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● *Original Contribution*

FAST SHEAR COMPOUNDING USING ROBUST 2-D SHEAR WAVE SPEED CALCULATION AND MULTI-DIRECTIONAL FILTERING

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Abstract—A fast shear compounding method was developed in this study using only one shear wave push-detect cycle, such that the shear wave imaging frame rate is preserved and motion artifacts are minimized. The proposed method is composed of the following steps: 1. Applying a comb-push to produce multiple differently angled shear waves at different spatial locations simultaneously; 2. Decomposing the complex shear wave field into individual shear wave fields with differently oriented shear waves using a multi-directional filter; 3. Using a robust 2-D shear wave speed calculation to reconstruct 2-D shear elasticity maps from each filter direction; and 4. Compounding these 2-D maps from different directions into a final map. An inclusion phantom study showed that the fast shear compounding method could achieve comparable performance to conventional shear compounding without sacrificing the imaging frame rate. A multi-inclusion phantom experiment showed that the fast shear compounding method could provide a full field-of-view, 2-D and compounded shear elasticity map with three types of inclusions clearly resolved and stiffness measurements showing excellent agreement to the nominal values. (E-mail: chen.shigao@mayo.edu) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Shear compounding, Shear wave elastography, 2-D shear wave speed, Directional filter, Comb-push, Acoustic radiation force.**

INTRODUCTION

Spatial compounding techniques are widely used in ultrasound to suppress speckle noise and improve image quality (Bercoff et al. 2004; Jespersen et al. 1998; Tanter et al. 2002). Ultrasound spatial compounding coherently sums the backscattered signals from ultrasound insonifications with different incident angles (Jespersen et al. 1998). Similarly, shear compounding coherently compounds the shear elasticity maps from shear wave fields that are illuminated by shear waves with different incident angles (Bercoff et al. 2004). Shear compounding improves the signal-to-noise-ratio of shear elasticity maps because random noise can be suppressed by averaging multiple reconstructed maps. Shear compounding also improves the contrast of shear elasticity maps for inclusions with complex geometries and various inhomogeneities, because differently angled shear waves can illuminate and produce good elasticity maps of different parts of the inclusion, which can then be compounded to obtain a robust elasticity map of the whole inclusion.

In practice, however, there are some challenges involved with shear compounding. First, shear compounding requires multiple cycles of transmission and detection of differently angled shear waves in several separate events (Bercoff et al. 2004). This can significantly reduce the frame rate of shear wave imaging and substantially compromise the efficacy of shear compounding for *in vivo* applications because of the non-negligible amount of gross physiologic motion between separate data acquisitions. Second, when the shear wave is angled and thus oblique, one can no longer assume that the shear wave propagates in a direction parallel to the lateral dimension of the ultrasound-imaging field. Therefore, conventional shear wave speed estimation methods that assume a lateral propagation direction produce biased estimates of shear wave speed (Palmeri et al. 2008; Rouze et al. 2010; Tanter et al. 2008; Wang et al. 2010). To address these challenges, this study proposes a fast shear compounding method that: (1) Uses a comb-push (Song et al. 2012; 2013) to produce

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multiple differently angled shear waves simultaneously to achieve shear compounding with only one push-detect data acquisition, so that shear wave imaging frame rate is preserved and motion artifacts are minimized; and (2) Uses a multi-directional filter to isolate shear waves with different propagation directions and a robust 2-D shear wave speed calculation method to accurately reconstruct 2-D shear wave speed maps from each direction, which are then compounded into a final map.

The article is structured as follows: we describe (1) a validation study of the proposed robust 2-D shear wave speed calculation method on a homogeneous phantom, (2) an inclusion phantom study that systematically compares the performance of the proposed fast shear compounding method to the conventional shear compounding method, and finally (3) demonstration of the fast shear compounding to reconstruct a full field-of-view (FOV) 2-D shear wave speed map with multiple different types of inclusions with different stiffness.

MATERIALS AND METHODS

Robust 2-D shear wave speed calculation

To realize shear compounding using acoustic radiation force excitation, shear waves with different propagation angles need to be induced and detected. When the shear wave propagates at an oblique angle from wave front 1 to 2 to 3 as shown in Figure 1 (a), the actual shear wave speed c_s is $a/\Delta t$, where Δt is the time interval from 1 to 2 and 2 to 3. However, if we only measure the shear wave speed along the x-direction as in Figure 1 (a), the apparent shear wave speed c_s' will be $b/\Delta t$, which is higher than the real shear wave speed c_s. Therefore, when the measurement direction is not aligned with the shear wave propagation direction, the estimated shear wave speed will be biased high. To measure the correct shear wave speed, a 2-D calculation is needed, as shown in Figure 1 (b). Let the shear wave signal detected at pixels a, b and c be $S_a(t)$, $S_b(t)$ and $S_c(t)$, respectively, where t is time. Let t_{ab} be the time delay between $S_a(t)$ and $S_b(t)$ [calculated by finding the delay associated with the peak of the cross-correlation of $S_a(t)$ and $S_b(t)$], and t_{ac} the time delay between $S_a(t)$ and $S_c(t)$ [calculated by finding the delay associated with the peak of the cross-correlation of $S_a(t)$ and $S_c(t)$]. Let the distance between pixels a and c be L_{ac} and between pixels a and b be L_{ab}. Then $V_X = L_{ac}/t_{ac}$, and $V_Z = L_{ab}/t_{ab}$. Considering the dimensions of the triangle defined by a, b and c, the true shear wave speed V can be calculated by:

$$V = \frac{V_X V_Z}{\sqrt{V_X^2 + V_Z^2}} \tag{1}$$

or

$$V = \frac{L_{ac} L_{ab}}{\sqrt{L_{ac}^2 t_{ab}^2 + L_{ab}^2 t_{ac}^2}} \tag{2}$$

Equation (2) is more stable than eqn (1) when either t_{ac} or t_{ab} is zero (if the wave propagation direction is aligned with axis z or x). This 2-D vector shear wave speed calculation given by eqns (1) and (2) does not require *a priori* knowledge of the direction of shear wave propagation, which can be difficult to know in practice. Note that a similar approach for 2-D shear wave speed calculation was used for crawling waves generated by external mechanical shakers (Hoyt et al. 2008). Note also that such 2-D methods still assume that the wave propagation is in the imaging plane, and a similar bias will result if some component of the wave propagation is out of the imaging plane (Zhao et al. 2011).

Two methods were developed to increase the robustness of the 2-D shear wave speed calculation method while preserving the spatial resolution of the shear wave speed maps. First, an algorithm used in numerical differential calculation developed by Anderssen and Hegland (1999) was adapted to calculate local shear wave speed. Conventional local shear wave speed measurement techniques as introduced in (Tanter et al. 2008) are performed by cross-correlating two shear wave signals from two imaging pixels [denoted by $S(m\text{-}w/2,n,t)$ and $S(m+w/2,n,t)$, where m is the lateral dimension, n is the axial dimension, t is the slow time dimension and w is the window size] that are a fixed distance apart (distance is equal to window size w), as shown in Figure 2 (a), to estimate the shear wave speed of the center pixel at location (m,n). The normalized cross-correlation is calculated by (Pinton et al. 2006):

$$CC(j) = \frac{\sum_{i=-M/2}^{M/2} \left[S(m-w/2,n,i) - \overline{S}(m-w/2,n)\right]\left[S(m+w/2,n,i+j) - \overline{S}(m+w/2,n)\right]}{\sqrt{\sum_{i=-M/2}^{M/2} \left[S(m-w/2,n,i) - \overline{S}(m-w/2,n)\right]^2 \sum_{i=-M/2}^{M/2} \left[S(m+w/2,n,i+j) - \overline{S}(m+w/2,n)\right]^2}}, \tag{3}$$