Most of us are familiar with the ability of transesophageal echocardiography (TEE) to make beautiful and detailed images of the heart and great vessels. What I would like to cover in this session is the less familiar use of TEE as a tool to assess hemodynamics. There are two broad categories of information provided by TEE: 1) images of the anatomy and motion of the cardiac structures obtained with two dimensional (2D) echo, and 2) velocity measurements of blood flow made with Doppler echo. Both of these can be used alone or together to provide useful information about a patient’s hemodynamics.

**Doppler Echocardiography**

Doppler echocardiography is based on the principle that the frequency of ultrasound (or any other form of transmitted wave) changes when reflected from a moving object, increasing when reflected from an object moving towards the transducer, and decreasing when reflected from an object moving away. The ultrasound in Doppler echo is reflected off red blood cells, and the instrument translates the frequency shift detected into the velocity (speed AND direction) of the blood relative to the transducer. There are two types of Doppler echo that work in different ways and are applied in different situations: pulsed wave Doppler (PWD) and continuous wave Doppler (CWD). PWD provides velocity measurements within an exact location called the sample volume but is limited in the peak velocity it can accurately measure. CWD has no limit in the velocity it can measure but only provides the direction that the velocities are coming from, not the exact location. In general, PWD is used to measure relatively low velocities (less than 150 cm/sec) in a specific location, such as the left upper pulmonary vein. CWD, on the other hand, is used to measure either very high velocities, such as with aortic stenosis (up to 500 cm/sec), or the peak velocity corresponding to the narrowest point of flow along a line of site from the transducer, such as with mitral stenosis. Color flow Doppler (CFD) is a special application of PWD in which the velocity for each point in a sector of the image is mapped as a color onto the 2D image. It is subject to the same constraint: limited maximum velocity measurements.

**Accurate Measurements**

In order to make accurate hemodynamic assessments with TEE, accurate 2D and Doppler velocity measurements must be made. They must be made in the proper location and at the proper time in the cardiac cycle. Foreshortening is a phenomenon that can introduce error into the size measurement with 2D echo (Figure 1). Any error in a linear measurement is squared when used to calculate an area (Figure 2). It causes underestimation of the true size if the imaging plane is not transecting the maximum diameter of the structure being measured. Because Doppler echo only detects the component of velocity that is directly towards or away from the transducer, it is important to align the ultrasound beam as parallel as possible to the flow being measured.
If the beam is perpendicular to the flow, the velocity detected and displayed will be zero. For practical purposes, the angle between the ultrasound beam and the direction of flow, called theta, should be less than 20° to achieve a result within 94% of the true velocity (cosine 20° = 0.94) (Figure 3). Remember that any deviation of the beam from the direction of flow will lead to underestimation of the velocity.

Pressure Measurement with Echo

The flow velocity information provided by Doppler echo can be used to calculate a number of important hemodynamic parameters. The pressure gradient between two chambers is calculated using the simplified Bernoulli equation, \( \Delta P = 4V^2 \), where pressure is in mmHg and velocity in meters/sec. Thus, if the velocity across a stenotic aortic valve (AV) is 5 m/sec, the gradient between the left ventricle (LV) and the aorta is 100 mmHg. It is important to remember that this equation is a simplified form of the much more complex relationship between flow velocity and pressure, and should only be used in applications that have been validated by comparison to actual pressure measurements. If the pressure gradient between two chambers can be measured and the absolute pressure of one chamber is known, the pressure in the other chamber can be deduced. In this way, peak right ventricular (RV) systolic pressure can be calculated by measuring the velocity of a jet of tricuspid regurgitation to determine the gradient between the RV and right atrium (RA) during systole. If the central venous pressure (CVP) is known, the RV systolic pressure is the gradient added to the CVP. If the pulmonic valve is normal this is the same as the pulmonary artery (PA) systolic pressure. Similar logic can be used to measure left atrial, PA diastolic, and LV end diastolic pressures by measuring the velocities of mitral regurgitation, pulmonic regurgitation, and aortic regurgitation jets and knowing the LV systolic (same as systolic BP), RV diastolic (same as CVP), and aortic diastolic (same as diastolic BP) pressures.

Flow Measurement with Echo

Calculating stroke volume (SV) with echo requires making two measurements: 1) the spectral velocity profile of flow with Doppler echo (PWD or CWD), and 2) the area through which the flow occurs with 2D echo. These measurements can be made with TEE in several locations; AV, left ventricular outflow tract (LVOT), mitral valve (MV), and PA. The velocity profile of the flow is traced and integrated through time to yield a value called the time velocity integral (TVI), which is in units of length, usually centimeters. Most echo machines can perform this integration automatically. Then the area (A) through which the flow passes is measured with 2D echo to give a value in units of length squared, usually cm². The product of TVI and A yields a value in units of length cubed, i.e. cm³ or ml, which is the volume of the blood flow, or SV (Figure 4). SV times the heart rate gives the total flow per minute or cardiac output. The accuracy of this technique depends on both the velocity and area measurements being made in the same location and at the same time in the cardiac cycle. This is usually done using PWD placing the sample volume in the exact location that the 2D area measurement is made. Another technique, however, uses CWD through the AV from the transgastric long axis view and assumes that the velocity profile obtained, which occurs at the narrowest place along CWD beam, is from the AV (Figure 5). The area of the valve is then ascertained from its mid esophageal short axis view by measuring the inter
commissural distance and applying the formula for the area of an equilateral triangle: \( A_\Delta = 0.433 \times S^2 \) (Figure 6). The flow area for circular structures such as the LVOT and the PA is obtained by measuring the diameter (D) and using the formula for the area of a circle: \( A_{\text{circle}} = \pi r^2 = 0.785 D^2 \). The MV annulus is more elliptical and its area best calculated by using two orthogonal diameters (\( D_1 \) & \( D_2 \)) in the formula for the area of an ellipse: \( A_{\text{ellipse}} = 0.785(D_1 \times D_2) \).

**PISA**

PISA (proximal isovelocity surface area) is another method with which one can assess hemodynamics by echocardiography.\(^3\) It involves the use of color flow Doppler (CFD) and is most commonly applied to MR or mitral stenosis (MS)\(^4\). As blood converges towards a narrow orifice, its velocity increases. When the velocity reaches the limit on the CFD scale, it aliases and changes color from red to blue for flow towards the transducer (MR) and blue to red for flow away from the transducer (MS). This shift in color shows a hemispherical shell of blood converging towards the orifice called the PISA. (Figure 7) If we determine the area of this hemisphere (\( A_{\text{PISA}} \)) and multiply it by the aliasing velocity (\( V_{\text{PISA}} \)-known from the CFD scale) we get the instantaneous flow in ml/sec. \( A_{\text{PISA}} \) is determined by measuring the radius of the PISA and using the formula for the area of a hemisphere: \( A_{\text{PISA}} = 2\pi r^2 = 6.28 r^2 \). Next we measure the peak instantaneous velocity of the orifice (\( V_{\text{orifice}} \)) with CWD. Now, the instantaneous flow (ml/sec) is the same at the PISA as at the orifice, both of which are the product of \( A \) and \( V \): \( A_{\text{PISA}} \times V_{\text{PISA}} = A_{\text{orifice}} \times V_{\text{orifice}} \) and, rearranging, \( A_{\text{orifice}} = (A_{\text{PISA}} \times V_{\text{PISA}}) / V_{\text{orifice}} \). The result is the size in cm\(^2\) of either the regurgitant orifice for MR or the area of the MV in MS. For MR, a regurgitant orifice of greater than .30 cm\(^2\) is considered significant.

This technique makes two important assumptions that are not valid in many clinical situations. First, that the orifice through which the flow occurs is circular, and second, that the blood converging on the orifice is not constrained by any adjacent structure such as the LV wall. (Figure 8) Despite these limitations, PISA can provide important corroborative information about the severity of a valvular lesion in many situations.


Principles of Echo Hemodynamics

Foreshortening

True Diameter

Foreshortened Diameter

Doppler Accuracy

\[ \Theta < 20^\circ \Rightarrow < 6\% \text{ error} \]

\[ \text{Area} \quad \text{cm}^2 \times \text{TVI} \quad \text{cm} = \text{Volume} \quad \text{mL} \]

CWD parallel to flow through AV

Deep transgastric LAX view

Area = 0.433*S^2

Mid esophageal AV SAX view

PISA

Proximal Isovelocity Surface Area

Flow_{PISA} \quad \text{Flow}_{Orifice} = \text{Velocity} \times \text{Area}

Constrained PISA Correction

\[ \text{AREA}_{PISA} = 2\pi \times \alpha/180^\circ \times r^2 \]