked automatically, also for the entire cycle. Therefore, the incremental displacements and strains corresponding to the preset points could be extracted. By accumulating these incremental displacements and strains, the cumulative displacements and strains were obtained representing the total motion and deformation starting from the first frame to the last frame of the ciné-loop, respectively.

2.2 Myocardial contour tracking

In section 1.2, the displacements and strains were estimated across the entire field-of-view. However, the estimates outside the myocardium may influence the interpretation of the displacements and strains due to noise (e.g., from blood echoes) or measurements in adjacent structures found in the same echocardiographic view (e.g., right ventricle or left atrium). An ROI was first determined through a 40-50 point manual selection performed by a cardiology expert for the first frame of the B-mode ciné-loop. The selected points coincided with the myocardial boundaries, i.e., epicardial and endocardial regions, and enclosed the entire left-ventricular myocardium in the long-axis view. Using the displacements obtained over the same cardiac cycle in the first step of the method, these traced points could then be automatically tracked over the entire cardiac cycle. This provided the updated ROI's corresponding to the borders of the myocardium at each frame obtained during the cycle. The steps of the method were as follows:

1) 40-50 points were manually selected defining the myocardial contour in the first frame;

2) Incremental displacements at those points occurring between the first and second frame (*m*=2) were calculated from the displacements previously estimated. Linear interpolation was used in order to calculate the displacements of the selected points, which were usually in between the centers of two successive RF windowed segments;

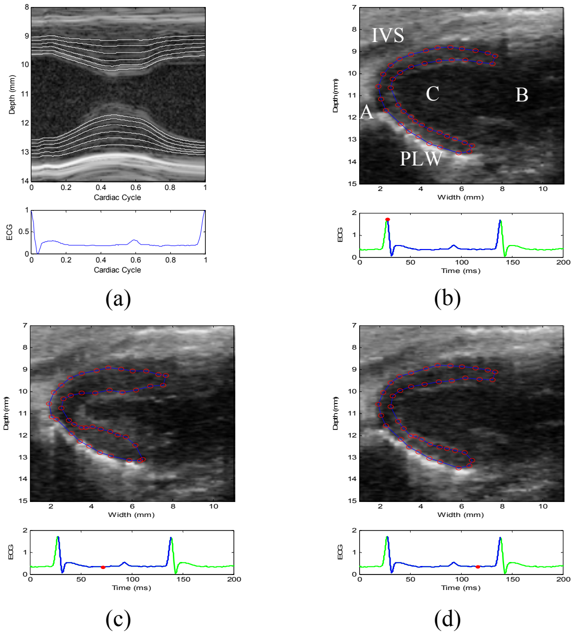
3) The contour points were mapped based on the interpolated displacements obtained in step 2 and the myocardial contour was then defined in the second frame. For example, an initially-selected point at depth d_1 in the first frame moved to $d_2 = d_1 + u_1$ in the second frame (*m*=2), where u1 was the incremental displacement of this point that occurred from the first to the second frame;

4) Steps 2 and 3 were repeated for all subsequent frames, i.e., the incremental displacements of the contour points that occurred between the m-1th and mth frames (*m*=3, 4, …, *n*, where n was the total number of RF frames) were estimated. The contour points were then tracked frame by frame to define the updated myocardial contour. For example, the tracked point at depth d_{m-1} in the m-1th frame move to $d_m = d_{m-1} + u_{m-1}$ in the mth frame (*m*=3, 4, …, *n*), where u_{m-1} was the incremental displacement of this point that occurred between the m-1th and the mth frames.

3. RESULTS

3.1. Epi- and endocardial contour tracking

Figure 1(a) shows the tracking curves of twelve preset points in the myocardium over one cardiac cycle. These curves were overlaid onto the M-mode image for first evaluation. The tracking was confirmed by a trained cardiologist and demonstrated the reliability of incremental displacement estimation and feasibility of cumulative displacement calculation. From the tracking curves, the cumulative displacements of the preset points could be observed. In addition, according to the distance change of the adjacent tracking plots, the regional strains at the different layers enclosed by each two tracking plots could be approximated.

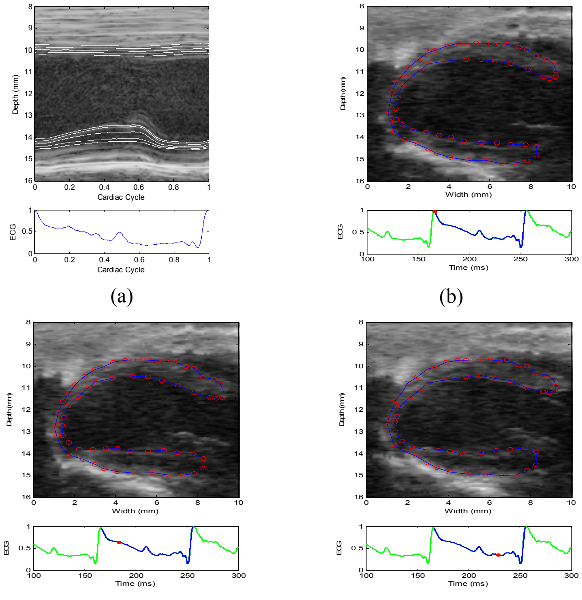


(a) (b)

(c) (d)

Figure 1. The tracking curves of some preset points in the (a) normal myocardium over one cardiac cycle, as well as the (b) manually-initialized, and the automatically-tracked contours in the (c) systolic and (d) diastolic phases, respectively. (IVS: interventricular septum, PLW: posterolateral wall, A: apex, B: base, C: cavity).

Figure 1(b) shows the preset points close to the myocardial boundaries (epicardium and endocardium) in the first frame at end-diastole, which defined the myocardial contour, i.e., the ROI of the 2-D image in this study. Figures 1(c) and (d) show the corresponding positions of these points in the systolic and diastolic phases. In Figs. 1(b)-(d), the dot on the ECG trace indicates the time in the cardiac cycle, at which the B-mode image above it was acquired. Figures 1(c) and (d) indicated that the tracked points outlined the updated myocardial contour, i.e., the new ROI, at the systolic and diastolic phases. By comparing the thickness or area of the myocardium outlined by the contour at end-diastole (Fig. 1(b)) and systole (Fig. 1(c)), thickening of the myocardium was evident in this case. Myocardial thinning was also identified, by comparing the myocardial thickness and area enclosed by the contour trace in Fig. 1(d) and Fig. 1(c). In the apical region on the left side of the images, the tracking of the preset endocardial contour points did not perform as well, because lateral motion was too large at the apical endocardial level in the normal case. The lateral displacement was not estimated due to limitations with the EKV acquisition (see Discussion). The technique was repeated over about 1000 frames, in both the normal and infarcted cases, in order to generate ciné-loops of the cumulative displacements and strains.



(a) (b)

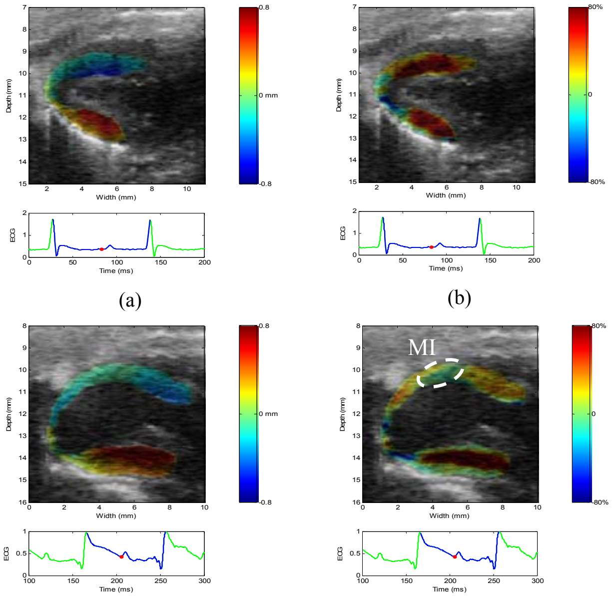
(c) (d)

Figure 2. The tracking curves of some preset points in the (a) infarcted myocardium over one cardiac cycle, as well as the (b) manually-initialized, and the automatically-tracked contours in the (c) systolic and (d) diastolic phases, respectively.

Figure 2 shows the contour tracking results in the infarcted myocardium. The LAD ligation induced an anterior-apical infarction, which was mainly found in parts of the interventricular septum of the infarcted heart. To compensate for the presence of infarction, the contractility of the myocardium was reduced and the LV acquired a larger cavity volume. In Figs. 2(b)-(d), it was evident that the deformation of the infarcted myocardium was significantly smaller. Due to the more constrained 3-D motion, the contour in the infarcted case could be tracked throughout the entire cardiac cycle and over the entire LV without limitations from large lateral motion as in the normal case.

3.2. End-systolic cumulative displacements and strains

Figure 3 compares the cumulative displacement images (a, c) and strain images (i.e., elastograms) (b, d) at the end-systolic phase of the normal (a, b) and infarcted (c, d) myocardia. The end-systolic phase was defined as the one corresponding to the largest cumulative displacements in the myocardium. Positive displacements (in red tones) denoted motion towards the transducer (located at the top), and negative displacements (in blue tones) motion away from the transducer. Positive and negative values (in red and blue, respectively) correctly depicted stretching (i.e., thickening) and compression (i.e., thinning) of the myocardium, respectively. Reduced motion and deformation in the infarcted myocardium was observed and quantified ((Figs. 3(c) and (d))). The negative strains found in the septum (Fig. 3(d)) accurately depicted the location of the myocardial infarction.



(a) (b)

(c) (d)

Figure 3. Cumulative (a, c) displacement images and (b, d) elastograms at the end-systolic phase of the (a, b) normal and (c, d) infarcted myocardia. Part of the infarct (MI) is detected by the thinning region (denoted by the dashed circle).

4. DISCUSSIONS

Myocardial elastography was previously implemented at high frame rate and full field-of-view using a retrospective ECG-gating technique in mice [2, 3]. The myocardial contour was deemed helpful for better interpretation of the results. Manual tracing of the myocardial contour can be tedious and time-consuming, especially considering the high frame rate of our system. Due to the high precision of the displacement estimation associated with high-frequency RF signals and high frame-rate data acquisition, a manually-initialized contour could be automatically tracked across the entire LV throughout a full cardiac cycle, which correctly determined the margins of the myocardium at different cardiac phases. This method could help cardiologists determine ejection fraction without the tedious process of tracing the myocardium at multiple frames.

In this study, only the axial component of the myocardial motion and deformation was estimated while hearts typically undergo complicated motion in 3-D. The long-axis view was used since the axial aligned with the radial direction in most of the myocardium in that case. However, this assumption did not always hold and lateral motion at the apex in the normal case was the most significant (Figs. 3(a) and (b)), resulting in the decorrelation of RF signals between consecutive frames; reducing thus the quality of estimation and contour tracking at the apical level. In the infarcted case, due to reduced overall myocardial motion, the contour was successfully tracked over the entire ventricle based on the axial displacement only (Figs. 3(c) and (d)). Therefore, endocardial contour tracking around the apex in the normal cases was found to be the noisiest. On the other hand, as shown in Fig 3, the contour tracking method performed more robustly along the epicardium than at the endocardium, in both the normal and infarcted cases, due to lower (lateral) motion in the former region. At the endocardium, pronounced out-of-plane motion was also evident. In the systolic phase, certain structures, such as the anterior and posterior papillary muscles, moved into the imaging plane while in the diastolic phase, certain structures moved out of plane. It was difficult to track these regions throughout a full cardiac cycle. As showed in Fig. 1(a), the contour tracking performed better at the beginning and end of the cardiac cycle when fewer myocardial regions underwent large out-of-plane motion while it performed worst at end-systole.

The solution to the above-mentioned problems is to use 2-D and even 3-D motion estimation and correction techniques [4, 5]. However, in this study, difficulties were identified for 2D tracking in conjunction with the ECG gating used. This is because the RF lines from different lateral positions were not acquired in real time. In fact, the misalignment of RF lines due to the motion of the sector-scan probe, the jitter in the data acquisition and variation of the ECG introduced large errors in the lateral estimation. The use of a larger window size at the expense of the reduced axial resolution, a 2-D kernel at the cost of reduced overall resolution [6] or, a B-mode-based tracking method at the cost of lower accuracy [7] might be helpful in the lateral motion estimation. A study in order to determine whether these limitations can be overcome, when ECG gating is employed, is ongoing.

5. CONCLUSIONS

A high frame-rate (up to 8 kHz), full-view (12-mm × 12-mm) myocardial elastography with automated contour tracking was implemented in vivo at high frequency (30 MHz) and in conjunction with ECG gating. Myocardial contour was manually initialized in the first frame of the ciné-loop and automatically tracked over the entire cardiac cycle. The end-systolic cumulative displacements and strains indicated reduced motion and deformation in the infarcted mice with the myocardium successfully isolated from surrounding regions. The method of automated contour tracking can further enhance the capability of the elastographic technique with minimal user intervention, especially under high frame-rate conditions, while providing accurate functional information for the detection of disease throughout the entire cardiac cycle.

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