Cardiac Output Monitoring in the Post PAC Era
Using the TEE to Determine Cardiac Output

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Objectives

1) Understand Doppler quantification method to determine Cardiac Output using TEE
2) Identify situations where Cardiac Output measured by TEE may be inaccurate
3) Understand the advantages/disadvantages of TEE to determine Cardiac Output vs. PAC or Contour Analysis

Quantification of Cardiac Output

Doppler techniques can be used to quantify cardiac flow, volume, and pressure. Basic hemodynamic formulas are used for these calculations. If performed properly, these relatively noninvasive techniques correlate well with other more invasive methods. As in any Doppler measurement, parallel beam alignment is crucial and cannot be overemphasized.

In quantifying cardiac volumes using Doppler techniques, it is important to differentiate between blood flow velocity, volumetric flow, and stroke volume. Often the units of measurement are helpful. Blood flow velocity is measured in cm/sec and is the speed at which blood travels. Volumetric flow is measured in cm$^3$/sec and is the amount of blood that is flowing per second. Stroke volume is expressed as cm$^3$/cycle and is the amount of blood flowing in a single cycle.

The flow rate through an orifice is the product of flow velocity and its cross sectional area (CSA)

Flow = Velocity x CSA

If flow is constant, the velocity measured at any point in time can be used for the equation. In the case of cardiovascular blood flow, flow is pulsatile and velocity varies throughout the cardiac cycle. To overcome this, individual velocities are sampled over one cardiac cycle and the sum of these velocities are integrated over time. This is known as the time velocity integral, TVI or VTI. When velocity is integrated over time the resulting units are a measure of distance, therefore the TVI units are expressed as centimeters. In this case the distance is termed stroke distance, expressed in centimeters, which is the cumulative distance the red cells have traveled during a systolic ejection phase.

The second variable, cross sectional area, is measured in centimeters$^2$. When TVI and CSA are measured at the same point, their product equals SV.

SV = TVI x CSA
SV quantifies the volume of blood ejected during one contraction and is measured as cM³. In the clinical setting, stroke volume is an important parameter of cardiac performance.

SV and cardiac output (CO) are most reliably and easily measured at the left ventricular outflow tract (LVOT) or at the level of the aortic valve. Flow at the LVOT or aortic valve is most often laminar. Keep in mind that Doppler estimation is most accurate when measuring laminar flow. During the cardiac cycle, the cross sectional area of some structures may vary but the cross sectional area of the LVOT and ascending aorta (because they are circular structures) change very little throughout the cardiac cycle. Finally the entire stroke volume travels through these large structures. SV and CO can be measured at the level of the mitral valve or the pulmonary artery but for the above reasons, this is less commonly done.

If measuring at the level of the aortic valve, the CSA of the valve can be measured using planimetry of a short axis view of the aortic valve. In reality this is often easier said than done. (Figure 1) TVI is measured using continuous wave Doppler with the Doppler beam directed through the valve orifice. Using transesophageal echocardiography, the transgastric long axis view or the deep transgastric long axis view are the most helpful for this interrogation. If

\[ \text{Flow} = \text{Velocity} \times \text{CSA} \]

The equation then becomes

\[ \text{Flow (SV)} = \text{TVI} \times \text{aortic valve area} \]

Another approach is to measure the diameter of the LVOT and simply calculate the area of it. The area of a circle is

\[ A = \pi r^2 \]

The diameter of the LVOT is what is actually measured, so if \( r = D/2 \), the formula is simplified to

\[ A = \pi D^2 /4 \text{ or } A = 3.14/4 D^2 \text{ or } A = .785 D^2 \]

Multiple measurements of diameter should be conducted. The largest diameter measured usually corresponds to the true diameter. The annular size does not vary much throughout the cardiac cycle, so the timing of this measurement is not crucial. The actual measurement is critical, in that the value is squared in the final formula. In this way, any error in measuring the LVOT will be exaggerated in the final outcome. (Figure 2)

If measuring at the level of the LVOT, TVI is measured using pulse wave Doppler with the sample volume positioned in the LVOT just proximal to the aortic valve. The best transesophageal views for this measurement are again the transgastric long axis view and the deep transgastric long axis view. (Figure 3) Therefore if measurements are taken at the level of the LVOT, stroke volume is simplified by the following steps

\[ \text{Flow} = \text{Velocity} \times \text{CSA} \]

\[ \text{Flow (or SV)} = \text{TVI} \times .785 D^2 \]
Of course, using either of these techniques, cardiac output can be calculated by merely multiplying by heart rate.

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\text{CO} = \text{SV} \times \text{HR}
\]

The following 3 figures are taken from Brady, MB. Basic Echo Doppler. IN: Practical Ultrasound in Anesthesia, Critical Care and Pain Management. Eds. PM Hopkins, A. Bodenham, ST Reeves. Marcel, Dekker, Taylor & Francis. Chapter 9. 2008

Figure 1 AV planimetry. The AV can be measured directly by planimetry. The valve opening is traced during systole in the ME AV short-axis view. This valve opens well and measures 4.3 cm².

Figure 2 LVOT measurement. The diameter of the LVOT is measured in this long-axis view. Here the diameter measures 1.8 cm. In the formula for CO, the LVOT diameter is squared; therefore any error in this measurement greatly affects the calculated CO.
Inaccuracies of Doppler derived CO measurements

There are many assumptions made using Doppler quantification. These assumptions play a part in the degree of inaccuracies that result.

1. One assumption is that the area measured for the calculation of SV is constant throughout systole. Obviously, this is not the case. The aortic valve is not closed one moment and completely open the next, which means that flow is not constant throughout a cardiac cycle.

2. Flow is assumed to be laminar and the recorded flow is assumed to represent the average flow. If significant aortic stenosis is present, flow distal to the valve is not laminar and therefore SV measurements will be inaccurate.

3. Errors in diameter measurements are quadrupled in that the formula requires squaring the diameter. Therefore very small errors in measurement make a dramatic difference in the calculation.

4. To guarantee accuracy, parallel blood flow is required in any of these calculations. In addition, the area and flow measurements must be made at the same anatomical site. Depending on if and how much the heart is rotated in the patient, these two criteria (parallel flow and anatomical site measurements) may not be easily achieved. One example of heart rotation is during off pump CABs. Another example is in patients who have had previous sternotomies. Often their hearts are rotated and parallel interrogation may be difficult.

Advantages - Comparing the techniques

1. There are many opportunities for operator error and miscalculation in TEE derived CO measurements, but if done properly, these measurements compare favorably with the thermodilution techniques of PAC.
2. Placement and manipulation of the probe puts patients at risk for dental, oral, and esophageal trauma but in appropriate patients these events are extremely rare.

3. The risk of infection and contamination is a risk of TEE placement, but if adequate management and cleaning of the equipment is closely monitored, these occurrences are rare as well.

4. Trauma to the PA is a concern with PACs, but not with TEE exam.

5. In terms of invasive procedures, PAC, contour analysis and TEE can all be considered to be invasive, but in different ways. Essentially, the extent of “invasiveness” is in the eye of the beholder.

6. CO is not the only measurement of systolic function that can be measured using TEE. (ie EF, fractional Shortening, fractional area change, acoustic quantification, tissue Doppler, Strain technology)

Disadvantages – Comparing the techniques

1. Time frame - One significant disadvantage is the time frame for use of TEE. It is not appropriate to use TEE for extended periods of time (days in the ICU). This is different from the PAC or Contour Analysis use.

2. Training and expertise - Adequate assessment of CO by TEE requires significant training and experience by personnel involved in conducting the exam. The extent of training required for PAC and Contour analysis is less than that required for TEE.

3. Portability - TEE equipment is portable, but somewhat less so than the equipment required for a PAC or Contour Analysis.

4. Time consuming - Measurements of CO require time for measurement and calculations, where Contour Analysis and PAC CO measurements, once calibrated, can be continuous and automatic. In a dramatically dynamic situation, it is unrealistic to be constantly measuring and re-measuring parameters in order to calculate CO using TEE.

5. PAC and Contour analysis can measure CO in a continuous fashion.

Suggested Readings


