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● *Original Contribution*

VISUALIZING ANGLE-INDEPENDENT PRINCIPAL STRAINS IN THE LONGITUDINAL VIEW OF THE CAROTID ARTERY: PHANTOM AND IN VIVO EVALUATION

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Abstract—Non-invasive vascular elastography can evaluate the stiffness of the carotid artery by visualizing the vascular strain distribution. Axial strain estimates of the longitudinal cross section of the carotid artery are sensitive to the angle between the artery and the transducer. Anatomical variations in branching and arching of the carotid artery can affect the assessment of arterial stiffness. In this study, we hypothesized that principal strain elastograms computed using compounded plane wave imaging can reliably visualize the strain distribution in the carotid artery, independent of the transducer angle. We corroborated this hypothesis by conducting phantom and in vivo studies using a commercial ultrasound scanner (Sonix RP, Ultrasonix Medical Corp., Richmond, BC, Canada). The phantom studies were conducted using a homogeneous cryogel vessel phantom. The goal of the phantom study was to assess the feasibility of visualizing the radial deformation in the longitudinal plane of the vessel phantom, independent of the transducer angle (±30°, ±20°, ±10° and 0°). The *in vivo* studies were conducted on 20 healthy human volunteers in the age group 50–60 y. All echo imaging was performed at a transmit frequency of 5 MHz and sampling frequency of 40 MHz. The elastograms obtained from the phantom study revealed that for straight vessels, which had their lumen parallel to the transducer, principal strains were similar to axial strains. At non-parallel configurations (angles ±30°, ±20° and ±10°), the magnitudes of the mean principal strains were within 2.5% of the parallel configuration (0° angle) estimates and, thus, were observed to be relatively unaffected by change in angle. However, in comparison, the magnitude of the axial strain decreased with increase in angle because of coordinate dependency. Further, the pilot in vivo study indicated that the principal and axial strain elastograms were similar for subjects with relatively straight arteries. However, for arteries with arched geometry, axial strains were significantly lower ($p < 0.01$) than the corresponding principal vascular strains, which was consistent with the results obtained from the phantom study. In conclusion, the results of the phantom and *in vivo* studies revealed that principal strain elastograms computed using CPW imaging could reliably visualize angle-independent vascular strains in the longitudinal plane of the carotid artery. (E-mail: reach.rohitnayak@gmail.com)

Key Words: **Atherosclerosis, Carotid elastography, Principal strain, Vascular Elastography, Plane Wave Imaging.**

INTRODUCTION

Atherosclerotic stiffening of the carotid artery is the leading cause of cerebrovascular diseases (Benjamin et al. 2017). Advanced stages of carotid atherosclerosis can lead to stroke and transient ischemic attacks (Redgrave et al. 2008). Non-invasive vascular elastography can evaluate the stiffness of the carotid artery by visualizing the vascular strain distribution (Bjällmark et al. 2010; Catalano et al. 2011; de Korte et al. 2000, 2016; Hansen et al. 2016a, 2016b; Kawasaki et al. 2009; Korshunov et al. 2017; Maurice et al. 2004); clinicians can use this information to assess the atherosclerotic burden and identify patients at high risk for life-threatening cerebrovascular events (Weber and Noels 2011).

Strain elastograms visualized across the longitudinal plane of the carotid artery are typically measured in Cartesian coordinates. Specifically, the radial and longitudinal strains in the carotid artery are visualized by computing the axial and lateral strains, respectively,

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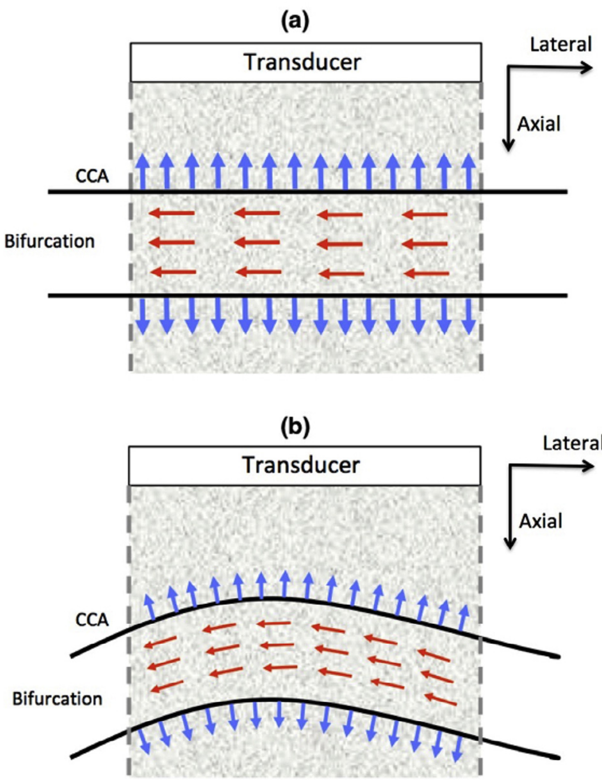

Fig. 1. Examples of the orientation of the carotid artery relative to the ultrasound transducer. The red and blue arrows indicate the direction of blood flow and the radial deformation in the vessel wall, respectively. The figures correspond to the instances when the radial deformation in the vessel wall is (a) aligned and (b) not aligned with the direction of beam propagation (axial). CCA = common carotid artery.

assuming that the corresponding axes are aligned (Fig. 1a). However, if the beam propagation direction is not aligned with the radial motion (e.g., Fig. 1b), axial strain may not accurately represent the radial deformation in the vessel (Maurice and Dahdah 2012; Mercure et al. 2008, 2011, 2014). Accordingly, vascular strains visualized in Cartesian coordinates are subject to anatomical variations in branching and arching of the carotid artery (Fig. 1b), which can limit the scope of vascular elastography. Mercure et al. (2014) proposed an angle compensation framework to correct the bias in axial strain estimates. However, the approach assumes that the arterial tissue is incompressible and vascular shear stains are non-existent, which may not be clinically valid (Chai et al. 2015; Holzapfel et al. 2004; Nayak et al. 2017a; Zhou and Fung 1997).

To estimate the vascular strain in the vessel reliably, it is important that the measured mechanical parameters are independent of vessel and transducer coordinate systems. The goal of the study described here was to evaluate the feasibility of using principal strain imaging to visualize coordinate-independent vascular strain in the longitudinal plane of the carotid artery. Principal strain elastograms visualize the maximum tensile and compressive strain at any spatial location, and are inherently coordinate independent (Dieter and Bacon 1986).

Several researchers have used principal strain imaging to improve the accuracy and robustness of elastographic assessment of tissue stiffness (Fung-Kee-Fung et al. 2005; Jia et al. 2009; Lee et al. 2008; Nayak et al. 2017a; Zervantonakis et al. 2007). Fung-Kee-Fung et al. (2005) and Zervantonakis et al. (2007) reported that principal strain imaging could visualize angle- and centroid-independent strain in myocardial elastographic imaging. They also highlighted the shortcomings of using Cartesian (axial and lateral) strain estimates for assessing the stiffness of the myocardium, because of its inherent dependence on the orientation of the transducer relative to myocardium motion. However, all of these studies reported a common limitation associated with visualizing principal strains—the subpar quality of the lateral displacements obtained using conventional ultrasound imaging. In a recent study (Nayak et al. 2017a), we addressed this limitation by using compounded plane wave (CPW) imaging and found that high-quality principal strain elastograms could be produced by beam steering and compounding plane waves over ±14°, in increments of 2°. It was also found that coordinate-independent principal strain elastograms could visualize the polar strains in the transverse cross section of the carotid artery when precise estimates of the vessel center are not known, which is common in stenosed vessels (Kumar and Balakrishnan 2005; McPherson et al. 1992).

We hypothesized that principal strains estimated using CPW imaging can reliably estimate the radial deformation in the carotid artery caused by the arterial blood pressure, independent of the transducer angle (Fig. 1b). We tested this hypothesis by conducting phantom and in vivo studies using a commercial ultrasound scanner implemented with CPW imaging. The phantom experiments were conducted to evaluate the impact of variation in the transducer angle on the axial and principal strain elastograms, in a controlled environment. Subsequently, the proposed technique was validated under more realistic physiological conditions, by conducting an *in vivo* pilot study on 20 healthy volunteers, in the age group 50–60 y. All experiments were conducted using a transmit frequency of 5 MHz and sampling frequency of 40 MHz.

METHODS

The following subsections describe the methods used in both the phantom and the *in vivo* studies. These include phantom fabrication, image acquisition and beam forming, displacement and strain estimation and data analysis.