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● *Original Contribution*

# NOVEL METHOD FOR VESSEL CROSS-SECTIONAL SHEAR WAVE IMAGING

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**Abstract—Many studies have investigated the applications of shear wave imaging (SWI) to vascular elastography, mainly on the longitudinal section of vessels. It is important to investigate SWI in the arterial cross section when evaluating anisotropy of the vessel wall or complete plaque composition. Here, we proposed a novel method based on the coordinate transformation and directional filter in the polar coordinate system to achieve vessel cross-sectional shear wave imaging. In particular, ultrasound radiofrequency data were transformed from the Cartesian to the polar coordinate system; the radial displacements were then estimated directly. Directional filtering was performed along the circumferential direction to filter out the reflected waves. The feasibility of the proposed vessel cross-sectional shear wave imaging method was investigated through phantom experiments and *ex vivo* and *in vivo* studies. Our results indicated that the dispersion relation of the shear wave (*i.e.*, the guided circumferential wave) within the vessel can be measured *via* the present method, and the elastic modulus of the vessel can be determined. (E-mail: luo_jianwen@tsinghua.edu.cn) © 2017 World Federation for Ultrasound in Medicine & Biology.**

***Key Words:*** **Circumferential, Cross section, Directional filter, Guided wave, Radial motion, Shear wave imaging, Vessel elastography.**

## INTRODUCTION

Two-dimensional ultrasound shear wave imaging (SWI) or shear wave elastography (SWE) (Bercoff et al. 2004; Sarvazyan et al. 1998) has been developed in the past two decades for visualization of the elastic properties of soft tissues. In this technique, shear waves are generated by either mechanical vibration or a radiation force produced by ultrasound beams. Thereafter, shear wave velocity (SWV), which is related to the mechanical properties of the tissues, is obtained by tracking the time evolution of shear wave propagation using ultrafast ultrasound imaging (Bercoff et al. 2004) or conventional ultrasound scanning (Song et al. 2015). With respect to the dispersion of the shear wave within a viscoelastic medium, shear wave dispersion ultrasound vibrometry (SDUV) has also been developed to quantify the viscoelasticity of soft tissues (Chen et al. 2004, 2009). Four-dimensional SWI has been used to reconstruct the 3-D distribution of tissue elasticity (Gennisson et al. 2015). To date, 2-D SWI has been used in many applications, such as quantitative assessment of breast lesion viscoelasticity and the biomechanical properties of arterial walls, mapping of myocardial fiber orientation and staging of liver fibrosis (Bavu et al. 2011; Couade et al. 2010; Lee et al. 2012; Muller et al. 2009; Tanter and Fink 2014; Tanter et al. 2008).

Evaluation of vascular elasticity (or stiffness) is clinically important because many cardiovascular diseases and conditions (*e.g.*, atherosclerotic plaques and hypertension) may alter the mechanical properties of vessels. Many techniques for imaging vascular elasticity have been developed, including intravascular ultrasound elastography (de Korte et al. 2000; Schaar et al. 2003), noninvasive vascular elastography (Huang et al. 2016; Maurice et al. 2004), pulse wave imaging (Luo et al. 2012), acoustic radiation force impulse (ARFI) imaging (Trahey et al. 2004) and SWI (Couade et al. 2010). Much effort has been extended to investigate the applicability of SWI to assessment of vascular elasticity (Bernal et al. 2011; Garrard and Ramnarine 2014; Li et al. 2017a; Messas et al. 2013; Ramnarine et al. 2014a, 2014b;

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Widman et al. 2015). These studies revealed that SWI-based vascular elastography is reproducible in both phantom and *in vivo* experiments, and can be applied to the detection of plaque compositions, that is, calcification and lipid-rich necrotic cores, on the vessel phantom consisting of inclusions with different stiffness (Ramnarine et al. 2014a, 2014b; Widman et al. 2015). However, owing to the anisotropy in the mechanical properties of vessel walls (Rose 2014; Shcherbakova et al. 2014), these studies cannot completely evaluate vessel elasticity because they focus mainly on longitudinal sections of the phantom or vessel. Plaques may also be located on the side walls of arteries and, thus, cannot be imaged in longitudinal sections. In addition, eccentric plaques have been found to be associated with a significantly increased incidence of ipsilateral cerebrovascular events in large clinical trials (Ohara et al. 2008). Therefore, vascular images and plaque composition analysis of longitudinal sections may not completely represent eccentric plaques.

To apply SWI methods in cross section, Hansen et al. (2015) developed a method for lipid content detection in transverse arterial cross sections. They assessed shear wave propagation behavior and SWV by calculating axial motion as a function of circumferential location and time. For the vessel SWI in the cross section, the acoustic radiation force is usually applied in the radial direction at the upper (or lower) region of the vessel, the shear wave propagates along the circumferential direction and the shear wave motion investigated is along the radial direction. In addition, the wavelength of the shear wave within the vessel is larger than the wall thickness of the vessel, making the shear wave strongly dispersive and guided within the vessel wall (Li et al. 2017a, 2017b; Liu and Qu 1998; Rose 2014). The guided wave propagation along the circumferential direction is the so-called guided circumferential wave (GCW). At each moment ($t$), the radial and circumferential particle velocity components, denoted by $V_{\mathrm{r}}$ and $V_\theta$, respectively, can be written as

$$V_{\mathrm{r}} = \int V_{0\mathrm{r}}(r)e^{i(k_\theta\theta-\omega t)}d\omega \tag{1}$$

$$V_\theta = \int V_{0\theta}(r)e^{i(k_\theta\theta-\omega t)}d\omega \tag{2}$$

where $r$ and $\theta$ represent the radial and circumferential directions in the polar coordinate system, respectively. $\omega$ is the angular frequency, and $k_\theta$ denotes the wavenumber in units of radians and depends on $\omega$. It should be noted that $k_\theta$ is dimensionless and therefore is different from the traditional definition of wavenumber (in units of $\mathrm{m}^{-1}$). The phase velocity of the GCW, denoted by $c$, is

$$c(r) = r\frac{\omega}{k_\theta} \tag{3}$$

As mentioned above, only $V_{\mathrm{r}}$ is investigated in this study. Equation (1) can be regarded as the superposition of GCWs with different frequencies, which makes the shape of the wavefront change continuously. And the group velocity of the SWV is therefore no longer equal to the bulk SWV in an infinite medium.

During shear wave propagation, reflected waves may appear and also propagate along the circumferential direction (Liu and Qu 1998; Rose 2014). In the Cartesian coordinate system, however, the directions of the shear wave and reflected wave vary spatially. Directional filtering has been proposed as an important step to filter out the reflected wave in SWI (Deffieux et al. 2011). In the cross section of vessels, however, it is challenging to design a spatially varying directional filter in the Cartesian coordinate system to filter out the reflected wave propagating along the circumferential direction (Rose 2014).

In this article, we propose a novel method based on coordinate transformation and directional filtering in the vessel's polar coordinate system to achieve vessel cross-sectional shear wave imaging (VCS-SWI), which can directly obtain the radial motion, effectively filter out the reflected waves in the circumferential direction and also provide the dispersion relation of the GCW. The feasibility of this method was investigated through phantom, *ex vivo* and *in vivo* experiments.

The remaining sections are organized as follows. The method of VCS-SWI and experimental configurations are described under Methods. The results of the phantom, *ex vivo* and *in vivo* experiments are presented under Results. The Discussion and Conclusions sections follow.

## METHODS

### *Vessel cross-sectional shear wave imaging*

Figure 1 is a flowchart of VCS-SWI. The process comprised the coordinate transformation of ultrasound radiofrequency (RF) data, motion estimation and directional filtering, quantitative analysis and visualization of shear wave propagation. The details are given below. It should be noted that to obtain the RF data for VCS-SWI, all in-phase and quadrature (IQ) data acquired in the experiments were modulated to RF data at a sampling frequency of 30 MHz as

$$S_{\mathrm{RF}}(t) = I(t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t) \tag{4}$$

where $S_{\mathrm{RF}}(t)$ is the RF data, $t$ is the time, $f_0$ is the center frequency of the RF data, $I$ ($t$) and $Q$ ($t$) are the