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● *Technical Note*

INVESTIGATION OF ULTRASOUND-MEASURED FLOW RATE AND WALL SHEAR RATE IN WRIST ARTERIES USING FLOW PHANTOMS

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Abstract—The aim of this study was to evaluate the errors in measurement of volumetric flow rate and wall shear rate measured in radial and ulnar arteries using a commercial ultrasound scanning system. The Womersley equations were used to estimate the flow rate and wall shear rate waveforms, based on the measured vessel diameter and centerline velocity waveform. In the experiments, each variable (vessel depth, diameter, flow rate, beam–vessel angle and different waveform) in the phantom was investigated in turn, and its value was varied within a normal range while others were fixed at their typical values. The outcomes revealed that flow rate and wall shear rate were overestimated in all cases, from around 13% to nearly 50%. It is concluded that measurements of flow rate and wall shear rate in radial and ulnar arteries with a clinical ultrasound scanner are vulnerable to overestimation. (E-mail: z.y.huang@dundee.ac.uk and cmxia@ecust.edu.cn) © 2015 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Radial artery, Ulnar artery, Flow rate, Wall shear rate, Womersley, Doppler ultrasound, Flow phantoms.**

INTRODUCTION

In the last decade, the number of cases in which blood flow in the radial and ulnar arteries is investigated with ultrasound imaging has increased. One common example is catheterization of the coronary arteries. Before catheterization, ultrasound imaging is often used to determine the blood flow rate in the ulnar artery to ensure that the collateral circulation via the ulnar artery is adequate to perfuse the hand (Habib et al. 2012). Measurement of the volumetric flow rate and resistive index of flow waveforms in the ulnar artery is also required in cannulation of the radial artery and radial harvesting for coronary surgery (Gaudino et al. 2005; Kim et al. 2012; Royse et al. 2008). Blood flow velocities and waveforms in the radial and ulnar arteries have been used to evaluate the sympathetic skin response of poststroke patients as compared with healthy subjects (Tiftik et al. 2014). Flow rates in the radial and ulnar arteries measured with ultrasound can also be used to distinguish different forms of Raynaud's disease caused by a lack of blood supply from the radial and ulnar arteries to the fingers (Toprak et al. 2009; 2011).

These studies simply estimated the flow rate as the product of maximum velocity and blood vessel area (Ozcan et al. 2011; Tiftik et al. 2014; Toprak et al. 2011). Furthermore, evaluation of the accuracy or reliability of these measurements has not been considered in the literature. Measurements of flow rate in arteries with ultrasound imaging are vulnerable to error (Li et al. 1993; Ponzini 2010; Steinman et al. 2001; Swillens et al. 2009). Researchers have validated arterial flow rates using an experimental system employing phantoms (Hoskins et al. 2010; Leguy et al. 2009; Ricci et al. 2013). The validation of arterial ultrasound imaging and blood flow has been reviewed by Hoskins (2008). Most of the aforementioned studies

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concerned measurement of flow rates in larger arteries such as the carotid and femoral, which have diameters in the range 5–10 mm. The radial and ulnar arteries have smaller diameters of 2–3 mm (Habib et al. 2012) and a lower flow rate of 50 mL/min (Manabe et al. 2005). There has been no specific investigation of errors in flow rate relevant to the ulnar and radial arteries.

In addition to flow rate, one other parameter investigated in this study is wall shear rate. The wall shear rate, which is relevant to wall shear stress being sensed through sensors within the endothelium and thought to be part of a control mechanism in the arterial wall (Davies 1995), has attracted great interest over the years (Blake et al. 2008; Hoeks et al. 1995; Mynard et al. 2013). Measurement of wall shear rates in the radial and ulnar arteries should provide more clinical information on diseases of these two arteries. However, there has been no study measuring wall shear rate in the radial and ulnar arteries or evaluating their errors.

The aim of this study was to evaluate these errors of volumetric flow rate (FR) and wall shear rate (WSR) on the basis of ultrasound measurements made in a flow phantom.

METHODS

Overview

A method developed by Blake et al. (2008) was used to estimate volumetric flow rate and wall shear rate simultaneously. It relies on measurement of the maximum Doppler frequency from spectral Doppler and of diameter from the B-mode image, which can be obtained from digital image data without the need for radiofrequency or IQ data. These are used as input in the Womersley equations. The output is the time-varying velocity profile from which the volumetric flow waveform and the wall shear rate waveform are calculated. It is noted that the method assumes fully developed flow.

Theory

The Womersley equations were used to derive the time-varying velocity profile of the pulsatile flow in a long, rigid wall pipe (Womersley 1955). The original Womersley equations estimated velocity profiles with input of the mean velocity–time waveform. Holdsworth et al. (1999) modified the Womersley equations so that the centerline velocity could be input instead of the mean velocity. The centerline velocity corresponds to the maximum velocity, apart from a brief period during which the flow changes direction. This formulation then allows the maximum velocity–time waveform obtained from spectral Doppler to be used as input in the Womersley equations. This method was used by Blake et al. (2008) for estimation of wall shear rate, and this study follows the same methodology. Vessel diameter is measured using B-mode imaging. The velocity profile $v_f(y,t)$ in arteries can be calculated as

$$v_f(y,t) = \sum_{k=0}^{+\infty} \mathrm{Re}\left\{ V_k e^{j(k\omega t-\varphi_k)} \left[\frac{J_0(\tau_k)-J_0(\tau_k y)}{J_0(\tau_k)-1} \right] \right\} \quad (1)$$

where Re represents the real part of a complex function; J_0 is the zero-order Bessel functions of the first kind; y is the normalized radial coordinate; ω is the angular frequency; t is time; φ_k represents the phase of each harmonic; V_k is the centerline velocity of each harmonic; and τ_k is represented by $\alpha_{k*} j^{3/2}$. α_k is the Womersley number for each harmonic,

$$\alpha_k = R\sqrt{\frac{k\omega}{v}} \quad (2)$$

where v is the kinematic viscosity of the fluid, and R is the diameter. After the time-varying velocity profile is obtained, the flow rate $Q(t)$ can be derived using the equation

$$Q(t) = 2\pi \int_0^R v_f(y,t)y\partial y \quad (3)$$

The wall shear rate, wsr(t), is calculated as

$$\mathrm{wsr}(t) = \left.\frac{\partial v_f(y,t)}{\partial y}\right|_{y=R} \quad (4)$$

Figure 1 is a schematic of the estimation of flow rate and wall shear rate using the Womersley equations.

Flow phantom

Flow phantoms were constructed with acoustically equivalent tissue-mimicking materials (Fig. 2). A straight blood vessel mimic made from polyvinyl alcohol cryogel (PVA-c) subjected to six freeze–thaw cycles (Dineley et al. 2006) was embedded at a known depth within the agar-based tissue mimic (Teirlinck et al. 1998). The PVA-c vessel set in a Perspex box was filled with water and sealed at both ends to generate resistance while pouring the tissue mimic. A blood mimic based on nylon particles was used with acoustic properties and viscosity matching those of blood (Ramnarine et al. 1998).

Pulsatile flow patterns were achieved by connecting a gear pump (Micropump Series GA-X21, Vancouver, WA, USA) to the inflow of the phantom loop. The pump was controlled with Labview 2010 (National Instruments, Austin, TX, USA) to generate different flow waveforms in the blood vessel.