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 derivation 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 atrioregional vessels 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 calculation 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.

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.

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\text{Equation 12.10} \quad \text{DSI (DVI)} = \frac{V_{\text{LVOT}}}{V_{\text{AV}}} = \frac{\text{peak velocity (or VTI in cm) at the LVOT}}{\text{peak velocity (or VTI in cm) across the aortic valve}}
\]

In particular, this index is independent of the cardiac output as the LVOT and AVR velocities are proportional. 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 underestimated and, therefore, the stroke volume within the LVOT will also be underestimated; if the sample volume is placed too far from the aortic valve, the peak velocity and VTI will be overestimated and, therefore, the stroke volume within the LVOT will also be overestimated. 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 12.4 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\text{LVOT}) is the same across the stroke volume across the mitral valve (SV\text{MV}), and that the stroke volume is derived from the cross-sectional area (CSA) and the velocity time integral (VTI), then:

\[
\text{MVA} = \text{CSA}_\text{MV} \times \text{VTI}_\text{LVOT} = \text{CSA}_\text{MV} \times \text{VTI}_\text{MV}
\]

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

\[
\text{MVA} = \text{CSA}_\text{MV} \times \text{VTI}_\text{LVOT} = \text{CSA}_\text{MV} \times \text{VTI}_\text{MV}
\]

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 underestimated 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, utilizing multiple transducer positions to obtain the peak velocity, is mandatory.

Non-Simultaneous Peaking of Signals
Calculation of the A V A 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 AVR 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 oriented in the same direction, and when AS is severe, both signals will be of a high velocity. Therefore, 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).

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).