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● *Original Contribution*

NON-INVASIVE VASCULAR RADIAL/CIRCUMFERENTIAL STRAIN IMAGING AND WALL SHEAR RATE ESTIMATION USING VIDEO IMAGES OF DIAGNOSTIC ULTRASOUND

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Abstract—The aim of this work was to develop a convenient method for radial/circumferential strain imaging and shear rate estimation that could be used as a supplement to the current routine screening for carotid atherosclerosis using video images of diagnostic ultrasound. A reflection model-based correction for gray-scale non-uniform distribution was applied to B-mode video images before strain estimation to improve the accuracy of radial/circumferential strain imaging when applied to vessel transverse cross sections. The incremental and cumulative radial/circumferential strain images can then be calculated based on the displacement field between consecutive B-mode images. Finally, the transverse Doppler spectra acquired at different depths along the vessel diameter were used to construct the spatially matched instantaneous wall shear values in a cardiac cycle. Vessel phantom simulation results revealed that the signal-to-noise ratio and contrast-to-noise ratio of the radial and circumferential strain images were increased by 2.8 and 5.9 dB and by 2.3 and 4.4 dB, respectively, after non-uniform correction. Preliminary results for 17 patients indicated that the accuracy of radial/circumferential strain images was improved in the lateral direction after non-uniform correction. The peak-to-peak value of incremental strain and the maximum cumulative strain for calcified plaques are evidently lower than those for other plaque types, and the echolucent plaques had higher values, on average, than the mixed plaques. Moreover, low oscillating wall shear rate values, found near the plaque and stenosis regions, are closely related to plaque formation. In conclusion, the method described can provide additional valuable results as a supplement to the current routine ultrasound examination for carotid atherosclerosis and, therefore, has significant potential as a feasible screening method for atherosclerosis diagnosis in the future. (E-mail: mxwan@mail.xjtu.edu.cn) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Carotid, Atherosclerosis, Routine screening, Gray-scale correction, Radial strain, Circumferential strain, Transverse Doppler, Wall shear rate.**

INTRODUCTION

Among the cardiovascular diseases, myocardial infarction and stroke are the two leading causes of death triggered by the destabilization of atherosclerotic plaques (Roger et al. 2012). Routine screening for early atherosclerosis diagnosis is paramount in monitoring and possibly in preventing acute events. Considering that atherosclerosis is a systemic disease, local changes in carotid arteries might serve as indicators of the risks of myocardial infarction and stroke (de Korte et al. 2011). Non-invasive vascular ultrasound, which is performed with linear array transducers operated at 7 to 18 MHz, is usually undertaken as a routine screening method to search for carotid plaques in the clinical setting; however, it cannot provide the mechanical parameters of the vessel wall.

Localized changes in the mechanical and hemodynamic properties of the arterial system are generally believed to be accompanied by early atherosclerosis (Chatzizisis et al. 2007; Humphrey 1995). Ultrasound strain imaging is a promising technique for characterizing the mechanical properties of tissues. This technique was

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first described by Ophir et al. (1991) to assess the strain distributions in breast, prostate, and liver tissues (Ophir et al. 2000). Given its ability to differentiate various tissues, strain imaging technique has been applied to intravascular ultrasound to estimate the radial strain distributions of coronary arteries (de Korte et al. 1997). To overcome the invasiveness limitation of intravascular ultrasound strain imaging, multiple transcutaneous vascular strain imaging methods have been developed for superficial arteries, from both the longitudinal and transverse cross sections of vessel walls (Behler et al. 2009; Kanai et al. 2003; Maurice et al. 2005; Ribbers et al. 2007; Shi and Varghese 2006). In longitudinal cross sections, the ultrasound beam is aligned with artery radial deformation, and the radial strains can be acquired directly from axial strains. However, longitudinal scanning sometimes cannot provide information on the whole plaque, thus necessitating strain imaging in vessel transverse cross sections (Nicolaides et al. 2012). During imaging of the transverse cross section, the radial strains of vessel wall have to be converted from axial and lateral strains because of the misalignment between the ultrasound beam and artery radial deformation in the lateral direction (Hansen et al. 2010a). Lateral strains cannot be estimated as accurately as axial strains because of the limited line density and absence of phase information; thus, the quality of radial/circumferential strain images would be eroded by the lateral contribution (Luo et al. 2007). An interesting method employing spatial compounding to improve lateral strain estimation has been described (Techavipoo et al. 2004). Radial strains can be derived from axial strains obtained at different beam steering angles. This method has also been applied to vascular strain imaging (Hansen et al. 2009, 2010b), with three limited steering angles from –30° to 30° to reduce motion artifacts during beam steering. *In vivo* experiments in multi-angle strain imaging produce more accurate results than conventional single-angle imaging in radial/circumferential strain estimation. However, this approach can be used only in the diastolic period. The large motion artifact in the systolic period during beam steering prevents the multi-angle strain imaging method from acquiring the strains over a cardiac cycle.

Most current strain imaging methods employ radiofrequency (RF) data to compute motion estimates, mainly because of the better resolution of RF data relative to the B-mode image under small applied strains (Varghese and Ophir 1998). However, B-mode data have the advantages of being conveniently obtained by end users and being less bulky; thus, such data can be expected to improve computation time (Zakaria et al. 2010). Moreover, B-mode data are widely used in commercial applications of cardiac strain imaging because of their good performance at higher applied deformations (Ma and Varghese 2013). Studies on B-mode image-based vascular strain imaging have reported the feasibility of using B-mode data in vascular applications (Wan et al. 2001; Zakaria et al. 2010). However, in transcutaneous ultrasound imaging of vessel transverse cross sections, different ultrasound incident angles on the circular structure of the vessel wall would result in a circumferential non-uniform gray-scale distribution in B-mode images (especially in the lateral direction) (Robinson et al. 1981). The unclear boundary of the vessel wall attributed to the circumferential non-uniformity of gray scale in B-mode images will limit the accuracy of the image-based strain estimation method (Wan et al. 2001). To acquire radial/circumferential strain images of vessel transverse cross sections with high accuracy, the circumferential non-uniform gray-scale distribution of B-mode images has to be corrected before strain calculation.

In addition to vascular strain imaging, studies on hemodynamic parameters have indicated that wall shear rate (WSR) is another important factor in plaque progression that may affect plaque growth and rupture (Chatzizisis et al. 2007). WSR can be calculated from the slope of the blood velocity profile near the wall. Most indirect methods for blood velocity profile estimation are based on assumed flow models (Struijk et al. 2005). However, these assumed models are frequently unrealistic estimations of actual human arteries. In comparison, direct methods *via* time-domain correlation or Doppler signals can estimate flow velocity at a high resolution in practice (Brands et al. 1995; Tortoli et al. 2002). To investigate blood flow as well as arterial wall strain, some methods combine vascular strain imaging with the blood flow or WSR estimation in longitudinal cross sections. In these studies, receive beam steering is required to obtain the Doppler signal of blood flow (Dumont et al. 2011; Hasegawa and Kanai 2008). However, in transverse scanning, the beam-to-flow angle is 90° at all times, and as such, receive beam steering cannot help in obtaining conventional Doppler signals of blood flow. With a beam-to-flow angle of 90°, our group developed a method to measure WSR using transverse Doppler. In comparison, the system used in our previous work is not standard in the clinical environment (Wan et al. 1999). Thus, in the current work, a clinically relevant WSR estimation method based on transverse Doppler spectra was proposed; it can be combined with radial strain imaging to evaluate the vessel wall without changing the receiving beam.

In this article, a combined strategy that includes radial/circumferential strain imaging and shear rate estimation is developed, using video images of diagnostic ultrasound. To improve the accuracy of radial strain imaging in vessel transverse cross sections, a reflection model-based correction for gray-scale non-uniform distribution is applied to B-mode images before strain