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● *Original Contribution*

SINGLE- AND MULTIPLE-TRACK-LOCATION SHEAR WAVE AND ACOUSTIC RADIATION FORCE IMPULSE IMAGING: MATCHED COMPARISON OF CONTRAST, CONTRAST-TO-NOISE RATIO AND RESOLUTION

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Abstract—Acoustic radiation force impulse imaging and shear wave elasticity imaging (SWEI) use the dynamic response of tissue to impulsive mechanical stimulus to characterize local elasticity. A variant of conventional, multiple-track-location SWEI, denoted single-track-location SWEI, offers the promise of creating speckle-free shear wave images. This work compares the three imaging modalities using a high push and track beam density combined acquisition sequence to image inclusions of different sizes and contrasts. Single-track-location SWEI is found to have a significantly higher contrast-to-noise ratio than multiple-track-location SWEI, allowing for operation at higher resolution. Acoustic radiation force impulse imaging and single-track-location SWEI perform similarly in the larger inclusions, with single-track-location SWEI providing better visualization of small targets ≤2.5 mm in diameter. The processing of each modality introduces different trade-offs between smoothness and resolution of edges and structures; these are discussed in detail. (E-mail: peter.hollender@duke.edu) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Acoustic radiation force, Shear wave elasticity imaging, Single-track location.**

BACKGROUND

Acoustic radiation force impulse imaging

Acoustic radiation force impulse (ARFI) imaging has been under investigation since the early 2000s (Nightingale et al. 2002), with early work proposing its use for identifying breast tumors (Sharma et al. 2004). ARFI images provide information about relative differences in tissue stiffness, similar to those generated with compressive strain imaging methods. However, ARFI imaging offers advantages resulting from the generation of the mechanical excitation within the structure of interest and its limited susceptibility to out-of-plane motion artifacts. To generate a 2-D image, ARFI ensembles are translated across the imaging field of view, in the same way that a color Doppler image is created. Images are typically generated of the tissue displacement response, located within the excitation region and measured for 1–2 ms after excitation. For a given force, displacement is inversely proportional to tissue stiffness, and ARFI images portray relative differences in the displacement response within each excited region, either as the displacement at a fixed time step or the maximum displacement. The 3-D distribution of radiation force, variations in acoustic attenuation and the transient nature of ARFI excitations complicate the specific relationship between absolute displacement and material stiffness such that quantitative elasticity estimates are only possible with careful calibration. In most *in vivo* imaging scenarios, ARFI images are considered to provide qualitative maps of relative elasticity. Structural edges can be seen within a push beam (Dahl et al. 2007), so the resolution in ARFI images may be limited by the resolution of the tracking beams (Palmeri et al. 2006a) and, as such, be comparable to that of B-mode. For imaging small structures, however, contrast-to-noise ratio (CNR) is often considered to be the limiting factor, and the contrast in ARFI images has been reported to be reduced when the size of the push beam exceeds the size of the structure being imaged (Nightingale et al. 2006; Palmeri et al. 2006a). The work described here

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explored these effects in further detail and examined their impact on imaging small targets.

Shear wave elasticity imaging

Shear wave elasticity imaging (SWEI), originally described by Sarvazyan et al. (1998) and first reported *in vivo* by our group (Nightingale et al. 2003), quantifies tissue stiffness by exciting the tissue with an ARFI push beam and monitoring the associated shear wave propagation through the region of interest. Time-of-flight-based reconstruction algorithms are then used to estimate the shear wave speed (SWS) (Chen et al. 2004; McAleavey et al. 2009; McLaughlin and Renzi 2006; Muller et al. 2009; Palmeri et al. 2008; Rouze et al. 2010; Tanter et al. 2008; Wang et al. 2010), which, in linear elastic materials, is proportional to the square root of the shear modulus G divided by the density ρ:

$$\mathrm{SWS} = \sqrt{\frac{G}{\rho}} \quad (1)$$

SWS typically is expressed in units of meters per second; G is expressed in kilopascals; and ρ is expressed in grams per cubic centimeter and is generally assumed to be close to 1 g/cm^3 in tissue.

For a set of push beam locations x_p and track beam locations x_t, shear wave images can be made from measuring the propagation of each shear wave from its source x_p through different locations x_t. The images created from each push can then be overlapped and averaged to expand the lateral field of view and/or suppress noise (Tanter et al. 2008). This is referred to as multiple-track-location SWEI (MTL-SWEI), because the velocity is estimated with respect to the tracking locations. Figure 1 illustrates the most complete configuration for a single depth, with the displacement depicted at different times after excitation for all combinations of x_t and x_p. This data set would be acquired one column at a time, as each column corresponds to a single push location and the full set of track locations. If we find the arrival time T for each combination of x_p and x_t, the MTL-SWEI estimate of velocity is found by taking the inverse of the partial derivative of T with respect to x_t, or tracking the waves as they propagate along the columns in Figure 1:

$$\mathrm{SWS_{MTL}}\left(z,x_t,x_p\right) = \mathrm{sgn}\left(x_t - x_p\right)\left(\frac{\partial T\left(z,x_t,x_p\right)}{\partial x_t}\right)^{-1} \quad (2)$$

Single-track-location SWEI

Single-track-location SWEI (STL-SWEI) is a novel variant of SWEI derived from the work of McAleavey et al. (2009). Mathematically, it can be considered as finding the partial derivative of the arrival times T with respect to x_p instead of x_t:

$$\mathrm{SWS_{STL}}\left(z,x_t,x_p\right) = \mathrm{sgn}\left(x_p - x_t\right)\left(\frac{\partial T\left(z,x_t,x_p\right)}{\partial x_p}\right)^{-1} \quad (3)$$

Rather than tracking the speed of a single propagating shear wave going through multiple tracking locations, this approach employs multiple, laterally offset push beams and a single tracking location. This is illustrated in Figure 1 as tracking the propagation across each row.

Because the velocity estimate in STL-SWEI is not dependent on the specific track beam location, it is only

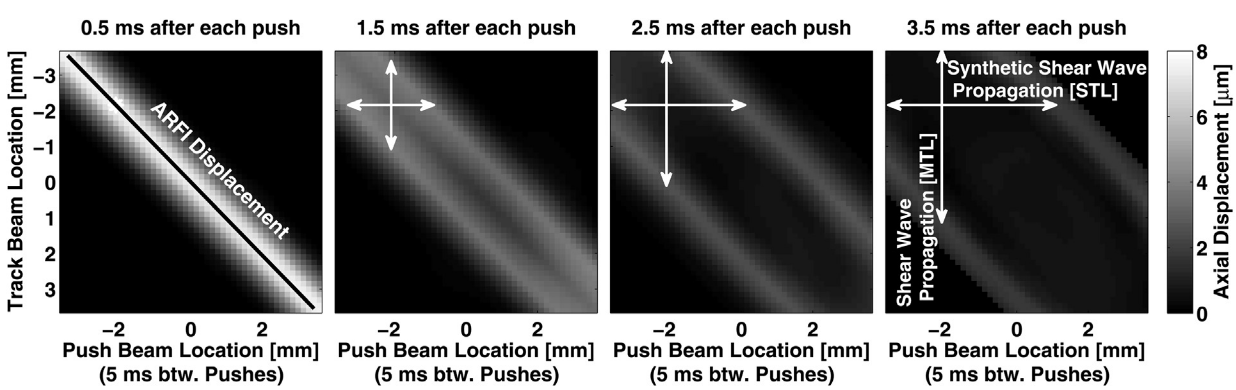

Fig. 1. Images of propagating shear wave displacement from a simulated data set. The y-axis represents track beam locations, which are monitored at the same time using parallel beamforming methods. The x-axis represents push beam locations, which are interrogated sequentially. Displacement through time is monitored for each push at all track beam locations. Multiple-track-location shear wave elasticity imaging employs linear regression along the vertical axis x_t (*i.e.*, between the wave arrival times and the track beam locations, indicated by the *white vertical arrows*), whereas single-track-location shear wave elasticity imaging employs linear regression along the horizontal axis x_t (*i.e.*, between the wave arrival times and the push beam locations, indicated by the *white horizontal arrows*). Acoustic radiation force impulse images are created from the early time displacements tracked at the push locations. STL = single track location; MTL = multiple track location.