An *In-Vivo* Study of Frame Rate Optimization For Myocardial Elastography

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***Abstract*—In this paper, the requirement and optimization of the frame rate for myocardial elastography was investigated in normal mice and humans *in vivo*. Using a retrospective electrocardiogram (ECG) gating technique, the highest frame rate was 8 kHz and 481 Hz, respectively. Axial displacement and strain of myocardium were estimated using an RF speckle tracking method consisting of a 1-D kernel in a 2-D search. The frame rate was then decimated to study its effects on the image quality of myocardial elastography, in terms of elastographic signal-to-noise (SNRe) and correlation coefficient. Trade-offs between SNRe and effective frame rate were identified in the murine case. The optimum range of frame rate was found to be between 2000 and 2700 Hz, or equivalently, 250-350 frames per cardiac cycle (fpc). In the human case, the image quality increased monotonously with the frame rate. A frame rate higher than 480 Hz (i.e., 350 fpc) was thus required for both systole and diastole.**

Keywords- ECG gating; frame rate; myocardial elastography; SNR; strain; trade-off

I. INTRODUCTION

Elastography has been shown successful in estimating and imaging the regional strains in tissues undergoing external, quasi-static compression [1]. Myocardial elastography is a novel technique for noninvasively imaging regional myocardial function. It utilizes the inherent myocardial function as the mechanical stimulus and continuously acquires consecutive radiofrequency (RF) signals of the myocardium to estimate myocardial displacements and strains during a cardiac cycle, using an RF-based, time-domain speckle tracking technique [2].

In order to accurately estimate myocardial displacement, the frame rate of RF signals becomes critical. There is a trade-off between the maximum frame rate obtainable and the field of view (FOV) of the image or the RF line density [2-5]. In order to overcome the tradeoffs between the frame rate and FOV or spatial resolution, the retrospective electrocardiogram (EGG)-gating technique [6-8] has recently been used in myocardial elastography in mice [9], dogs [10] and humans [11, 12]. Studies have shown that myocardial elastography is capable of imaging myocardial deformation comparable to that of MR cardiac tagging [11], with the additional advantages of higher temporal and spatial resolution [9], and could detect and localize myocardial ischemia and infarction [9, 11].

The frame rate of RF signals determines the amount of deformation estimated between consecutive frames. It is well known that there exists an optimum strain range in elastography [13, 14]. Similar trade-offs are expected for the selection of the frame rate. If the frame rate is too low, the interframe deformation may be too large and cause high decorrelation. At that low frame rate, the temporal resolution may not be sufficient to capture the rapid variations of myocardial motion [8, 9]. On the other hand, if the frame rate is too high, the interframe motion and deformation may be too small. The ambiguity noise, or bias errors, such as that induced by the interpolation on the correlation functions [15], may dominate the estimation results.

Frame rate requirements for myocardial elastography were identified previously by using uniformly elastic tissue-mimicking phantoms that underwent cyclic compressions at variable frequencies [16]. Some in-vivo studies using a small FOV indicated that the frame rate should be as high as about 200 to 300 Hz [17, 18]. However, the requirement and optimization of the frame rate for myocardial elastography has not been thoroughly studied *in vivo* in a full FOV. In this paper, the effects of frame rate on the image quality of myocardial elastography were studied *in vivo* using the RF frame obtained from the left ventricle of a normal mouse and a healthy human subject acquired at extremely high frame rates of 8 kHz and 481 Hz, respectively, for full-view imaging. These high frame rates were achieved by using a retrospective electrocardiogram (ECG) gating technique [9, 12].

II. METHODS

A. Data acquisition

In-vivo, transthoracic RF frame of the left ventricle of a normal mouse (heart rate: 466 bpm) and a healthy human subject (heart rate: 81 bpm) were acquired at the extremely high frame rates of 8 kHz and 481 Hz, respectively, using a retrospective ECG-gating technique [9, 12].

In the mouse case, a Vevo 770 system (VisualSonics Inc., Toronto, ON, Canada) was used with a single-element mechanical sector probe (30 MHz) working on a line-by-line basis [9]. The field of view (FOV) was 12-mm x 12-mm, with a line density of 190 lines. The RF signals were digitized at a sampling frequency of 200 MHz and a sampling resolution of 14 bits.

This study was supported in part by the National Institutes of Health (R01EB006042-01), American Heart Association (SDG 0435444T) and Wallace H. Coulter Foundation (WHCF CU02650301).

In the human case, a Sonix RP system (Ultrasonix Medical Corp., Burnaby, BC, Canada) was used with a phased array (3.3 MHz) working on a sector-by-sector basis. [12]. The FOV was 11-cm x 15-cm, with a line density of 64 lines. The RF signals were digitized at a sampling frequency of 20 MHz and a sampling resolution of 16 bits.

2-D full long-axis view RF frames were reconstructed from multiple RF beams or narrow RF sector frames at high frame rates of 8 kHz and 480 Hz, or equivalently 1030 and 356 frames per cardiac cycle (fpc), for the murine and human subjects, respectively.

B. Data processing

The incremental axial displacements were estimated using an RF speckle tracking method consisting of a 1-D kernel in a 2-D search [11]. The window sizes were 0.48 and 6.9 mm, with overlaps of 90% and 80%, for the mouse and human cases, respectively. The incremental axial strains were calculated form the displacements using the least squares strain estimator (LSQSE) [19] with a kernel size of 0.24 mm and 6.9 mm, respectively.

The frames at peak systole and diastole were selected where the strain was the highest and therefore requirements of the frame rate are the most critical based on the ciné-loop of the strain images (elastograms). The frame-rate effects were studied by using different frame-rate decimation applied to the original RF data. The decimation was achieved by increasing the number of interleaved RF frames (i.e., frame step). The unit (i.e, Hz) of the effective frame rate was also converted to frame per cardiac cycle (fpc) in order to adjust the heart rate difference between the mouse and human.

The correlation coefficient and elastographic signal-to-noise ratios (SNR_e) [13] calculated in small regions were used to evaluate the quality of the elastograms. The average and stand deviation (SD) of the SNR_e and the correlation coefficients in different regions (with overlap) were calculated.

III. RESULTS

A. Murine subject

Figure 1 shows the elastograms of the murine case at different frames. Positive and negative strains denote stretching (i.e., thickening) and compression (i.e., thinning) of myocardium, respectively. In the systolic phase, the strain obtained at frame rates of (a) 8000 and (c) 500 Hz were noisier than that at (b) 2000 Hz. The difference is the most significant in the posterior wall at 8000 Hz and the septum at 500 Hz. In the systolic phase, a frame rate of (e) 2000 Hz also achieved higher image quality than (d) 8000 Hz and (f) 500 Hz. The image was severely deteriorated at the frame rate of 500 Hz.

The SNR_e and correlation coefficient varied with the frame rate in Hz or fpc in the murine case are showed in Fig. 2. In both (b) systole and (d) diastole, as expected, the correlation coefficient increases with the frame rate because of the decreased de-correlation. In the systolic phase, the correlation coefficient exceeds 0.85, as long as the frame rate is higher than 1000 and 1333 Hz (i.e., 129 and 172 fpc) in the septum and posterior wall, respectively. In diastole, a frame rate higher than 2000 and 1600 Hz (i.e., 257 and 206 fpc) is required to get a correlation coefficient higher than 0.85, in the septum and posterior wall, respectively.

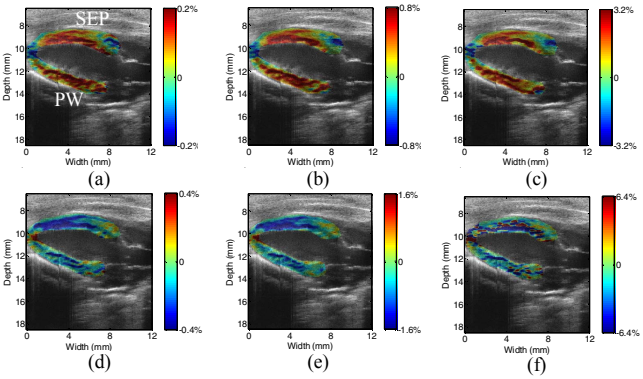

Figure 1. The elastograms in the murine subject in the (a-c) peak systolic and (d-f) diastolic phases, at frame rates of (a, d) 8000, (b, e) 2000 and (c, f) 500 Hz, respectively. (SEP: interventricular septum, PW: posterior wall)

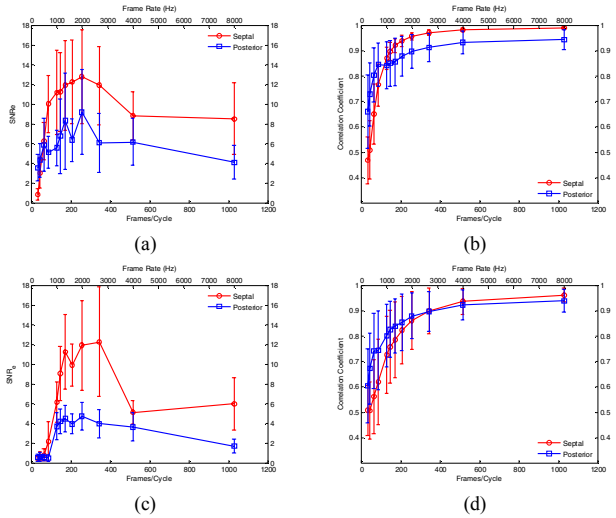

Figure 2. The (a, c) SNR_e and (b, d) correlation coefficient as a function of frame rate and fpc in the (a, b) peak systolic and (c-d) diastolic phases in the murine subject. Frame rates in Hz and fpc are both shown the horizontal axes.

As shown in Figs. 2 (a) and (c), the SNR_e in the septum is higher than that in the posterior wall, because the structures are more complex and the myocardium undergoes more out-of-plane motion in the posterior wall. In the systole (Fig. 2(a)), the SNR_e is significantly smaller when the frame rate is decreased to 667 and 1143 Hz (i.e, 86 and 147 fpc) in the septum and posterior wall, respectively. On the other hand, if the frame rate is higher than 4000 and 2667 Hz (i.e., 515 and 343 fpc) in the septum and posterior wall, respectively, the SNR_e is also decreased. In the systole, a frame rate between 667 and 2667 Hz (i.e., 86-343 fpc) is required in order to obtain an SNR_e higher than 10 in the septum, while a frame rate between 1143 and 4000 Hz (i.e., 147-515 fpc) is necessary to get an SNR_e of 6 in the posterior wall. A frame rate of 2000 Hz (i.e., 257 fpc) can achieve the highest SNR_e, which is 12.76 and 9.15 in the septum and posterior wall, respectively.

In the diastole (Fig. 2(c)), similar tradeoffs are observed. A frame rate between 1333 and 2666 Hz (172 and 343 fpc) is desirable in order to obtain an SNR_e no lower than 10 in the septum. A frame rate between 1000 and 4000 Hz (i.e., 129 and 515 fpc) is required to obtain an SNR_e higher than 3.5 in the posterior wall. The optimum frame rate is 2667 and 2000 Hz (i.e., 343 and 257 fpc), with the highest SNR_e of 12.28 and 4.70 in the septum and posterior wall, respectively.

B. Human subject

Figure 3 displays the elastograms in the human subject at different frame rates. The best image quality is obtained at a frame rate of 481 Hz, in terms of smaller variation and correct depiction of myocardial deformation in the systolic and diastolic phases.

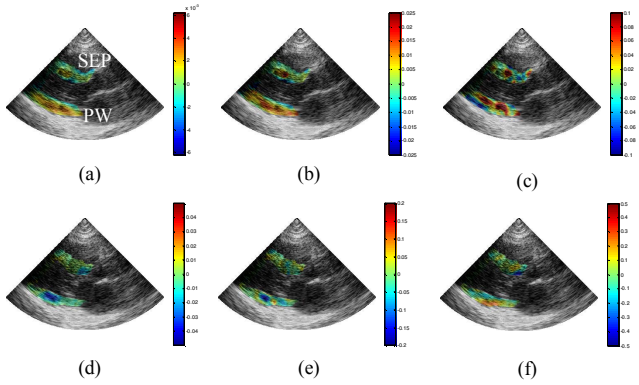

Figure 3. The elastograms in the human subject in the (a-c) peak systolic and (d-f) diastolic phases, at frame rates of (a, d) 481, (b, e) 120 and (c, f) 30 Hz, respectively. (SEP: interventricular septum, PW: posterior wall)

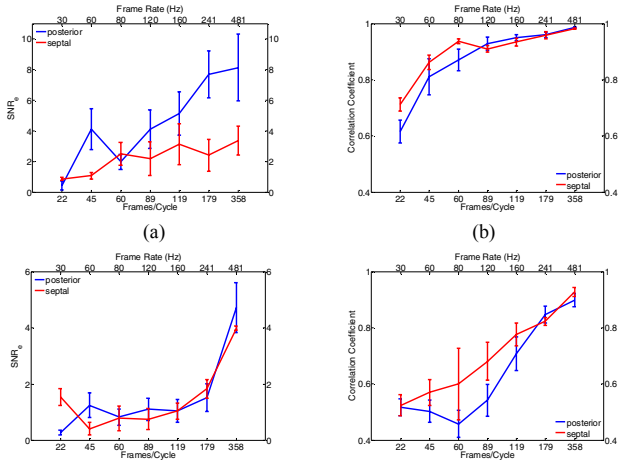

Figure 4. The (a, c) SNRe and (b, d) correlation coefficient as a function of frame rate and fpc in the (a, b) peak systolic and (c-d) diastolic phases in the human subject. Frame rates in Hz and fpc are both shown the horizontal axes.

Figure 4 shows the SNR_e and correlation coefficient versus the frame rates in Hz and fpc in the human case. As shown, the (a, c) SNR_e and (b, d) correlation coefficient typically increase with frame rate. In order to obtain an SNR_e higher than 6 in the posterior wall during systole, the frame rate should be no lower than 160 Hz or 179 fpc. In the diastolic phase, a frame rate of 481 (358 fpc) is required to achieve an SNR_e higher than 3.5 in both posterior wall and septum. Once the frame rate is higher than 120 and 481 Hz (i.e. 89 and 358 fpc) in systole and diastole, respectively, the correlation coefficient is higher than 0.90.

IV. Discussion

Because of the extreme high frame rate available in the murine case (8000 Hz or 1029 fpc), the SNR_e as a function of the effective frame rate demonstrated the trade-offs of frame rates in the image quality of myocardial elastography. In the murine case, in the systolic phase, a frame rate between 1143 and 2667 Hz (i.e, 147-343 fpc) is the optimum range of the best image quality in both the septum and posterior wall, while in the diastolic phase, a frame rate between 1333 and 2667 Hz (i.e., 172-343 fpc) is the optimum range.

In the human case, the SNR_e curve has not reached the plateau in the optimum range of frame rates shown in the murine case. Therefore, the higher the frame rate is, the higher the SNR_e, as shown in Fig. 4. The highest frame rate (481 Hz or 358 fpc) guarantees the highest SNR_e. However, trade-offs similar to the murine case are expected if the frame rate continues increasing (e.g., to 700 Hz).

It is worthwhile mentioning that the peak systolic phase requires a higher frame rate than the peak systolic phase. This is because that the peak incremental diastolic strain is typically 2-3 times higher than the peak incremental systolic strain, as shown in Figs. 1 and 3.

In this paper, the effects of frame rate were studied only at peak systole and diastole, when the highest frame rates were required through the entire cardiac cycle. In other phases (e.g, the isovolumic contraction and relaxation phases), the strains are smaller and therefore the minimum requirement and the optimum range of the frame rate were expected to be lower. However, in order to estimate myocardial motion and deformation over the entire cardiac cycle, the requirements at the peak systole and diastole should be satisfied. After acquiring the RF data over the whole cycle at a high frame rate required by the peak systole and diastole, the frame rate used in other phases could be decimated accordingly. Finally, an adaptive method for the frame rate selection could be developed.

In the ischemic myocardium, the strain was found to have a similar amplitude as in the normal myocardium but with the opposite sign [11]. The frame rate-rate requirement is thus similar to that in the normal case. In the infarcted myocardium, significantly reduced strains were observed [9], resulting in a lower frame-rate requirement but potentially higher precision requirement for the accurate localization and characterization of infarcted regions. The optimum frame rate should be properly adjusted in order to obtain the best image quality in the infarcted case, in conjunction with an accurate estimation algorithm to accurately localize and characterize the infarction.

V. Conclusion

In this paper, the effects of frame rate on the image quality of myocardial elastography were studied *in vivo* in both mouse

and human cases, taking advantage of the high frame rate achieved by using a retrospective ECG gating technique. Results indicated that higher frame rates were required in the diastolic phase than in the systolic phase because higher incremental strains occur. For the murine case, frame rates between 250-350 frames/cycle (i.e., 2000-2700 Hz) were optimum for both systole and diastole. For the human case, frame rates higher than 350 frames/cycle (i.e., >480 Hz) were required for both systole and diastole. The difference between murine and human results may be attributed to the different motion and deformation amplitudes between mice and humans, as well as the different ultrasound systems used. Ongoing work includes theoretical analysis on finite-element (FE) model [11] with a physiologic cardiac cycle, including ejection, filling, isovolumic contraction and relaxation, as well as experiments on a left-ventricular phantom under physiologic motion [20].

ACKNOWLEDGMENT

We thank Shunichi Homma, M.D., Department of Medicine, Columbia University, for allowing access to the Vevo 770 system and Kana Fujikura, M. D. Ph.D., Department of Biomedical Engineering, Columbia University, for acquiring echocardiograms.

REFERENCES

[1] J. Ophir, I. Céspedes, H. Ponnekanti, Y. Yazdi, and X. Li, "Elastography: A quantitative method for imaging the elasticity of biological tissues," Ultrason. Imaging, vol. 13, pp. 111-134, 1991.

[2] E. E. Konofagou, J. D'hooge, and J. Ophir, "Myocardial elastography - A feasibility study in vivo," Ultrasound Med. Biol., vol. 28, pp. 475-482, 2002.

[3] J. D'hooge, E. Konofagou, F. Jamal, A. Heimdal, L. Barrios, B. Bijnens, J. Thoen, F. Van de Werf, G. Sutherland, and P. Suetens, "Two-dimensional ultrasonic strain rate measurement of the human heart in vivo," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 49, pp. 281-286, 2002.

[4] T. Varghese, J. A. Zagzebski, P. Rahko, and C. S. Breburda, "Ultrasonic imaging of myocardial strain using cardiac elastography," Ultrason. Imaging, vol. 25, pp. 1-16, 2003.

[5] H. Kanai and Y. Koiwa, "Myocardial rapid velocity distribution," Ultrasound Med. Biol., vol. 27, pp. 481-498, 2001.

[6] E. Cherin, R. Williams, A. Needles, G. W. Liu, C. White, A. S. Brown, Y. Q. Zhou, and F. S. Foster, "Ultrahigh frame rate retrospective ultrasound microimaging and blood flow visualization in mice in vivo," Ultrasound Med. Biol., vol. 32, pp. 683-691, 2006.

[7] J. H. Liu, G. S. Jeng, T. K. Wu, and P. C. Li, "ECG triggering and gating for ultrasonic small animal imaging," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 53, pp. 1590-1596, 2006.

[8] M. Pernot, K. Fujikura, S. D. Fung-Kee-Fung, and E. E. Konofagou, "ECG-gated, mechanical and electromechanical wave imaging of cardiovascular tissues in vivo," Ultrasound Med. Biol., vol. 33, pp. 1075-1085, 2007.

[9] J. Luo, K. Fujikura, S. Homma, and E. E. Konofagou, "Myocardial elastography at both high temporal and spatial resolution for the detection of infarcts," Ultrasound Med. Biol., vol. 33, pp. 1206-1223, 2007.

[10] E. E. Konofagou, S. Fung-Kee-Fung, J. Luo, and M. Pernot, "Imaging the mechanics and electromechanics of the heart," Proc. of IEEE EMBS Conf., pp. 6648-6651, 2006.

[11] W.-N. Lee, C. M. Ingrassia, S. D. Fung-Kee-Fung, K. D. Costa, J. W. Holmes, and E. E. Konofagou, "Theoretical quality assessment of myocardial elastography with in vivo validation," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 54, pp. 2233-2245, 2007.

[12] S. Wang, W.-N. Lee, J. Luo, and E. E. Konofagou, "An ECG gated clinical ultrasound system for high frame-rate cardiovascular ultrasound and elastography imaging," presented in IEEE International Ultrasonics Symposium, Oct 28-31, 2007, New York, NY, USA.

[13] T. Varghese and J. Ophir, "A theoretical framework for performance characterization of elastography: The strain filter," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 44, pp. 164-172, 1997.

[14] T. Varghese, J. Ophir, E. Konofagou, F. Kallel, and R. Righetti, "Tradeoffs in elastographic imaging," Ultrason. Imaging, vol. 23, pp. 216-248, 2001.

[15] I. Céspedes, Y. Huang, J. Ophir, and S. Spratt, "Methods for estimation of subsample time delays of digitized echo signals," Ultrason. Imaging, vol. 17, pp. 142-171, 1995.

[16] H. Chen, T. varghese, P. S. Rahko, and J. A. Zagzebski, "Analysis of ultrasound frame rate requirements for cardiac elastography," Proc. of the 5th Intern. Conf. on the Ultrasonic Measurement and Imaging of Tissue Elasticity,Snowbird, Utah, USA, Oct 8-11, 2006.

[17] H. Kanai, H. Hasegawa, N. Chubachi, Y. Koiwa, and M. Tanaka, "Noninvasive evaluation of local myocardial thickening and its color coded imaging," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 44, pp. 752-768, 1997.

[18] J. D'hooge, F. Jamal, B. Bijnens, A. Heimdal, J. Thoen, F. Van de Werf, G. R. Sutherland, and P. Suetens, "Calculation of Strain Values from Strain Rate Curves: How Should This Be Done?," IEEE Ultrasonics Symp Proc, pp. 1269-1272, 2002.

[19] F. Kallel and J. Ophir, "A least-squares strain estimator for elastography," Ultrason. Imaging, vol. 19, pp. 195-208, 1997.

[20] V. Gamarnik, J. Luo, W.-N. Lee, and E. E. Konofagou, "Experimental assessment of angle-independent myocardial elastography performance using a left-ventricular phantom under physiologic motion," presented in IEEE International Ultrasonics Symposium, Oct 28-31, 2007, New York, NY, USA.