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● *Original Contribution*

VECTOR FLOW IMAGING COMPARED WITH PULSE WAVE DOPPLER FOR ESTIMATION OF PEAK VELOCITY IN THE PORTAL VEIN

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Abstract—The study described here investigated whether angle-independent vector flow imaging (VFI) technique estimates peak velocities in the portal vein comparably to pulsed wave Doppler (PWD). Furthermore, intra- and inter-observer agreement was assessed in a substudy. VFI and PWD peak velocities were estimated with from intercostal and subcostal views for 32 healthy volunteers, and precision analyses were conducted. Blinded to estimates, three physicians rescanned 10 volunteers for intra- and inter-observer agreement analyses. The precision of VFI and PWD was 18% and 28% from an intercostal view and 23% and 77% from a subcostal view, respectively. Bias between VFI and PWD was 0.57 cm/s ($p = 0.38$) with an intercostal view and 9.89 cm/s ($p < 0.001$) with a subcostal view. Intra- and inter-observer agreement was highest for VFI (inter-observer intra-class correlation coefficient: VFI 0.80, PWD 0.3; intra-observer intra-class correlation coefficient: VFI 0.90, PWD 0.69). Regardless of scan view, VFI was more precise than PWD. (E-mail: andreas.hjelm.brandt@regionh.dk)

Key Words: **Vector velocity, Vector flow imaging, Pulsed wave Doppler, Portal vein, Abdominal ultrasound, Agreement analysis, Precision analysis.**

INTRODUCTION

Transabdominal ultrasound is used worldwide as a non-invasive technique for examination of patients suspected of having liver disease. In addition to assessment of liver texture, size and surface, pulsed wave Doppler (PWD) is used for evaluation of blood flow in the main portal vein (Berzigotti and Piscaglia 2012). Portal hypertension can lead to reduced peak velocity and, in advanced stages, reversed flow (Davis and Chong 2014; Kok et al. 1999). PWD is accepted as a standard clinical technique for peak velocity estimation in the portal vein (Berzigotti and Piscaglia 2012; Kruskal et al. 2004), and has a sensitivity and specificity of 95% for the diagnosis of portal hypertension (Singal et al. 2010). However, errors in velocity estimation with PWD are well described at beam-to-flow angles >70° (Hoskins 1999; Park et al. 2012; Stewart 2001), which offer only one reliable scan position (intercostal) of the portal vein (Berzigotti and Piscaglia 2012). Furthermore, PWD assumes that a fixed single beam-to-flow angle for angle correction during the cardiac cycle is sufficient, thus ignoring that *in vivo* blood flow seldom is laminar throughout a cardiac cycle, which manifests itself in spectral broadening (Hoskins 1999; Tortoli et al. 2015). Spectral broadening causes PWD velocity estimation error at any insonation angle, although the errors are more pronounced at higher beam-to-flow angles (80°–90°) (Hoskins 1999; Steel et al. 2003; Yang et al. 2013). Furthermore, manual angle correction adds to the velocity estimation error (Lui et al. 2005), and inter- and intra-observer agreement has been reported to be low for portal vein velocity estimation with PWD (O'Donohue et al. 2004).

The ultrasound vector flow imaging (VFI) technique, based on the transverse oscillation (TO) method, is an angle-independent technique for vector velocity estimation (Jensen and Munk 1998). VFI has no restrictions on scan position and is less operator dependent than PWD

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because no manual angle correction is applied. The vector velocity is calculated from the axial and transverse velocities, where the axial velocity is found as in conventional Doppler ultrasound, whereas the transverse velocity is found by manipulating the receive beamforming (Jensen 2001; Udesen and Jensen 2006). TO has been validated in simulation studies and against conventional PWD and magnetic resonance angiography of flow in the carotid artery (Hansen et al. 2009a, 2009b; Pedersen et al. 2012; Udesen and Jensen 2006).

To date, VFI has been investigated on a linear array transducer setup with a maximum scan depth of 60 mm (Hansen et al. 2013, 2014, 2015; Pedersen et al. 2012; Tortoli et al. 2015). For abdominal vessel scanning, for example, measurements of portal flow, a penetration depth of 70–90 mm is needed. VFI was for this purpose developed for a convex array transducer, where the maximum scan depth of VFI is increased to approximately 80–90 mm (Brandt et al. 2015; Jensen et al. 2014, 2015).

Because VFI has no restrictions on scan position, the operator can potentially achieve more reliable assessment of the portal flow. The hypothesis was that the angle-independent VFI technique has the same precision and can estimate the same peak velocity as PWD. The VFI estimation algorithm was investigated in a phantom using a flow rig to evaluate precision and accuracy in a controlled setup. The precision and peak velocity VFI estimates *in vivo* were compared with those of PWD in two scan positions of the portal vein. Additionally, the intra- and inter-observer agreement for VFI and PWD was assessed *in vivo* in a substudy.

METHODS

Thirty-five healthy volunteers were asked to participate after informed consent and approval were obtained from the National Committee on Biomedical Research Ethics (Journal No. 15000104). Exclusion criteria were any known liver diseases (n = 0) and portal vein location outside (>9.5 cm) the VFI scan range (n = 3). Thus, 32 volunteers entered the study. Among the volunteers were 20 women and 12 men, ranging in age from 25 to 66 y (mean ± SD: 39.0 ± 11.9 y) and in body mass index from 17.6 to 25.9 kg/m^2 (mean ± SD: 21.9 ± 2.2 kg/m^2). Among the excluded volunteers were 1 women and 2 men, age ranging in age from 32 to 42 y (mean ± SD: 37.3 ± 5.0 y) and in body mass index from 26.3 to 28.4 kg/m^2 (mean ± SD: 27.4 ± 1.1 kg/m^2).

A commercially available ultrasound scanner equipped with VFI (BK3000, BK Ultrasound, Herlev, Denmark) and a 3-MHz convex probe (6C2, BK Ultrasound) were used to obtain vector velocity data. Vector velocities are displayed in real time on the B-mode image as both color-coded pixels given by a 2-D color wheel and as *arrows* superimposed on the color map (Fig. 1). While scanning with VFI, the color box was adjusted to cover the lumen of the portal vein, and the pulse repetition frequency (PRF) was adjusted to the highest velocities to prevent aliasing (1.2–2.0 kHz). Wall filter and color gain were set to obtain filling of the entire vessel without blooming artifacts. Recorded VFI data were processed offline in MATLAB (The MathWorks, Natick, MA, USA) using an algorithm developed in-house (Jensen et al. 2014; Moshavegh et al. 2016). The algorithm estimates the VFI peak velocity after the operator places two points on each side of the portal vein. A line is automatically created between the points (Fig. 1). The line was placed corresponding to the same position and depth as the range gate placed for the corresponding PWD estimation. Several vector velocity magnitudes are estimated along the placed line, and the pixel with the highest vector velocity is indicated as the VFI peak velocity. VFI peak velocity was the highest velocity over approximately 100 (range: 91–135) frames of data (mean ± standard deviation [STD]: 101.39 ± 5.96), corresponding to the highest velocity over on average of five heartbeats (mean ± STD: 5.46 ± 0.83). Along with VFI peak velocity, the beam-to flow angle mean and standard deviation (STD) were obtained at the same location for the same cardiac cycle. PWD data were obtained with the same conventional ultrasound scanner and probe as used for the VFI scans with a standard spectral Doppler setup (Fig. 1). The operator performed angle corrections parallel to the vessel wall, and the PRF was set to avoid aliasing (1.2–2.0 kHz). The scanner determined PWD peak velocity in real time, and the value was displayed on the screen. PWD peak velocity was the maximum velocity over 3–5 heartbeats (mean ± STD: 4.54 ± 0.76), depending on the volunteer's heart rate.

For flow rig validation of VFI, a flow system (CompuFlow 1000, Shelley Medical Imaging Technologies, Toronto, ON, Canada) circulating a blood-mimicking fluid (BMF-US, Shelley Medical Imaging Technologies, Toronto, Canada) in a closed-loop circuit was used. Calibrated volume flow measurements were performed with a magnetic flowmeter (Danfoss Magflow, Nordborg, Denmark) measuring the mass flow with an accuracy of at least 1%, as specified in the manufacturer's data sheet. The convex transducer was fixed at 70 mm from the 12-mm-diameter vessel at a beam-to-flow angle of 90°. VFI data were recorded for increasing constant flow rig peak velocities from 5 to 49 cm/s. For precision analysis, each velocity setting was recorded twice. At a peak velocity of 25 cm/s, the STD of VFI peak velocity was estimated with 10 repeated recordings.

For *in vivo* comparison, the scans were performed by the same physician (A.H.B.). The 32 volunteers fasted 4–6 hours prior to the examination. Scans were performed in the supine position with intercostal and subcostal views