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Analysis of 2-D motion tracking in ultrasound with dual transducers

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ABSTRACT

We study displacement and strain measurement error of dual transducers (two linear arrays, aligned orthogonally and coplanar). Displacements along the beam of each transducer are used to obtain measurements in two-dimensions. Simulations (5 MHz) and experiments (10 MHz) are compared to measurements with a single linear array, with and without angular compounding. Translation simulations demonstrate factors of 1.07 larger and 8.0 smaller biases in the axial and lateral directions respectively, for dual transducers compared to angular compounding. As the angle between dual transducers decreases from 90° to 40°, for 1% compression simulations, the lateral RMS error ranges from 2.1 to 3.9 μm compared to 9 μm with angular compounding. Simulation of dual transducer misalignment of 1 mm and 2° result in errors of less than 9 μm. Experiments demonstrate factors of 3.0 and 5.2 lower biases for dual transducers in the axial and lateral directions respectively compared to angular compounding.

1. Introduction

1.1. Overview

Elastography is an imaging technique for depicting the mechanical properties of tissues. Images of elasticity and other mechanical parameters are created by applying an excitation to the tissue, measuring the corresponding displacement field, and using the displacement field to infer the mechanical parameters of interest (see [1] for a recent overview of the field). Displacement is usually tracked with either ultrasound or magnetic resonance imaging (MRI). The acquisition time for displacement tracking with MRI is typically 10–120 s per slice [2]. Ultrasound displacement tracking can be done at typical speeds of 0.03 s per slice with conventional beamforming and image formation, thus allowing for real-time use for guided interventions [3,4]. However, MRI can provide isotropic in-plane resolution, related to the number of samples in the frequency and phase encoding directions. Ultrasound resolution in the axial direction (i.e. along the beam axis) is related to the system bandwidth and transducer frequency, whereas the resolution in the lateral direction is related to the width of the beam and transducer element spacing [5]. The highly anisotropic nature of ultrasound is observed in displacement measurements, where axial measurements contain smaller variance compared to lateral measurements [6,7]. For example, Walker and Trahey [6] found lateral jitter is approximately ten times greater than axial jitter. Elasticity estimation benefits from having all three components of the displacement field [8,9]. Extending the accuracy and precision of ultrasound displacement measurements from one component to two (or even three) components would enable an ultrasound elastography system to incorporate inversion techniques designed for higher dimensional MRI data, with the goal of improving the quality of ultrasound elastograms. Here accuracy refers to a mean shift or bias in the measurement, and precision describes the inverse of the measurement standard deviation when compared to a constant gold standard.

1.2. Objective

The goal of this work is to examine the displacement tracking performance of two coplanar orthogonal linear array ultrasound transducers, which we call the dual transducer approach. Linear arrays have been chosen since they are suitable for imaging the breast, which is the most common application of elastography on women, and the focus of our group's ongoing clinical studies [10]. In addition, the geometry of linear arrays creates full separation of the axial and lateral components of tissue motion when two arrays are placed orthogonally. Each of the two displacement components are measured independently along the direction of sound propagation for the two transducers. This geometry simplifies data analysis and comparisons. We will compare to conventional single linear array 2D tracking using cross correlation and 2D tracking with angular compounding, both commonly used in elastography. Since dual transducers need to be aligned and calibrated [11], estimates on the error caused by misalignment or poor calibration of

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the two transducers are studied. A practical challenge of the dual transducer approach is obtaining two clear orthogonal views of the anatomy with a single combined hand-held device. In particular, some applications such as breast and neck imaging may allow a wider range of views compared to other applications such as abdominal imaging. Given this potential limitation, we will quantify the displacement measurement error as the angle between the two transducers is reduced from 90°. In summary, we aim to quantify the potential performance enhancements that may be provided by dual transducers and also estimate the sensitivity of the technique to expected errors.

1.3. Background and motivation

Displacement can be measured with ultrasound by identifying the maximum of the normalized correlation function between sequences of backscattered radio frequency (RF) echo signals [12–14], finding the zero phase lag of the autocorrelation function of baseband signals [15–17], minimizing the sum of absolute differences [18], minimizing the sum of squared differences [19], matching peaks of RF signals detected by a wavelet transform [20], minimizing a cost functional [21], or other matching techniques. Angular compounding can reduce lateral measurement error by electronically steering the beam [22,23], and the acquisition rate is reduced by a half by employing a single pair of steered angles [24,25]. Measurement error generally decreases as the angle between between the beams increases, however for breast imaging with linear arrays, the elastographic contrast- and signal-to-noise ratios do not improve for electronic steering angles greater than approximately ±10° due to decorrelation of the RF signals [26]. Alternatively, larger angles can be achieved by physically separating the sources with the use of a second transducer.

There has been previous work on estimating displacement and velocity with multiple ultrasound transducers in the field of Doppler Velocimetry (see for example [27]). In these works, typically single element transducers are used and a measure of blood velocity independent of scanning angle is desired. Some of the issues encountered in Doppler Velocimetry are aligning the transducers to create intersecting beams, operating the transducers simultaneously, and errors caused by refraction of the beams. Refraction is also a critical factor in ultrasound tomography where multiple views are obtained by rotating a transducer around a region of interest [28].

Other studies with multiple transducers have looked at linear arrays in a bi-plane configuration such that the two perpendicular image planes intersect along a line. By measuring displacement in 2D with each transducer, a 3D vector can be computed along the line of intersection of the two planes [29]. Mounting the transducers on stepper motors and translating them in their elevation direction creates a 3D grid of 3D displacement measurements, which has shown potential for elastography applications [30].

A recent study used two coplanar orthogonal linear array ultrasound transducers to measure principal strains *in vitro* in a rabbit heart to provide a gold standard comparison for a single linear array transducer strain estimation technique [31]. In other studies, strain orthogonal to the compression direction was measured, suggesting beam direction should coincide with the desired component of the measured displacement [32,33]. Given the continued interest in combining displacement measurements from multiple ultrasound transducers, a detailed study of the accuracy and precision of the measurements and their sources of error is warranted.

1.4. Novelty

This work includes a quantitative comparative analysis of displacement measurement and elastography using conventional techniques with a single linear array transducer, and dual transducers. It also provides results as the angle of separation between the dual transducers is varied between 40° and 90°. In addition, this work examines practical issues of applying the technique for breast cancer imaging, for example feasible scanning geometry, possible excitation methods, and potential limitations of the dual transducer technique due to errors caused by transducer misalignment are studied. Finally, since the breast contains tissues with different sound speeds, errors due to refraction and depth misplacement are modeled in Appendix A.

1.5. Organization

The rest of this paper is organized as follows. In the Section 2, the techniques for modeling displacement in a virtual phantom, simulating RF signals from the distributed scatterers, applying the dual transducer method experimentally, and evaluating the performance of the different tracking techniques are explained. Next, Section 3 presents tracking error for translation and compression motion, performance of strain estimation, tracking error as the angle between the dual transducers is decreased, and tracking error caused by misalignment of the dual transducers. Section 4 provides details of a practical clinical implementation of the dual transducer technique, followed by conclusions and a statement of clinical relevance in Section 5. Appendix A studies errors due to refraction and speed of sound (SOS).

2. Methods

For this study, three displacement measurement techniques are applied to estimate 2D displacement; 2D tracking, 2D tracking with angular compounding, and the dual transducer method. The methods for estimating tissue displacement from the RF signals for each of the three techniques are presented in the following sections. The methods for evaluating and comparing these tracking techniques for translational and compressional displacements are also presented. A simulation of dual transducer misalignment is studied to test its sensitivity to calibration, and the improvements in strain images produced by the dual transducer method are evaluated.

2.1. Simulated motion

For this study, translational and compressional displacements were investigated separately. First, to evaluate the displacement tracking accuracy and precision of each method we applied displacements with step sizes of 30 μm in the axial and lateral directions, creating an 11×11 grid with 121 distinct displacement poses. Note that from this point on, axial and lateral will refer to the axes defined in Fig. 1. A $40 \times 40 \times 20$ mm^3 virtual phantom was simulated by randomly placing 40 scatterers per mm^3 with random amplitudes assigned with a uniform distribution. The scatterer concentration is similar to what others have used in the literature for generating fully developed speckle [34]. The size of the elevational direction was chosen to envelop the beam width in that direction. The displacements were added to the nominal phantom positions to create images of the phantom at each of the 121 poses.

The second method of displacement modeling studied the effects of mechanical compression and possible decorrelation noise. This was accomplished by solving a 3D model with finite element analysis (FEA) software ANSYS (Ansys Inc., Canonsburg, PA, USA). A $10 \times 10 \times 20$ mm^3 cube inclusion was modeled in the center of the phantom (Fig. 1). Similar phantom and inclusion sizes have been used in other 3D elastography studies [35]. A cube was chosen over the more commonly used cylindrical inclusion because it