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● *Original Contribution*

ESTIMATING CYCLIC SHEAR STRAIN IN THE COMMON CAROTID ARTERY USING RADIOFREQUENCY ULTRASOUND

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Abstract—There is increasing evidence that supports the hypothesis that elevated cyclic shear strain in the adventitia of the common carotid artery promotes plaque progression. In this article, we estimated cyclic shear strain in the carotid arterial wall in 16 asymptomatic human participants using radio-frequency (RF) ultrasound. In each participant, we acquired two separate RF ultrasound recordings. We correlated the cyclic shear strain with the distension waveform (representing the blood pressure waveform) of the carotid artery and the brachial blood pressure. There were no significant differences between the shear strains estimated from the two separate RF ultrasound recordings. The point-in-time of the maximum shear strain showed a significant correlation with that of the dicrotic notch in the distension waveform (Spearman's coefficient = 0.7, $p < 0.001$). The pulse shear strain (difference between maximum and minimum shear strain) was significantly correlated with the pulse pressure as measured in the brachial artery (Spearman's coefficient = 0.4, $p < 0.01$). In this study, we show that the cyclic shear strain in the adventitia of the common carotid artery can be estimated using RF ultrasound. We found indications that the estimated cyclic shear strain was induced by the pulsating blood pressure and it was found to be higher in participants with an elevated pulse pressure. (E-mail: t.idzenga@rad.umcn.nl) © **2012 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Cyclic shear strain, Vulnerable plaques, Distension waveform, Pulse pressure, Blood pressure, Carotid artery.**

INTRODUCTION

Myocardial infarction and stroke are two leading causes of death (Roger et al. 2011; Weintraub 2008). The primary trigger for these causes is destabilization of atherosclerotic plaques that can develop into advanced vulnerable plaques. The latter are prone to rupture and mostly consist of a large pool of lipids and thrombogenic material, covered by a thin fibrous cap (Schaar et al. 2004). When the thin cap ruptures, blood comes in contact with the contents of the core, and this leads to thrombus formation. Such a thrombus may cause a myocardial infarction or stroke by blocking a coronary or cerebral artery, respectively. Blood is a viscous fluid and induces in combination with the cardiac cycle, a consequently pulsating friction between blood and the arterial wall. This results in shear strain in the arterial wall. Arterial stiffness increases with age and may facilitate a transfer of the shear strain from the arterial wall toward the adventitial layer (*i.e.*, between artery and surrounding tissue). In this layer, inflammatory cells (Libby 2002) and perivascular structures are present that are subjected to this cyclic shear strain. Application of this cyclic strain to endothelial cells stimulates neovascularisation *via* different pathways (Gijsen et al. 2011; Hasaneen et al. 2007; Kou et al. 2008; Morrow et al. 2007; Ohayon et al. 2011; Techavipoo et al. 2004; Von Offenberg et al. 2005). Increased plaque neovascularisation in turn makes plaques more prone to rupture.

Assessment of this cyclic shear strain is, however, very challenging. In the past, it has been shown that longitudinal movement in the carotid arterial wall is present during the cardiac cycle (Ahlgren et al. 2012; Cinthio et al. 2005, 2006; Shi et al. 2008). The resulting cyclic shear strain in the arterial wall was measured using an echo-tracking technique based on block matching (as described by Person et al. [Persson et al. 2002]). Two regions-of-interest (ROI)

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were manually selected that contained distinct anatomic structures, one in the adventitia layer and one in the surrounding tissue. However, a major drawback of this method was that the distinct echoes needed to be present in both ROIs during the full cardiac cycle. To overcome this problem, we developed a shear strain estimation algorithm based on radio-frequency (RF) ultrasound. This method increases the accuracy of shear strain estimation as has been shown in phantom experiments (Idzenga et al. 2011; Lopata et al. 2009a, 2009b). This also enables estimating strain at any point in the imaged section of the carotid arterial wall. In this article, we estimated cyclic shear strain in the carotid arterial wall in 16 asymptomatic participants using RF ultrasound. In each participant, we acquired two separate acquisitions of RF data and compared the results from the two acquisitions. We also compared specific parameters from the estimated cyclic shear strain waveform with comparable parameters from the distension waveform in the carotid artery (CA) and with the brachial pulse pressure.

MATERIALS AND METHODS

Measurement protocol

We included 16 asymptomatic participants in the study. The research has been carried out in accordance with the Declaration of Helsinki (World Medical Association 2008) of the World Medical Association and was approved by the local ethical committee. All participants provided a written informed consent. Participants were placed in the supine position. Measurements were started after at least 5 min of rest. Systolic and diastolic blood pressures were measured in the right brachial artery before each measurement using a sphygmomanometer (Criticon model 1846; Criticon Inc., Tampa, FL, USA). Subsequently, we acquired two separate recordings of RF ultrasound data of the right CA at ~2 cm proximal to the bifurcation. Each recording contained 3 s of RF data. In between the two recordings, the transducer was removed from the skin for ~5 min. The RF data were recorded using a Medison Accuvix V10 ultrasound system (Samsung Medison America Inc., Cypress, CA, USA), equipped with an L5–13 linear array transducer (pitch 200 μm, f_c = 8 MHz, f_{sample} = 61.6 MHz, −20 dB bandwidth from 4–13 MHz) at a frame rate of 43 frames/s. RF data were acquired at three beam-steered angles (*i.e.*, three angles in the image plane of the linear array transducer) and stored for offline analysis. The beam-steered angle was dependent on the depth of the CA. The more superficial the CA is located, the larger the beam-steered angle that could be used. The first angle varied between −18° and −30°, the second was always 0° and the third angle varied between +18° and +30°. After the second recording, the systolic and diastolic blood pressures were measured again in the brachial artery. The pulse pressure before and after the experiment was calculated by subtracting the diastolic from the systolic pressure.

Data analysis

The Medison Accuvix V10 ultrasound system was set to acquire 3 s of RF data. Depending on the heart rate, this resulted in one or more complete cardiac cycles that were recorded. In acquisitions with more than one cardiac cycle, the complete cardiac cycles were identified from the distension curve of the CA derived from the RF data using a custom MATLAB®-algorithm (Mathworks, Natick, MA, USA) (see Appendix I). The start of one cardiac cycle (systole) was defined as a minimum in the distension curve and the end of the cardiac cycle as the following minimum (see Fig. 1). In each cardiac cycle, the points-in-time of the maximum distension and the dicrotic notch in the distension curve during the cardiac cycle were identified. In each acquisition, an ROI was selected that encompassed the far wall of the common carotid artery (see Fig. 2). In this ROI, deformation of the tissue was estimated between sequentially acquired ultrasound frames. The deformation was estimated using a coarse-to-fine cross-correlation based strain algorithm (Lopata et al. 2009a, 2009b). The first (coarse) iteration was based on the envelope of the raw RF-signals (calculated by demodulation of the RF-signals (*i.e.*, the absolute value of the Hilbert-transformed RF-signals). The following iterations (fine) were based on the raw RF-signals. The finest "pre-deformation" search window size was set at 32 pixels by 9 lines (0.64 × 1.80 mm^2). The "post-deformation" window was twice this size. The overlap between successive search windows was 50% in axial direction and 89% in lateral direction. The estimated axial and lateral displacements were median-filtered (axial: 0.52 × 0.60 mm^2 and lateral: 0.12 × 2.60 mm^2). To improve the final displacement estimate, local aligning and stretching was applied (Alam and Ophir 1997; Lopata et al. 2009a, 2009b). Following the displacement estimation, the axial displacements from the three acquisition angles were projected to a zero angle and compounded (Hansen et al. 2010). Subsequently, the shear strain was derived from the compounded displacements as the gradient (in the axial direction) of lateral displacements (as illustrated in Fig. 3). A larger lateral displacement of the posterior intima-media complex in the direction of flow with respect to the surrounding tissue results in a positive shear strain. The size of the two-dimensional (2-D) least-squares-strain-estimators (LSQSE) (Kallel and Ophir 1997; Lopata et al. 2009a, 2009b) used were equal to the size of the median filters.

For quantification of the shear strain in the CA, we selected an ROI in the adventitia of the far arterial wall,