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● *Original Contribution*

MEASUREMENT OF THE DOPPLER POWER OF FLOWING BLOOD USING ULTRASOUND DOPPLER DEVICES

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Abstract—Measurement of the Doppler power of signals backscattered from flowing blood (henceforth referred to as the Doppler power of flowing blood) and the echogenicity of flowing blood have been used widely to assess the degree of red blood cell (RBC) aggregation for more than 20 y. Many studies have used Doppler flowmeters based on an analogue circuit design to obtain the Doppler shifts in the signals backscattered from flowing blood; however, some recent studies have mentioned that the analogue Doppler flowmeter exhibits a frequency-response problem whereby the backscattered energy is lost at higher Doppler shift frequencies. Therefore, the measured Doppler power of flowing blood and evaluations of RBC aggregation obtained using an analogue Doppler device may be inaccurate. To overcome this problem, the present study implemented a field-programmable gate array-based digital pulsed-wave Doppler flowmeter to measure the Doppler power of flowing blood, in the aim of providing more accurate assessments of RBC aggregation. A clinical duplex ultrasound imaging system that can acquire pulsed-wave Doppler spectrograms is now available, but its usefulness for estimating the ultrasound scattering properties of blood is still in doubt. Therefore, the echogenicity and Doppler power of flowing blood under the same flow conditions were measured using a laboratory pulser–receiver system and a clinical ultrasound system, respectively, for comparisons. The experiments were carried out using porcine blood under steady laminar flow with both RBC suspensions and whole blood. The experimental results indicated that a clinical ultrasound system used to measure the Doppler spectrograms is not suitable for quantifying Doppler power. However, the Doppler power measured using a digital Doppler flowmeter can reveal the relationship between backscattering signals and the properties of blood cells because the effects of frequency response are eliminated. The measurements of the Doppler power and echogenicity of flowing blood were compared with those obtained in several previous studies. (E-mail: cchuang@mail.ncku.edu.tw) **© 2015 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Red blood cell aggregation, Hematocrit, Doppler power, Laminar flow, Digital Doppler flowmeter.**

INTRODUCTION

Blood is a heterogeneous tissue that consists mainly of red blood cells (RBCs), white blood cells, platelets and plasma. The phenomenon of RBC aggregation is a reversible physiologic process occurring in normal flowing whole blood. However, excessive RBC aggregation may increase blood viscosity, flow resistance, and interactions between white blood cells and the endothelium and may promote vascular thrombosis (Thomson 1991). Therefore, estimating the degree of RBC aggregation is important in quantifying flow abnormalities in pathologic situations. Ultrasound scatter has been used extensively in the assessment of blood properties, including its aggregation and coagulation, because the increase in particle size associated with the formation of rouleaux or clots can be evaluated by measuring the echogenicity of flowing blood and the Doppler power of signals backscattered from flowing blood (henceforth referred to as the *Doppler power of flowing blood*) (Huang et al. 2005a, 2005b; Shung and Thieme 1993).

Two kinds of flow conditions, steady and pulsatile, have been used in ultrasound-based measurements to provide a better understanding of the physical and biological mechanisms of RBC aggregation involved in the echogenicity and Doppler power of flowing blood. For instance, Yuan and Shung (1988a, 1988b) measured the signals backscattered from porcine blood with different hematocrit values under a steady laminar flow using a 7.5-MHz transducer. The spatial distribution of RBC aggregation in a flowing tube was found by analyzing the

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statistics of 10-MHz signals backscattered from blood under steady laminar flow at velocities ranging from 1.2 to 60 cm/s (Huang and Wang 2007; Huang et al. 2009). In addition to echogenicity measurements, most studies have used Doppler flowmeters to measure the Doppler power of flowing blood when exploring the phenomenon of RBC aggregation under the condition of steady laminar flow. Shung et al. (1992) used a 10-MHz pulsed-wave (PW) Doppler flowmeter to explore the effect of RBC aggregation on Doppler power at high shear rates of 200 and 600 s^{-1}. The rheologic effects of RBC aggregation at low shear rates ranging from 1 to 10 s^{-1} were also studied by measuring the Doppler power of flowing blood (Cloutier and Qin 1997; Cloutier et al. 1996). The effects of Doppler angle, fibrinogen and hematocrit on ultrasound Doppler power were studied by Wu and Shung (1999). These investigations revealed that RBC aggregation under steady laminar flow is generally promoted at a higher hematocrit, lower shear rate and higher fibrinogen concentration. The phenomenon of RBC aggregation under the condition of pulsatile flow has also been studied by measuring the echogenicity and Doppler power of flowing blood. For instance, a cyclic variation in echogenicity was observed in flowing whole blood when using ultrasound at frequencies from 10 to 50 MHz under pulsatile flow (Huang 2009, 2011; Huang et al. 2013; Nguyen et al 2008). However, no obvious cyclic variation in echogenicity was found in RBC suspensions because RBCs do not aggregate in a saline solution. In addition to echogenicity, many studies have measured the Doppler power of whole flowing blood to assess RBC aggregation under a pulsatile flow using a 10-MHz PW Doppler flowmeter (*e.g.,* Lin and Shung 1999; Paeng et al. 2001). The Doppler power was found to increase during the flow acceleration phase and decrease to baseline after a certain flow velocity was reached because of RBC aggregation. The effects of hematocrit, turbulence, fibrinogen concentration, stroke rate and wall compliance on RBC aggregation have also been studied using a 10-MHz PW Doppler flowmeter (Missaridis and Shung 1999; Wu and Shung 1996).

The aforementioned studies indicated that measurement of the Doppler power of flowing blood is useful in assessing RBC aggregation under different flow conditions. However, all of the above studies indicate that the transfer function between the output power and frequency for a 10-MHz PW Doppler flowmeter must be known to compensate for the energy loss at higher Doppler shift frequencies. This PW Doppler flowmeter is implemented using analogue electronic components, including radio-frequency amplifiers/filters, demodulators, sample/hold circuitry and audio-frequency amplifiers/filters. These electronic components exhibit frequency-dependent properties that will result in a decrease in the amplitude of the output audio Doppler shift signal from flowing blood as flow velocity increases. This is caused by the increased Doppler shift frequency. Even though these analogue Doppler devices can provide accurate measurements of blood flow velocity (Doppler shift frequency), the measurements of Doppler power may be inaccurate because of the limited frequency response of analogue circuits. Consequently, a full digital design for Doppler signal processing may be an option to overcome this frequency-response problem.

Field-programmable gate arrays (FPGAs) have recently been used successfully for digital signal processing in many ultrasound imaging applications. Both hardware circuits and software algorithms for signal processing can be replaced by FPGAs. The major advantages of FPGAs are fast processing speed and programmability, which provide great potential for the flexible implementation of a Doppler flowmeter (Ricci et al. 2006). For instance, a 2-MHz multigate transcranial Doppler system was developed using an FPGA chip as a core unit for digital signal processing (Fu et al. 2006; Gittins et al. 2007). FPGA-based ultrasound imaging open platforms were implemented for real-time PW Doppler measurements (Qiu et al. 2012; Tortoli et al. 2009). A digital FPGA-based PW Doppler flowmeter was previously designed for high-frequency ultrasound applications (Hu et al. 2008). However, all of these studies considered only the accuracy of the measurements of blood flow velocity, rather than the performance for Doppler power measurements. The frequency-response limitations of an analogue Doppler system can be eliminated by processing the Doppler signals using a single FPGA chip, particularly for implementing the demodulators, sample/hold circuitry and filters. In other words, an FPGA-based PW Doppler flowmeter is more suitable for measuring the Doppler power of flowing blood when assessing the degree of RBC aggregation.

Both analogue and digital Doppler systems have been implemented by manufacturers and laboratories. However, there is no literature on the relationship between the measured Doppler power and Doppler devices, particularly for assessment of the level of RBC aggregation. Because the frequency-response problem of the analogue Doppler flowmeter is discussed in previous literature, the measured Doppler power from blood should be confirmed in this study. A 10-MHz FPGA-based PW Doppler flowmeter was implemented in the present study to control the hardware specifications for Doppler power measurements. The Doppler power and echogenicity of flowing blood were measured using three different apparatuses to explore the ultrasound scattering properties of flowing blood: a clinical ultrasound system, a commercial pulser–receiver and a FPGA-based PW