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

Suhyun Park¹, Heechul Yoon², Stanislav Emelianov²⁺³ and Salavat Aglyamov¹
(¹ Univ. of Texas at Austin; ² Georgia Inst. of Tech.; ³ Emory Univ. Sch. of Med.)

1. Introduction

Hydrocephalus is a condition with an excessive accumulation of cerebrospinal fluid (CSF) in the brain¹. 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., ventricular-peritoneal (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 dependency². In our recent study³, 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 response⁴. 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-inversion⁵ 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.

The displacements of the bubbles in the catheter were estimated by a cross-correlation based speckle tracking algorithm⁶ (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 width⁷. 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).

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
This work was supported by the National Institute of Health under a grant NS090336.

References
1. NIH: Hydrocephalus. (National Institute of Neurological Disorders and Stroke, Maryland, 2008)