Echocardiographic Determination of Cardiac Output

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Introduction

Managing patients with hemodynamic instability can be very challenging. Determination of cardiac output (CO) is one of the most important tasks when caring for such patients. Echocardiography can be used non-invasively to achieve this goal with simplicity.

Echocardiographic methods for cardiac output measurements are well validated and may provide an alternative to thermodilution methods. Measurement of CO can be done at the bedside with echocardiographic machine based on volumetric flow across any heart structure. Both transthoracic (TTE) and transesophageal (TEE) echocardiography can be used to calculate CO.

The continuity equation is the basis for CO measurements. It states that in the absence of valvular dysfunction or intracardiac shunt blood flow is constant throughout the heart. Based on this assumption, CO is equal to the forward flow across each of the cardiac valves. Although any cardiac structure that has a measurable cross sectional area (CSA) may be used, most commonly the left ventricular outflow track (LVOT) is used because its cross section is essentially a circle, unlike other structures (i.e. mitral valve annulus, aortic valve or tricuspid annulus, etc.). The first step in measuring CO with echocardiography is to determine stroke volume.

Stroke volume calculation

Assuming a circular geometry, the LVOT can be thought of as a cylinder (figure 1), and as such its volume is calculated as the base times its height.

? How is the volume of a cylinder calculated?

A Volume of a cylinder is calculated as the cylinder's base times its hight:

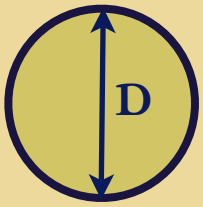
volume = base x hight

Calculating the cylinder's base: The base of a cylinder is its cross-sectional area (in cm^2). The CSA of a circle is calculated from its diameter as πr^2 or $\pi(D/2)^2$. When measuring CO from the LVOT, its diameter is used to calculate the cylinder's CSA, or base.

How is the cross sectional area of a circle calculated?

A Cross sectional area of a circle calculated as

πr^2 or $\pi(D/2)^2$



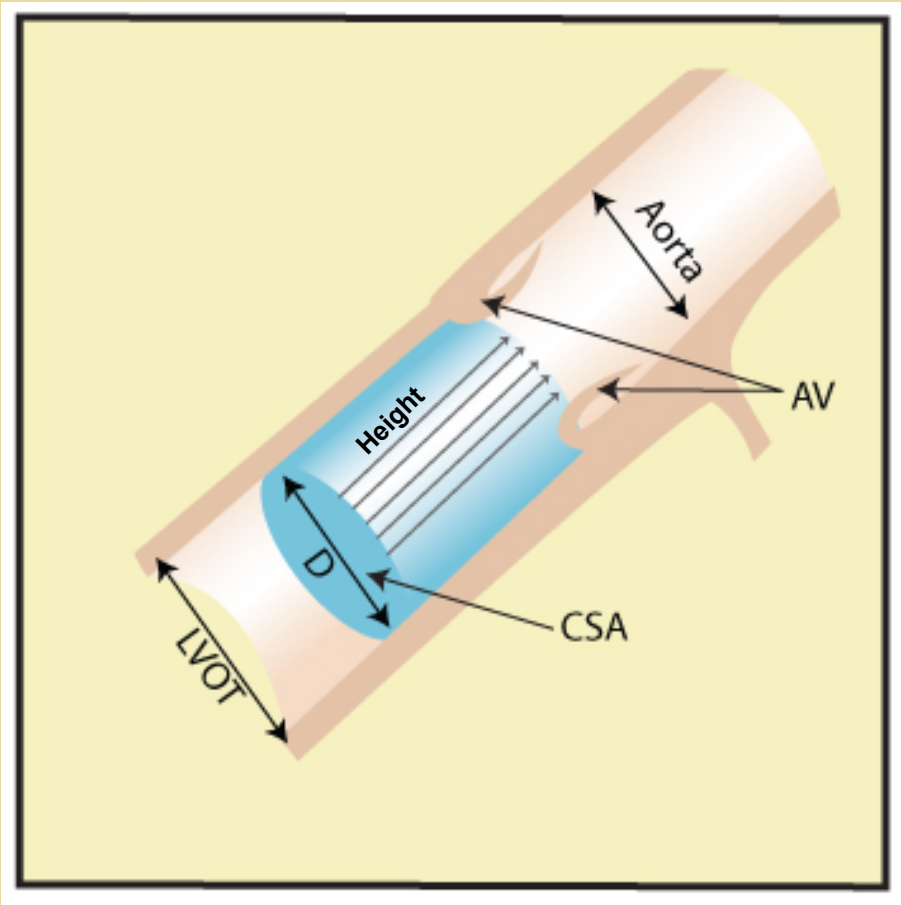


Figure 1: Schematic representation of the LVOT as a cylinder. A. To calculate the volume of a cylinder, the base is multiplied by its height. In the LVOT, the cylinder's base is the LVOT CSA, which is calculated from the LVOT diameter as $\pi(D/2)^2$. LVOT-Left ventricular outflow tract, D-Diameter, CSA-Cross sectional area, AV-Aortic valve.

Calculating the cylinder's height: The height of the cylinder (in cm) is calculated from interrogation of the LVOT with the pulse wave Doppler (PWD). The height, or distance, can be calculated from the velocities measured by the PWD during the ejection phase as the integral of these velocities. Since velocity is the first derivative of distance, the distance can be expressed as the integral of the Doppler systolic Velocity Time Integral (VTI) (figure 2). This distance (in cm) — commonly referred as the stroke distance — is the distance an average blood cell travels during systole, the ejection phase of the cardiac cycle.

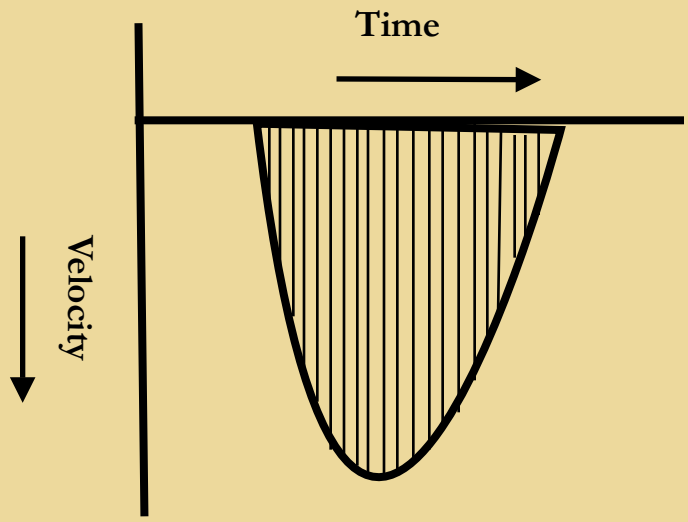


Figure 2: Since blood flow through the cardiac system is pulsatile, the instantaneous velocities during the ejection phase should be sampled and then integrated. VTI is the sum of the instantaneous velocities, which is equal to the area enveloped by the Doppler velocity profile. The distance an average blood cell travels during systole is calculated automatically by the echocardiographic computer as an integral of the VTI area under the curve.

What does the VTI represent?

A The VTI represents the sum of instantaneous velocities during one ejection phase of the cardiac cycle.

Finally, the SV is calculated by multiplying the base (LVOT CSA) and the height (LVOT VTI) of the cylinder:

$$SV\ (cm^3) = LVOT_{CSA}(cm^2) \times LVOT_{VTI}(cm)$$

Summary — steps in determination of stroke volume

To calculate SV (in cm^3), the CSA of a circular structure (i.e. LVOT in cm^2) is multiplied by the velocity time integral (VTI in cm) of flow through it.

The first step in determination of SV is to calculate the cross sectional area of the LVOT (although as mentioned above, any cardiac structure can be used, realizing that the geometry of that structure may not be cylinder-like and thus, CO measurements may not be as accurate).

CSA is calculated by using the formula for the area of a circle – πr^2 – where r is the cross sectional diameter (D) divided by 2. In practice, one measures the LVOT diameter and the computer automatically calculates the CSA of the LVOT based on this formula.

The next step in SV determination is measuring the VTI of the LVOT. This is done first by interrogating the LVOT with a PWD at exactly the same level where the diameter of the LVOT was measured, then tracing the VTI spectral display profile. Once traced, the internal software package of the echocardiographic system calculates the VTI, and from this the stroke distance.

Finally, SV is calculated by multiplying the CSA with the VTI:

$$SV = CSA \times VTI$$

How is SV calculated with the volumentric flow method across the LVOT?

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$$SV = CSA_{LVOT} \times VTI_{LVOT}$$

1. CSA of the LVOT is determined via measurement of the LVOT diameter as = $\pi(D/2)^2$
2. VTI is determined by the echocarigraphic machine after tracing the PWD spectral display of the LVOT

Echocardiographic windows for measuring LVOT diameter

TTE windows: measurement of LVOT diameter is done in the parasternal long axis view (figure 3). To minimize calculations error, it is important to maximally zoom on the LVOT while measuring its diameter, since an error in this measurement will result in the highest inaccuracy of CO measurement. This is because the radius of the LVOT (D/2) is squared: CSA = $\pi(D/2)^2$.

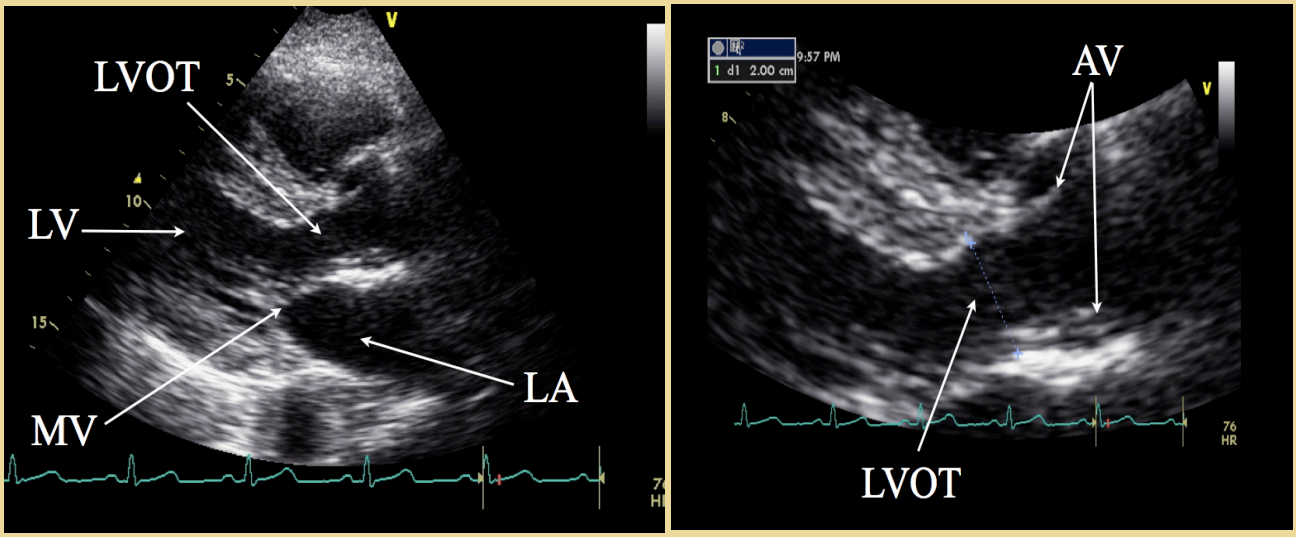

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FIGURE 3: TTE measurement of LVOT diameter.
A: Parasternal long axis view. LA-left atrium, MV-mitral valve, LV-left ventricular, LVOT-left ventricular outflow tract. B: Zooming of LVOT to achieve accurate measurement. LVOT-left ventricular outflow tract, AV-aortic valve leaflets open in systole. This LVOT measures 2 cm. The CSA is calculated as $\pi(D/2)^2$ to be 3.14 cm^2

TEE windows: measurement of LVOT diameter is done in the midesophageal long axis view (figure 4)

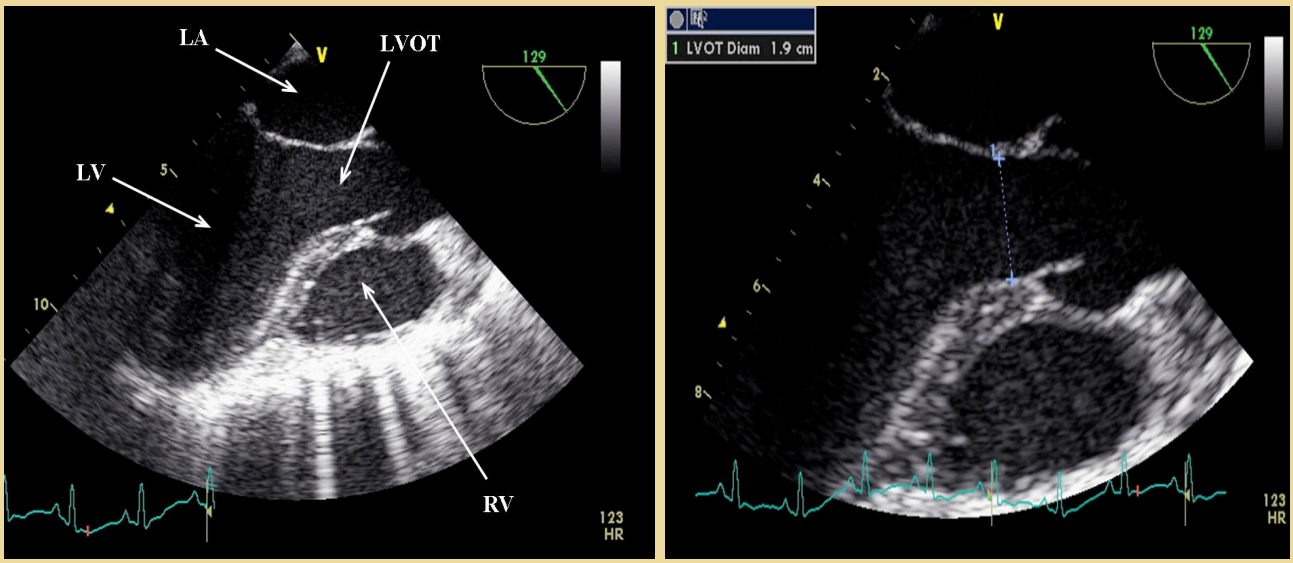

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FIGURE 4: TEE measurement of LVOT diameter. A. Midesophageal long axis view. LVOT-left ventricular outflow tract, RV-right ventricle. B. Zooming on the LVOT to minimize measurement error. LVOT measurement is 1.9 cm. The CSA is calculated as $\pi(D/2)^2$ to be 2.83 cm^2.

Echocardiographic windows for measuring VTI

TTE windows: PWD interrogation of the LVOT is done in the 5-chamber view (Figure 5). It is important to align the LVOT in parallel to the ultrasound beam to minimize error (see below).

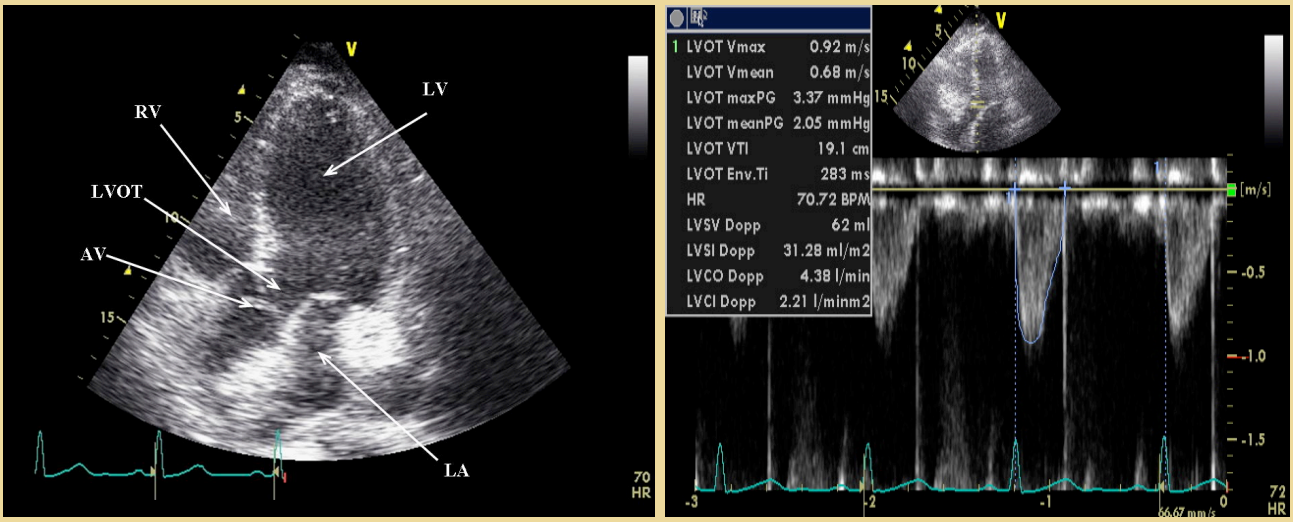

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FIGURE 5: Transthoracic 5-chamber view. A. LA-left atrium, LV-left ventricle, RV-right ventricle, LVOT-left ventricular outflow tract, AV-aortic valve. B. PWD interrogation of the LVOT. By tracing the spectral display and measuring the VTI, the computer calculates SV based on previous calculation of the cross sectional area of the LVOT. By multiplying SV and HR, CO and cardiac index are calculated automatically by the echocardiographic computer.

TEE windows: PWD interrogation of the LVOT is done in the deep transgastric view where alignment of the LVOT is most easily achieved (figure 6).

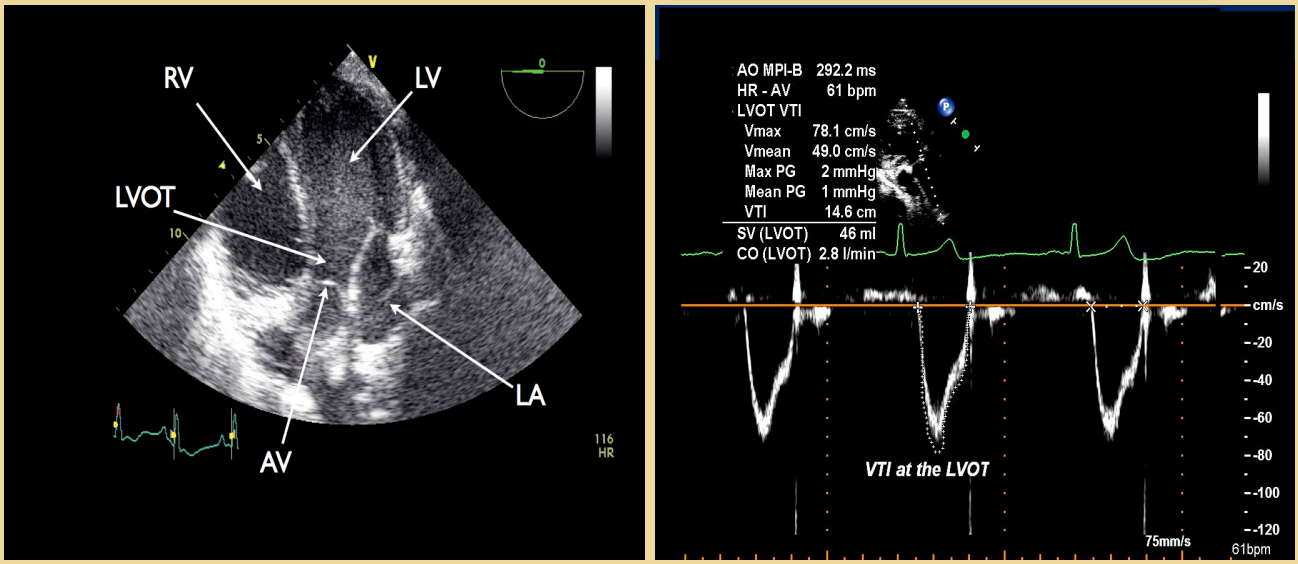

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FIGURE 6: TEE deep transgastric view. A. LA-left atrium, LV-left ventricle, RV-right ventricle, AV-aortic valve, LVOT-left ventricular outflow tract. B. Deep transgastric long axis view using a PWD directed through the LVOT. VTI is calculated by the computer through tracing the outer envelope of the spectral signal and is determined to be 14.6 cm. SV is the product of CSA and VTI: 3.14 cm^2 x 14.6 cm = 46 cm^3. CO= SV x HR: 46 x 61 = 2.8 l/min

To summarize, once the diameter of the LVOT is determined (and thus its CSA), and then the LVOT VTI is traced, SV (cm^3) is calculated by multiplying the CSA (in cm^2) by the VTI (stroke distance in cm): SV = CSA x VTI. This is done automatically by the echocardiographic computer.

Finally, the CO is easily derived by multiplying the calculated SV by the heart rate:

$$CO\ (cm^3/min) = SV \times HR$$

Limitations

This approach to SV and CO calculations has shown very good correlation with thermodilution-derived cardiac output measurements. However, one has to be aware of several potential sources of error:

A. CSA determination often leads to the greatest source of error. When using any diameter for CSA determination, any error in measurement will be squared ($CSA = \pi(D/2)^2$). This translates to a 20% error in calculation of cardiac output for each 2-mm error when measuring a 2.0-cm diameter LV outflow tract. Studies have shown that while the Doppler velocity curves can be recorded consistently with little inter-observer measurement variability (2% to 5%), the variability in 2D LVOT diameter measurements for CSA is significantly greater (8% to 12 %).

B. The Doppler signal is assumed to have been recorded at a parallel or near parallel intercept angle, called θ, to blood flow. The Doppler equation has a cos θ term in its denominator. With an intercept angle of 0°, the cos θ term equals 1. Deviations up to 20° in intercept angle are acceptable since only a 6 % error in measurement is introduced.

C. Velocity and diameter measurements should be made at the same anatomic site. When the two are measured at different places the accuracy of SV and CO calculations are decreased.

D. While the pattern of flow is assumed to be laminar, in reality the flow profile is parabolic. This does have some impact on velocity based calculations. However, in routine clinical practice this factor is of little significance and can be essentially ignored.