Limitations of the Continuity Equation by the Stroke Volume Method

Assumptions of Volumetric Flow Calculations

Calculation of the EOA 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.

CSA of the LVOT

The CSA of the LVOT is derived from the LVOT diameter. The CSA is then calculated by squaring this diameter and multiplying this value by 0.785. Therefore, any error in the diameter measurement is magnified (see Practical Example 11.1). Suboptimal imaging and excessive calcification of the LVOT annulus further affects the accuracy of this measurement.

When calculating the EOA of a 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 the AVR. Therefore, the direct substitution of the prosthetic ring size for the LVOT is not recommended.

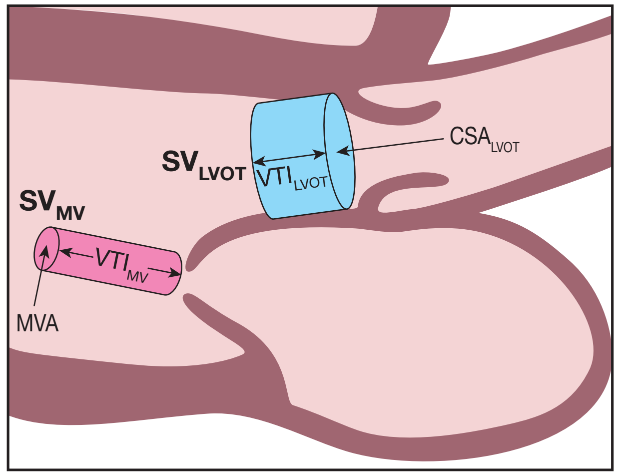

Figure 12.4 This schematic illustrates the calculation of the mitral valve area (MVA) via the stroke volume continuity principle. Assuming that the stroke volume through the left ventricular outflow tract (SV_{LVOT}) is the same across the stroke volume across the mitral valve (SV_{MV}) and that the stroke volume is derived from the cross-sectional area (CSA) and the velocity time integral (VTI), then:

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

If the CSA of the LVOT (CSA_{LVOT}), the VTI of the LVOT (VTI_{LVOT}) and the VTI of the mitral valve (VTI_{MV}) can be measured, then the MVA can be derived as:

$$MVA = (CSA_{LVOT} \times VTI_{LVOT}) \div VTI_{MV}$$

When accurate measurement of the LVOT diameter is not possible, the degree of aortic stenosis (AS) or the performance of the AVR can also be determined from the ratio of the LVOT VTI (or peak velocity) to the aortic valve VTI (or peak velocity). This ratio is referred to as the dimensionless severity index (DSI) in the case of AS or the Doppler velocity index (DVI) in the case of an AVR:

Equation 12.10

$$DSI\ (DVI) = V_{LVOT} \div V_{AV}$$

where DSI (DVI) = dimensionless severity index or Doppler velocity index (unitless)
V_{LVOT} = peak velocity (or VTI in cm) at the LVOT (m/s)
V_{AV} = peak velocity (or VTI in cm) across the aortic valve (m/s)

In particular, this index 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.

Incorrect LVOT Sample Volume Placement

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 PW Doppler sample volume should be positioned within the LVOT approximately 0.5 cm proximal to the 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. To ensure appropriate positioning of the PW Doppler sample volume within the LVOT, the sample volume should be placed through the aortic valve and then slowly stepped 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 (Fig. 12.5).

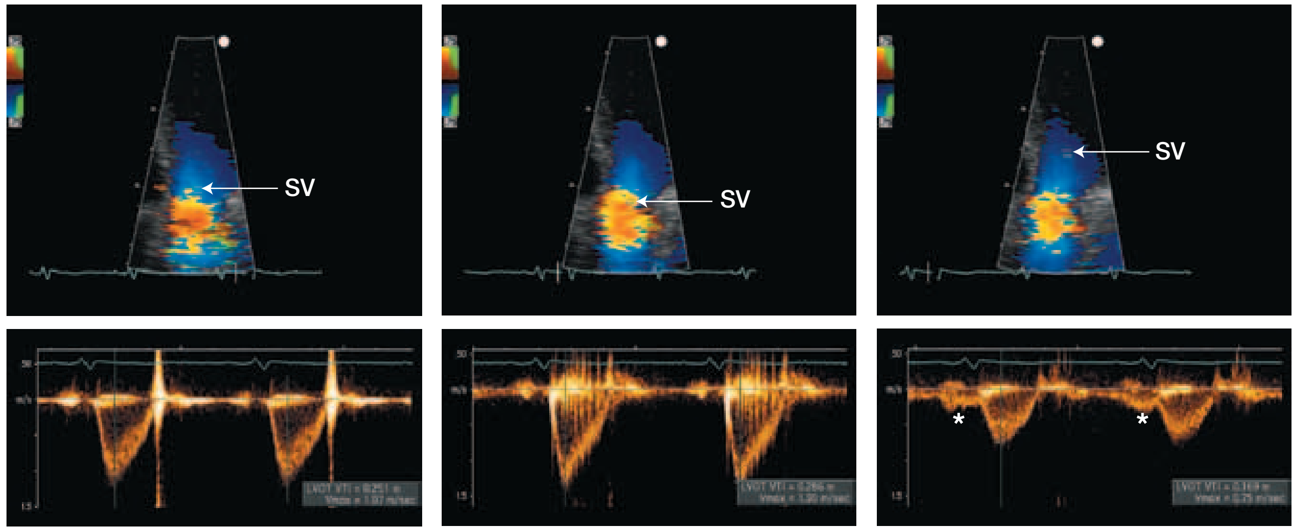

Figure 12.5 This series of images shows the effect of the sample volume position on LVOT velocity profile. The images on the left were recorded with the sample volume (SV) optimally positioned about 0.5 cm from the aortic valve. The spectral Doppler trace displays a laminar LVOT flow profile and a closing 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, no closing click and pre-systolic flow (*) which occurs as blood circles within the left ventricle prior to true systole; both the peak velocity and the VTI are underestimated at 0.75 m/s and 0.169 m, respectively.

Failure to Obtain the Peak Velocity

As previously mentioned, when there is a large incident angle (θ) between the ultrasound beam and the direction of blood flow, 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 EOA 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 no intracardiac shunt or significant aortic regurgitation or pulmonary regurgitation).

Misinterpretation of Doppler Signals

In patients with AS and MR, the MR jet may sometimes be mistaken for the AS jet. This is because both signals occur in systole, both signals are orientated in the same direction, and when AS is severe, both signals will be of a high velocity. Differentiation between these two signals can be made by observation of the duration of the signals, associated diastolic signals, the shape of the signals, and the peak velocity of the signals (Fig. 12.6).

> Aortic stenotic jets can be quite eccentric. For this reason, the search for the maximum aortic velocity requires careful and persistent interrogation from multiple windows and use of the non-imaging CW Doppler probe (see Fig. 12.3).

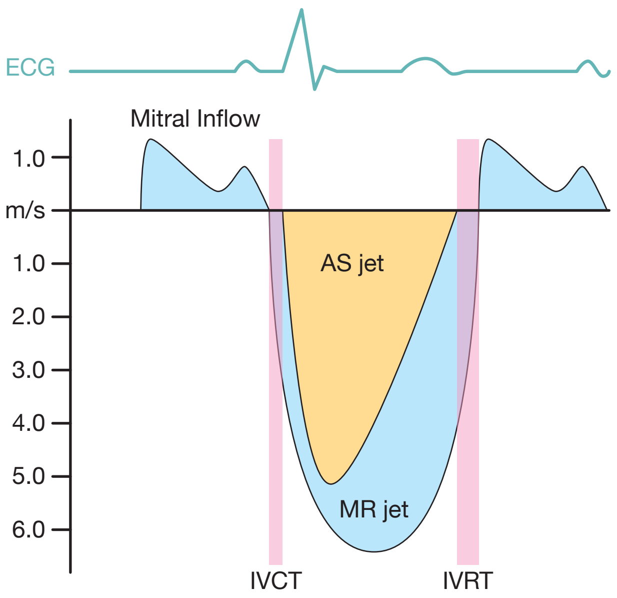

Figure 12.6 This schematic illustrates how an aortic stenotic (AS) jet can be differentiated from a mitral regurgitant (MR) jet. The AS signal has been superimposed on the MR signal to illustrate these differences. The isovolumic contraction time (IVCT) is the time interval between mitral valve closure and aortic valve opening; the isovolumic relaxation time (IVRT) is the time interval between aortic valve closure and mitral valve opening. Observe that the MR signal which begins at mitral valve closure and terminates at the following mitral valve opening is longer than the AS signal which commences after the IVCT and terminates at the onset of the IVRT. The MR signal is in continuity with the mitral inflow signal while the AS signal is not. The AS signal peaks in early systole and is V-shaped while the MR signal peaks in mid systole and has a parabolic shape. The peak MR velocity is always higher than the peak AS velocity.