A mathematical approach to mitigate the impact of compression waves in shear wave elastography

Hamidreza Asemani*[a,b], Jannick P. Rolland[a,c], Kevin J. Parker[b,c]
[a]The Institute of Optics, University of Rochester, Rochester, NY, USA
[b]Department of Electrical and Computer Engineering, University of Rochester, Rochester, NY, USA
[c]Department of Biomedical Engineering, University of Rochester, Rochester, NY, USA

ABSTRACT

Shear wave elastography (SWE) has emerged as a valuable imaging technique across several modalities such as ultrasound, magnetic resonance imaging, and optical coherence tomography. Its capacity to assess tissue stiffness and identify lesions positions it as a promising clinical tool for diagnosing a wide range of diseases. The primary aim of SWE is to measure shear wave speed (SWS); however, unwanted compression waves and bulk tissue motion can complicate this process. Conventional methods, in many cases, face challenges in separating shear and compression waves, resulting in inaccurate SWS measurements. This study introduces a novel estimator, called integrated difference autocorrelation (IDA), designed to specifically estimate reverberant shear wave speed in the presence of compression waves and noise. Unlike conventional methods, the IDA estimator computes the velocity differences between adjacent particles, effectively mitigating the impact of long-wavelength compression waves and other wide-area movements like those induced by respiration. The effectiveness of the IDA estimator was assessed through several approaches: elastography simulation of a y-shaped cylinder in a soft background, magnetic resonance elastography (MRE) on a brain phantom with two lesions, ultrasound elastography on a breast phantom with a lesion, and ultrasound elastography in the human liver-kidney region. Our findings indicate that the IDA estimator provides accurate SWS estimates (within 19% of reference) even in the presence of strong compression waves that can cause earlier estimators to completely fail. Moreover, the IDA estimator demonstrates consistent performance across different modalities and excitation scenarios, underscoring its robustness and potential clinical applicability.

Keywords: Autocorrelation, shear wave elastography, reverberant shear wave, compression waves

1. INTRODUCTION

Shear wave elastography (SWE) is an emerging imaging technique utilized in multiple medical imaging modalities including optical coherence tomography (OCT) [1-3], magnetic resonance imaging (MRI) [4,5], and ultrasound [6,7]. Its capability to evaluate tissue biomechanical properties and detect diverse lesions [8,9] establishes this technique as a reliable clinical tool for diagnosing a broad spectrum of diseases [10,11]. In SWE, the focus lies on measuring the speed of shear waves rather than compression waves, as unwanted compression waves and translational motions can introduce challenges in accurately assessing tissue stiffness. In this study, we introduce the difference autocorrelation estimator to calculate shear wave speed (SWS) in the presence of compression waves. By subtracting the velocity between two neighboring particles, we effectively minimize the impact of compression waves. This technique is capable of estimating SWS in fully reverberant shear wave fields, as well as imperfect or more directionally oriented shear wave fields. The application of the proposed approach is studied using (1) elastography simulation in k-Wave toolbox of MATLAB featuring a stiff branching cylinder in a soft background, (2) magnetic resonance elastography (MRE) of a brain phantom with two lesions (3) ultrasound elastography of a breast phantom with a lesion, and (4) ultrasound elastography of the human liver kidney region.

*hasemani@ur.rochester.edu

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2. METHODOLOGY

The particle velocity $\boldsymbol{V}$ within a fully reverberant shear wave field is described as [12,13] as

$$\boldsymbol{V}(\boldsymbol{\varepsilon}, t) = \sum_{q,l} \hat{\boldsymbol{n}}_{ql}\, v_{ql}\, e^{i(k\hat{\boldsymbol{n}}_q \cdot \boldsymbol{\varepsilon} - \omega_0 t)} \tag{1}$$

where $\boldsymbol{\varepsilon}$ signifies the position vector, t is time, ω_0 is the angular frequency, and the indices q and l correspond to realizations of the random unit vectors $\hat{\boldsymbol{n}}_{\boldsymbol{q}}$ and $\hat{\boldsymbol{n}}_{ql}$, respectively. The vector $\hat{\boldsymbol{n}}_q$ denotes the random direction of wave propagation, $\hat{\boldsymbol{n}}_{ql}$ indicates a random unit vector representing the direction of particle motion and v_{ql} represents an independent, identically distributed random variable signifying the magnitude of the particle velocity within a given realization. In order to minimize the influence of compression waves and whole tissue motion, we propose to compute the autocorrelation of the quantity $V_{\boldsymbol{z}}(\boldsymbol{\varepsilon} - \Delta\boldsymbol{\varepsilon}) - V_{\boldsymbol{z}}(\boldsymbol{\varepsilon} + \Delta\boldsymbol{\varepsilon})$ instead of the autocorrelation of only the velocity field $V_{\boldsymbol{z}}$. The subtraction of particle velocities between neighboring particles effectively cancels out the contribution of compression waves with large wavelengths, leaving only the SWS component. Thus, the difference autocorrelation estimator $B_{DA_{V_zV_z}}$ is defined, for simplicity when Δt is zero, as follows

$$B_{DA_{V_zV_z}}(\Delta\varepsilon) = E\left\{ \begin{matrix} [V_z(\varepsilon - \Delta\varepsilon) - V_z(\varepsilon + \Delta\varepsilon)] \\ [V_z(\varepsilon - \Delta\varepsilon) - V_z(\varepsilon + \Delta\varepsilon)]^* \end{matrix} \right\} = 2\left(\overline{V_{\boldsymbol{z}}}^2 - B_{V_zV_z}(2\Delta\boldsymbol{\varepsilon})\right) \tag{2}$$

where $\Delta\boldsymbol{\varepsilon}$ represents the small difference in position vector, E signifies an ensemble average, the asterisk (*) indicates the complex conjugate, and $\overline{V_{\boldsymbol{z}}}^2$ is the ensemble average velocity-squared. Let us note that the simplified form is based on the fundamental definition of each of the terms, assuming spatially stationary statistics. Figure 1 compares the angular integral autocorrelation (AIA) [13,14] and integrated difference autocorrelation (IDA) as a function $k\Delta\rho$ where k denotes the wavenumber, and $\Delta\rho$ represents the small positional difference or lag. At zero lag the AIA value is *one,* while the IDA value is *zero*.

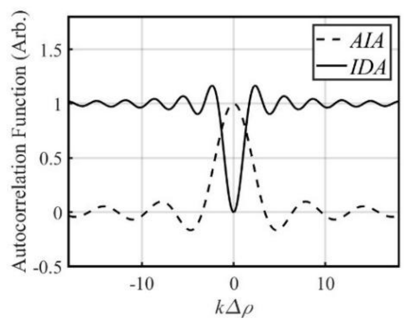

Fig. 1. Angular integral autocorrelation (AIA) and integrated difference autocorrelation (IDA) curves as a function of lag

3. RESULTS

Elastography Simulation

The effectiveness of the proposed IDA approach was assessed through an elastography simulation in the k-Wave toolbox of MATLAB, featuring a stiff branching cylinder with an SWS of 2 m/s embedded in a soft background with an SWS of 1 m/s (see Fig. 2(a)). A complex wave field, comprising both small scale shear wave field and larger scale compression wave field at a frequency of 2000 Hz, was generated via multiple shear wave point sources (see Fig. 2(b)). Applying IDA to the unfiltered wave field showed significant improvement in estimation accuracy, and particularly highlighting the y-shaped (see Fig. 2(c)), while AIA struggled to accurately estimate SWS in shear + compression wave fields (see Fig. 2(d)). The average SWS in the background was calculated using IDA to be 0.98 m/s (i.e., 2% error).

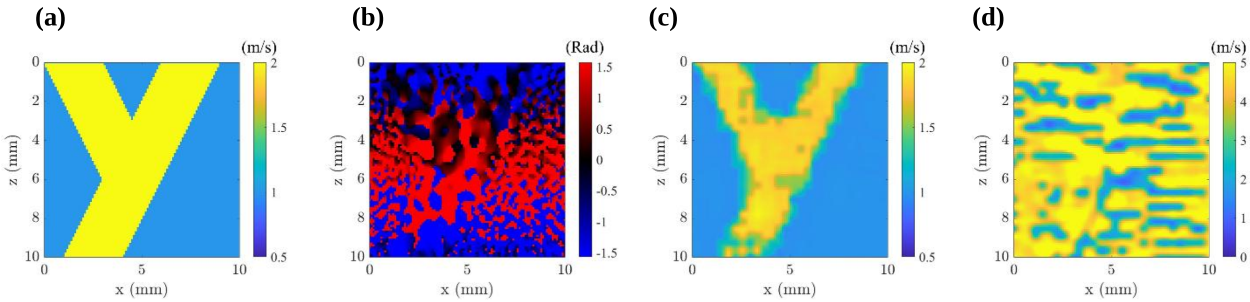

Fig. 2. Elastography simulation in the k-Wave toolbox of MATLAB, featuring a (a) stiff branching cylinder in a soft background, (b) shear + compression wave field, (c) SWS map estimated by IDA, (d) SWS map estimated by AIA

Brain Phantom MRE

To assess the effectiveness of the developed IDA approach across different modalities and excitation scenarios, its performance was assessed using an MRE dataset of a brain phantom containing two lesions (see Fig. 3(a)) with a shear + compression wave field at a frequency of 200 Hz (see Fig. 3(b)). While AIA failed to visualize the lesions in the SWS map and struggled to estimate the SWS in the unfiltered shear + compression wave field, IDA successfully highlighted the lesions in the SWS map (see Fig. 3(c)). Additionally, the average background SWS was estimated at 2.18 m/s, compared to a ground truth of 1.83 m/s (i.e., 19% error).

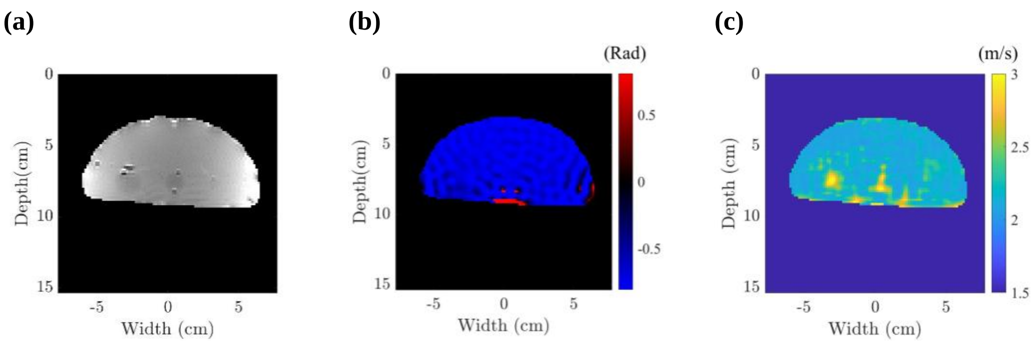

Fig. 3. (a) Bmode MRI scan of a brain phantom with two lesions (b) shear + compression wave field, (c) SWS map estimated by IDA

Breast Phantom Ultrasound Elastography

In the following assessment, the IDA estimator was employed in ultrasound elastography of a phantom featuring a lesion (see Fig. 4(a)) within a shear + compression wave field at a frequency of 900 Hz (see Fig. 4(b)). The results underscored the effectiveness and accuracy of SWS estimation using IDA in comparison to the conventional approach. Notably, the lesion in the SWS map is effectively highlighted against the uniform background (see Fig. 4(c)). The average SWS using IDA was estimated to be 2.09 m/s in the background, compared to a ground truth of 2.27m/s (i.e., 8% error).

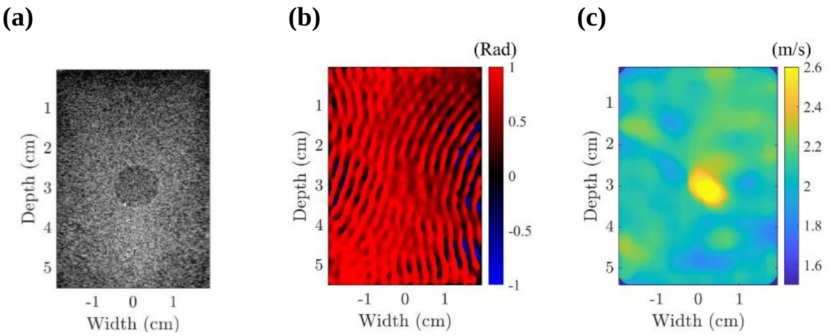

Fig. 4. (a) Bmode ultrasound scan of a breast phantom with a lesion (b) shear + compression wave field, (c) SWS map estimated by IDA

Liver-Kidney Ultrasound Elastography

In our final assessment, the performance of the IDA estimator was evaluated in ultrasound elastography of the liver-kidney (see Fig. 5(a)), with a shear + compression wave field at a frequency of 702 Hz (see Fig. 5(b)). While the AIA failed in estimating the SWS on the unfiltered wave field, the IDA estimator yielded useful results. Remarkably, the estimated SWS using the IDA estimator accurately visualized the details of the liver and kidney, mirroring the observations from the B-mode scan (see Fig. 5(c)).

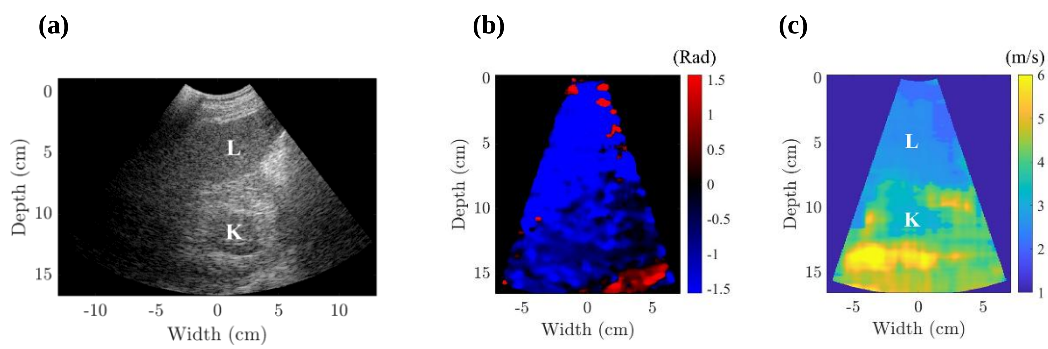

Fig. 5. (a) Bmode ultrasound scan of a liver kidney region, (b) shear + compression wave field, (c) SWS map estimated by IDA

4. CONCLUSIONS

This study describes the novel difference autocorrelation estimator for SWS estimation in the presence of compression waves. By computing the angular integral of a spatial-difference autocorrelation, the IDA estimator is derived. Through comprehensive evaluations using an elastography simulation and experimental data from ultrasound elastography and MRE, we have demonstrated the effectiveness and robustness of IDA in accurately estimating SWS across various tissue types and imaging modalities where the presence of long wavelength compression waves complicates the calculation of shear wave properties. There are several advantages to the newer IDA approach. There is no need to have 3D vector data to implement the vector curl operator. Further, careful a priori estimates of wavelengths to fine tune a bandpass filter is not required.

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