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● *Original Contribution*

SHEAR WAVE SPEED ESTIMATION USING REVERBERANT SHEAR WAVE FIELDS: IMPLEMENTATION AND FEASIBILITY STUDIES

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Abstract—Elastography is a modality that estimates tissue stiffness and, thus, provides useful information for clinical diagnosis. Attention has focused on the measurement of shear wave propagation; however, many methods assume shear wave propagation is unidirectional and aligned with the lateral imaging direction. Any deviations from the assumed propagation result in biased estimates of shear wave speed. To address these challenges, directional filters have been applied to isolate shear waves with different propagation directions. Recently, a new method was proposed for tissue stiffness estimation involving creation of a reverberant shear wave field propagating in all directions within the medium. These reverberant conditions lead to simple solutions, facile implementation and rapid viscoelasticity estimation of local tissue. In this work, this new approach based on reverberant shear waves was evaluated and compared with another well-known elastography technique using two calibrated elastic and viscoelastic phantoms. Additionally, the clinical feasibility of this technique was analyzed by assessing shear wave speed in human liver and breast tissues, *in vivo*. The results indicate that it is possible to estimate the viscoelastic properties in each scanned medium. Moreover, a better approach to estimation of shear wave speed was obtained when only the phase information was taken from the reverberant waves, which is equivalent to setting all magnitudes within the bandpass equal to unity: an idealization of a perfectly isotropic reverberant shear wave field. (E-mail: jormache@ur.rochester.edu) © 2018 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Elastography, Shear waves, Reverberant fields, Ultrasound, Tissue stiffness, Shear wave speed estimators.**

INTRODUCTION

Elastography is an imaging modality that estimates the biomechanical properties of tissues, providing additional useful information for clinical diagnosis (Parker et al. 2011; Shiina et al. 2015). Several elastography modalities have proposed different approaches to measure shear wave speed, shear modulus, and other mechanical parameters (Doyley 2012; Shiina et al. 2015). Particular attention has been focused on the measurement of shear wave propagation; however, reflected waves from organ boundaries and internal inhomogeneities cause modal patterns in continuous wave applications (Parker and Lerner 1992; Taylor et al. 2000) and cause backward traveling waves in transient wave experiments (Ringleb et al. 2005). Reflected waves also may affect the propagation direction of the induced shear waves; thus, some biased estimates of shear wave speed (SWS) may result because conventional methods for SWS estimation assume shear wave propagation parallel to the lateral direction (Palmeri et al. 2008; Rouze et al. 2010; Song et al. 2014). To address these challenges, directional filters have been applied to avoid some reflections and to isolate shear waves with a different propagation direction (Castaneda et al. 2009; Catheline et al. 2013; Deffieux et al. 2011; Engel and Bashford 2015; Hah et al. 2012; Manduca et al. 2003; McLaughlin and Renzi 2006; Song et al. 2012, 2014; Tzschätzsch et al. 2015; Zhao et al. 2014).

Many continuous shear wave inversion approaches have been developed to estimate the unknown tissue stiffness. These include inversions of the Helmoltz equation in magnetic resonance elastography (MRE) (Oliphant et al. 2001; Ringleb et al. 2005; Van Houten et al. 2001) and sonoelastography (Fu et al. 2000; Parker and Lerner 1992; Yeung et al. 1998). Another class of estimations has been developed for underwater acoustics and geomechanics using

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random signals (Roux et al. 2005), and these have been extended to noise correlation measurements in soft tissues (Brum et al. 2008, 2015; Catheline et al. 2008, 2013; Gallot et al. 2011). These estimations involve spatial coherence of noise functions measured at two points, and can be recast as Green's functions and time reversal solutions.

Parker et al. (2017) proposed and analyzed a limiting case of a fully reverberant shear wave field in an organ. Mathematically, this limiting case is modeled as the condition where, at an observation point in a tissue, shear waves of random amplitude and phase are found to be propagating in all directions as a statistically isotropic distribution across 4π steradians. Practically speaking, all tissue boundaries with reflections and sources in the vicinity of the observation point contribute to the overall distribution. Analytic solutions were obtained for the expected value of the autocorrelation function for the vector velocity field as a function of space and time, and then for the projection (or dot product) of this along a single direction, taken as the axis of motion detection of an imaging system. From these analytical solutions, the reverberant or diffuse field approach leads to simple estimators of shear wave speed. The mathematical framework and assumptions of a reverberant field are a departure from previous approaches in which directional filters are employed to isolate and characterize one or several principal components of an unknown shear wave field. In contrast, the reverberant or diffuse field explicitly treats a statistically isotropic distribution from all directions, in the imaging plane and out of plane as well, and derives all subsequent processing and estimators from that limiting condition. Thus, strategies for identifying principal directions and the use of directional filters are obviated.

In this work, the reverberant shear wave field elastography (R-SWE) approach was evaluated and compared with another well-known elastography technique (single-tracking-location shear wave elastography [STL-SWE]) by estimating the SWS in two CIRS-calibrated, elastic and viscoelastic, phantoms. Additionally, the clinical feasibility of the R-SWE modality was analyzed by assessing SWS in human liver and breast tissues, *in vivo*. Moreover, the linear dispersion slope and viscoelastic parameter (extracted from a mechanical model) from each scanned medium were measured for additional characterization of the medium.

METHODS

Experimental setup

To create a reverberant field, multiple sources can be applied to ensure multiple directions of direct and reflected waves. Figure 1(a) illustrates the schematic setup using the breast phantom; a similar setup was used for the custom viscoelastic phantom. Moreover, as illustrated in Figure 1(b), two MISCO loudspeakers were embedded as part of the examination bed used to scan an *in vivo* liver from a volunteer patient. Two power amplifiers (Model 2718, Bruel and Kjaer, Naerum, Denmark; Model BKA1000-4A, ButtKicker, Westerville, OH, USA) and a digital power amplifier (Model LP-2020 A + , Lepai, Bukang, China) driven by a dual-channel function generator (Model AFG3022B, Tektronix, Beaverton, OR, USA)

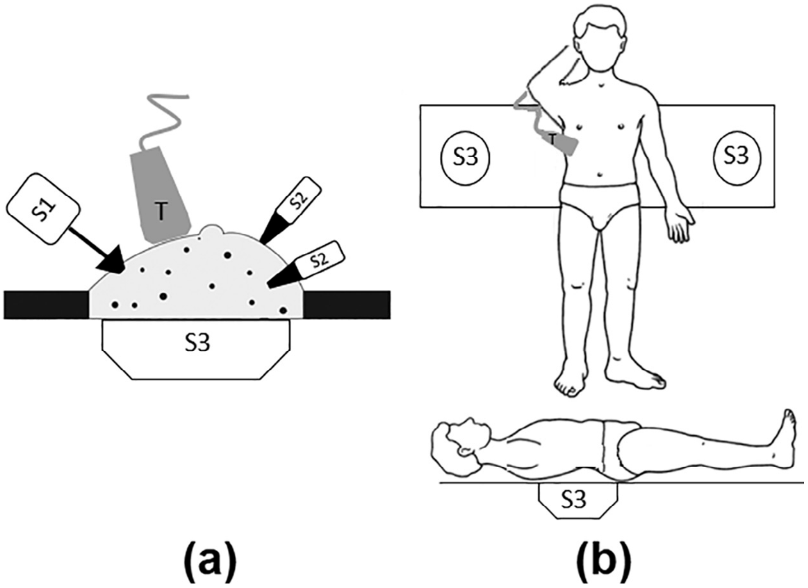

Fig. 1. Schematic setup used in experiments. (a) Three different vibration sources were used for the breast and the viscoelastic phantom. (b) Two MISCO loudspeakers (S3) were coupled to a table for the *in vivo* human liver experiment.