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Color Doppler Flow Mapping of a Moving Orifice: Proximal Flow Convergence

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ABSTRACT

Color Doppler flow mapping (CDFM) was performed on an in vitro experimental setup with a regurgitant moving orifice using the proximal isovelocity surface area (PISA) technique. PISA flow rates underestimated actual flow rates by as much as 65%, which is very important in diagnosing patients with valvular regurgitations or stenosis. The correction factor considering the velocity of the orifice improved the PISA flow rates.

INTRODUCTION

The standard CDFM approaches to estimate the accuracy of valvular regurgitation, stenosis, and shunt lesions focused on quantitating the area, width, or momentum in the jet distal to a narrowed orifice. However, these methods are significantly influenced by instrument settings and hemodynamic variables [1-3].

Recently, an alternate approach, known as the PISA technique, has been proposed and used in vivo and in vitro for the CDFM jet quantification. The laminar pattern in the proximal convergence region of the flow field can provide a measure of orifice flow unaffectedly by the complexities of the turbulent jet [4]. This measure is based on the conservation of mass, and assumes that fluid converges uniformly and radially toward an orifice, forming concentric isovelocity layers. For small orifices relative to the region of acceleration, these isovelocity surfaces are hemispherical [5,6]. CDFM can display this acceleration and demonstrate a proximal isovelocity surface along which color changes or aliases as flow accelerates above a selected velocity. Reports on the PISA technique have shown that a good correlation exists between the calculated PISA flow rate and the actual flow rate [5,7].

However, previous in vitro studies employed the stationary regurgitant orifice which is not realistic in vivo, since the valve leaflets are moving during the cardiac cycle. The motion of these leaflets, caused by the pulsatile nature of the flow, imparts an overall velocity to the flow field with respect to the stationary transducer. Therefore, the purpose of the present study is to determine the error of PISA estimation due to the motion of the regurgitant orifice within the flow field and to modify the PISA technique to account for the orifice motion.

METHODS

Figure 1 shows the schematic of the PISA experiment with a moving orifice. The model consists of two cylindrical tubes and the inner one, having an orifice of 2.5, 3.5 or 6.0 mm diameter at the bottom, is directly connected to a dual-acting pneumatic cylinder. The pulse duplicator, controlling two 3-way solenoid valves, activates the air cylinder of 5 cm stroke. The speed of the air cylinder was controlled by an on-line air cylinder speed controller. Water solution with 2% of corn starch was used as the working fluid.

CDFM measurements were obtained on Toshiba Sonolayer SSA 270A color Doppler echocardiographic ultrasound machine with phased array probe PSF 37DF. The following machine settings were used during the experiments: Transducer carrier frequency = 3.0 MHz; PRF = 3.0kHz; wall filter = 310Hz; Nyquist velocity = 10, 20, and 29 cm/s; packet size = low (10 for color 2D, 32 for M-mode); scan depth = 12 cm; frame rate = 14. Imaging was performed with the color 2D, the color M-mode, and M+B mode. The velocity of the moving orifice and the PISA radius were measured in M-mode images, while the orifice was moving towards the transducer. The output of the electromagnetic flow meter was fed to the ultrasound machine and flow traces were obtained on the monitor of the ultrasound machine.

Figure 2 shows the typical hemispherical isovelocity contours for a regurgitant orifice. The flow rate, Q_p, through this hemispherical isovelocity surface is

$$Q_p = 2\pi r^2 \times V_n \qquad (1)$$

where V_n is the 1st Nyquist aliasing velocity towards the orifice and r is the PISA radius at that velocity position. Measurements were obtained initially on the stationary orifice in order to verify the validity of the model. For the moving orifice, the regurgitant orifice moved with constant velocities of 2 - 9 cm/s which is physiologically realistic.

RESULTS AND DISCUSSION

For stationary orifices, as shown in Figure 3, PISA flow rates were in good agreements with the actual flow rates measured by the electromagnetic flow meter. Figure 4 represents the M+B mode imaging while the 6 mm orifice was moving towards the transducer with velocity of 8.6 cm/s. Since the orifice motion was fairly linear, the slope of the plate with respect to the time window in the color M-mode imaging becomes the orifice velocity. Figure 5 shows various PISA flow rates during the orifice motion towards the transducer. The corrected PISA flow rate, $Q_{p.c}$, and the correction factor, C, were calculated with the orifice velocity and the PISA radius:

$$Q_{p.c} = 2\pi r^2 \times (V_n - V_m) \qquad (2)$$

$$C = (V_n - V_m) / V_n \qquad (3)$$

where V_n is the orifice velocity and has negative values while the orifice moves towards the transducer.

The underestimated error was defined by

$$E = 1 - Q_p / Q_a \text{ or } 1 - Q_{p.c} / Q_a \qquad (4)$$

where Q_a is the actual flow rate through the orifice. Figure 6 represents the underestimated error in measuring flow rate using the PISA technique. It is noted that the error in estimating PISA flow rates increases with increased orifice velocity. The corrected PISA flow rate, based on eq.(2) showed better agreements with the actual values, even though they were still in underestimation. Theoretically, the error, $E_t = V_m/V_n$, decreases with increased Nyquist velocity. One restriction of the present study is on the assumption of the hemispherical isovelocity surface, which is good for relatively far from the small orifice. However, the PISA technique may require modification for larger defects with a diameter comparable to the distance from the orifice to the aliasing boundary [7]. In such cases, the isovelocity contours flatten out near the orifice and hemispherical formula underestimates flow rates. Considering the PISA radius of approximately 5 mm at high Nyquist velocity setting, the results from the present study is rather plausible.

The present study was performed by considering the motion of the regurgitant orifice within the flow field, which mimics in vivo situation. The PISA flow rate underestimates the actual flow rate by as much as 65% due to the orifice motion towards the transducer. This amount of error in flow rates corresponds to approximately 30% underestimation in PISA radius. In this particular case, the PISA radius was about 10 mm and those amount of error must be very important in diagnosing the patients with valvular regurgitation or stenosis.

CONCLUSIONS

The proximal flow convergence technique promises to be an important quantitative application of Doppler flow mapping. It potentially capable of providing direct measures of regurgitant and shunt flow, and is sufficiently simple and rapid to be incorporated into routine clinical practice. The present study presented the effects of a moving orifice on the PISA method of measuring regurgitant flow rate. The motion causes the PISA method to underestimate the actual flow rate significantly. The correction factor proposed in this study is very simple to use clinically. Future work with pulsatile flow conditions would be very helpfulto improve the accuracy of the PISA techniques.

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convergence region imaged by color Doppler flow mapping proximal to restrictive orifices: an in vitro study (abstr). J. Am. Coll. Cardol. 15:109A, 1990.

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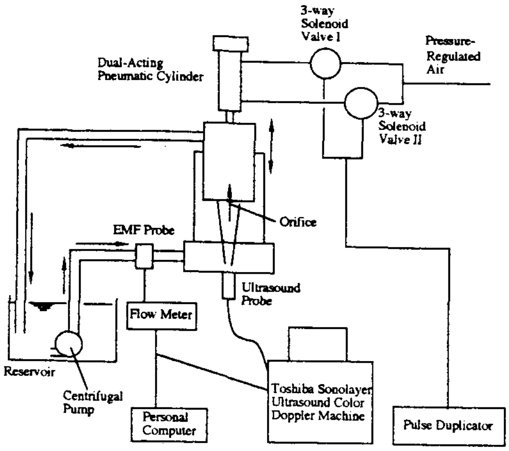

Figure 1. Schematic of the current PISA experiment.

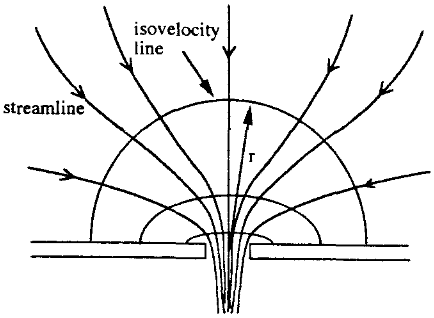

Figure 2. Isovelocity contours in the proximal convergence region.

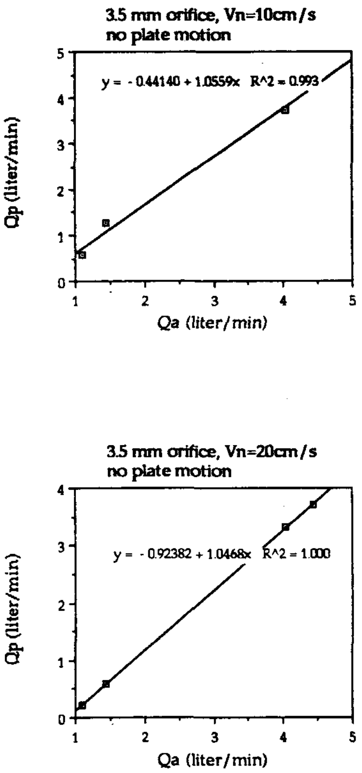

Figure 3. PISA flow rates for the stationary orifice.

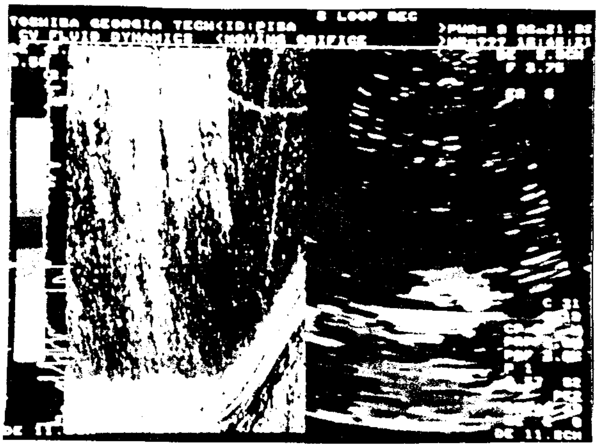

Figure 4. A typical image (M+B mode) from the experiment. In this figure, the orifice diameter was 6 mm and the orifice was moving toward the transducer with a speed of 8.6 cm/s.

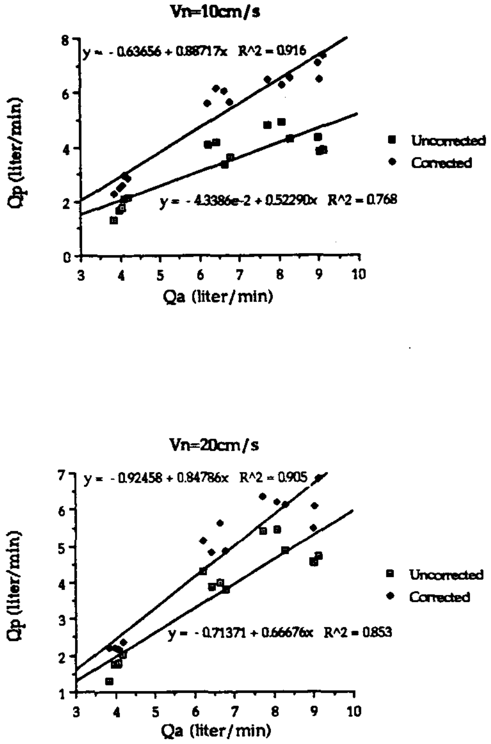

Figure 5. The comparison between the PISA flow rate and the actual flow rate during the orifice motion.

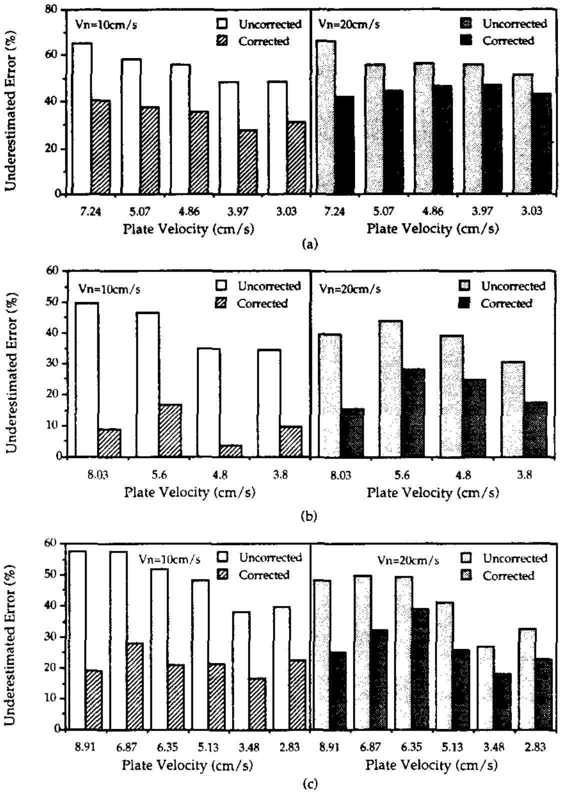

Figure 6. Underestimated error in measuring flow rate using the PISA tecnhnique.
(a) orifice diameter 2.5 mm
(b) orifice diameter 3.5 mm
(c) orifice diameter 6.0 mm