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● *Original Contribution*

THE ROLE OF VISCOSITY ESTIMATION FOR OIL-IN-GELATIN PHANTOM IN SHEAR WAVE BASED ULTRASOUND ELASTOGRAPHY

Ying Zhu,* Changfeng Dong,† Yin Yin,* Xin Chen,* Yanrong Guo,* Yi Zheng,‡ Yuanyuan Shen,* Tianfu Wang,* Xinyu Zhang,* and Siping Chen*

*National-Regional Key Technology Engineering Laboratory for Medical Ultrasound, Guangdong Key Laboratory for Biomedical Measurements and Ultrasound Imaging, Department of Biomedical Engineering, School of Medicine, Shenzhen University, Shenzhen, China; †Department of Ultrasonography, The Third People's Hospital of Shenzhen, Shenzhen, China; and ‡Department of Electrical and Computer Engineering, St. Cloud State University, St. Cloud, MN, USA

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Abstract—Shear wave based ultrasound elastography utilizes mechanical excitation or acoustic radiation force to induce shear waves in deep tissue. The tissue response is monitored to obtain elasticity information about the tissue. During the past two decades, tissue elasticity has been extensively studied and has been used in clinical disease diagnosis. However, biological soft tissues are viscoelastic in nature. Therefore, they should be simultaneously characterized in terms of elasticity and viscosity. In this study, two shear wave-based elasticity imaging methods, shear wave dispersion ultrasound vibrometry (SDUV) and acoustic radiation force impulsive (ARFI) imaging, were compared. The discrepancy between the measurements obtained by the two methods was analyzed, and the role of viscosity was investigated. To this end, four types of gelatin phantoms containing 0%, 20%, 30% and 40% castor oil were fabricated to mimic different viscosities of soft tissue. For the SDUV method, the shear elasticity μ_1 was 3.90 ± 0.27 kPa, 4.49 ± 0.16 kPa, 2.41 ± 0.33 kPa and 1.31 ± 0.09 kPa; and the shear viscosity μ_2 was 1.82 ± 0.31 Pa•s, 2.41 ± 0.35 Pa•s, 2.65 ± 0.13 Pa•s and 2.89 ± 0.14 Pa•s for 0%, 20%, 30% and 40% oil, respectively in both cases. For the ARFI measurements, the shear elasticity μ was 7.30 ± 0.20 kPa, 8.20 ± 0.31 kPa, 7.42 ± 0.21 kPa and 5.90 ± 0.36 kPa for 0%, 20%, 30% and 40% oil, respectively. The SDUV results demonstrated that the elasticity first increased from 0% to 20% oil and then decreased for the 30% and 40% oil. The viscosity decreased consistently as the concentration of castor oil increased from 0% to 40%. The elasticity measured by ARFI showed the same trend as that of the SDUV but exceeded the results measured by SDUV. To clearly validate the impact of viscosity on the elasticity estimation, an independent measurement of the elasticity and viscosity by dynamic mechanical analysis (DMA) was conducted on these four types of gelatin phantoms and then compared with SDUV and ARFI results. The shear elasticities obtained by DMA (3.44 ± 0.31 kPa, 4.29 ± 0.13 kPa, 2.05 ± 0.29 kPa and 1.06 ± 0.18 kPa for 0%, 20%, 30% and 40% oil, respectively) were lower than those by SDUV, whereas the shear viscosities obtained by DMA (2.52 ± 0.32 Pa·s, 3.18 ± 0.12 Pa·s, 3.98 ± 0.19 Pa·s and 4.90 ± 0.20 Pa·s for 0%, 20%, 30% and 40% oil, respectively) were greater than those obtained by SDUV. However, the DMA results showed that the trend in the elasticity and viscosity data was the same as that obtained from the SDUV and ARFI. The SDUV results demonstrated that adding castor oil changed the viscoelastic properties of the phantoms and resulted in increased dispersion of the shear waves. Viscosity can provide important and independent information about the inner state of the phantoms, in addition to the elasticity. Because the ARFI method ignores the dispersion of the shear waves, namely viscosity, it may bias the estimation of the true elasticity. This study sheds further light on the significance of the viscosity measurements in shear wave based elasticity imaging methods. (E-mail: xyzhang9@szu.edu.cn or chensiping@szu.edu.cn) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Shear wave, SDUV, ARFI, DMA, Elasticity, Viscosity, Oil-in-gelatin phantom.**

INTRODUCTION

Shear wave based ultrasound elastography has been studied in the past two decades and shows promise for use in disease diagnosis. This technique uses mechanical excitation or acoustic radiation force to induce shear waves in deep tissue and monitors the resulting displacement of tissue to derive elasticity information about the inner structure of tissue. The main types of this technique include shear wave elasticity imaging (SWEI) (Sarvazyan et al. 1998), supersonic shear imaging (SSI) (Bercoff et al.

Address correspondence to: Xinyu Zhang and Siping Chen, School of Medicine, Shenzhen University, Shenzhen 518160, China. E-mail: xyzhang9@szu.edu.cn or chensiping@szu.edu.cn

2004a), acoustic radiation force impulse (ARFI) imaging (Nightingale et al. 2001), harmonic motion imaging (Konofagou and Hynynen 2003), shearwave dispersion ultrasound vibrometry (SDUV) (Chen et al. 2004), sonoelastography (Lerner et al. 1990) and transient elastography (TE) (Catheline et al. 1999, Sandrin et al. 2002). Of these, SDUV and TE are localized point measurement methods, whereas the others are imaging methods. Moreover, sonoelastography and TE are mechanical excitation methods, whereas the others are acoustic radiation force methods.

Currently, shear wave based ultrasound elastography has been applied to analyze various types of soft tissue, such as liver, skeletal muscle, prostate, kidney, artery, breast and brain (Amador et al. 2011b; Bercoff et al. 2003; Chen et al. 2009; Macé et al. 2011; Mitri et al. 2011; Palmeri et al. 2008; Zhang and Greenleaf 2006). Many studies demonstrate that shear wave velocity is closely correlated with the severity of disease, especially in the diagnosis of liver disease. Shear wave based ultrasound elastography has achieved good results in the gradation of liver fibrosis (Chen et al. 2013; Chen et al. 2013; Wang et al. 2009; Zhu et al. 2014). However, liver fibrosis is clinically often associated with fatty liver, and studies about the influence of the degree of steatosis on shear wave velocity have provided conflicting results. A study by Guzmán et al. (2010) found that the mean shear wave velocity measured by ARFI imaging increased with the severity of liver steatosis in chicken livers. However, Yoneda et al. (2010) concluded that the shear wave velocity measured by ARFI imaging decreased with increasing steatosis grade in patients with non-alcoholic fatty liver disease. Similarly, research by Fierbinteanu-Braticevici et al. (2013) indicated that the shear wave velocity in ARFI decreased with increasing steatosis severity in patients with non-alcoholic fatty liver disease. Some studies on shear viscosity have shown that it may have potential in grading disease. Barry et al. (2012) found that an increase in the degree of steatosis in the liver evidently increases the viscosity and results in increased dispersion of the shear wave. Later, he concluded that shear wave dispersion is an indicator of the grade of steatosis in mouse livers (Barry et al. 2014). Chen et al. (2013) reported on a study of liver fibrosis in a rat model and suggested that although viscosity is not as good as elasticity for staging fibrosis, viscosity is important for the accurate estimation of elasticity. Nguyen et al. (2014) studied viscous tissue-mimicking phantoms and concluded that the addition of castor oil decreases shear elasticity, but increases shear viscosity in gelatin phantoms. Some magnetic resonance elastography studies also suggested that viscosity may provide useful information about the amount of fibrosis in the liver (Huwart et al. 2006, Salameh et al. 2007).

Unlike the other shear wave based elasticity imaging methods, which only assess the elasticity of tissue, SDUV also uses the dispersion of shear wave phase velocity to simultaneously estimate the viscoelastic properties of tissue. In fact, soft biological tissue is inherently viscoelastic (Fung 1993). Therefore, the viscosity of tissue must not be ignored as an influencing factor on variations in shear wave velocity. To this end, four types of gelatin phantoms containing different concentrations of castor oil were fabricated to mimic different viscosities of soft tissue in this study. The elasticity and viscosity of these phantoms were measured by the SDUV and ARFI methods. Additionally, to validate the impact of viscosity on the elasticity estimation, an independent dynamic mechanical analysis (DMA) test was performed on these phantoms, and its results were compared with those obtained using the SDUV and ARFI methods.

BACKGROUND

ARFI imaging uses impulsive acoustic radiation force to map the mechanical responses of tissue (Nightingale et al. 2001). The force induces a localized displacement of the tissue, which is displayed in an image. The lateral time-to-peak algorithm (Palmri et al. 2008) is used to measure the shear wave group velocity by finding its peak displacement time at locations lateral to the region of excitation (ROE). The shear wave velocity propagating away from the ROE has been correlated with the shear elasticity and density of the tissue. The ARFI method assumes that the medium is a purely elastic isotropic or non-dispersive material; thus, the shear wave group velocity c is related to the shear elasticity μ and the density ρ (typically assumed to be 1000 kg/m^3 for tissue) by:

$$c = \sqrt{\frac{\mu}{\rho}} \tag{1}$$

Shear wave dispersion ultrasound vibrometry (SDUV) uses repeated pulses to create a localized acoustic radiation force that generates harmonic shear waves that propagate outward from the vibration center. SDUV estimates the viscoelastic parameters of a medium by measuring the phase velocity of the shear wave at multiple frequencies. Assuming that this is carried out in an isotropic, homogenous and viscoelastic medium, the phase velocity of the shear wave $c(\omega)$ is dispersive, that is, it varies with the angular frequency ω ($\omega = 2\pi f$). If we adopt the Voigt rheological model to describe the viscoelastic material, then the relationship between the shear wave phase velocity $c(\omega)$ and the frequency ω is defined as in Chen et al. (2004)