Ultrasound in Med. & Biol., Vol. ■, No. ■, pp. 1–14, 2016

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2016.07.020

● *Original Contribution*

PRINCIPAL COMPONENT ANALYSIS OF THE LONGITUDINAL CAROTID WALL MOTION IN ASSOCIATION WITH VASCULAR STIFFNESS: A PILOT STUDY

Heikki Yli-Ollila,[*†‡] Mika P. Tarvainen,[*†] Tomi P. Laitinen,[*§] and Tiina M. Laitinen[*]
[*] Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital, Kuopio, Finland; [†] Department of Applied Physics, University of Eastern Finland, Kuopio, Finland; [‡] Department of Clinical Physiology and Nuclear Medicine, Kanta-Häme Central Hospital, Hämeenlinna, Finland; and [§] Department of Clinical Physiology and Nuclear Medicine, University of Eastern Finland, Kuopio, Finland

(*Received* 17 *January* 2016; *revised* 29 *June* 2016; *in final form* 25 *July* 2016)

Abstract—The longitudinal motion of the carotid wall during a heart cycle has a multiphasic waveform. Recent studies have examined the amplitude of this motion. Instead of amplitude measurements, we focus on making a detailed characterization of the motion waveform. Two-minute carotid ultrasound videos were obtained for 19 healthy volunteers, and a speckle tracking algorithm was used to measure the motion of the carotid wall. Principal component analysis revealed the characteristic features of wall motion and their relation to known arterial stiffness indices. By estimating two principal components, we could account for more than 92% of the variation in the motion graphs. The first principal component derived from the longitudinal motion curves was significantly correlated to pulse pressure, indicating that the main dominant base waveform of the longitudinal motion was related to blood pressure. The second principal component derived from the longitudinal motion curves had multiple significant correlations to known stiffness indices, indicating that the stronger biphasic structure of the motion curve, especially on the adventitia layer, was associated with higher distensibility and compliance, as well as reduced carotid artery stiffness. According to this study, the second principal component of the longitudinal motion may be a useful parameter reflecting vascular health. (E-mail: heikki.yli-ollila@khshp.fi) © 2016 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Arterial stiffness, Carotid artery, Eigenvalue, Eigenvector, Ultrasound imaging.**

INTRODUCTION

The prodromal phase of cardiovascular disease, which is often long lasting and symptomless, may later develop into life-threatening symptomatic disease. Arterial stiffening has often started during childhood and young adulthood (Juonala et al. 2005; Veijalainen et al. 2013), but at present there are no quick, inexpensive and non-invasive screening methods that accurately detect this early stage. The need for new methods to study early arterial stiffness has been emphasized (Naghavi et al. 2003). One novel line of study is focused on the longitudinal (*i.e.,* in the direction of the blood flow) wall motion of the inner wall of the blood vessel. Multiple techniques to measure the small, aberrant longitudinal motion of the carotid wall have been reported (Albinsson et al. 2014; Cinthio et al. 2005; Gastounioti et al. 2011; Golemati et al. 2003, 2012; Persson et al. 2003; Svedlund and Gan 2011a; Yli-Ollila et al. 2013; Zahnd et al. 2011b, 2013, 2014, 2015b). Our group has also developed a motion tracking method that uses contrast optimization to reduce the noise in the ultrasound images; this can be used with clinical ultrasound devices without requiring access to the raw radio frequency ultrasound signal (Yli-Ollila et al. 2013).

In preliminary clinical studies, carotid longitudinal wall motion has been linked to arterial stiffness (Bukac and Canic 2013; Taivainen et al. 2015; Yli-Ollila et al. 2014, 2016), ageing (Zahnd et al. 2012), plaque burden (Svedlund and Gan 2011b), diabetes (Zahnd et al. 2011a) and cardiac well-being (Svedlund et al. 2011), reflecting the reduction in amplitude and rapidity of longitudinal wall motion in unhealthy/stiffer arteries. Despite the multiple studies on the subject, the actual force initiating longitudinal motion is still unclear, as is the manner in which the motion is affected by pathophysiology. In addition, the temporal characteristics of longitudinal motion are still far from clear. It has been reported that

---

Address correspondence to: Heikki Yli-Ollila, Kanta-Häme Central Hospital, Ahvenistontie 20, Hämeenlinna FI-13530, Finland. E-mail: heikki.yli-ollila@khshp.fi

longitudinal motion displays a multiphasic waveform and, furthermore, that the main direction of the motion can vary from subject to subject (Ahlgren et al. 2012; Cinthio et al. 2006; Yli-Ollila et al. 2013). It also has been reported that there is decay in longitudinal amplitude moving along the vessel length further from the heart (Zahnd et al. 2015a). More research is needed to understand the biomechanics of longitudinal motion so that it can serve as an independent arterial stiffness index.

There are only a few publications focusing on mathematical approaches to the study of longitudinal artery wall motion. Finite-element and fluid–structure interaction models have been used to represent the anatomy and the physiology of an artery and to estimate the kinetics of the arterial wall (Bukac and Canic 2013; Warriner et al. 2008). Bukac and Canic (2013) used an atherosclerotic artery model and revealed that unlike radial motion, longitudinal motion is highly dependent on atherosclerotic lesion geometry. Warriner et al. (2008) created a working carotid artery fluid–structure model and concluded that the presence of longitudinal wall motion should always be considered when studying the effect of arterial wall motion on fluid velocity. Mathematical modeling has also been used to create an ultrasound imaging phantom, including the longitudinal motion component (Stoitsis et al. 2008). In addition to the modeling-based studies, a different mathematical approach linking artery wall motion and the stage of atherosclerosis has been reported (Gastounioti et al. 2014). In the study, hidden Markov models were used to build a computer-aided diagnosis scheme for potential clinical use. The scheme used the motion characteristics of the measured carotid arteries, including the longitudinal motion component, and was able to discriminate atherosclerotic high-risk patients from low-risk patients with good accuracy. In addition, a mathematical Fourier series-based approximation has been successfully adapted to the longitudinal motion signal to assess arterial stress from the measured *in vivo* data (Soleimani et al. 2016). In healthy common carotid arteries, the maximum stress in the longitudinal direction was measured as 1.7 kPa (±0.6 kPa).

In this study, we applied mathematical principal component analysis (PCA) to characterize the longitudinal carotid wall motion waveform in detail in a study population of 20 healthy volunteers. The PCA compresses the common features of the arterial motion waveform into a few parameters. For comparison, the PCA was also performed for the radial motion of the carotid wall. Previous studies on longitudinal motion have focused on its amplitude, but to better understand longitudinal motion and its relation to arterial stiffness, the characteristics of the motion waveform need to be clarified in detail. Multiple referential arterial stiffness measurements were performed in this study to investigate how early arterial stiffening affects longitudinal waveforms (principal component [PC] values). This kind of PCA approach to clarifying the wall motion waveform has not been conducted previously.

METHODS

Patients and study protocol

Twenty healthy, non-smoking patients of normal weight were recruited, but one volunteer was omitted from the final analysis because left bundle branch block was detected. After at least 10 min of rest in the supine position, a 2-min ultrasound imaging video of the longitudinal section of the left common carotid artery was recorded with a Philips EPIQ 7 equipped with an 18-MHz linear transducer (Philips, L18-5, Best, Netherlands) and electrocardiography (ECG) electrodes. The ultrasound video frame (1.25 × 1.5 cm, width × height) was positioned so that the carotid bifurcation was merely visible on the right side of the image and the focus of the ultrasound was positioned on the far wall of the artery. The imaging rate achieved with the setup was 85 Hz.

The 2-min video was cut into two 1-min signals for principal component analysis and repeatability analysis. Ultrasound imaging was performed by an experienced physician. The large amount of video data allowed the removal from the analysis of such artifacts subject swallowing; the variation in longitudinal motion amplitude caused by breathing was averaged out by collecting data over multiple breathing cycles.

After ultrasound imaging, both applanation tonometry and pulse wave velocity measurements were conducted with the SphygmoCor system (Version 9, AtCor Medical, Itasca, IL, USA) on the radial and carotid arteries to obtain referential stiffness indices. The systolic and diastolic brachial blood pressures (SBP and DBP) were measured in the left arm with an automatic blood pressure monitor (Omron, M4-I, Matsusaka, Kyoto, Japan) before and after ultrasound imaging and before the tonometry measurements. The carotid applanation tonometry measurement was used convert the brachial blood pressure values into carotid pressures that were used in the computation of stiffness indices.

All of measurements described here are pain-free, non-invasive and non-harmful to the volunteers. Written informed consent was obtained from every participant, and the ethics committee of Kuopio University Hospital approved the study protocol.

Carotid wall motion tracking

Longitudinal motion tracking was performed for the far arterial wall, using our in-house MATLAB code