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● *Original Contribution*

SHUNT FLOW EVALUATION IN CONGENITAL HEART DISEASE BASED ON TWO-DIMENSIONAL SPECKLE TRACKING

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Abstract—High-frame-rate ultrasound speckle tracking was used for quantification of peak velocity in shunt flows resulting from septal defects in congenital heart disease. In a duplex acquisition scheme implemented on a research scanner, unfocused transmit beams and full parallel receive beamforming were used to achieve a frame rate of 107 frames/s for full field-of-view flow images with high accuracy, while also ensuring high-quality focused B-mode tissue imaging. The setup was evaluated *in vivo* for neonates with atrial and ventricular septal defects. The shunt position was automatically tracked in B-mode images and further used in blood speckle tracking to obtain calibrated shunt flow velocities throughout the cardiac cycle. Validation toward color flow imaging and pulsed wave Doppler with manual angle correction indicated that blood speckle tracking could provide accurate estimates of shunt flow velocities. The approach was less biased by clutter filtering compared with color flow imaging and was able to provide velocity estimates beyond the Nyquist range. Possible placements of sample volumes (and angle corrections) for conventional Doppler resulted in a peak shunt velocity variations of 0.49–0.56 m/s for the ventricular septal defect of patient 1 and 0.38–0.58 m/s for the atrial septal defect of patient 2. In comparison, the peak velocities found from speckle tracking were 0.77 and 0.33 m/s for patients 1 and 2, respectively. Results indicated that complex intraventricular flow velocity patterns could be quantified using high-frame-rate speckle tracking of both blood and tissue movement. This could potentially help increase diagnostic accuracy and decrease interobserver variability when measuring peak velocity in shunt flows. (E-mail: solveig.fadnes@ntnu.no) © 2014 World Federation for Ultrasound in Medicine & Biology.

Key Words: **2-D blood flow imaging, Speckle tracking, *In vivo*, Atrial septal defect, Ventricular septal defect.**

INTRODUCTION

Atrial (ASDs) and ventricular (VSDs) septal defects are the two most common forms of congenital heart defects (van der Linde et al. 2011). The natural history of small septal defects may be regression or spontaneous closure (Hanslik et al. 2006; Penny and Vick 2011), whereas more severe defects must be repaired by catheter closure or corrective surgery. The management of an ASD or VSD depends on the location, size, hemodynamic consequences, associated defects and the symptomatology of the patient. Generally, the clinical approach is to repair an isolated ASD or VSD when there is a large left-to-right shunt (Driscoll et al. 1994). In pediatric cardiology today, 2-D echocardiography with color flow imaging (CFI) is used to detect and visualize septal defects. Continuous wave Doppler and pulsed wave (PW) Doppler are utilized to estimate the peak velocity and evaluate the shunt flow (Forbus and Shirali 2009).

Color flow imaging and continuous wave and pulsed wave Doppler have been extensively validated and are used in a wide range of clinical settings, but the methods have fundamental limitations. The frequency shifts between the transmitted and received ultrasound waves are used to estimate the blood velocity components along the ultrasound beam axis. The velocity estimates are thus limited to one component of the velocity vector and dependent on the angle between the ultrasound beam and the blood flow direction, and the resulting color flow images can be difficult to interpret. In addition, CFI and PW Doppler are based on pulsed transmission of ultrasound waves, and the pulse repetition frequency limits the highest measurable velocities according to the Nyquist sampling theorem. Velocities above the Nyquist limit are commonly encountered and will give aliasing

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artifacts in the image where high velocities will not be displayed correctly. These fundamental limitations may lead to undetected defects and misdiagnosis (Benavidez et al. 2008).

To improve imaging and evaluation of shunt flows, other modalities have been suggested. Real-time 3-D echocardiography has yielded promising results in the visualization of septal defects (Acar et al. 2007; Cheng et al. 2004), but the blood flow estimation is still angle dependent. In transesophageal echocardiography, the probe is led down the patient's esophagus, and cardiac images of higher quality are achieved. Also, cardiac magnetic resonance imaging is a useful modality, not limited by the acoustic window, but the need for general anesthesia or sedation in these methods limits their use in pediatric cardiology (Oliver-Ruiz and Bret-Zurita 2007).

Several flow velocity estimators for estimating both the axial and lateral velocity components have been proposed. Speckle tracking (Bohs et al. 2000) and vector Doppler (Dunmire et al. 2000) are the two main research lines for 2-D flow estimation, but recently new techniques such as echo particle image velocimetry (PIV) (Poelma et al. 2009; Zheng et al. 2006) have been suggested. For the latter, the need for contrast agents makes it currently not suitable for pediatric imaging. The speckle tracking technique uses the speckle in the ultrasound image, which is a result of the constructive and destructive interference from the backscattered echoes, to estimate the velocity of the scatterers. The movement of the blood speckle is correlated with the movement of the blood, and the speckle can be tracked from frame to frame to obtain information on blood velocities. The vector Doppler technique combines the Doppler estimates from two transmit and/or receive angles to obtain angle-independent velocity measurements. Several studies have been performed to evaluate the speckle tracking and vector Doppler techniques for numerically simulated flow patterns, *in vitro* flow phantoms and *in vivo* in human vessels (Bohs and Gebhart 2001; Bohs et al. 1995; Pastorelli et al. 2008; Steel et al. 2004; Swillens et al. 2010; Tortoli et al. 2010). However, neither speckle tracking nor vector Doppler has yet been established for clinical use in blood flow estimation. This can, in our experience, be attributed to a lack of robustness and limitations related to data acquisition and processing capabilities for real-time imaging.

Recent developments in ultrasound imaging technology provide a substantially higher acquisition rate which offers new possibilities in 2-D flow estimation. By transmitting broad unfocused ultrasound pulses, parallel receive beamforming can be used to increase the acquisition rate, resulting in instantaneous full field-of-view images at high frame rates. The technique has been suggested for elastography (Tanter et al. 2002), compound Doppler imaging (Bercoff et al. 2011) and vector velocity imaging (Udesen et al. 2008). The high acquisition rate also makes it possible to have a higher ensemble size for improved clutter filtering possibilities and to achieve more robust velocity estimates without compromising a high frame rate, which is advantageous when imaging complex blood flow (Ekroll et al. 2013).

Quantitative vector velocity imaging has, to the authors' knowledge, not previously been evaluated for use in pediatric cardiology. However, a qualitative method based on the direct visualization of blood speckle has been suggested, and was shown to increase the certainty in ASD shunt flow evaluation (Lovstakken et al. 2006; Nyrnes et al. 2007). In this work, we investigate 2-D speckle tracking for quantitative blood flow velocity estimation in ASDs and VSDs in newborns. The overall objective was to achieve angle-independent peak shunt flow velocity estimates for better shunt evaluation. To find the true peak velocity throughout the cardiac cycle, we further propose the use of tissue speckle tracking to follow the shunt position in the 2-D image plane throughout the cardiac cycle.

METHODS

Two patients from the ongoing feasibility study are the subjects in this study. Patient 1, a boy, was 8 days old and 3340 g at the time of the ultrasound recordings. He had a perimembranous VSD, which was focused on in this study. He was also born with a secundum ASD, a pulmonary artery sling (the left pulmonary artery anomalously originating from the right pulmonary artery) and an anal atresia. Patient 2, a girl, was born prematurely at 31 + 4 weeks and diagnosed with a secundum ASD. She was 25 days old and 2165 g when included and had no additional congenital malformations. Written informed consent was obtained from the parents of the participants before the examination. The study was approved by the Norwegian Regional Committee for Medical and Health Research Ethics, and patient safety measurements were within the guidelines from the U.S. Food and Drug Administration.

In vivo *and* in vitro *setup*

We used a SonixMDP ultrasound scanner (Ultrasonix, Richmond, BC, Canada) with a 4- to 9-MHz linear transducer and a Sonix DAQ for channel data acquisition for *in vivo* and *in vitro* recordings. In the duplex acquisition scheme implemented, separate acquisition setups were used for B-mode and flow imaging to ensure sufficient image quality for both modalities. Figure 1 is a schematic of data acquisition and post-processing used in this