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Fluid flow measurement for diagnosis of ventricular shunt malfunction using nonlinear response of microbubbles in the contrast-enhanced ultrasound imaging

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1. Introduction

Hydrocephalus is a condition with an excessive accumulation of cerebrospinal fluid (CSF) in the brain[1)]. It can be caused by improper drainage of CSF from the ventricles and subarachnoid space. A common treatment for hydrocephalus is placing a drainage tube (i.e., ventricularperitoneal (VP) shunt) between the brain ventricles and abdominal cavity. However, complications including blockage, breakage, and leakage are associated with malfunctions of the ventricular shunts. To diagnose shunt malfunctions noninvasively, measuring CSF flow in a shunt is necessary. Doppler ultrasound imaging has been proposed previously to monitor the flow; but it has limited sensitivity to low flow rates, and has high angle dependency[2)]. In our recent study[3)], we demonstrated that contrast-enhanced ultrasound speckle tracking imaging has potential to diagnose shunt malfunctions, even in low flow rates.

Contrast-enhanced ultrasound imaging utilizes gas microbubbles that are acoustic scatterers with a strong nonlinear response[4)]. Although the nonlinear response helps differentiate between the gas microbubbles and other tissues, it has another significant safety implication to measuring CSF flow in a shunt using low doses of microbubbles. In this study, we utilize nonlinear response of the microbubbles to estimate the fluid flow in a VP shunt, and investigate the influence of bubble concentration on the estimation of fluid velocity in the shunt.

2. Materials and Methods

Experimental setup to simulate fluid flow in a shunt catheter (1.2 mm inner and 2.4 mm outer diameters) is shown in **Fig. 1**. The catheter was placed parallel to the face of the transducer along the lateral direction of the imaging plane, and was submerged in water. The flow within the catheter was controlled by a syringe pump (Cole Parmer, Vernon Hills, Illinois, USA). A microbubble solution (Optison, GE Healthcare, Little Chalfont, United Kingdom) was diluted to 1% of the original concentration and 0.5 ml aliquot was injected into the shunt valve (Medtronic, Minneapolis, Minnesota, USA). The flow rate of the fluid was set to 0.1 ml/min.

To image the bubble flow in the shunt catheter, pulse-inversion[5)] was implemented using an ultrasound imaging system (V1, Verasonics Inc., Kirkland, WA, USA). An L7-4 linear array transducer (128 elements) was used to transmit a pulse at 3.75 MHz center frequency and the received signal (IQ data) was sampled at 22.5 MHz. Linear (i.e., B-mode) data were obtained from the received signals of the first pulse, and nonlinear (i.e., contrast-mode) data were generated by summation of the responses from the first and the second pulses, where the second pulse was inverted replica of the first pulse. As the bolus of injected microbubbles was passing through the shunt, the concentration of bubbles within the shunt catheter progressively decreased. Then, linear and nonlinear data were collected and named as conc. #1, conc. #2, and conc. #3 in an order of reduced concentration.

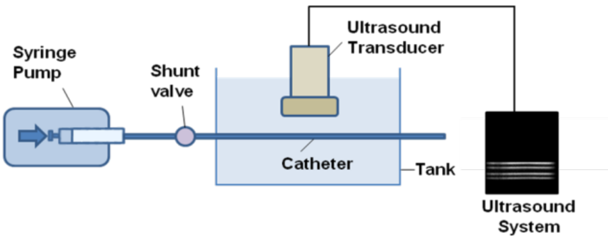

Fig. 1 Experimental setup to image the flow in a VP shunt catheter using an ultrasound imaging system.

The displacements of the bubbles in the catheter were estimated by a cross-correlation based speckle tracking algorithm[6)] (1.8 mm lateral by 0.15 mm axial kernel). The velocities in the lateral direction were calculated from the estimates of the displacements for both the linear and nonlinear responses. Then, the velocity values in the catheter were compensated by a correction factor (1.33 when the elevational beam width was 1.2 mm) due to the averaging effect from the elevational beam width[3)]. The velocity profiles from linear and nonlinear responses were compared with the velocity profile of the fully developed laminar flow.

3. Result and Discussion

Frequency responses of microbubbles within the shunt catheter is shown in **Fig. 2.** In case of no microbubbles in the catheter, the signal reflected from the wall of the catheter was received; and, as expected, the response mainly contained a fundamental frequency (3.75 MHz) component. Once the microbubbles were injected, nonlinear components in sub-harmonic and 2nd harmonic were observed but fundamental frequency was still dominant in the linear mode. In the nonlinear mode, nonlinear fundamental and harmonics from bubbles were obtained.

Velocity maps estimated from linear (left column) and nonlinear (right column) responses are presented in **Fig. 3**. As microbubble concentration progressively decreased, the velocities in the linear mode were considerably underestimated. In the nonlinear mode, however, the flow is clearly visible even at the lowest concentration (i.e., conc #3). The velocity underestimation was mainly due to the influence of the stationary wall of the catheter. Thus, it is noted that the effect of bubble concentration is significant in the velocity estimation.

Velocity profiles in the shunt catheter are displayed in **Fig. 4**. The expected laminar velocity profile for the flow rate (0.1 ml/min) is presented for comparison. It is clearly seen that the estimated velocities from nonlinear response (bottom) are more accurate than those from linear response (top).

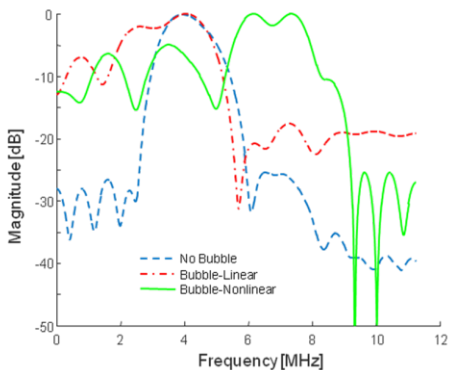

Fig. 2 Frequency responses from VP shunt and microbubbles.

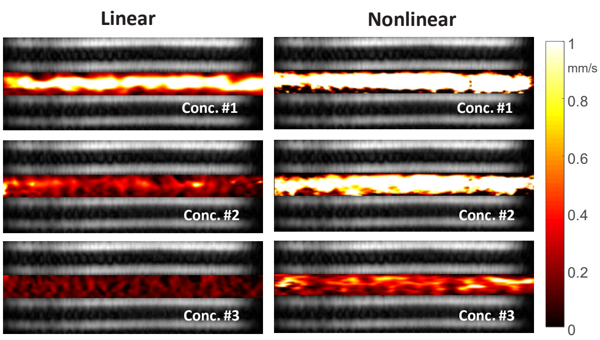

Fig. 3 Velocity maps for different concentrations of bubbles in linear and nonlinear modes.

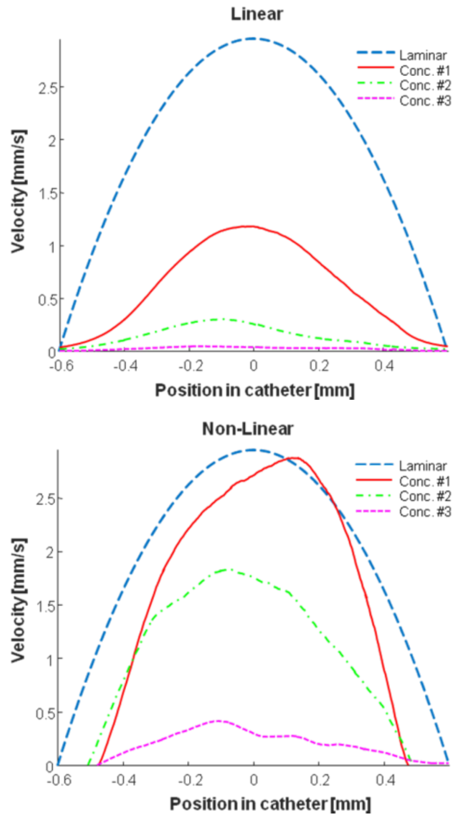

Fig. 4 Velocity profiles in VP shunt catheter in linear (top) and nonlinear (bottom) modes.

This study demonstrates that the nonlinear responses from microbubbles can be utilized to improve detection of the fluid flow in a VP shunt system using low concentration of bubbles.

Acknowledgment

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