

Proximal Isovelocity Surface Area Should Be Routinely Measured in Evaluating Mitral Regurgitation: A Core Review

A. Stephane Lambert, MD,
FRCPC

The proximal isovelocity surface area (PISA) measurement, also known as the “flow convergence” method, can be used in echocardiography to estimate the area of an orifice through which blood flows. It has many applications, but this review focuses only on its use in the intraoperative evaluation of mitral regurgitation. In that setting, PISA provides a quantitative assessment of the severity of mitral regurgitation and it is useful in clinical decision-making in the operating room. In this review, I discuss the physical principles behind the PISA method, along with the various mathematical formulas used to calculate the effective mitral regurgitant orifice area, the regurgitant volume, and the regurgitant fraction. A step-by-step approach is presented and illustrated with graphic and video demonstrations. Finally, I will discuss the various limitations and technical considerations of PISA measurement in the operating room.

(Anesth Analg 2007;105:940–3)

Proximal isovelocity surface area (PISA) measurement, also known as the “flow convergence” method, can be used in echocardiography to estimate the area of an orifice through which blood flows. Since its development in the early 1990s, the PISA method has been applied clinically to the evaluation of mitral regurgitation (MR) (1–3), mitral stenosis (4,5), tricuspid regurgitation (6), aortic insufficiency (7), and intracardiac shunts (8–10) with variable degrees of success. The basic principles of PISA discussed below hold true for all these applications but, for the purposes of this discussion, we will focus on MR only.

The PISA method is based on 1) the properties of flow dynamics and 2) the continuity principle.

1. When a liquid (in this case blood) is forced from a large chamber into an orifice at a constant flow, its particles accelerate towards the orifice until the velocity is greatest at the narrowest point of the orifice. This acceleration occurs along a series of concentric “hemispheres” or “hemishells” whose center is at the orifice itself. Those hemispheres are contained in an area referred to as the flow convergence area.
2. The volume of a liquid going through a conduit per unit time, called the flow rate, equals the cross-sectional area of that conduit times

the velocity of the liquid: Flow rate = area $\times$ velocity. Liquids, by definition, are essentially incompressible. Therefore, the continuity principle dictates that in the absence of a leak in the conduit or additional input, the flow rate is constant along the length of the conduit (11). If the cross-sectional area decreases, the velocity must increase to compensate and *vice versa*. The same holds true for the heart and, assuming there is no shunt, the flow rate throughout the heart is constant. What changes is the area and velocity of the column of blood as it flows through the various parts of the heart. As the area changes, the velocity of the blood must change also, according to the following equation:

$$A_1 \times V_1 = A_2 \times V_2$$

It is important to realize that the continuity principle applies equally to blood flowing forward through the heart (for example in the assessment of valve area in aortic stenosis), or backward (as in the case of MR).

EFFECTIVE REGURGITANT ORIFICE AREA

MR is usually caused by a coaptation defect in the mitral valve and the severity of MR depends, in large part, on the size of that defect. The goal of the PISA method is to calculate the area of the defect, also known as the effective regurgitant orifice area (EROA).

The continuity principle, as explained above, dictates that flow be constant throughout the heart. It also dictates that flow be constant along the MR jet. If one can calculate the flow at one point within the flow convergence area, then one knows the flow at any another point along the MR jet, including at the regurgitant orifice itself. Then, once the peak velocity

From the Division of Cardiac Anesthesiology, University of Ottawa Heart Institute, Ottawa, Ontario, Canada.

Accepted for publication May 24, 2007.

Address correspondence to A. Stephane Lambert, MD, FRCPC, H2410, 40 Ruskin St., Ottawa, Ontario, K1Y 4W7, Canada. Address e-mail to slambert@ottawaheart.ca.

Reprints will not be available from the author.

Copyright © 2007 International Anesthesia Research Society
DOI: 10.1213/01.ane.0000278084.35122.4e

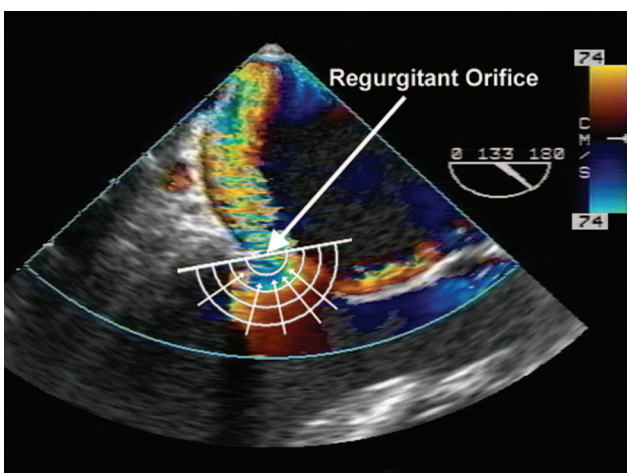


Figure 1. Still image of flow convergence area. As they are forced from the left ventricle into the mitral regurgitant orifice, the red blood cells accelerate along a series of concentric hemispheres until they reach their maximum velocity at the orifice itself.

at the regurgitant orifice is known, one can calculate the area of that orifice.

The first step in the PISA method is to demonstrate the MR jet by color flow Doppler and to calculate the flow of blood within the flow convergence area. This is most commonly done in the midesophageal views of the mitral valve. The flow convergence area is the colored area on the ventricular side of the mitral valve in systole (please see video 1 available at www.anesthesia-analgesia.org). This area contains an infinite number of concentric hemispheres along which the blood accelerates towards the regurgitant orifice, as described above (Fig. 1).

By Doppler convention, the MR jet is displayed in shades of red, because the blood flow is directed towards the transducer in midesophageal views. As blood cells accelerate, the color goes from dark red to bright red, to orange, to yellow (along the white arrow on Fig. 2a). When the cells reach the aliasing velocity (also known as the Nyquist limit), the color suddenly changes to blue (x mark on Fig. 2a). This is the point of interest, at which the velocity is known with certainty. (The Nyquist limit is defined as the velocity at which the color flow switches from red to blue or blue to red.) This number is displayed beside the color scheme on the video screen and one must select the number in the direction of blood flow.

If one measures the distance from this point to the center of the mitral regurgitant orifice (= the radius of the hemisphere, Fig. 2b), one can then calculate the surface area of this hemisphere (i.e., the PISA) using the equation:

$$A_{\text{hemisphere}} = 2\pi r^2$$

(Note that it is important to measure this radius between the edge of the blue hemisphere and the center of the regurgitant orifice itself. Freezing the

image and toggling the color on/off will help to determine exactly where the center of the orifice is.)

The next step consists of measuring the maximum velocity of blood at the mitral regurgitant orifice using continuous wave (CW) Doppler of the MR jet (Fig. 3). As usual, one must make sure that the Doppler beam is lined-up with the MR jet.

Finally, one calculates the EROA using the initial formula:

$$A_1 \times V_1 = A_2 \times V_2$$

$$\text{EROA} \times V_{\text{max (CW)}} = 2\pi r^2 \times \text{Nyquist Limit}$$

$$\text{EROA} = \frac{2\pi r^2 \times \text{Nyquist Limit}}{V_{\text{max (CW)}}$$

REGURGITANT VOLUME (RV) AND REGURGITANT FRACTION

These are useful quantitative measurements of MR, and they can be calculated from the regurgitant orifice area.

Knowing that Volume = area $\times$ VTI, one can trace the velocity-time integral (VTI) of the MR jet on the CW signal, and one can calculate the mitral RV (RV_{MR}), using the following equation:

$$\text{RV}_{\text{MR}} = \text{EROA} \times \text{VTI}_{\text{MR}}$$

Once the RV is known, one can calculate the ratio of RV over total stroke volume, a value known as mitral regurgitant fraction. All these calculations can be done manually and they can be time-consuming. Fortunately, if one traces the VTI of the MR jet on CW, many modern echocardiography machines will automatically calculate and display the EROA and the RV when measuring the radius of the PISA hemisphere.

LIMITATIONS OF THE PISA METHOD

First, the proximal flow convergence technique is a Doppler technique and it is limited by all the usual considerations of Doppler echocardiography, especially alignment. Like any other application of Doppler, if the MR jet is eccentric and not aligned with the Doppler beam, the usefulness of this technique can be significantly compromised.

Also, the PISA method is based on a number of assumptions, some of which may or may not be true in individual cases.

1. It assumes that the mitral regurgitant orifice is circular. $2\pi r^2$ describes the surface area of a hemisphere. If the orifice is oval shaped or irregular, which unfortunately is often the case in clinical practice, then the flow convergence area does not consist of hemispheres, and the equation does not apply.
2. As color Doppler parameters are adjusted, the hemispheres may become more flattened or

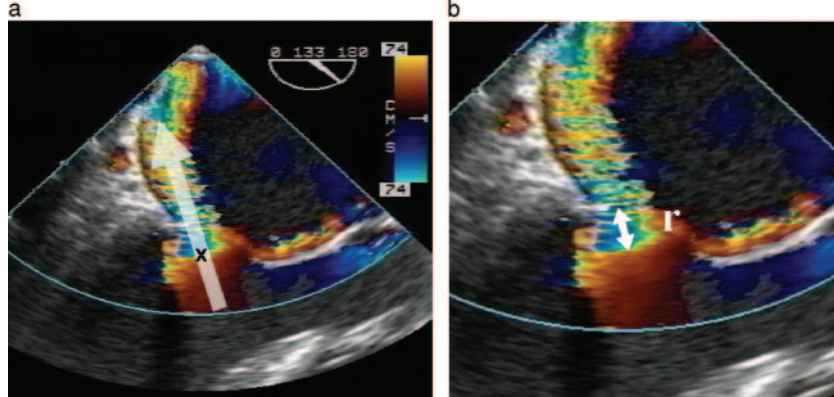


Figure 2. (a) As the blood cells accelerate along the white arrow, the color flow Doppler signal changes from dark red, to bright red, to orange, to yellow and eventually to blue as it reaches the aliasing velocity (in this case 74 cm/s). This is the point of interest marked by an "x." (b) The radius of the hemisphere r is measured from the edge of the blue color to the regurgitant orifice. It helps to toggle the color on and off to see the precise location of the regurgitant orifice.

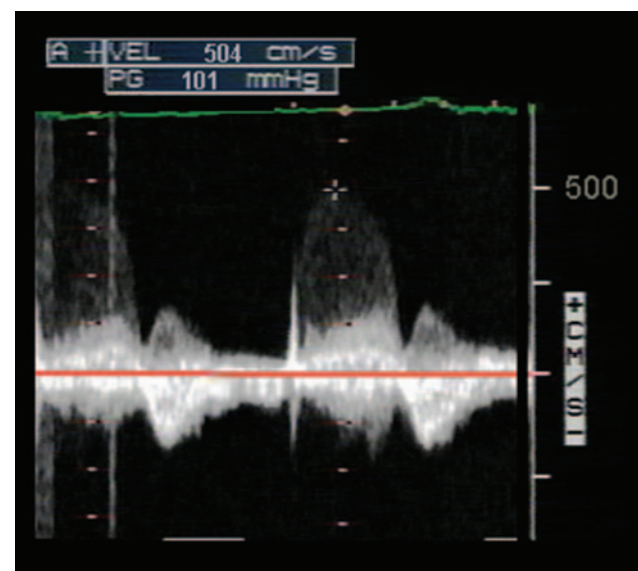


Figure 3. The peak velocity ($V_{\max}$) of the mitral regurgitant jet is measured by continuous wave Doppler. Care must be taken to align the Doppler signal with the mitral regurgitant jet and to use the same units as the Nyquist limit. One can also trace the velocity-time integral of the regurgitant jet to calculate the regurgitant volume.

more cone-shaped, even if the regurgitant orifice is circular. Again the equation $2\pi r^2$ may not apply. It has been reported that the PISA hemispheres are closest to being true hemispheres when their radius is between 11 and 15 mm. To achieve that, the baseline and/or Nyquist limit can be adjusted (12). On most echocardiography machines, this is done by turning a knob identified as "pulse repetition frequency" or "color Doppler scale."

3. The PISA method assumes that the hemisphere is a complete hemisphere. If the flow is restricted laterally by one of the mitral leaflets, or by a ventricular wall, then the PISA calculation must be multiplied by an "angle correction factor" (13). That correction factor is the actual angle-width (α) of the flow convergence hemisphere divided by 180 (Fig. 4). This angle is not automatically measured by the echocardiography machine and must be estimated

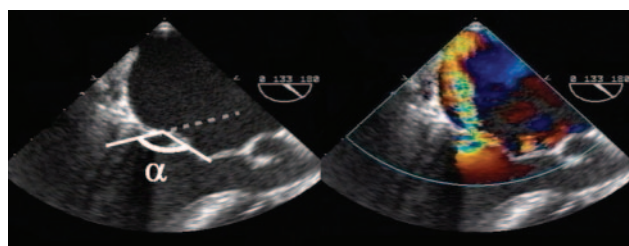


Figure 4. The proximal isovelocity surface area technique assumes that the hemispheres are complete hemispheres, in other words it assumes that $\alpha = 180^\circ$ (dotted line). If it is not, because it is restricted by a leaflet or a ventricular wall, the angle-width of the proximal isovelocity surface area hemisphere must be measured and included in the "angle correction factor."

by the operator. This can be a significant source of error.

$$\text{EROA} = \frac{2\pi r^2 \times \text{Nyquist Limit}}{V_{\max}(\text{CW})} \times \frac{\alpha}{180}$$

4. Finally, if there are multiple regurgitant orifices, the flow convergence method may be completely inaccurate in estimating the EROA. In theory, one could measure each smaller orifice independently, but it would be too cumbersome to be practical. Besides, the various flow convergence areas might overlap and mask each other, rendering the technique inaccurate.

The technical considerations of PISA measurements become obvious when one remembers the above limitations of the technique. If the Nyquist limit and gain are adjusted to optimize the shape of the hemispheres in the flow convergence area, and if the technique is reserved for reasonably central jets, where the PISA shells are less distorted and where there is minimal need for angle correction, then the diagnostic accuracy of the method is improved.

SIMPLIFIED METHODS

PISA calculations can be time-consuming, and a simplified formula was developed and validated, provided that certain hemodynamic conditions are present. Indeed, if the Nyquist limit is set at 40 cm/s on the

Table 1. Values for Effective Regurgitant Orifice Area (EROA), Regurgitant Volume (RV_{MR}), and Mitral Regurgitant Fraction (RF_{MR}) by the Proximal Isovelocity Surface Area (PISA) Method

Doppler parameters	Mild MR	Moderate MR	Severe MR
EROA (cm ²)	<0.20	0.20–0.40	≥0.40
RV _{MR} (mL)	<30	30–60	≥60
RF _{MR} (%)	<30	30–50	>50

MR = mitral regurgitation.

Table 2. Summary of the Steps in Measuring the Effective Regurgitant Orifice Area (EROA) by the Proximal Isovelocity Surface Area (PISA) Method

- Center the mitral valve in the sector screen and apply color flow Doppler (CFD)
- Zoom in on the flow convergence area on the ventricular side of the mitral valve. Adjust the Nyquist limit and the CFD baseline on the machine to obtain a hemispheric flow convergence area, about 1 cm, then freeze the screen. Scroll the image to find the frame that best demonstrates the PISA hemisphere
- Toggle the color on and off, measure the distance between the edge of the hemisphere where the CFD changes from red to blue and the center of the mitral regurgitant orifice (visible coaptation defect in the MV on 2D). This value is “r”
- Note the value of the Nyquist limit at the top of the CFD scale on the screen
- Obtain a continuous wave (CW) signal of the mitral regurgitant (MR) jet and measure the peak velocity. This value is “V_{max}.” (Be careful to align the Doppler signal with the MR jet. Also, make sure you use the same units as those used for the Nyquist limit. This can be m/s or cm/s but it has to be the same for both.)
- Estimate the angle-width of the PISA hemisphere. Once again, it may help to toggle the color on and off
- Calculate the regurgitant orifice using the formula:

$$EROA = \frac{2\pi r^2 \times \text{Nyquist Limit}}{V_{\text{max (CW)}}} \times \frac{\alpha}{180}$$

CFD = color flow Doppler; MV on 2D = mitral valve on two-dimensional echo.

machine, and if the MR velocity is 500 cm/s, then the equation simplifies to:

$$EROA = \frac{r^2}{2}$$

Hemodynamically, the MR velocity can reasonably be assumed to be about 500 cm/s when the left ventricle to left atrium gradient is about 100 mm Hg; that is, when the difference between the systolic arterial blood pressure and the wedge pressure is about 100 mm Hg. Because the simplified PISA equation introduces additional assumptions and potential sources of errors, it is strongly recommended that it be used only as a quick screening method, and that the detailed method be used whenever clinical decisions depend on the information.

The values of EROA and RV_{MR} and mitral regurgitant fraction for various degrees of MR are listed in

Table 1 (4). Table 2 summarizes the steps in the measurement of PISA and Video 2 (please see video 2 available at www.anesthesia-analgesia.org) is a step-by-step demonstration of this technique.

CONCLUSION

In summary, the flow convergence method is based on principles of flow dynamics and on the continuity equation. It can be used to calculate orifice sizes within the heart, including mitral regurgitant orifice. Its use, however, is restricted by a number of technical limitations, and it may not be applicable to every patient.

REFERENCES

- Recusani F, Bargiggia GS, Yoganathan AP, Raisaro A, Valdes-Cruz LM, Sung HW, Bertucci C, Gallati M, Moises VA, Simpson IA. A new method for quantification of regurgitant flow rate using color Doppler flow imaging of the flow convergence region proximal to a discrete orifice. An in vitro study. *Circulation* 1991;83:594–604
- Utsunomiya T, Ogawa T, Doshi R, Patel D, Quan M, Henry WL, Gardin JM. Doppler color flow “proximal isovelocity surface area” method for estimating volume flow rate: effects of orifice shape and machine factors. *J Am Coll Cardiol* 1991;17:1103–11
- Enriquez-Sarano M, Miller FA Jr, Hayes SN, Bailey KR, Tajik AJ, Seward JB. Effective mitral regurgitant orifice area: clinical use and pitfalls of the proximal isovelocity surface area method. *J Am Coll Cardiol* 1995;25:703–9
- Rifkin RD, Harper K, Tighe D. Comparison of proximal isovelocity surface area method with pressure half-time and planimetry in evaluation of mitral stenosis. *J Am Coll Cardiol* 1995;26:458–65
- Rodriguez L, Thomas JD, Monterroso JD, Weyman AE, Harrigan P, Mueller LN, Levine RA. Validation of the proximal flow convergence method. Calculation of orifice area in patients with mitral stenosis. *Circulation* 1993;88:1157–65
- Rivera JM, Vandervoort PM, Mele D, Siu S, Morris E, Weyman AE, Thomas JD. Quantification of tricuspid regurgitation by means of the proximal flow convergence method: a clinical study. *Am Heart J* 1994;127:1354–62
- Tribouilloy CM, Enriquez-Sarano M, Fett SL, Bailey KR, Seward JB, Tajik AJ. Application of the proximal flow convergence method to calculate the effective regurgitant orifice area in aortic regurgitation. *J Am Coll Cardiol* 1998;32:1032–9
- Kurotobi S, Sano T, Matsushita T, Takeuchi M, Kogaki S, Miwatani T, Okada S. Quantitative, non-invasive assessment of ventricular septal defect shunt flow by measuring proximal isovelocity surface area on color Doppler mapping. *Heart* 1997;78:305–9
- Shiota T, Omoto R, Cobanoglu A, Kyo S, Rice MJ, Sandhu SK, Smith LS, Sahn DJ. Usefulness of transesophageal imaging of flow convergence region in the operating room for evaluating isolated patent ductus arteriosus. *Am J Cardiol* 1997;80:1108–12
- Rittoo D, Sutherland GR, Shaw TR. Quantification of left-to-right atrial shunting and defect size after balloon mitral commissurotomy using biplane transesophageal echocardiography, color flow Doppler mapping, and the principle of proximal flow convergence. *Circulation* 1993;87:1591–1603
- Weyman AE. Principles and practice of echocardiography. 2nd ed. Philadelphia: Lea & Febiger, 1994:193
- Utsunomiya T, Doshi R, Patel D, Mehta K, Nguyen D, Henry WL, Gardin JM. Calculation of volume flow rate by the proximal isovelocity surface area method: simplified approach using color Doppler zero baseline shift. *J Am Coll Cardiol* 1993;22:277–82
- Pu M, Vandervoort PM, Greenberg NL, Powell KA, Griffin BP, Thomas JD. Impact of wall constraint on velocity distribution in proximal flow convergence zone. Implications for color Doppler quantification of mitral regurgitation. *J Am Coll Cardiol* 1996;27:706–13
- Zoghbi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD, Levine RA, Nihoyannopoulos P, Otto CM, Quinones MA, Rakowski H, Stewart WJ, Waggoner A, Weissman NJ. Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. *J Am Soc Echocardiogr* 2003;16:777–802