Ultrasound in Med. & Biol., Vol. 33, No. 8, pp. 1206–1223, 2007
Copyright © 2007 World Federation for Ultrasound in Medicine & Biology
Printed in the USA. All rights reserved
0301-5629/07/$–see front matter

ELSEVIER

doi:10.1016/j.ultrasmedbio.2007.01.019

● *Original Contribution*

MYOCARDIAL ELASTOGRAPHY AT BOTH HIGH TEMPORAL AND SPATIAL RESOLUTION FOR THE DETECTION OF INFARCTS

JIANWEN LUO,* KANA FUJIKURA,* SHUNICHI HOMMA,† and ELISA E. KONOFAGOU*‡
*Department of Biomedical Engineering; †Department of Medicine; and ‡Department of Radiology, Columbia University, New York, NY, USA

(*Received* 6 *September* 2006, *revised* 23 *January* 2007, *in final form* 31 *January* 2007)

Abstract—Myocardial elastography is a novel method for noninvasively assessing regional myocardial function, with the advantages of high spatial and temporal resolution and high signal-to-noise ratio (SNR). In this paper, *in-vivo* experiments were performed in anesthetized normal and infarcted mice (one day after left anterior descending coronary artery [LAD] ligation) using a high-resolution (30 MHz) ultrasound system (Vevo 770, VisualSonics Inc., Toronto, ON, Canada). Radiofrequency (RF) signals of the left ventricle (LV) in longitudinal (long-axis) view and the associated electrocardiogram (ECG) were simultaneously acquired. Using a retrospective ECG gating technique, 2-D full field-of-view RF frames were acquired at an extremely high frame rate (8 kHz) that resulted in high-quality incremental displacement and strain estimation of the myocardium. The incremental results were further accumulated to obtain the cumulative displacements and strains. Two-dimensional and M-mode displacement images and strain images (elastograms), as well as displacement and strain profiles as a function of time, were compared between normal and infarcted mice. Incremental results clearly depicted cardiac events including LV contraction, LV relaxation and isovolumetric phases in both normal and infarcted mice, and also evidently indicated reduced motion and deformation in the infarcted myocardium. The elastograms indicated that the infarcted regions underwent thinning during systole rather than thickening, as in the normal case. The cumulative elastograms were found to have higher elastographic SNR (SNR_e) than the incremental elastograms (*e.g.*, 10.6 *vs.* 4.7 in a normal myocardium, and 6.0 *vs.* 2.4 in an infarcted myocardium). Finally, preliminary statistical results from nine normal ($m = 9$) and seven infarcted ($n = 7$) mice indicated the capability of the cumulative strain in differentiating infracted from normal myocardia. In conclusion, myocardial elastography could provide regional strain information at simultaneously high temporal ($\geq$0.125 ms) and spatial ($\sim$55 μm) resolution as well as high precision ($\sim$0.05 μm displacement). This technique was thus capable of accurately characterizing normal myocardial function throughout an entire cardiac cycle, at the same high resolution, and detecting and localizing myocardial infarction *in vivo*. (E-mail: ek2191@columbia.edu) © 2007 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Cardiac, Contraction, Contractility, Deformation, Displacement, ECG gating, Elastogram, Elastography, Heart, High frequency, High resolution, Infarction, Mice, Motion, Myocardium, Strain, Stretching, Systole, Tethering, Thickening, Thinning, Ultrasound.**

INTRODUCTION

The noninvasive estimation of regional myocardial function plays a crucial role in clinical cardiology (Feigenbaum et al. 2005). Echocardiography has been the predominant imaging modality in diagnostic cardiology because it is portable, readily available and in real time. M-mode measurements can be made to estimate the wall thickening during ejection (Feigenbaum et al. 2005). However, diagnosis based on M-mode images requires a tremendous amount of training. In addition, the calculated wall thickening represents the deformation characteristics of the entire wall, *i.e.*, the global strain, rather than providing the regional deformation. Stress echocardiography (Willenheimer et al. 1997) can assess regional wall motion and thickening. However, this approach is only qualitative, or semiquantitative, and may heavily depend on experience and expertise of the operator. Tissue Doppler imaging (TDI) and Doppler myocardial imaging (DMI) (McDicken et al. 1992) use Doppler-based techniques to obtain regional velocity estimates of the myocardium. However, overall heart translation, heart rotation and

---

Address correspondence to: Elisa E. Konofagou, Columbia University, Department of Biomedical Engineering, 351 Engineering Terrace, mail code 8904, 1210 Amsterdam Avenue, New York, NY 10027. E-mail: ek2191@columbia.edu

tethering of adjacent segments can all influence regional velocity estimates. Velocity estimates cannot differentiate between active contraction and simple rotation or translation of the heart, nor can they differentiate passive tethering from active contraction. The strain rate can be obtained by calculating the spatial gradient of the velocity estimates, which can be further temporally integrated to obtain the strain. This technique is called strain rate imaging (SRI) (Heimdal et al. 1998). However, Doppler-based methods typically use frequency-domain estimation on small-bandwidth signals and therefore have the disadvantage of low axial resolution. In addition to the echocardiography-based techniques, magnetic resonance (MR) cardiac tagging (Declerck et al. 2000) has been shown capable of estimating the 3-D strain tensor at high precision, but at the cost of low spatial resolution, limited by the tag spacing, low temporal resolution and long examination time.

Elastography has been shown successful in estimating and imaging the local strains in tissues undergoing external, quasi-static compression (Ophir et al. 1991). Myocardial elastography is a novel technique for noninvasively imaging regional myocardial function. It uses the inherent cardiac contractile function as the mechanical stimulus and continuously acquires consecutive radiofrequency (RF) signals to estimate the displacements and strains of the myocardium during a cardiac cycle (Konofagou et al. 2000, 2002). A preliminary clinical study in patients with a known myocardial infarction also showed the infarcted regions could be identified and differentiated from noninfarcted ones using envelope-detected signals at low frame rates (Konofagou et al. 2001). Another clinical study on seven normal human subjects also indicated that myocardial elastography could offer comparable quality estimates to those obtained with MR cardiac tagging, with the added advantages of higher temporal and spatial resolution (Konofagou et al. 2003). In addition to axial displacements and strains, myocardial elastography has been shown capable of obtaining lateral displacements and strains (Konofagou and Ophir 1998; Konofagou et al. 2002, 2005). By combining the two components of the strain tensors calculated from 2-D displacements, the radial, circumferential and principal strains can be calculated as angle-independent measurements of the myocardial function (Fung-Kee-Fung et al. 2005; Langeland et al. 2005).

Konofagou et al. (2002) estimated the displacement and strain images (elastograms) over small segments of the cardiac muscle. The frame rate of the RF images varied between 60 and 710 Hz, with the subsequent observed trade-off in spatial resolution. D'hooge et al. (2002c) reduced the angle of the ultrasonic sector image and number of RF image lines, and increased the frame rate of the RF images to approximately 260 Hz. These methods resulted in a smaller field of view. Varghese et al. (2003) produced elastograms over the entire echocardiography image sector in loops that displayed a cardiac cycle. However, the frame rate used was limited to 50 Hz, whereas some studies indicated that the frame rate should be as high as about 200 to 300 Hz (Kanai et al. 1997; Kaluzynski et al. 2001; D'hooge et al. 2002b). D'hooge et al. (2002a) used time-domain estimation methods to generate strain and strain rate images in partial ventricular views of the heart and overcame several limitations with Doppler-based methods.

High-frequency, small animal ultrasound systems have recently become commercially available. To overcome frame rate limitations in high-frequency systems, retrospective electrocardiogram (ECG) gating and prospective ECG triggering were used (Pernot and Konofagou 2005; Cherin et al. 2006; Liu et al. 2006; Pernot et al. 2007). Pernot and Konofagou (2005) developed an ultrafast data acquisition system based on a high-resolution Vevo 770 system (VisualSonics Inc., Toronto, ON, Canada) and the retrospective ECG-gating technique. RF data and ECG signals were acquired simultaneously, and RF data corresponding to a complete cardiac cycle were then gated using the ECG to reconstruct the 2-D full-view images. The RF images of the murine myocardium and aorta were obtained at an extremely high frame rate (8 kHz) and were used to estimate the small motion of the murine myocardium and abdominal aorta (Pernot and Konofagou 2005; Pernot et al. 2007). The 2-D displacement maps indicated mechanical wave propagation in the myocardium and aorta over a full cardiac cycle (Pernot and Konofagou 2005; Pernot et al. 2007).

In this paper, the same system (Pernot and Konofagou 2005; Pernot et al. 2007) was used to acquire ECG-gated RF frames of murine left ventricles (LV) at the high frame rate of 8 kHz. Because of the high frame rate of the data acquisition system and high resolution of the ultrasound system, myocardial elastography at both high temporal and spatial resolution were obtained. The incremental displacements and strains were estimated from the RF image sequence. Then, the cumulative displacements and strains were calculated from the incremental results. The results from nine normal and seven infarcted myocardia were finally compared to study the potential of myocardial elastography for infarct detection and localization.

METHODS

Animal preparation

Brown CB57/BL6 type mice (Charles River Laboratories, Wilmington, MA, USA) were used in this study with the approval from the Institutional Animal Care and Use Committee (IACUC) of Columbia University. Nine