Chapter 12

Valve Area Calculations

Valve areas can be estimated by Doppler echocardiography by application of the continuity principle. Using this principle, it is theoretically possible to determine any valve area, native or prosthetic. Stenotic mitral valve areas can also be estimated by the pressure half-time ($P\frac{1}{2}t$) method. The clinical significance of valve areas to the degree of valvular stenosis is listed in Table 12.1.

Continuity Equation for the Calculation of Valve Areas

Typically, the severity of valvular stenosis is determined by the maximum and/or mean pressure gradient across that valve. However, pressure gradients are flow dependent and, therefore, are affected by the stroke volume and cardiac output. Thus, the transvalvular pressure gradients may be high in the absence of a significant stenosis; for example, in patients with severe mitral regurgitation, the transmitral pressure gradient may be significantly elevated due to an increased stroke volume across the valve. Conversely, transvalvular pressure gradients may be low in the presence of significant stenosis; for example, in patients with poor left ventricular systolic function, the transaortic pressure gradients may be low despite the presence of severe aortic stenosis. Therefore, overestimation or underestimation of the severity of valvular stenosis may occur if the Doppler-derived pressure gradients are used in isolation.

Flow conditions also affect prosthetic valve pressure gradients; for example, high pressure gradients may occur across a normally functioning prosthetic valve when examined under high flow rates.

For these reasons, calculation of the effective valve area by the continuity equation provides a better indication of the severity of valvular stenosis and prosthetic valve function.

Table 12.1: Clinical Significance of Valve Areas in Valvular Stenosis.

AORTIC STENOSIS	
Aortic Valve Area (1)	
Mild	> 1.0 cm^2
Moderate	0.76 - 1.0 cm^2
Severe	≤ 0.75 cm^2
Aortic Valve Area Index (2)	
Mild	> 0.9 cm^2/m^2
Moderate	> 0.6 – 0.9 cm^2/m^2
Severe	≤ 0.4 - 0.6 cm^2/m^2
MITRAL STENOSIS (3)	
Mitral Valve Area	
Mild	> 1.5 cm^2
Moderate	1.0 - 1.5 cm^2
Severe	< 1.0 cm^2
TRICUSPID STENOSIS (4)	
Tricuspid Valve Area	
Severe	< 1.0 cm^2

Sources: (1) Oh JK, Taliercio CP, Holmes DR Jr, et al. *Journal of the American College of Cardiology 11:1227-1234,1988;* **(2)** Rahimtoola SH. *Perspective on Valvular Heart Disease:* Update II page 50, 1991 [in: Kroebel S ed. An Era in Cardiovascular Medicine. Elsevier, New York]; **(3)** Nishimura RA and Tajik AJ. *Progress in Cardiovascular Disease 34:309-342,1994;* **(4)** Bonow RO, Carabello BA, Chatterjee K, et al. *Journal of the American College of Cardiology 48:605, 2006.*

Theoretical Considerations

As previously discussed, the continuity principle is based on the principle of the conservation of mass which simply states "what goes in must come out". Providing that there is no loss of fluid from the system, flow through a stenotic valve (Q_{sten}) must equal the flow proximal to it (Q_{prox}) so that $Q_{sten} = Q_{prox}$. Since flow (Q) is equal to the product of the mean velocity ($\overline{V}$) and the cross-sectional area (CSA), this relationship can be written:

(Equation 12.1)

$$CSA_{prox} \times \overline{V}_{prox} = CSA_{sten} \times \overline{V}_{sten}$$

Therefore, to calculate the stenotic valve area, Equation 12.1 is simply rearranged to:

(Equation 12.2)

$$CSA_{sten} = \frac{CSA_{prox} \times \overline{V}_{prox}}{\overline{V}_{sten}}$$

where CSA_{prox} = cross-sectional area proximal to a stenosis (cm^2)
CSA_{sten} = cross-sectional area of stenotic valve (cm^2)
$\overline{V}_{prox}$ = mean velocity proximal to stenosis (m/s)
$\overline{V}_{sten}$ = mean velocity through stenosis (m/s)

As discussed in Chapter 11, there are two methods that can be used to calculate the area of a narrowed orifice using the continuity principle in echocardiography: (1) the stroke volume method and (2) the proximal isovelocity surface area (PISA) method.

Calculation of Valve Area by the Stroke Volume Method

The stroke volume method is based on the calculation of the volumetric flow using the CSA and the VTI rather than the CSA and mean velocity. This is because flow within the heart is pulsatile, so the velocity time integral (VTI) rather than the mean velocity is used:

(Equation 12.3)

$$CSA_{sten} = \frac{CSA_{prox} \times VTI_{prox}}{VTI_{sten}}$$

where CSA_{prox} = cross-sectional area proximal to a stenosis (cm^2)
CSA_{sten} = cross-sectional area of stenotic valve (cm^2)
VTI_{prox} = velocity time integral proximal to stenosis (cm)
VTI_{sten} = velocity time integral at the stenosis (cm)

Studies validating the accuracy and reliability of the continuity equation in the determination of native and prosthetic valve areas are tabulated in Appendix 6.

Determination of the Aortic Valve Area

The continuity principle via the stroke volume method is most commonly used in the calculation of the stenotic aortic valve area (Figure 12.1 and Practical Example 12.1). Using this principle it is assumed that the stroke volume through the stenotic aortic valve is equal to the stroke volume proximal to the stenotic valve (that is, the stroke volume within the LVOT). As the stroke volume is a product of the CSA and the VTI, the stenotic aortic valve area (AVA) can then be derived by the application of the following equation:

(Equation 12.4)

$$AVA = \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{AV}}$$

where AVA = aortic valve area (cm^2)
CSA_{LVOT} = cross-sectional area of left ventricular outflow tract (cm^2)
VTI_{LVOT} = velocity time integral through the left ventricular outflow tract (cm)
VTI_{AV} = velocity time integral across the aortic valve (cm)

The prosthetic aortic valve area can also be calculated in the same manner.

Furthermore, because the flow duration through the LVOT and across the aortic valve is the same, the aortic valve area can also be derived by substituting the peak velocities obtained from the LVOT and across the aortic valve for the VTI (Practical Example 12.1):

(Equation 12.5)

$$AVA = \frac{CSA_{LVOT} \times V_{LVOT}}{V_{AV}}$$

where AVA = aortic valve area (cm^2)
CSA_{LVOT} = cross-sectional area of left ventricular outflow tract (cm^2)
V_{LVOT} = peak velocity through the left ventricular outflow tract (m/s)
V_{AV} = peak velocity across the aortic valve (m/s)

Indexing the Aortic Valve Area

As stated in Table 12.1, an AVA of 0.9 cm^2 is considered to reflect moderate aortic stenosis. However, an aortic valve with an AVA of 0.9 cm^2 in a large patient with associated high transaortic pressure gradients may, in fact, be severe aortic stenosis for this patient. Conversely, an aortic valve with an AVA of 0.9 cm^2 in a very small patient might only be mild aortic stenosis for this patient.

Therefore, in very large patients or very small patients, indexing the AVA to the BSA may assist in determining the severity of aortic stenosis (see Table 12.1):

(Equation 12.6)

$$AVA\ indexed\ (cm^2/m^2) = \frac{AVA}{BSA}$$

where AVA = aortic valve area (cm^2)
BSA = body surface area (m^2)

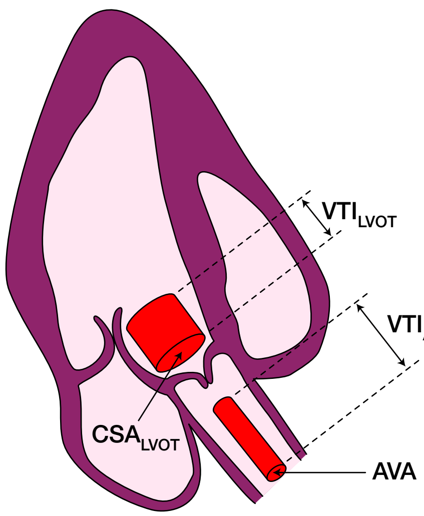
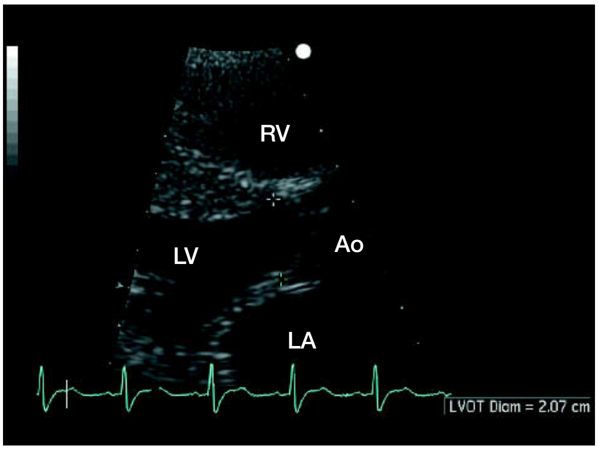
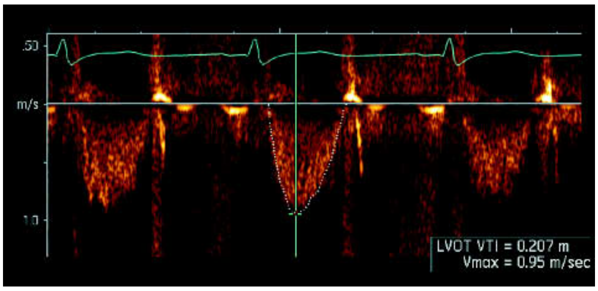
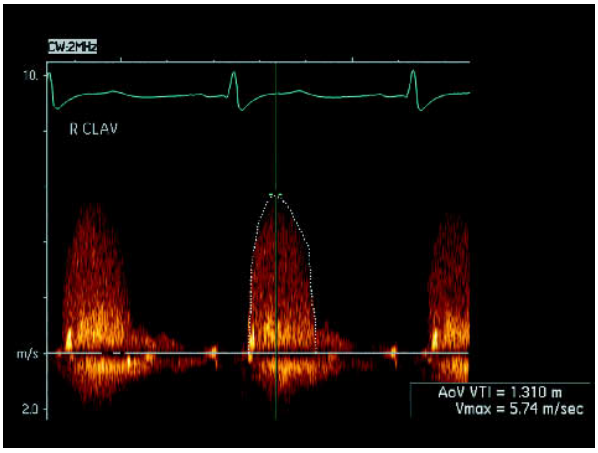


Figure 12.1: Calculation of the Aortic Valve Area. The continuity principle states that stroke volume through the stenotic aortic valve (SV_{AV}) must be equal to the stroke volume proximal to the stenotic valve (the stroke volume within the LVOT [SV_{LVOT}]). Thus, $SV_{AV} = SV_{LVOT}$. As the stroke volume is a product of the integrated velocity over time (VTI) and the cross-sectional area (CSA), $CSA_{LVOT} \times VTI_{LVOT} = AVA \times VTI_{AV}$. If the CSA_{LVOT}, VTI_{LVOT} and VTI_{AV} can be measured, then the stenotic aortic valve area (AVA) can be derived using Equation 12.4.

Practical Example 12.1







From the images provided on the left, calculate the aortic valve area by: (1) the VTI method and (2) the peak velocity (V_{max}) method.

The image on the top shows the measurement of the LVOT diameter from the parasternal long axis view of the left ventricle; the middle trace was recorded using pulsed-wave Doppler with the sample volume within the LVOT and the bottom trace is the transaortic valve (AoV) signal recorded from the right supraclavicular fossa using continuous-wave Doppler.

AVA via the VTI Method

Using Equation 12.4:

$$AVA = \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{AV}}$$

$$= \frac{0.785 \times d^2 \times VTI_{LVOT}}{VTI_{AV}}$$

$$= \frac{0.785 \times 2.07^2 \times 20.7}{131}$$

$$= \frac{3.36 \times 20.7}{131}$$

$$= \frac{69.55}{131}$$

$$= 0.53 \text{ cm}^2$$

AVA via the V_{max} Method

Using Equation 12.5:

$$AVA = \frac{CSA_{LVOT} \times V_{LVOT}}{V_{AV}}$$

$$= \frac{3.36 \times 0.95}{5.74}$$

$$= \frac{3.19}{5.74}$$

$$= 0.56 \text{ cm}^2$$

Determination of the Mitral, Tricuspid, and Pulmonary Valve Areas

The mitral, tricuspid, and pulmonary valve areas (native or prosthetic) can also be derived by application of the continuity principle. As discussed above, calculation of the valve area by this method requires the measurement of the stroke volume proximal to the stenotic/prosthetic valve. However, it is not always easy to measure the stroke volume proximal to the mitral, tricuspid or pulmonary valves (this is especially true for the atrioventricular [AV] valves). Fortunately, measurement of stroke volume through the LVOT is relatively easy and, providing that the stroke volume through the AV/pulmonary valve and the LVOT are equal, the stroke volume of the LVOT can be substituted for the stroke volume proximal to the AV/pulmonary valve. Hence, the unknown valve area can be calculated by application of the following equation:

(Equation 12.7)

$$CSA_{sten} = \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{sten}}$$

where CSA_{LVOT} = cross-sectional area of left ventricular outflow tract (cm^2)

CSA_{sten} = cross-sectional area of stenotic/prosthetic valve (cm^2)

VTI_{LVOT} = velocity time integral through left ventricular outflow tract (cm)

VTI_{sten} = velocity time integral through stenotic/prosthetic valve (cm)

For example, calculation of the mitral valve area can be derived from the stroke volume through the LVOT and the VTI across the mitral valve (Figure 12.2 and Practical Example 12.2). This assumes that the stroke volume through the stenotic mitral valve is equal to the stroke volume within the LVOT. As the stroke volume is a product of the CSA and the VTI, the stenotic mitral valve area (MVA) can then be derived by the application of the following equation:

(Equation 12.8)

$$MVA = \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{MV}}$$

where MVA = mitral valve area (cm^2)
CSA_{LVOT} = cross-sectional area of left ventricular outflow tract (cm^2)
VTI_{LVOT} = velocity time integral through the left ventricular outflow tract (cm)
VTI_{MV} = velocity time integral across the mitral valve (cm)

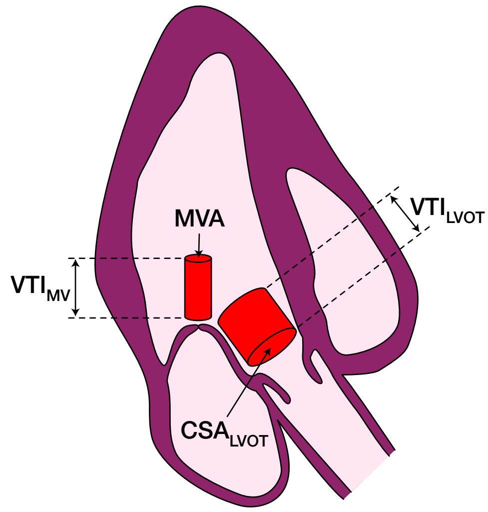
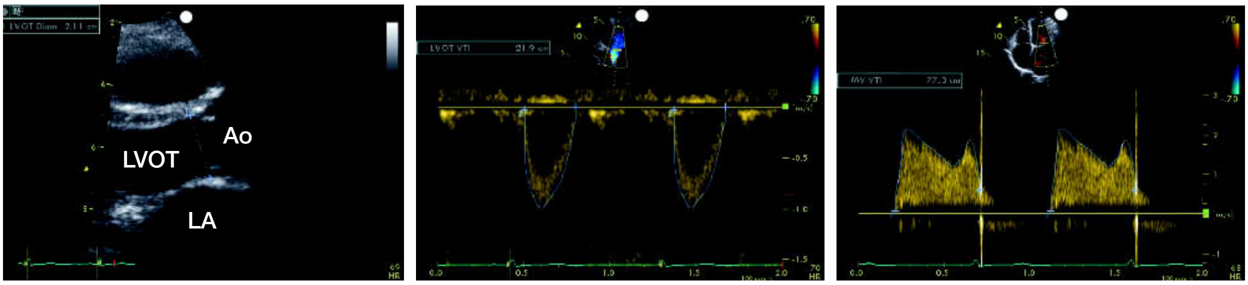


Figure 12.2: Calculation of the Mitral Valve Area by the Continuity Equation.
Using the continuity principle it is assumed that the stroke volume through the stenotic mitral valve (SV_{MV}) is equal to the stroke volume within the LVOT [SV_{LVOT}]). As the stroke volume is a product of the integrated velocity over time (VTI) and the cross-sectional area (CSA), $CSA_{LVOT} \times VTI_{LVOT} = MVA \times VTI_{MV}$. If the CSA_{LVOT}, VTI_{LVOT} and VTI_{MV} can be measured, then the stenotic mitral valve area (MVA) can then be derived using Equation 12.8.

Practical Example 12.2



From the images provided above, calculate the mitral valve area by application of the continuity equation.

The image on the left shows the measurement of the LVOT diameter from the parasternal long axis view of the left ventricle; the middle trace was recorded using PW Doppler with the sample volume within the LVOT and the trace on the right is the transmitral valve (MV) signal recorded from the apical window using continuous-wave Doppler.

MVA via the Stroke Volume Method
Using Equation 12.8:

$$\begin{aligned} MVA &= \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{MV}} \\ &= \frac{0.785 \times d^2 \times VTI_{LVOT}}{VTI_{MV}} \\ &= \frac{0.785 \times 2.11^2 \times 21.9}{77.3} \\ &= \frac{3.49 \times 21.9}{77.3} \\ &= \frac{76.43}{77.3} \\ &= 0.99\ cm^2 \end{aligned}$$

Method for calculation of valve area by the stroke volume method

Assuming that the stroke volume through the LVOT is the same as the stroke volume across a stenotic/prosthetic valve.

Step 1: Measure the CSA of the LVOT (CSA_{LVOT}): from the parasternal long axis view, measure the LVOT diameter (D):
- measure during systole
- measure from inner edge to inner edge determine CSA of LVOT annulus (cm^2):
- $CSA = 0.785 \times d^2$

Step 2: Measure the VTI of the LVOT (VTI_{LVOT}): from the apical 5 chamber view, measure the VTI of the LVOT:
- using PW Doppler, place the sample volume approximately 0.5 cm proximal to the aortic valve
- trace along the leading edge velocity to obtain the VTI (cm)

Step 3: Measure the VTI of the stenotic/prosthetic valve (VTI_{sten}): using CW Doppler, measure the VTI across the stenotic valve:
- interrogate from multiple windows to the ensure highest velocity signal is obtained
- trace along the leading edge velocity to obtain the VTI (cm)

Step 4: Calculate the unknown stenotic/prosthetic valve area (CSA_{sten}):

$$CSA_{sten}\,(cm^2) = \frac{CSA_{LVOT} \times VTI_{LVOT}}{VTI_{sten}}$$

Limitations of the Continuity Equation by the Stroke Volume Method

Assumptions of Volumetric Flow Calculations

Calculation of the valve area by the continuity equation is based on the determination of the stroke volume. Stroke volume calculations are, in turn, based on a simple hydraulic formula which determines the volumetric flow through a cylindrical tube under steady flow conditions. In order to apply this concept to the heart, certain assumptions regarding flow properties and conditions are made. These assumptions include that: (1) flow is occurring in a rigid, circular tube, (2) there is a uniform velocity across the vessel, (3) the derived CSA is circular, (4) the CSA remains constant throughout the period of flow, and (5) the sample volume remains in a constant position throughout the period of flow.

However, blood vessels are elastic and, therefore, change throughout the duration of flow within the cardiac cycle. In addition, annular diameters may change throughout the period of flow and, while the left and right ventricular outflow tracts assume a circular configuration, the same may not be said for the atrioventricular valves that assume a more elliptical shape.

Determination of the CSA of the LVOT

Determination of the LVOT CSA is derived by measuring the diameter of the LVOT during systole. The CSA is then calculated by squaring the diameter and multiplying this value by 0.785. Therefore, any error in the measurement of the diameter is magnified. Suboptimal imaging and excessive calcification of the LVOT annulus further affects the accuracy of this measurement.

When calculating the effective orifice area of the prosthetic aortic valve replacement (AVR), measurement of the LVOT diameter may prove difficult due to reverberations arising from the dense sewing ring of the prosthesis. Therefore, it is sometimes necessary to substitute the AVR size for the LVOT diameter. However, the sonographer should be aware that the LVOT diameter and the AVR size are not always the same. For example, the AVR size is usually slightly larger than the LVOT diameter when the AVR is implanted superior to the valve annulus or when there is progressive narrowing of the LVOT due to fibrosis, scarring or calcification which may occur with "aging" of AVR. Therefore, the direct substitution of the prosthetic ring size for the LVOT is not recommended. Substitution of the prosthetic valve size for the LVOT diameter should only be done when the LVOT cannot be accurately measured.

Dimensionless Severity Index (DSI)

When accurate measurement of the LVOT diameter is not possible, the degree of aortic valve stenosis can also be determined by the calculation of the DSI. The DSI (or velocity ratio) is simply the ratio of the LVOT VTI (or peak velocity) to the aortic valve VTI (or peak velocity):

(Equation 12.9)

$$DSI = \frac{LVOT_{VTI/V}}{AV_{VTI/V}}$$

Using this index, a value of 0.25 or less is associated with severe aortic stenosis [59].

This index is also useful in the serial assessment of prosthetic aortic valves (referred to as the Dimensionless Performance Index [DPI]). The DPI is independent of the cardiac output as the LVOT and AVR velocities change proportionally. For example, an increase in the LVOT velocity which may occur due to an increase in the cardiac output coincides with a proportional increase in the AVR velocity. Thus, this index can serve as a 'fingerprint' or 'control value' for an individual's prosthetic valve.

59: Oh JK, Taliercio CP, Holmes DR Jr, et al. *Journal of the American College of Cardiology 11:1227-1234,1988*

Incorrect Sample Volume Placement within the LVOT

Calculation of the valve area assumes that flow proximal to a narrowed valve is laminar. Therefore, for accurate results, it is necessary to position the sample volume where the flow profile is uniform.

The pulsed-wave sample volume should be positioned within the LVOT approximately 0.5 cm proximal to aortic valve avoiding the flow acceleration region which occurs immediately proximal to the aortic valve. If the sample volume is placed too close to the aortic valve, the peak velocity and VTI will be overestimated and, therefore, the stroke volume within the LVOT will also be overestimated; if the sample volume is placed too far from the aortic valve, the peak velocity and VTI will be underestimated and, therefore, the stroke volume within the LVOT will also be underestimated.

> **Technical Tip**
> To ensure appropriate positioning of the pulsed-wave sample volume within the LVOT, place the sample volume through the aortic valve and then slowly step the sample volume back towards the LVOT. When the signal displays a laminar profile with minimal spectral broadening and a closing click, the sample volume is in the correct position (Figure 12.3).

Failure to Obtain the Peak Velocity

As previously mentioned, when there is a large incident angle (θ) between ultrasound beam and the direction of blood flow, a significant underestimation of the true velocity occurs. Therefore, failure to align the ultrasound beam parallel to the direction of blood flow will result in the underestimation of the true peak velocity. This underestimation of the peak velocity will ultimately result in the overestimation of the valve area by the application of the continuity equation. Consequently, meticulous Doppler interrogation, utilising multiple transducer positions to obtain the peak velocity, is mandatory.

Non-Simultaneous Peaking of Signals

Calculation of the AVA via the continuity equation is inaccurate in situations where the peak velocities through the LVOT and through the aortic valve do not occur simultaneously. This situation typically occurs in the presence of dynamic LVOT obstruction whereby the LVOT velocity peaks in late systole. In this situation, the AVA can be derived by substituting the stroke volume derived from the right ventricular outflow tract (RVOT) for the LVOT stroke volume (providing that there is insignificant aortic regurgitation and pulmonary regurgitation and in the absence of an intracardiac shunt).

Differential Flow

Determination of the valve area by the continuity equation requires that the stroke volumes through the region proximal to the stenosis and through the stenotic orifice are equal. Therefore, differential flow such as valvular regurgitation or intracardiac shunt flow may invalidate the calculation of the valve area by the continuity equation. For example, using the LVOT stroke volume for the calculation of the MVA when there is **coexistent aortic regurgitation** will **overestimate the MVA**. This is because the stroke volumes through the LVOT and across the mitral valve are no longer equal as there is greater flow through the LVOT which includes the forward stroke volume plus the regurgitant volume.

Likewise, using the LVOT stroke volume for the calculation of the MVA when there is **coexistent mitral regurgitation** will **underestimate the MVA**. In this instance, the stroke volume across the mitral valve will be greater than that through the LVOT as the transmitral stroke volume includes the forward stroke volume plus

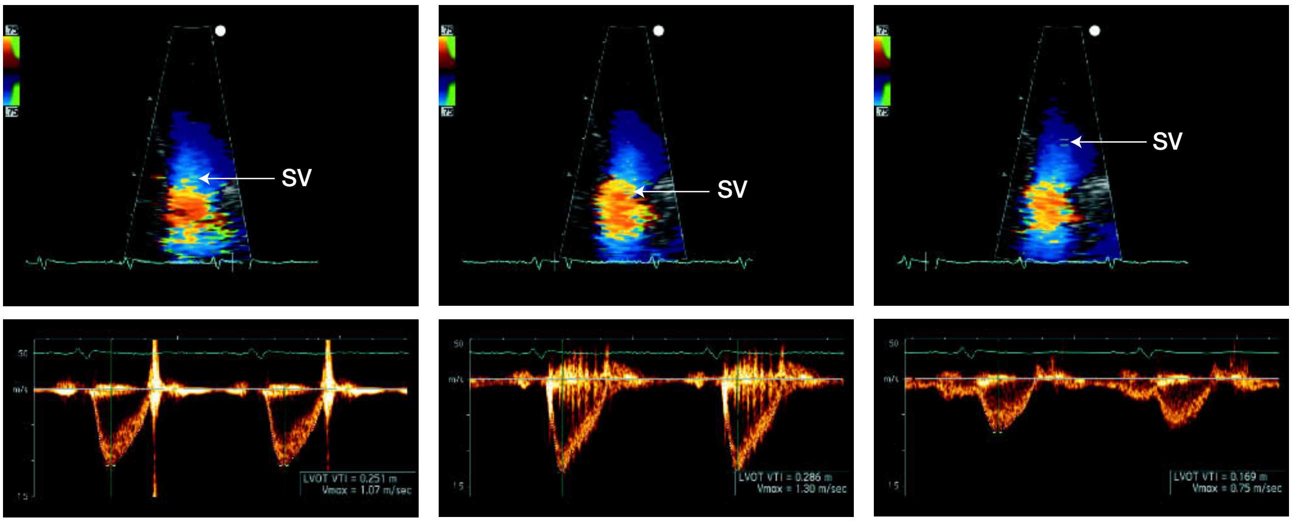


Figure 12.3: Affect of Sample Volume Position on LVOT Velocity Profile.
The images on the left were recorded with the sample volume (SV) optimally positioned about 0.5 cm from the aortic valve. The spectral Doppler trace displays a laminar LVOT flow profile and a closing click; the peak velocity is 1.07 m/s and the VTI is 0.25 m.
The middle images were recorded with the SV positioned into the flow acceleration zone. The spectral Doppler trace displays a 'messy' flow profile with spectral broadening; both the peak velocity and VTI are overestimated at 1.3 m/s and 0.286 m, respectively.
The images on the right were recorded with the SV positioned too far into the LV cavity. The spectral Doppler trace displays a flat flow profile and no closing click; both the peak velocity and the VTI are underestimated at 0.75 m/s and 0.169 m, respectively.

the regurgitant volume.

Using the LVOT stroke volume for the calculation of the AVA in the presence of a **coexistent membraneous ventricular septal defect** will **overestimate the AVA** as flow through the aortic valve will be less than flow through the LVOT as some flow through the LVOT will be shunted across the ventricular septal defect into the right ventricle and, therefore, the stroke volume through the aortic valve will be less.

> **Technical Tips**
> In the presence of aortic regurgitation, the MVA area can be derived by substituting the RVOT stroke volume for the LVOT stroke volume providing that there is no intracardiac shunt or significant pulmonary regurgitation (Figure 12.4).
> The presence of aortic regurgitation does not affect the accuracy of the AVA calculation as the stroke volumes through the LVOT and across the aortic valve are still the same.

Low Cardiac Output States

An apparent underestimation of the AVA (overestimation of aortic stenosis severity) may occur in patients with a low cardiac output. For example, in situations where there is poor myocardial contractility and/or reduced flow through the aortic valve, calculation of the "resting" AVA may significantly underestimate the true anatomical valve area. Small valve areas due to a low cardiac output ("pseudo-aortic stenosis") can be differentiated from small valve areas due to significant stenosis (true aortic stenosis) by "normalising" or increasing the cardiac output through the valve. "Normalisation" of the cardiac output can be achieved by exercise or dobutamine infusion; increasing the cardiac output results in an increase in both the LVOT and transaortic valve velocities.

In patients with "pseudo-aortic stenosis", the increase in the cardiac output leads to a greater opening of the valve leaflets and the increase in the LVOT velocity is greater than the increase in the transaortic velocity and the "effective" AVA will increase. In patients with true severe aortic stenosis, the increase in the transaortic velocity is proportionally similar to the increase in the LVOT velocity and the AVA will remain unchanged.

Estimation of Prosthetic Effective Orifice Areas

The accuracy of the Doppler-derived effective orifice area (EOA) in prosthetic valves is dependent upon the valve type and size. Significant 'underestimation' of the EOA compared with invasive measurements has been reported in small St. Jude prostheses in the aortic position. This is thought to be related to the valve's bileaflet design resulting in localised high velocities through the central divergent orifice compared with the two larger side orifices as well as rapid pressure recovery distal to the valve. In this situation, the peak aortic velocities recorded by CW Doppler may not be representative of the mean velocity distribution across the prosthetic orifice. Thus, Doppler-derived prosthetic valve areas should always be referenced against normal Doppler data specific for the patient's valve type and size.

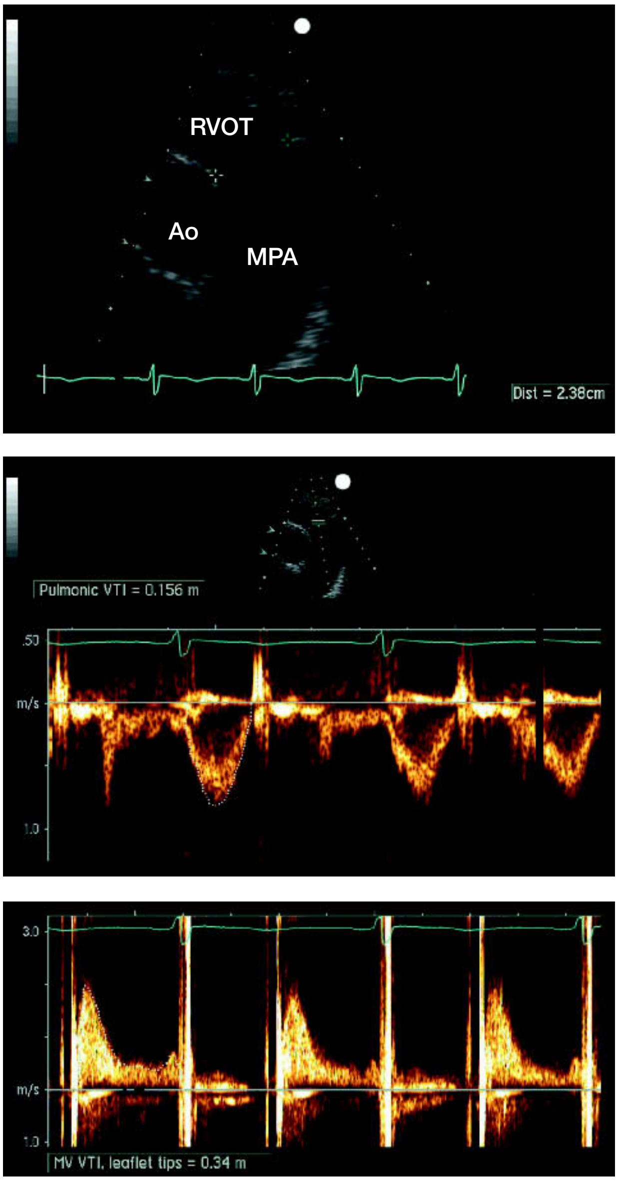


Figure 12.4: Calculation of the MVA using the RVOT Stroke Volume. The top image shows measurement of the right ventricular outflow tract (RVOT) diameter from a zoomed parasternal short axis view. The RVOT diameter is measured at 2.38 cm. The middle image shows measurement of the RVOT VTI with the sample volume placed just proximal to the pulmonary valve. The RVOT VTI is measured at 0.156 m or 15.6 cm. The bottom image shows measurement of the transmitral VTI via continuous-wave Doppler; the VTI is measured at 0.34 m or 34 cm. Using Equation 12.8 and substituting the RVOT for the LVOT parameters, the MVA is calculated as follows:

$$MVA = \frac{CSA_{RVOT} \times VTI_{RVOT}}{VTI_{MV}}$$

$$= \frac{0.785 \times 2.38^2 \times 15.6}{34}$$

$$= 2.0\ cm^2$$

> **Clinical Consideration**
> The normal EOA value for prosthetic valves is dependent on the valve type, size and position of the valve (refer to Appendix 3). Therefore, when evaluating possible obstruction of a prosthetic valve, the ranges that are used in the assessment of the severity of native valve stenoses do not apply.

Calculation of the Mitral Valve Areas by the Proximal Isovelocity Surface Area Method

As discussed in Chapter 11, the proximal isovelocity surface area (PISA) principle can be applied in the calculation of the area of a narrowed orifice (regurgitant or stenotic). This technique has been used in the calculation of the MVA in patients with mitral stenosis.

The principal advantage of the PISA technique in the estimation of the MVA lies in the fact that this method is unaffected by many factors which are known to significantly hamper the calculation of the MVA by other echocardiographic techniques such as 2-D planimetry, the continuity equation and the pressure half-time methods. For example, the PISA method can be used when there is mitral leaflet calcification, thickening or distortion of the leaflets, and/or associated mitral or aortic regurgitation.

Studies validating the accuracy and reliability of the PISA method in the calculation of the MVA are tabulated in Appendix 7.

Theoretical Considerations

The theoretical concepts for the calculation of the area of a narrowed orifice by the PISA method are discussed in detail in Chapter 11. Recall that this principle calculates the proximal flow rate by measuring the surface area of the hemispheric shell and the velocity at this hemispheric shell (Figure 12.5):

(Equation 12.10)

$$Q = 2\,\pi\, r^2 \times V_N$$

where Q = flow rate (mL/s)
$2\pi r^2$ = surface area of a hemispheric shell derived from the proximal flow convergence radius [r] (cm^2)
V_N = velocity at the radius of the hemispheric shell (colour aliased velocity or Nyquist limit) (cm/s)

Assuming that the flow rate through any given hemispheric shell is equal to the flow rate through the narrowed valve, then:

(Equation 12.11)

$$2\,\pi\, r^2 \times V_N = EOA \times V_{max}$$

where $2\pi r^2$ = surface area of a hemispheric shell derived from the proximal flow convergence radius [r] (cm^2)
V_N = velocity at the radius of the hemispheric shell (colour aliased velocity or Nyquist limit) (cm/s)
EOA = effective orifice area (cm^2)
V_{max} = peak velocity through the narrowed orifice (cm/s)

The effective orifice area can then be derived by application of the following equation:

(Equation 12.12)

$$EOA = \frac{2\pi\, r^2 \times V_N}{V_{max}}$$

where EOA = effective orifice area (cm^2)
$2\pi r^2$ = surface area of a hemispheric shell derived from the proximal flow convergence radius [r] (cm^2)
V_N = velocity at the radius of the hemispheric shell (colour aliased velocity or Nyquist limit) (cm/s)
V_{max} = peak velocity across the narrowed orifice (cm/s)

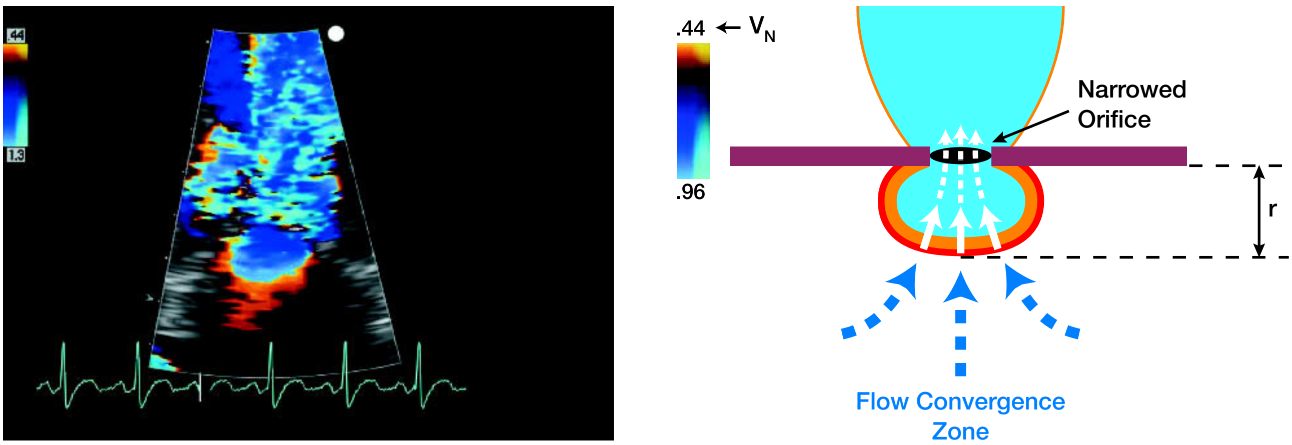


Figure 12.5: The Proximal Isovelocity Surface Area (PISA) Principle applied in the Calculation of a Stenotic or Regurgitant Orifice Area. Flow proximal to a stenotic orifice streamlines towards this orifice forming concentric hemispheric shells of the same velocities (isovelocities). These hemispheres are easily identified by colour flow imaging as aliasing which occurs as velocities exceed the Nyquist limit. The surface area of the isovelocity dome is equal to $2\pi r^2$, where r is the radial distance from the orifice to the first aliased velocity. The velocity at this radius is equal to the Nyquist limit of the colour bar (V_N).
In this example, flow is towards from the transducer; hence, the first aliased velocity is identified as the velocity at which flow changes from red to blue (that is, 0.44 m/s). By measuring the radial distance (r) from the narrowed orifice to this first aliased velocity, the surface area of this hemispheric shell can be derived using $2\pi r^2$. Thus, the flow rate proximal to the narrowed orifice can be derived using Equation 12.10: Q (mL/s) = $2\pi r^2 \times V_N$.

Application of the PISA Principle in Mitral Valve Stenosis

The MVA calculated by the PISA technique has correlated well with other methods for measuring the MVA (see Appendix 8).

The PISA principle can be applied to the estimation of the MVA in mitral stenosis when (1) the stenotic MVA is the narrowed orifice and (2) the peak velocity through the narrowed orifice is the peak early diastolic velocity (peak E wave velocity) through the stenotic mitral valve:

(Equation 12.13)

$$MVA = \frac{2\pi r^2 \times V_N}{V_{MS}}$$

where MVA = mitral valve area (cm^2)
$2\pi r^2$ = surface area of a hemispheric shell derived from the proximal flow convergence radius [r] (cm^2)
V_N = velocity at the radius of the hemispheric shell (colour aliased velocity or Nyquist limit) (cm/s)
V_{MS} = peak early diastolic velocity across the mitral valve [E velocity] (cm/s)

Calculation of the MVA by the PISA method, however, is not this simple. The PISA principle is based on flow approaching a narrowed orifice that conforms to a flat planar surface. In mitral stenosis, the mitral leaflets form a funnel (at an angle of α) which effectively constrains the proximal flow convergence zone and pushes the flow convergence zone outwards (Figure 12.6). To account for this flow constraint, an angle correction factor of α/180 has been derived. This angle correction factor is based upon the following facts: (1) if the mitral valve leaflets were laid out flat, flow would converge toward the orifice over an arc of 180° from any direction and (2) in mitral stenosis, flow can only converge to the narrowed orifice over an arc of α degrees. Therefore, accounting for the angle correction factor, the MVA can be derived from the following equation (Practical Example 12.3):

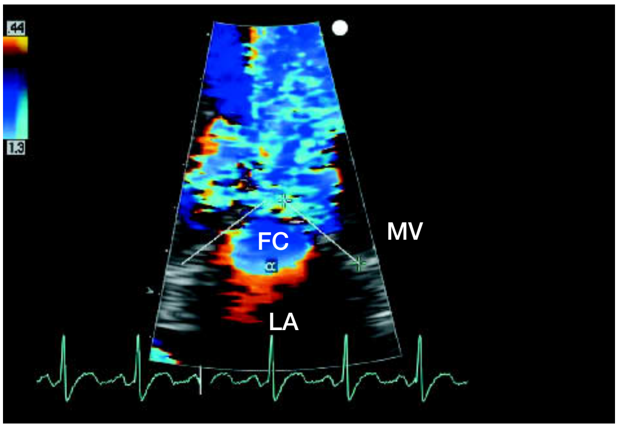


Figure 12.6: Funnel-shaped Flow Convergence Region Proximal to the Mitral Valve Orifice.
Angle α is measured as the angle of the mitral valve leaflets (MV) proximal to the stenotic orifice in the flow convergence (FC) region; that is, the angle is measured from the left atrial (LA) side of the stenotic valve.

(Equation 12.14)

$$MVA = \frac{2\pi r^2 \times V_N}{V_{MS}} \times \left(\frac{\alpha}{180}\right)$$

where MVA = mitral valve area (cm^2)
$2\pi r^2$ = surface area of a hemispheric shell derived from the proximal flow convergence radius [r] (cm^2)
V_N = velocity at the radial distance of the hemispheric shell (colour aliased velocity or Nyquist limit) (cm/s)
V_{MS} = peak early diastolic mitral velocity (cm/s)
α/180 = angle correction factor

> **Technical Tip**
> Most errors arising from the calculation of the orifice area using the PISA principle occur due to failure to convert velocity units from m/s to cm/s.

Limitations of the PISA Method for Calculating the MVA

Assumptions of PISA Calculations

The PISA model is based on the hemispherical flow convergence area. However, the mitral stenotic orifice may be elliptical. Furthermore, the geometry of the isovelocity shell changes with: (1) the flow rate, (2) the pressure gradient, and (3) the orifice size and shape.

Radius Measurements

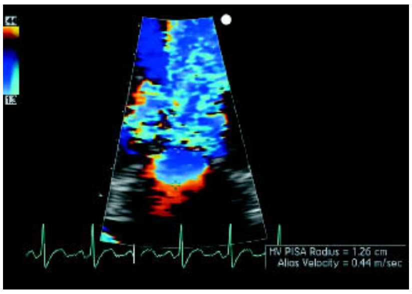
Accurate calculations of the MVA by the PISA technique are dependent upon the precise measurement of the radius between the stenotic orifice and the first aliased velocity. Since the valve area is derived by squaring the radius (Equation 12.14), failure to measure the correct radius may result in a significant underestimation or overestimation of the MVA. Furthermore, the relatively small size of the proximal convergence region to the field of view may limit the accuracy of this measurement. Methods that may be employed to overcome problems in this measurement include magnification of the proximal flow convergence region and reduction of the aliasing velocity. Reduction of the aliased velocity effectively increases the radius and this can be achieved by shifting the colour baseline toward the direction of flow. However, reducing the aliased velocity also has potential limitations. At very low aliasing velocities, overestimation of the mean velocity displayed by the colour Doppler may result due to suppression of low velocities by colour wall filters; therefore, resulting in an overestimation of the radius measurement.

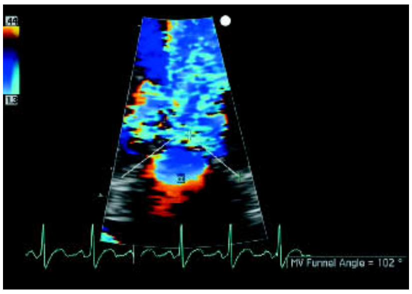
Measurement of Angle α

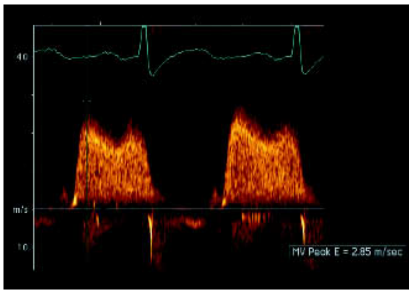
As the measurement of angle α is not possible to perform on-line on many ultrasound systems, the measurement of angle α must be performed off-line using a protractor.

Furthermore, the angle formed by the stenotic mitral valve leaflets is three dimensional. Therefore, the correction for angle α which is performed in one imaging plane (usually

Practical Example 12.3







From the images provided, calculate the mitral valve area by the PISA method.

The image on the left shows the measurement of the PISA radius (MV PISA radius) from a zoomed apical 4 chamber view of the mitral valve, the aliased velocity at this radius is 0.44 m/s (44 cm/s). The middle image shows the measurement of the angle of the mitral valve funnel (α) recorded from a zoomed apical 4 chamber view of the mitral valve and the right trace displays the measurement of the peak transmitral E velocity (MV E velocity) recorded from the apical window using continuous-wave Doppler.

MVA via the PISA Method

Using Equation 12.14:

$$MVA = \frac{2\pi r^2 \times V_N}{V_{MS}} \times \left(\frac{\alpha}{180}\right)$$

$$= \frac{6.28 \times (1.26)^2 \times 44}{285} \times \frac{102}{180}$$

$$= \frac{438.69}{285} \times 0.57$$

$$= 1.54 \times 0.57$$

$$= 0.88\,cm^2$$

the apical four chamber view) may not be representative of the true leaflet geometry and may not account for variations within the geometry of the leaflets.

Atrial Fibrillation

As mentioned, precise measurement of the radius between the stenotic orifice to the first aliased velocity is crucial to the accuracy of the calculated MVA via the PISA method as the radius is squared. Failure to measure the correct radius may result in a significant underestimation or overestimation of the MVA. Beat-to-beat variations that occur with atrial fibrillation may magnify errors in the radius measurement. Minimisation of this potential error can be achieved by averaging multiple measurements of the radius.

Technical Tip

It has recently been suggested that the MVA via the PISA method can be simplified by assuming that the angle of the MV funnel is 100° [60]. Thus, instead of using a correction factor of α/180, a correction value of 0.56 (100/180) could be used.

Calculation of Mitral Valve Areas by the Pressure Half-Time and Deceleration Time Methods

The pressure half-time (P½t) and deceleration time (DT) can be used in the estimation of the MVA in patients with native mitral valve stenosis. The principal advantage of the P½t in the estimation of the MVA is that it is independent of the cardiac output or coexistent mitral regurgitation. Therefore, this method is useful in the assessment of the severity of mitral stenosis in situations where the mean transmitral pressure gradients may be misleading. For example, overestimation of the severity of mitral stenosis using the transmitral pressure gradient may occur when there is coexistent mitral regurgitation. In this instance, increased transmitral gradients occur because of increased flow across the regurgitant valve. Conversely, underestimation in the severity of mitral stenosis may occur when there is a low mean transmitral pressure gradient in the setting of a low cardiac output. Calculation of the MVA by the P½t can readily overcome these potential misinterpretations. For example, patients with mitral regurgitation but only mild mitral stenosis will have a short P½t despite increased transmitral pressure gradients. Conversely, in patients with a low cardiac output, prolongation of the P½t will be evident with significant stenosis even when there is a low transmitral pressure gradient. Studies validating the accuracy and reliability of the P½t in the calculation of the MVA are tabulated in Appendix 8.

Theoretical Considerations

In the presence of mitral stenosis, the pressure gradient between the left atrium (LA) and left ventricle (LV) is increased throughout the diastolic period and this is reflected in the transmitral velocity trace as the prolongation of the rate of decline of the early diastolic velocity. Prolongation of this diastolic deceleration slope occurs because a longer time is required for the LA to empty, through the stenotic mitral valve, into the LV. The rate of decline of the pressure difference between the LA and LV can be measured by the P½t. The P½t is defined as the time required for the pressure to decay to half its original value.

60: Messika-Zeitoun D, Cachier A, Brochet E, et al. *European Journal of Echocardiography. 8:116-121, 2007.*

In Doppler echocardiography, velocity rather than pressure is displayed on the Doppler spectrum. Since velocity and pressure are related, the P½t can also be measured from the velocity spectrum (Figure 12.7). It is important to note, however, that the P½t is not equal to the velocity half-time. The velocity that corresponds to one-half of the peak pressure is derived from the following equation:

(Equation 12.15)

$$V_{half} = \frac{V_{peak}}{\sqrt{2}}$$

$$or$$

$$= \frac{V_{peak}}{1.414}$$

where V_{half} = velocity corresponding to one-half of the peak pressure (m/s)
V_{peak} = peak velocity (m/s)

Due to the relationship between pressure and velocity, the P½t can be derived from the velocity spectrum. Recall that the relationship between pressure (P) and velocity (V) is expressed by the following equation:

(Equation 12.16)

$$\Delta P = 4V^2$$

One-half of the peak pressure (P_{half}) is derived by dividing the peak pressure (P_{peak}) by:

(Equation 12.17)

$$P_{half} = \frac{P_{peak}}{2}$$

Therefore, by substituting the $4V^2$ for P (as per Equation 12.16) into Equation 12.17 the velocity which corresponds to one-half of the peak pressure (V_{half}) can be derived as follows:

$$4V_{half}^2 = \frac{4V_{peak}^2}{2}$$

$$V_{half}^2 = \frac{4V_{peak}^2}{4 \times 2}$$

$$= \frac{V_{peak}^2}{2}$$

$$V_{half} = \frac{\sqrt{V_{peak}^2}}{\sqrt{2}}$$

$$= \frac{V_{peak}}{\sqrt{2}}$$

$$= \frac{V_{peak}}{1.414}$$

The velocity corresponding to the one-half of the pressure (V_{half}) can also be derived as follows:

(Equation 12.18)

$$V_{half} = V_{peak} \times 0.707$$

Hatle and Angelsen [61], observed that a P½t of 220 ms usually equated to a MVA of 1.0 cm^2 and based on this observation, a formula for the calculation of the MVA using the P½t and an empirical constant of 220 was derived:

(Equation 12.19)

$$MVA = \frac{220}{P^{1}\!/_{2}\,t}$$

where MVA = mitral valve area (cm^2)
220 = empirical constant
P½t = pressure half-time (ms)

The P½t is also related to the deceleration time (DT). The DT is the time taken for the peak early diastolic velocity to fall to zero. The early diastolic velocity does not always fall to zero but since the deceleration slope of the transmitral velocity spectrum is usually linear, this slope can be easily extrapolated to the zero baseline enabling the measurement of the DT (Figure 12.8). The relationship between the P½t and the DT is such that the P½t is equal to 29% of the DT and, therefore, the P½t can be derived from the DT:

(Equation 12.20)

$$P^{1}\!/_{2}\,t = 0.29 \times DT$$

where P½t = pressure half-time (ms)
DT = deceleration time (ms)

Due to the relationship between P½t and the DT, the MVA can also be directly derived from the DT:

(Equation 12.21)

$$MVA = \frac{759}{DT}$$

where MVA = mitral valve area (cm^2)
759 = 220 ÷ 0.29
DT = deceleration time (ms)

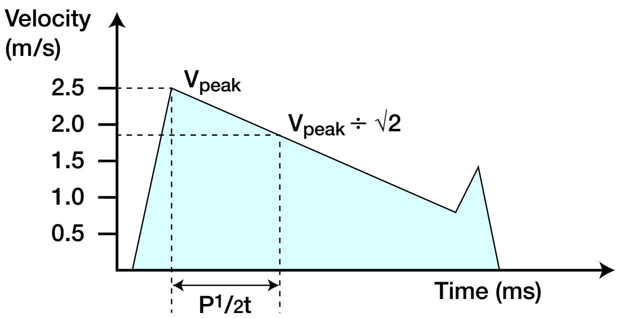


Figure 12.7: Method of Measuring the Pressure Half-Time from the Doppler Velocity Spectrum.
This schematic illustrates how the pressure half-time (P½t) is measured from the transmitral velocity spectrum. The P½t is the time required for the pressure to decay to half its original value. Using the velocity spectrum, the P½t is equal to the time taken for the peak velocity (V_{peak}) to fall to a value equivalent to Vpeak ÷ √ 2. In this example, if the Vpeak is 2.5 m/s; the V_{peak} ÷ √ 2 is 1.77 m/s. Hence, the P½t is equal to the time taken for the velocity to fall from 2.5 m/s to 1.77 m/s.

61: Hatle L and Angelsen B. *Doppler Ultrasound in Cardiology*. Physical Principles and Clinical Applications. U.S.A. Lea and Febiger, pages 118-122, 1985.

By combining Equations 12.19 and 12.20, it is also possible to calculate the MVA from the DT:

(Equation 12.19)

$$MVA = \frac{220}{P^{1/2}t}$$

(Equation 12.20)

$$P^{1/2}t = 0.29 \times DT$$

Therefore, by substituting the (0.29 x DT) for the P1/2t, the MVA can be derived as follows:

$$MVA\ (cm^2) = \frac{220}{P^{1/2}t} = \frac{220}{0.29 \times DT} = \frac{759}{DT}$$

Limitations of the P1/2t in the Calculation of the MVA

Non-linear (Curvilinear) Early Diastolic Slope

In the majority of cases, the diastolic pressure decay between the left atrium and left ventricle follows a straight line, thus, enabling accurate measurements of the P1/2t and the MVA. A non-linear or curvilinear decay of the diastolic pressure gradient can lead to erroneous calculations of the MVA if the P1/2t is measured incorrectly. The portion of the curvilinear slope measured is dependent on (1) the end-diastolic pressure gradient and (2) the part of the slope considered being most representative. Figure 12.9 illustrates the various methods that may be used in the determination of the P1/2t when there is a curvilinear slope and a high end-diastolic gradient. Of these methods, method C appears to provide the most accurate estimation of the MVA by the P1/2t.

Post Balloon Mitral Valvuloplasty

Immediately following balloon mitral valvuloplasty the accuracy of the calculated MVA by the P1/2t declines. This has been attributed to the fact that the P1/2t is not only inversely related to the MVA but is also directly proportional to other factors such as the peak transmitral gradient and chamber compliance. In the normal clinical situation, left atrial and left ventricular compliance counteract one another. However, immediately following balloon mitral valvuloplasty abrupt changes in left atrial pressure and left atrial compliance occurs altering the relationship between the P1/2t and the MVA. This adverse effect on the P1/2t appears to be short-term as studies performed 24 to 48 hours after balloon mitral valvuloplasty correlate equally as well with the haemodynamic valve areas determined prior to the procedure.

Significant Aortic Regurgitation

Misinterpretation between the mitral stenotic signal and the aortic regurgitant signal is possible. Differentiation between these two signals can be easily recognised by observation of the timing of each signal. Aortic regurgitation commences at the closure of the aortic valve while transmitral flow begins following the isovolumic relaxation period (time interval between aortic valve closure and mitral valve opening).

Severe aortic regurgitation may also lead to overestimation of the MVA by shortening the P1/2t. In this instance, the P1/2t is shortened due to a marked and rapid increase in the left ventricular diastolic pressure which effectively reduces the diastolic pressure gradient between the left atrium and the left ventricle during diastole (Figure 12.10).

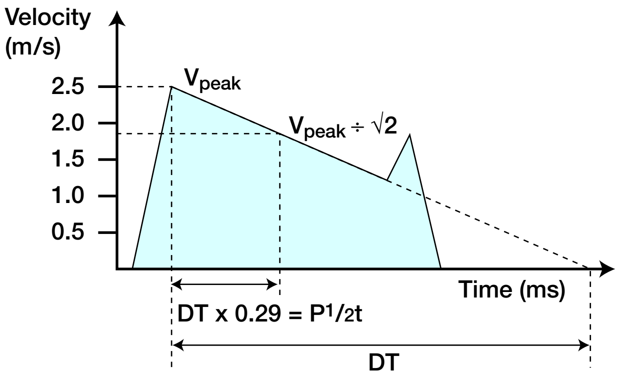


Figure 12.8: Method of Measuring the Deceleration Time from the Doppler Velocity Spectrum.
This schematic illustrates how the deceleration time (DT) is measured from the transmitral velocity spectrum. The DT is the time required for the velocity slope to fall from the peak velocity (V_{peak}) to zero. Normally, the transmitral velocity does not fall all the way to the zero baseline in early diastole and, hence, the deceleration slope must be extrapolated to the zero baseline. The P1/2t is equal to 29% of the DT; hence, the P1/2t can be derived by multiplying the DT by 0.29.

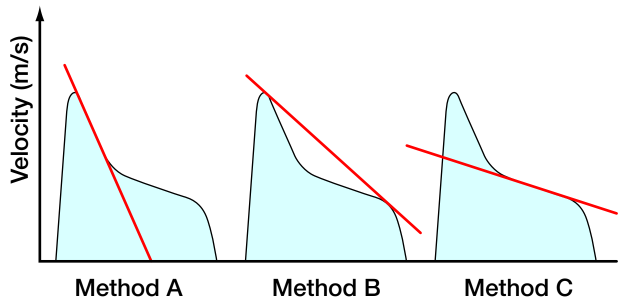


Figure 12.9: Methods used in the Determination of the Pressure Half-Time (P1/2t) in Curvilinear Doppler Spectrums.
Method A measures the P1/2t in early diastole by following the early diastolic slope.
Method B measures the P1/2t by the "mean" slope method which measures the slope from the peak early diastolic velocity to the peak end-diastolic velocity.
Method C measures the P1/2t by measuring the slope from mid-diastole to end-diastolic velocity.

Cardiac Rhythm Disturbances

In the presence of sinus tachycardia or first degree atrioventricular heart block, the deceleration slope prior to atrial contraction may be so short that accurate measurement of the P½t is not possible. In addition, atrial flutter with frequent atrial contractions may produce a falsely short P½t and, therefore, will overestimate the MVA.

Prosthetic Mitral Valve Areas

The P½t method for determining MVA in prosthetic valves has not been validated. Studies have found that the calculation of the prosthetic mitral valve area via the P½t method overestimates the MVA [62-64]. Application of the continuity equation in the estimation of the effective valve area should be used to derive the area of a prosthetic mitral valve.

To the right, are "step-by-step" methods for calculation of the MVA using the P½t and the DT.

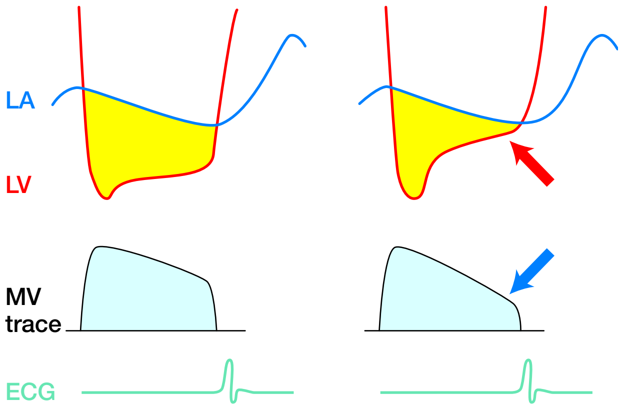


Figure 12.10: Affect of Severe Aortic Regurgitation on the Pressure Half-Time (P½t).
The schematic illustration on the left displays the pressure difference between the left atrium (LA) and the left ventricle (LV) during diastole in severe mitral stenosis. This pressure gradient is reflected on the transmitral Doppler spectrum. Observe that the diastolic pressure gradient remains high throughout the diastolic period.
The schematic illustration on the right depicts the affect of severe aortic regurgitation (AR) when there is a significant increase in the left ventricular end-diastolic pressure (LVEDP) (red arrow). Increased LVEDP occurs secondary to an increase in the LV volume from the AR regurgitant volume. When the LVEDP is increased the pressure gradient between the LA and LV at the end of diastole is decreased despite the LA pressure still being high (blue arrow). The resultant P½t is decreased in this instance and the resultant MVA will be overestimated.

Method for calculation of the mitral valve area by the P½t

Step 1: Optimise the CW Doppler signal through the mitral valve:
a) usually best from apical window
b) colour flow imaging may facilitate alignment with stenotic jet

Step 2: Measure the peak E velocity (V_{peak})

Step 3: Calculate the pressure half-time (ms):
a) using Equation 12.15, determine point on the velocity spectrum that corresponds with ½ of the peak pressure (V_{half})

$$V_{half} = V_{peak} \div \sqrt{2}$$
$$= V_{peak} \div 1.4$$

b) draw vertical lines to the baseline from V_{peak} and V_{half}
c) measure the time interval between these two points – this is the P½t

Step 4: Calculate the mitral valve area (MVA) using Equation 12.19:

$$MVA = \frac{220}{P\frac{1}{2}t}$$

Method for calculation of the mitral valve area by the DT

Step 1: Optimise the CW Doppler signal through the mitral valve:
a) usually best from apical window
b) colour flow imaging may facilitate alignment with stenotic jet

Step 2: Measure the peak E velocity (V_{peak})

Step 3: Calculate the deceleration time (ms):
a) from the Vpeak extrapolate a line to the zero baseline
b) measure the time interval between the V_{peak} and the zero baseline – this is the DT

Step 4: Calculate the mitral valve area (MVA) using Equation 12.21:

$$MVA = \frac{759}{DT}$$

62: Dumesnil JG, Honos GN, Lemieux M, Beauchemin J. *American Journal of Cardiology 65:1443-1448, 1990*
63: Scalia GM, Anderson BA, Burstow DJ. *Journal of the American College of Cardiology 41(6 Suppl A):512, 2003*
64: Malouf JF, Ballo M, Hodge DO, et al. *Journal of the American Society of Echocardiography 18:1399-1403, 2005*

Effective Valve Area versus Anatomical Valve Area
Valve areas determined by the Doppler principles described in this chapter are derived by measuring the highest velocity across the valve. The highest velocity is located at the narrowest area which is usually located downstream from the stenotic jet. The smallest cross-sectional area of a jet downstream from a restricted orifice is referred to as the **vena contracta** (VC). Therefore, when calculating the valve area, it is this "effective" orifice area at the VC that is calculated and not the true "anatomical" valve orifice. Because the VC converges downstream from the anatomical orifice, the effective orifice area (EOA) is generally smaller than the anatomical valve area (Figure 12.11). Hence, the anatomical valve area measured via 2-D planimetry will usually be slightly larger than EOA.

(Omitted from this promotional file for copyright reasons)

Figure 12.11: Effective Orifice Area versus Anatomic Orifice Area
This schematic illustrates flow through a narrowed orifice as displayed with colour Doppler. Flow physiology produces proximal flow convergence (PFC) zone, vena contracta (VC), and jet. Zoom box illustrates continued contraction of jet as it propagates through anatomic orifice to create physiologic, or effective orifice. The VC refers to the narrowest area of the jet which is located downstream from a narrowed orifice. The valve area derived by the continuity equation calculates the area at the VC; this is referred to as the physiological or effective orifice area (EOA). The EOA is typically smaller than the true anatomic orifice area.
Reprinted from the *Journal of the American Society of Echocardiography* Volume 16 number 9, Roberts BR and Grayburn PA. Color Flow Imaging of the Vena Contracta in Mitral Regurgitation: Technical Considerations, page 1003, 2003 with permission from The American Society of Echocardiography.

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Pressure Half-time Method for Calculation of Mitral Valve Areas

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