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● *Original Contribution*

COMMON CAROTID ARTERY FLOW MEASURED BY 3-D ULTRASONIC VECTOR FLOW IMAGING AND VALIDATED WITH MAGNETIC RESONANCE IMAGING

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Abstract—Ultrasound (US) examination of the common carotid artery was compared with a through-plane magnetic resonance imaging (MRI) sequence to validate a recently proposed technique for 3-D US vector flow imaging. Data from the first volunteer examined were used as the training set, before volume flow and peak velocities were calculated for the remaining eight volunteers. Peak systolic velocities (PSVs) and volume flow obtained with 3-D US were, on average, 34% higher and 24% lower than those obtained with MRI, respectively. A high correlation was observed for PSV ($r = 0.79$), whereas a lower correlation was observed for volume flow ($r = 0.43$). The overall standard deviations were ±5.7% and ±5.7% for volume flow and PSV with 3-D US, compared with ±2.7% and ±3.2% for MRI. Finally, the data were re-processed with a change in the parameter settings for the echo-canceling filter to investigate its influence on overall performance. PSV was less affected by the re-processing, whereas the difference in volume flow between 3-D vector flow imaging and MRI was reduced to −9%, and with an improved overall standard deviation of ±4.7%. The results illustrate the feasibility of using 3-D US for precise and angle-independent volume flow and PSV estimation *in vivo*. (E-mail: sholbek@elektro.dtu.dk) © **2017 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Vector flow imaging, Transverse oscillation, 3-Dimensional, Blood flow quantification, Magnetic resonance imaging, Volume flow.**

INTRODUCTION

Pathology in the vessels is often reflected directly in the related hemodynamics. For instance, increased blood velocity is observed in stenotic vessels (Alexandrov et al. 1997; Phillips et al. 1980), and the change in volume flow in patients with arteriovenous fistulas is used to monitor the risk of developing a stenosis (Whittier 2009; Wiese and Nonnast-Daniel 2004). Ultrasound (US) is an easily accessible imaging modality that can provide the required information in real time. Currently, 1-D Doppler techniques and 2-D vector flow imaging (VFI) techniques can be used to estimate both velocities and volume flow, and have been applied clinically (Brandt et al. 2016). In this article, *D* refers to the dimension of known velocity components mapped on a 2-D image. The exception is 1-D spectral Doppler ultrasound (SDUS), which provides 1-D velocity information in a single point.

One-dimensional US methods, however, are subject to errors in velocity estimation because of, for example, geometric spectral broadening, which depends on the transducer dimension and relative examination location (Hoskins et al. 1999) and angle dependency (Picot and Embree 1994). The angle dependency encountered in 1-D US requires an operator to manually compensate for the flow direction and to assume that the out-of-plane velocity component is insignificant. It also assumes a fixed angle throughout the cardiac cycle, which is generally incorrect (Udesen et al. 2008). For 2-D vector flow methods (Bohs and Trahey 1991; Fadnes et al. 2015; Jensen 2001; Lenge et al. 2015; Nikolov and Jensen 2003; Udesen et al. 2008; Villagomez-Hoyos et al. 2016b; Yiu et al. 2014), angle dependency has been solved, but still relies on the assumption that the out-of-plane velocity component does not contribute to the flow.

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Volumetric flow rates can be estimated with either 1-D Doppler techniques (Struijk et al. 2005) or 2-D vector flow techniques (Hansen et al. 2017). Both types of techniques rely on several operator decisions and necessary mathematical assumptions about flow and vessel geometry symmetry, which influence the accuracy of the estimates (Jensen et al. 2016). These decisions and assumptions are significantly reduced for 3-D US VFI techniques, for which there are a variety of approaches (Correia et al. 2016; Holbek et al. 2016, 2017; Pihl and Jensen 2014; Pihl et al. 2014; Provost et al. 2014; Villagomez-Hoyos et al. 2016a; Wigen and Løvstakken 2016).

The purpose of the work described here was to determine the accuracy of the angle-independent 3-D US method proposed in previous work (Holbek et al. 2017) for accurate flow quantification. The method is validated in a clinical setup by scanning the common carotid artery (CCA) in nine healthy volunteers and comparing the results with magnetic resonance imaging (MRI) results. Several studies have compared MRI with US (Harloff et al. 2009, 2013; Hansen et al. 2009); however, this work presents the first comparison of 3-D VFI with MRI.

METHODS

Three measurements were performed in each volunteer: two US measurements (SDUS and 3-D US) and one MRI measurement. The US and the MRI examinations were conducted by two clinicians (K.L.H. and C.E), each with more than 10 years of experience in radiology.

Volunteers

Nine healthy volunteers were included in this study. The study was performed after approval by the Danish National Committee on Biomedical Research Ethics (H-1-2014-FSP-072), and written informed consent was obtained from all volunteers.

Two women and 7 men ranging in age from 27 to 52 y (median 30) and ranging in body mass index from 20 to 27 kg/m^2 (mean 24 $\pm$ 2.7 kg/m^2) were included in the study.

Experimental procedure

All volunteers fasted for at least 2 h and rested in the supine position for 15 min before all examinations. The right CCA was examined in all volunteer using 1-D SDUS, 3-D US and MRI. Data were acquired on 2 consecutive days for each volunteer. On day 1, the 3-D US measurement was conducted, and on day 2, the MRI examination was performed. The examinations were carried out on two different days, as the experimental scanner used for 3-D US and the MRI scanner were permanently installed at different locations.

After each 3-D US acquisition, a maximum of 0.5 s of data was processed and inspected to ensure that data were not corrupted. The only exception to this were data from volunteer 1, which were used as the training sample to lock all the various parameters in the post-processing stage. Data from the remaining eight volunteers were processed according to the training sample. This was first done after the last volunteer had completed both the MRI examination and the 3-D US measurement.

Spectral Doppler measurements

A reference measurement with SDUS was made prior to both the 3-D US measurement and MRI examination. The reference measurement consisted of an approximately 10-s cine loop with SDUS velocity information, recorded 2–3 cm upstream of the bifurcation in the common carotid artery. A 5.2–MHz linear array transducer (9032, BK Ultrasound, Herlev, Denmark) and a commercial scanner (BK 5000, BK Ultrasound) were used for these measurements.

The SDUS cine loop for each volunteer was stored and processed offline. The entire cine loop was evaluated, and the peak velocities displayed were manually noted for each of the recorded heart cycles, from which the mean values and standard deviations were calculated.

3-D US measurements

Three-dimensional US measurements were performed in an experimental laboratory, where a 2-D 32 $\times$ 32-element phased array transducer with a center frequency of 3.5 MHz was used (Vermon S.A., Tours, France). The transducer was connected to the experimental ultrasound scanner SARUS (Jensen et al. 2013), which sampled from all 1024 channels at a sampling frequency of 17.5 MHz.

An interleaved flow and B-mode emission sequence described in previous work was used (Holbek et al. 2017). The flow sequence contained focused steered emission and had a field-of-view of 30°, whereas the B-mode emissions consisted of diverging waves, which provided a 60° $\times$ 60° field-of-view volume using synthetic aperture imaging techniques. The transverse oscillation (TO) method (Jensen 2001; Jensen and Munk 1998) was used for velocity estimation. The pulse repetition frequency (f_{prf}) was 12.6 kHz. Intensities of the applied 3-D US sequence were as follows: mechanical index (MI) = 1.14, and $I_{spta.3}$ = 439 mW/cm^2, which are below U.S. Food and Drug Administration limits (FDA 2008). A total of 7.5 s of data were recorded for each measurement and stored offline for further processing.

3-D US data analysis

Processing of the 3-D US data was identical to the procedure described in previous work (Holbek et al.