NEW METHODS

Calculation of Volume Flow Rate by the Proximal Isovelocity Surface Area Method: Simplified Approach Using Color Doppler Zero Baseline Shift

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Objectives. The goal of this study was to develop an accurate, simplified proximal isovelocity surface area (PISA) method for calculating volume flow rate using lower blue-red interface velocity produced by a color Doppler zero baseline shift technique.

Background. The Doppler color proximal isovelocity surface area method has been shown to be accurate for calculating the volume flow rate (Q) across a narrowed orifice by the formula Q = PISA × Blue-red interface velocity. A hemispheric model is generally used to calculate proximal isovelocity surface area (PISA = $2\pi a^2$, where a = the radius corresponding to the blue-red interface velocity). Although a hemispheric model is simple, requiring measurement of one radius, it may underestimate the actual volume flow rate because, in the general case, the shape of a proximal isovelocity surface area is hemielliptic. Although a hemielliptic model is generally more accurate for calculating proximal isovelocity surface area, it is more complex, requiring measurement of two orthogonal radii.

Methods. Sixteen in vitro constant flow model studies were performed using planar circular orifices (diameter range 6 to 16 mm). The blue-red interface velocity was changed from 3 to 54 cm/s using color Doppler zero baseline shift.

Results. 1) With decreasing blue-red interface velocity, the size of the proximal isovelocity surface area was increased, and its shape changed from hemielliptic to hemispheric. 2) With the blue-red interface velocity in the range 11 to 15 cm/s, the proximal isovelocity surface area became nearly hemispheric; however, it was difficult to determine the blue-red interface radius at a blue-red interface velocity <10 cm/s because of interface fluctuations. 3) Calculated volume flow rate using the hemispheric proximal isovelocity surface area model with a single radius was relatively accurate at a blue-red interface velocity of 11 to 15 cm/s (mean percent difference from actual volume flow rate was −3.6%).

Conclusions. Because the shape of the proximal isovelocity surface area is nearly hemispheric at a blue-red interface velocity of 11 to 15 cm/s, volume flow rate can be accurately calculated in this proximal isovelocity surface area interface velocity range (produced by zero baseline shift) by measuring a single-interface radius. This approach should be clinically useful for calculating the volume flow rate across stenotic and regurgitant valves and across shunt defects.

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Doppler color flow mapping estimation of a proximal isovelocity surface area (PISA) proximal to a narrowed orifice, calculated from a blue-red (apparent aliasing) interface radius displayed in the flow convergence region, has been shown to be accurate for calculating volume flow rate (Q) across the orifice by the formula Q = PISA × Blue-red interface velocity (1–13). Estimation of volume flow rate using a hemispheric mathematical model to approximate proximal isovelocity surface area is relatively simple, requiring measurement of a single long-axis blue-red interface radius in the center of the ultrasound beam. In previous in vitro studies, a hemispheric model was found to underestimate actual volume flow rate: The apparent shape of the proximal isovelocity surface area was generally hemielliptic (2,5); however, a hemielliptic model requires measurement of a second orthogonal (short-axis) blue-red interface radius. The purpose of the current study was to test the hypothesis that use of a larger displayed blue-red interface velocity radius, produced by color zero baseline shift, would result in accurate calculation of volume flow rate using a hemispheric model for the proximal isovelocity surface area.

Methods

Principle (Fig. 1). Flow proximal to a narrowed orifice is characterized by the convergence of radial streamlines of uniform velocity (Fig. 1, left). Tangential to these converging streamlines, a series of isovelocity surface areas can be described. If a given proximal isovelocity surface area can be quantified, then volume flow rate (in cm^3) can be calculated as proximal isovelocity surface area (in cm^2) × Blue-

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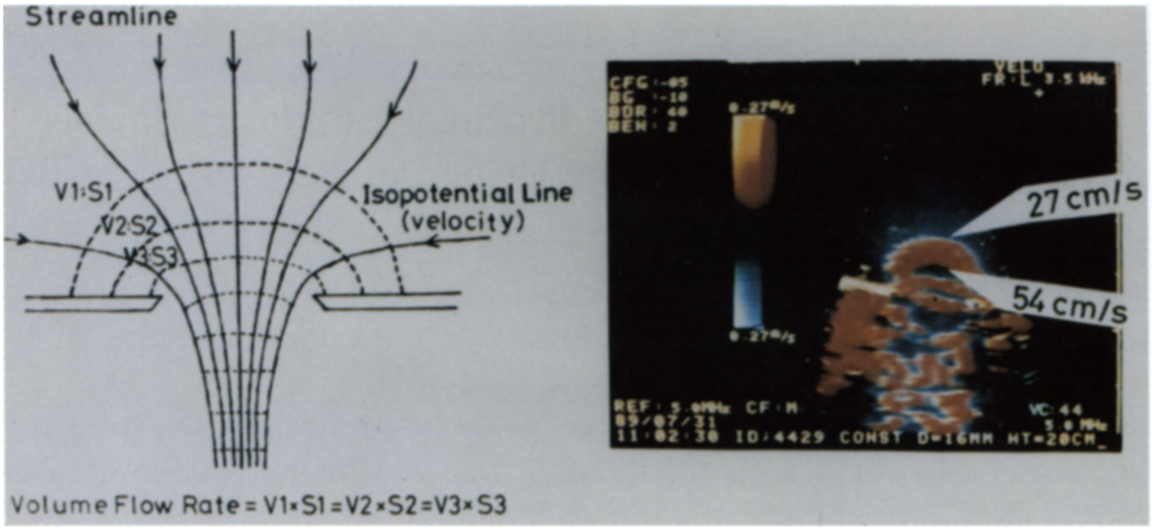


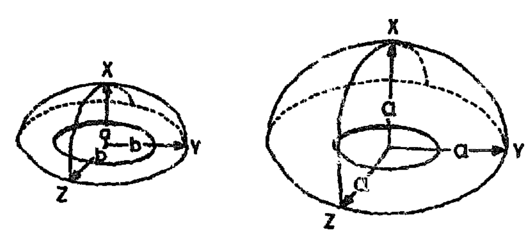
Figure 1. Principle of proximal isovelocity surface area method. **Left panel,** Streamlines of increasing velocity **(solid lines)** and tangential isovelocity lines **(dotted lines)** proximal to the orifice. If a proximal isovelocity surface area can be identified and quantified, then the volume flow rate can be calculated as Proximal isovelocity surface area × Isovelocity. **Right panel,** Color Doppler flow recording with identification of proximal isovelocity surface areas. The isovelocity line at 27 cm/s can be identified as the first blue-red velocity interface, and the isovelocity line at 54 cm/s can be identified as the second blue-red interface. Reprinted, with permission, from Utsunomiya et al. (4).

red interface velocity (cm/s) (1–13). In Figure 1, left, S1, S2 and S3 represent a series of proximal isovelocity surface areas, and V1, V2 and V3 represent the corresponding isovelocities. Using color Doppler flow mapping, one or more concentric isovelocity surfaces can be identified as blue-red interfaces, with corresponding radii (and their velocities) measured parallel to the center of the ultrasound beam (Fig. 1, right).

Both hemielliptic and hemispheric proximal isovelocity surface areas are present in every flow convergence region. The shape of the proximal isovelocity surface area calculated from the color Doppler technique is generally a hemiellipse (Fig. 2, left) but approximates a hemisphere (Fig. 2, right) in situations associated with larger proximal isovelocity surface areas (e.g., higher flow rates, smaller orifices and lower apparent aliasing (blue-red interface) velocities [5]). Each of the two mathematic models has advantages and limitations. Calculation of the proximal isovelocity surface area using a hemispheric model is relatively simple, requiring measurement of only one blue-red interface radius (from the long-axis view). However, in previous in vitro flow experiments, this hemispheric model underestimated the volume flow rate at lower volume flow rates or with larger orifice sizes, both of which produce lower orifice velocities (5). In these experiments, the shape of the proximal isovelocity surface area was more nearly hemielliptic (rather than hemispheric) when using higher color Doppler blue-red interface velocities (e.g., 27 cm/s) (2,5). Although, in most cases, calculation of the proximal isovelocity surface area using the hemielliptic model is more accurate, this model requires measurement of two orthogonal blue-red interface radii to calculate the surface area (2). In patients it is often not easy to obtain the short-axis radius using color Doppler flow mapping.

Constant flow systems (Fig. 3). The tank system used to produce constant flow in our experiments consisted of an upper tank, a lower tank, a wooden box and a motorized pump. All tanks were filled with a cornstarch suspension, approximately 2% cornstarch by volume. The cornstarch suspension was maintained at a constant level in the upper tank by means of an overflow tank. A vinyl tube from the upper tank was connected to the inlet of a wooden box submerged in the lower tank. The outlet of this box was connected to planar circular orifices, ranging from 6 to 16 mm in diameter, producing constant flow across the orifice. The overflow cornstarch suspension from the lower tank, equal to the actual flow rate through the orifice of the wooden box, was measured using a cylinder and stopwatch. The height of the cornstarch suspension column between the upper and lower tanks was maintained constant during each

Figure 2. Mathematic models to describe the proximal isovelocity surface area shape. **Left,** *Hemielliptic model.* The proximal isovelocity surface area is calculated using two orthogonal radii (a and b). **Right,** Hemispheric model. The proximal isovelocity surface area is calculated using the long-axis radius (a). Note that the size of the proximal isovelocity surface area is larger in the hemispheric model *than in the hemielliptic model.* (See text for details.)



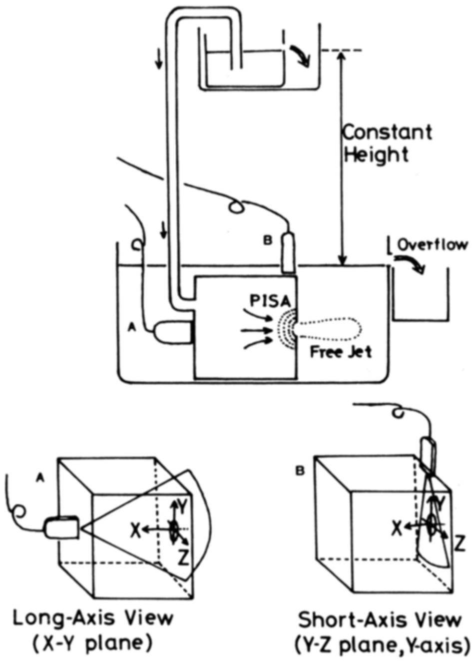


Figure 3. Flow system and recording planes. **Upper,** The height between the upper and lower tanks was set constant for each experiment. Constant flow was produced at the orifice of the submerged box system. Overflow volume (equal to volume flow rate at the orifice) was measured using a stopwatch and cylinder. **Lower left,** Long-axis views were recorded from the window on the side opposite the orifice (A). **Lower right,** Short-axis views were recorded from the window on the top side perpendicular to the plane of the orifice (B).

of the experimental trials; however, in different experiments, the height of this column was varied from 10 to 25 cm so that the flow velocity at the orifice was varied from 1.5 to 2.2 m/s. The corresponding volume flow rate was varied from 1.0 to 16.6 liters/min. The cornstarch suspension was pumped up from the lower tank to the upper tank using a motorized pump.

Color Doppler and continuous wave Doppler recording. Color Doppler and continuous-wave Doppler recordings were performed using a Hitachi-Biosound CVC-151 ultrasound machine with a 5-MHz transducer. Scanning was performed with the transducer placed on the side opposite the outflow orifice of the box to record the long-axis view (Fig. 3, lower left) and at the top of the box to record the short-axis view (Fig. 3, lower right). The proximal flow convergence image was recorded with changing of color Doppler blue-red interface velocities from 3 to 54 cm/s using the zero baseline shift technique. Continuous wave Doppler recordings of jet velocities were performed from the same window used to record the color Doppler long-axis image.

Measurement of Doppler blue-red interface radii (Fig. 4). The radial distance between the orifice and the color Doppler blue-red interface was measured in the long-axis view from the leading edge of the extension of the wall echo to the blue-red interface (Fig. 4, upper panels). The radial distance from the extension of the wall echo to the proximal color Doppler blue-red interface was also measured in the short-axis view (Fig. 4, lower panels). A Dextra D-200 off-line image analysis computer (Dextra Medical) was used to perform these linear measurements.

Proximal isovelocity surface area calculations. The proximal isovelocity surface area (PISA) was calculated using the hemispheric and hemielliptic mathematical models to describe its shape (Fig. 2).

Hemispheric model. PISA = $2\pi a^2$, where π equals 3.1416 (i.e., the ratio of the circumference of a circle to its diameter), a is the distance between the orifice and the color Doppler blue-red interface (interface radius) in the long-axis view.

Hemielliptic model

$$\text{PISA} = \pi \times b \times \left[\left(b + \frac{a^2}{\sqrt{b^2 - a^2}}\right) \times \ln\left(b + \frac{\sqrt{b^2 - a^2}}{a}\right)\right],$$

where a and PISA are as defined in the hemispheric model, b is the distance between the center of the orifice and the blue-red interface (radius) in the short-axis view and ln is the natural logarithm.

Volume flow rate calculation. The volume flow rate (Q) (cm^3/s) was calculated from the following equation: Q = PISA × V, where PISA is the proximal isovelocity surface area (in cm^2), and V is the color Doppler blue-red interface velocity of the proximal isovelocity surface area (cm/s). Volume flow rate was calculated at a series of color Doppler blue-red interface velocities.

Results

Examples of proximal isovelocity surface recordings. Figure 4 shows examples of the proximal isovelocity surface recorded using color Doppler blue-red interface velocities of 27 and 15 cm/s. The upper panels demonstrate long-axis views, and the lower panels demonstrate short-axis views. Note that the blue-red interface radius is greater at a color Doppler blue-red interface velocity of 15 than of 27 cm/s in both long- and short-axis views, and radius a nearly equals radius b (i.e., the displayed shape of the proximal isovelocity surface area is nearly hemispheric) at a color Doppler blue-red interface velocity of 15 cm/s.

The b/a ratio of proximal isovelocity surface area shape and color Doppler blue-red interface velocity (Fig. 5). The shape of the proximal isovelocity surface area is most generally described by a hemielliptic model. The ratio of the major to the minor axis (b/a ratio) can be used to describe this shape. In the specific case of a b/a ratio of 1, the proximal isovelocity surface area shape is described by a hemisphere. Figure 5 shows the relation between the b/a ratio and the color Doppler blue-red interface velocity. The color Doppler blue-red interface velocity is indicated on the X axis and the b/a ratio on the Y axis. Figure 5 shows the relation of the b/a ratio, on average, and blue-red interface ("aliasing") veloc-

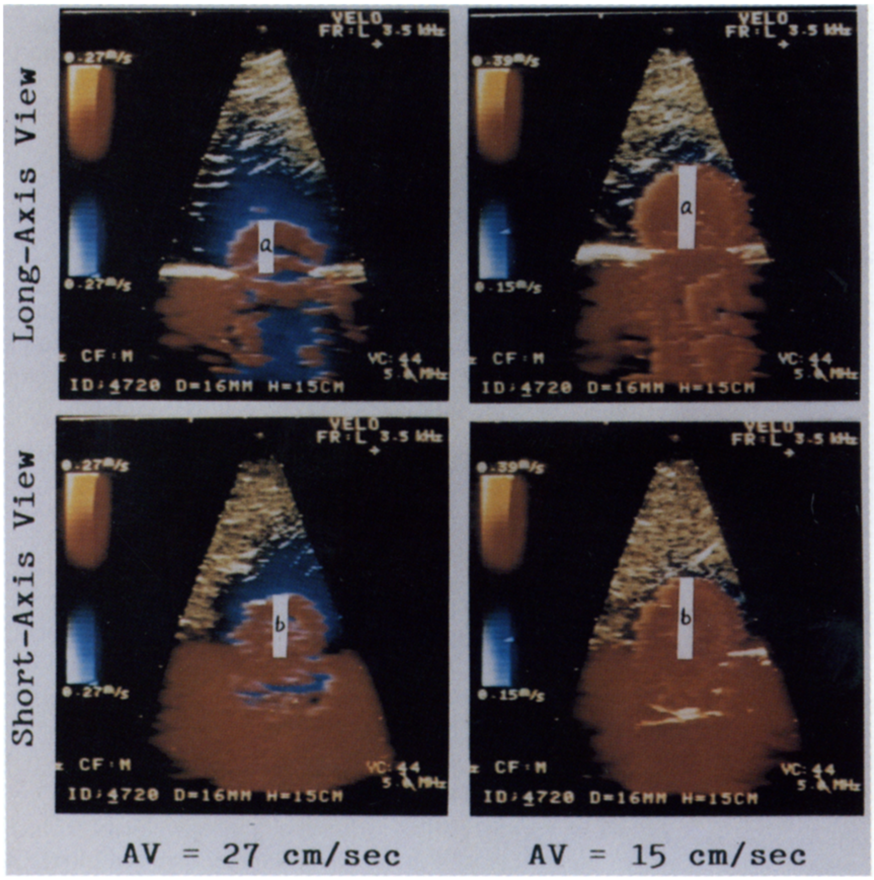


Figure 4. Examples of proximal isovelocity surface areas recorded at color Doppler blue-red interface velocities of 27 and 15 cm/s. **Upper panels,** Long-axis views. **Lower panels,** Short-axis views. Blue-red interface radii a and b were measured as shown from the blue-red interface to the leading edge of the orifice. **Right panels,** Zero-baseline shift was used to set blue-red interface velocity at 15 cm/s, as shown on the color bar. Note that blue-red interface radii a and b are larger at a color Doppler blue-red interface velocity of 15 than of 27 cm/s. Furthermore, a nearly equals b at a color Doppler blue-red interface velocity of 15 cm/s.

ity for an orifice diameter of 6 mm. Although the b/a ratio depends on flow velocity at the orifice, the b/a ratio approximated 1.0 at color Doppler blue-red interface velocities of 11 to 15 cm/s (under conditions of a 6-mm orifice diameter and flow velocities ranging from 1.5 to 2.2 m/s). For orifice diameters ranging from 6 to 15 mm, the b/a ratio was nearly 1.0 (and the proximal isovelocity surface area nearly hemispheric) at color Doppler blue-red interface velocities of 11 to 15 cm/s.

Comparison of actual and calculated volume flow rates at a color Doppler blue-red interface velocity of 27 cm/s (Fig. 6). Figure 6 shows the relation between actual and calculated volume flow rates using the hemielliptic and hemispheric models for proximal isovelocity surface area shape. Volume flow rate was calculated using the interface radius at a color Doppler blue-red interface velocity of 27 cm/s. Solid circles indicate the calculated flow rate using a hemielliptic model, and crosses indicate the calculated flow rate using a hemi-

Figure 5. The b/a ratio of the proximal isovelocity surface area versus color Doppler blue-red interface (aliasing) velocity. At color Doppler blue-red interface velocities in the range of 11 to 15 cm/s, the b/a ratio was nearly 1.0. The proximal isovelocity surface area shape was nearly hemispheric at these color Doppler blue-red interface velocities.

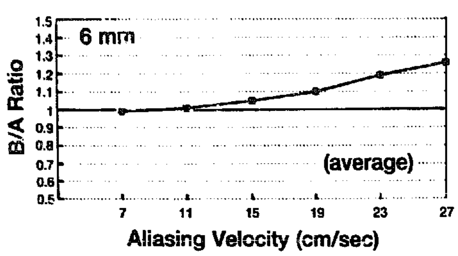
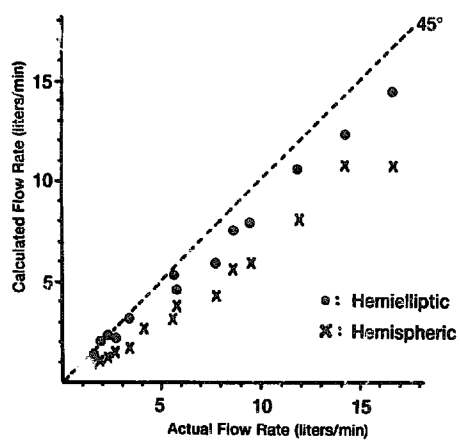


Figure 6. Calculated flow rates using hemispheric and hemielliptic models. The flow rate was calculated at an aliasing velocity of 27 cm/s. **Solid circles** indicate data obtained using a hemielliptic model, and **crosses** indicate data obtained using a hemispheric model. Note that the hemispheric model underestimated the actual flow rate. (See text for details.)



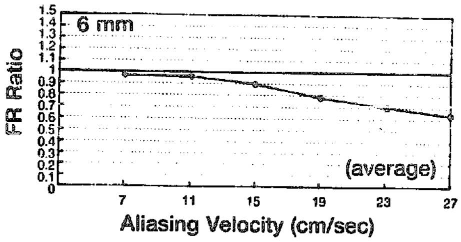


Figure 7. Flow rate (FR) ratio and color Doppler blue-red interface ("aliasing") velocity. Flow rate ratio was calculated as: Calculated flow rate using the hemispheric model for proximal isovelocity surface area ÷ Actual flow rate. Note that the flow rate ratio was nearly 1.0 at color Doppler blue-red interface velocities of 11 to 15 cm/s. At these velocities, the volume flow rate can be accurately calculated using a hemispheric model with a single long-axis radius.

spheric model. The dashed line indicates the line of identity (45° line). The correlation between actual and calculated volume flow rates using the hemielliptic model was r = 0.99 and SEE = 0.35 liters/min. The correlation between actual and calculated volume flow rates using the hemispheric model was r = 0.98, and SEE = 0.51 liters/min.

Although there was good correlation between actual and calculated volume flow rates using the hemispheric model, the calculated flow rate in our experiments underestimated the actual flow rate, on average, by 34.8%. At low flow rates, the calculated volume flow rate using the hemispheric model underestimated the actual volume flow rate by 35% to 45%.

Comparison between actual and calculated flow rates using the hemispheric model at various color Doppler blue-red interface velocities (Fig. 7). Volume flow rate was calculated using a hemispheric model at each color Doppler blue-red interface velocity. The flow rate ratio was calculated as: Calculated flow rate using a hemispheric model for PISA ÷ Actual flow rate, where PISA is the proximal isovelocity surface area. A flow rate ratio of 1.0 implied that the calculated flow rate using a hemispheric model accurately estimated the actual volume flow rate.

Figure 7 shows the relation between the color Doppler blue-red interface velocity on the X axis and average flow rate ratio on the Y axis for a 6-mm diameter orifice. The calculated volume flow rate using a hemispheric model underestimated the actual volume flow rate by 35% at a blue-red interface velocity of 27 cm/s. At color Doppler blue-red interface velocities of 11 to 15 cm/s, the b/a ratio ranged from 0.90 to 0.97 at conditions of flow velocity ranging from 1.5 to 2.2 m/s and orifice diameters of 6 to 16 mm.

Differences between actual and calculated flow rates using a hemispheric model at blue-red interface velocities of 11 to 15 cm/s (Table 1). Table 1 demonstrates the differences, for four orifice diameters, between actual and calculated flow rates using a hemispheric model at a color Doppler blue-red interface velocity of 11 cm/s. The actual difference was calculated as: Calculated flow rate using the hemispheric model at a color Doppler blue-red interface velocity of 11 cm/s − Actual flow rate. Percent difference was calculated as: Actual difference ÷ Actual flow rate × 100%. At a color Doppler blue-red interface velocity of 11 cm/s, the actual differences ranged from −0.56 to +0.07 liters/min, and the percent differences ranged from −7.25% to +0.01%. At color Doppler blue-red interface velocities of 11 to 19 cm/s, the percent difference was −6.7%, on average; however, at a color Doppler blue-red interface velocity of 27 cm/s, the percent difference was −35.0%, on average.

Table 1. Differences Between Actual and Calculated Flow Rates Using a Hemispheric Model, Proximal Isovelocity Surface Area Method at a Color Doppler Blue-Red Interface Velocity of 11 cm/s

	Orifice Diameter (mm)			
	6	9	12	16
Actual difference (liters/min)	−0.01	−0.39	−0.56	+0.07
Percent difference	−0.75	−7.25	−6.25	+0.01

Discussion

Previous studies using the proximal isovelocity surface area method. The proximal isovelocity surface area method has been previously reported to be accurate for calculating the volume flow rate across a narrowed orifice and in valvular regurgitation (1–13). Of importance, this method has been shown to have advantages over previous color Doppler flow methods in estimating volume flow rate because its results appear to be relatively insensitive to differences in machine factors and orifice shapes (4).

Hemispheric and hemielliptic models have been used to describe the shape of the displayed proximal isovelocity surface area (2,5). Although the hemispheric model is simple (requiring measurement of one long-axis blue-red interface radius), it may underestimate the actual flow rate, especially at low flow velocities (5). Although the hemielliptic model is relatively accurate for calculating volume flow rate, its application requires measurement of two orthogonal blue-red interface radii (from long- and short-axis views). In clinical cases, it may be difficult to accurately image the short-axis radius.

Effects of orifice size, flow velocity and color Doppler blue-red interface velocity on displayed proximal isovelocity surface area shape. Displayed proximal isovelocity surface area shape is affected by orifice size, flow velocity and color Doppler aliasing velocity (5–9). The shape is most generally described by a hemielliptic equation, which involves a major axis (b) and a minor axis (a). In the special case of b/a = 1.0, displayed proximal isovelocity surface area shape is hemispheric. For the same flow velocity and color Doppler blue-red interface velocity, displayed proximal isovelocity surface area shape is a (flat) hemiellipse (b/a >1.0) for larger orifice sizes and nearly hemispheric (b/a = 1.0) for smaller orifice sizes. For the same orifice size and color Doppler

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blue-red interface velocity, displayed proximal isovelocity surface area shape is a flat hemiellipse at low flow velocities and nearly hemispheric at higher flow velocities. For the same orifice size and flow velocity, displayed proximal isovelocity surface area shape is a flat hemiellipse at high blue-red interface velocities and nearly hemispheric at lower blue-red interface velocities (5).

Simplified proximal isovelocity surface area method using the color Doppler zero-baseline shift. Color Doppler blue-red interface velocity can be changed using a color Doppler zero-baseline shift approach. When the zero-baseline shift technique is used to produce low color Doppler blue-red interface velocities, the volume flow rate can be accurately calculated using a hemispheric model with one radius because the displayed proximal isovelocity surface area shape is nearly hemispheric.

In this study, the optimal color Doppler blue-red interface velocity range was 11 to 15 cm/s at flow velocities of 1.5 to 2.2 m/s over a range of orifice areas of 0.3 to 2.0 cm^2. Under these conditions, the b/a ratio was nearly equal to 1.0, and the volume flow rate was accurately calculated using a hemispheric model with one (long-axis) blue-red interface radius to measure the proximal isovelocity surface area. At a color Doppler blue-red interface velocity <11 cm/s, it was difficult to measure the color radius because of surface fluctuations in the interface. Moises et al. (7) reported that using a color Doppler blue-red interface velocity of 14 cm/s, calculated volume flow rates using a hemispheric model for proximal isovelocity surface area were accurate in the range 0.70 to 5.6 liters/min at orifice diameters of 3.4 to 6.8 mm.

Potential limitations. Doppler color flow mapping at relatively low color Doppler blue-red interface velocities should be useful for calculating regurgitant volumes in patients; however, the optimal blue-red interface velocities to use for producing a hemispheric shape for the displayed proximal isovelocity surface area may be different for orifice sizes and flow velocities different from those used in the current study. The optimal color Doppler blue-red interface velocity must be determined for each range of flow conditions encountered clinically (9). Furthermore, the data in this study were derived under constant flow conditions using a flat-plate orifice. We (10) and others (11) have shown that the effect of nonplanar geometry, as well as changes in proximal isovelocity surface area produced by pulsatile flow, must be taken into account. For example, in the case of a funnel-shaped orifice (such as encountered in mitral stenosis), it has been suggested that proximal isovelocity surface area should be corrected by multiplying by $\theta/180°$, where θ is the internal angle of the orifice. Similarly, in pulsatile flow situations, maximal proximal isovelocity surface area must be corrected for its variation over the cardiac cycle. Strategies for accomplishing this correction include 1) integrating the blue-red velocity interface radius from the M-mode/color Doppler (M-Q) display over systole (12,13), or 2) multiplying by the ratio of the time-velocity integral to the peak flow velocity of the jet recorded by continuous wave Doppler (10). Nevertheless, the zero-baseline shift technique should be a useful addition to our application of the color Doppler proximal isovelocity surface area method for calculating volume flow rate in estimating the severity of regurgitant and shunt lesions (14).

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