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● *Original Contribution*

ANALYSIS OF 2-D ULTRASOUND CARDIAC STRAIN IMAGING USING JOINT PROBABILITY DENSITY FUNCTIONS

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Abstract—Ultrasound frame rates play a key role for accurate cardiac deformation tracking. Insufficient frame rates lead to an increase in signal de-correlation artifacts resulting in erroneous displacement and strain estimation. Joint probability density distributions generated from estimated axial strain and its associated signal-to-noise ratio provide a useful approach to assess the minimum frame rate requirements. Previous reports have demonstrated that bi-modal distributions in the joint probability density indicate inaccurate strain estimation over a cardiac cycle. In this study, we utilize similar analysis to evaluate a 2-D multi-level displacement tracking and strain estimation algorithm for cardiac strain imaging. The effect of different frame rates, final kernel dimensions and a comparison of radio frequency and envelope based processing are evaluated using echo signals derived from a 3-D finite element cardiac model and five healthy volunteers. Cardiac simulation model analysis demonstrates that the minimum frame rates required to obtain accurate joint probability distributions for the signal-to-noise ratio and strain, for a final kernel dimension of 1 λ by 3 A-lines, was around 42 Hz for radio frequency signals. On the other hand, even a frame rate of 250 Hz with envelope signals did not replicate the ideal joint probability distribution. For the volunteer study, clinical data was acquired only at a 34 Hz frame rate, which appears to be sufficient for radio frequency analysis. We also show that an increase in the final kernel dimensions significantly affect the strain probability distribution and joint probability density function generated, with a smaller effect on the variation in the accumulated mean strain estimated over a cardiac cycle. Our results demonstrate that radio frequency frame rates currently achievable on clinical cardiac ultrasound systems are sufficient for accurate analysis of the strain probability distribution, when a multi-level 2-D algorithm and kernel dimensions on the order of 1 λ by 3 A-lines or smaller are utilized. (E-mail: tvarghese@wisc.edu or cma8@wisc.edu) **© 2014 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Ultrasound, Elastography, Echocardiographic strain imaging, Deformation imaging, Cardiac strain imaging.**

INTRODUCTION

Ultrasound based elasticity imaging was first developed in the early 1990s primarily for the detection and characterization of masses in the breast and prostate (Cespedes et al. 1993; Garra et al. 1997; Hall et al. 2003; Insana et al. 2000; Krouskop et al. 1987; Nightingale et al. 2002; O'Donnell et al. 1994; Ophir et al. 1991; Parker et al. 1990; Varghese 2009; Varghese et al. 2001; Wilson and Robinson 1982). For strain imaging, local and accessible tissues were deformed externally with local displacements estimated by tracking tissue deformation between two snapshots of ultrasound echo signals; acquired before and after the applied deformation using normalized cross-correlation based echo signal analysis (Cespedes et al. 1993; Garra et al. 1997; Hall et al. 2003; Insana et al. 2000; O'Donnell et al. 1994; Ophir et al. 1991; Varghese 2009; Varghese et al. 2001; Wilson and Robinson 1982).

Unlike traditional strain imaging for tumor detection, in cardiac strain imaging (Bouchard et al. 2011; D'Hooge et al. 2000; Geyer et al. 2010; Hsu et al. 2012; Jia et al. 2009; Konofagou et al. 2002; Varghese et al. 2003) and for plaque characterization, the deformation of tissue is not initiated by forces applied externally, but rather, by the constant physiologic excitation initiated by the heart itself (*e.g.*, during the systolic phase the left ventricular wall contracts to propel blood into the aorta, while during the diastolic phase it expands to enable blood to flow in from the left atrium). While the cardiac wall deformation has been extracted utilizing strain imaging of cardiac

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muscle the vascular deformations generated by cardiac pulsation provide the deformation source for plaque characterization (O'Donnell et al. 1994; Talhami et al. 1994; van der Steen et al. 1998). In order to thoroughly investigate functional characteristics of cardiac muscle under these variable and pulsatile deformations, ultrasound signals are acquired and deformations tracked over each phase of cardiac cycle for strain imaging. Incremental strain maps obtained between these echo signal frames can also be accumulated to obtain localized and accumulated strain variations across cardiac cycles.

Insufficient temporal frame rates in the ultrasound echo signal data acquired may introduce signal de-correlation artifacts between consecutive echo signal frames due to high tissue deformation rate and significant out-of-plane motion, especially during the systolic phase (Lopata et al. 2010). Increased signal de-correlation will produce both erroneous incremental strains and corrupt the cumulative displacement and strain estimated (Alam and Ophir 1997).

The minimum frame rate needed to successfully recover cardiac strain has been studied by several groups (Chen et al. 2009; Langeland et al. 2005; Provost et al. 2012). Chen et al. (2009) conducted uniformly elastic tissue-mimicking (TM) phantom studies using a cyclic compression platform. Their phantom experiment results obtained using a two-step 1-D cross-correlation method (Shi and Varghese 2007) showed that frame rates higher than 10 times the cyclic compression frequency was necessary to maintain high elastographic signal-to-noise ratio (SNR_e) levels ($\approx$16 dB) using radio frequency (RF) signals.

Open-chest sheep studies by Langeland et al. (2005) showed good agreement on longitudinal and radial strain estimated using 2-D tracking using RF signals compared with sonomicrometry at a frame rate of 168 Hz. However, they did not explore the effect of lower frame rates in their study (Langeland et al. 2005). Recently, Provost et al. (2012) proposed the use of a joint probability density function (pdf) map of the SNR_e and strain probability distribution to analyze the frame rate problem for cardiac applications. They reported a sharp decline in the SNR_e values in the joint pdf maps near 4% strain in their open-chest canine heart study using a phased array transducer operated at a 3.3 MHz center frequency (Provost et al. 2012). Their results showed that a minimum frame rate of 350 Hz was needed to eliminate distortions in the strain probability distribution and to obtain a uni-modal distribution in the joint pdf. This minimum frame rate corresponds to roughly 210 frames/cardiac cycle, although this was not directly specified in their paper. They reported that lower frame rates resulted in an artifactual bi-modal distribution in the joint pdf corresponding to increased errors in the strain estimated. Displacement and strain were estimated using a 1-D normalized cross-correlation algorithm with a processing window length of 4.6 mm and a 90% overlap between the data segments in their study.

In this study, we utilize the same joint pdf concept proposed by Provost et al. (2012) to assess the frame rate requirement for cardiac strain imaging using a multi-level 2-D cross-correlation algorithm previously developed in our laboratory (Shi and Varghese 2007). The joint pdf was first demonstrated for an inclusion phantom by Varghese and Ophir (1998) (see Figure 12 in Varghese and Ophir (1998)). The impact of the final processing 2D cross-correlation kernel dimensions (denoted as "final kernel dimensions" for the rest of the article) of the multi-level algorithm on the joint pdf obtained will be evaluated on a 3-D finite element based cardiac simulation data set (Chen and Varghese 2010) and echo signal data acquired on five normal healthy volunteers. In addition, we also compare axial strain estimation results on short axis echocardiographic views estimated using RF and envelope echo signals.

MATERIALS AND METHODS

Finite element cardiac simulation

A 3-D canine cardiac simulation model previously developed in our laboratory was utilized for this study (Chen and Varghese 2010). This model is based on a 3-D finite element analysis (FEA) model of a canine heart developed by the Cardiac Mechanics Research Group at University of California San Diego. The heart rate of the canine heart model was 2 cycles/second, with a sampling/frame rate of 250 Hz. This frame rate corresponds to 125 frames/cardiac cycle. The initial data contained movement information of 1296 points located in the canine heart, which then are interpolated into over 1 million points for our analysis. This interpolation was essential to include sufficient number of scatterers on the order of 10 scatterers per cubic millimeter of tissue, to ensure Rayleigh scattering statistics for ultrasound echo signals.

In this study, a mid-cavity slice of the left ventricle along the short axis view was selected to generate simulated ultrasound echo signals. A frequency domain ultrasound simulation previously developed in our laboratory (Li and Zagzebski 1999) was utilized. Simulated RF signals were generated using inverse Fourier transformation of the frequency domain results. The purpose of the simulation study was to take advantage of the known displacement/strain information that can be extracted from the FEA model as a comparison standard for displacement/strain estimation accuracy obtained using our algorithm.