DOPPLER ULTRASOUND
AND MEASUREMENT OF
CARDIAC OUTPUT

Todd W. Sarge, MD
Instructor in Anesthesia, Harvard Medical School
Program Director, Critical Care Fellowship
Department of Anesthesia, Critical Care and Pain Medicine
Beth Israel Deaconess Medical Center, Boston
Uses of Doppler Ultrasound

• Detection of Valvular Pathology
• Estimation of Intra-Cardiac Pressures
• Measurement of cardiac output
• Detection of Intra-Cardiac Shunt
One of the easiest to understand the Doppler shift is looking at this video clip of a tennis ball machine. You’ll notice that the machine shoot the balls at a constant frequency, let’s say of one ball a second. Now, imagine the machine moving towards you while continuing shooting the balls at a frequency of 1/sec. Since the machine is moving towards you, the perceived frequency of balls coming at you is higher than 1/sec. This is similar to the Doppler shift. Likewise, if you stand behind the machine where it is moving away from you, the perceived frequency of balls shooting from the machine will be smaller than 1/sec. This concept is reinforced by the second clip of a plane flying across the screen.
One of the easiest to understand the Doppler shift is looking at this video clip of a tennis ball machine. You’ll notice that the machine shoot the balls at a constant frequency, let’s say of one ball a second. Now, imagine the machine moving towards you while continuing shooting the balls at a frequency of 1/sec. Since the machine is moving towards you, the perceived frequency of balls coming at you is higher than 1/sec. This is similar to the Doppler shift. Likewise, if you stand behind the machine where it is moving away from you, the perceived frequency of balls shooting from the machine will be smaller than 1/sec. This concept is reinforced by the second clip of a plane flying across the screen.
So the Doppler shift is the difference between the perceived frequency and the original frequency. If the object is moving towards you than the Doppler shift will be positive. If, however, the object is moving away from you, the perceived frequency will be smaller than the original one, and thus the Doppler shift will be negative.

This phenomenon surrounds us on a daily basis. The classical example is of a moving car towards and then away from us with a siren (e.g. ambulance), where the pitch of the siren changes as the car passes by us. This clip demonstrates the Doppler shift with such an example.
So the Doppler shift is the difference between the perceived frequency and the original frequency. If the object is moving towards you, the Doppler shift will be positive. If, however, the object is moving away from you, the perceived frequency will be smaller than the original one, and thus the Doppler shift will be negative. This phenomenon surrounds us on a daily basis. The classical example is of a moving car towards and then away from us with a siren (e.g. ambulance), where the pitch of the siren changes as the car passes by us. This clip demonstrates the Doppler shift with such an example.
Doppler physics

www.echoincontext.com/doppler01.pdf
The concept to be conveyed in this slide is the importance of angle intersection with Doppler interrogation. The Cos of θ is a key component in the equation - as the interrogation angle is further away from parallel the measured flow will be smaller, meaning that the measured flow will underestimate the actual flow.
Frequency Shift Equation

\[ F_d = \frac{2 \cdot f_0 \cdot V \cdot \theta}{c} \]

- \( F_d \) = Frequency shift (Doppler shift)
- \( f_0 \) = Transmitted frequency
- \( V \) = Velocity of blood
- \( \theta \) = Angle between ultrasound beam and direction of moving RBCs
- \( c \) = Velocity of sound in blood (constant)

Same concept, not breaking this in more details
Frequency Shift Equation

\[ F_d = \frac{2f_o \cdot V}{c} \]
Frequency Shift Equation

\[ F_d = \frac{2 \cdot f_o \cdot V}{c} \]

\[ V = \frac{F_d \cdot c}{2 \cdot f_o} \]
The concept to be conveyed in this slide is the appearance of the spectral display in relation to the flow of blood; if towards (left), spectral display will be above baseline and if away (right) spectral display will be below baseline.
The concept to be conveyed in the next four slides is examples of how this is seen in “real life”. In this first example of TTE, flow is towards the probe; blood is flowing from LA to LV, and thus when we use Pulse Wave Doppler to evaluate MV inflow we can see the spectral display (next slide) above the baseline.
The concept to be conveyed in the next four slides is examples of how this is seen in “real life”. In this first example of TTE, flow is towards the probe; blood is flowing from LA to LV, and thus when we use Pulse Wave Doppler to evaluate MV inflow we can see the spectral display (next slide) above the baseline.
The concept to be conveyed in the next four slides is examples of how this is seen in "real life". In this first example of TTE, flow is towards the probe; blood is flowing from LA to LV, and thus when we use Pulse Wave Doppler to evaluate MV inflow we can see the spectral display (next slide) above the baseline.
Doppler display

FLOW TOWARDS PROBE
Doppler display

FLOW TOWARDS PROBE

WAVEFORM ABOVE BASELINE

BASELINE
The concept to be conveyed in this slide is continuation of the one of blood flow and spectral display. In this case we use TEE, which is reversed from the previous example. In this case the blood still flows from LA to LV, however the image is reversed from TTE which means that blood is flowing away from the probe.
The concept to be conveyed in this slide is continuation of the one of blood flow and spectral display. In this case we use TEE, which is reversed from the previous example. In this case the blood still flows from LA to LV, however the image is reversed from TTE which means that blood is flowing away from the probe.
The concept to be conveyed in this slide is continuation of the one of blood flow and spectral display. In this case we use TEE, which is reversed from the previous example. In this case the blood still flows from LA to LV, however the image is reversed from TTE which means that blood is flowing away from the probe.
The concept to be conveyed in this slide is the directionality of the blood away from the probe in this TEE example.
The concept to be conveyed in this slide is the directionality of the blood away from the probe in this TEE example.
The concept to be conveyed in this slide is the concept of the angle interrogation, in this case more mathematically – to show what happens when we deviate from parallel angle (0 degrees); a 20 deviation will result in approximately 6% error, conventionally the “maximum” allowed in clinical echocardiography. A perpendicular interrogation will result in “no flow”
The concept to be conveyed in this slide is the concept of the angle interrogation, in this case more mathematically – to show what happens when we deviate from parallel angle (0 degrees); a 20° deviation will result in approximately 6% error, conventionally the “maximum” allowed in clinical echocardiography. A perpendicular interrogation will result in “no flow”.

\[ V = \frac{F_d \cdot c}{2 \cdot f_o \cdot \cos \theta} \]

\[ \cos 0^\circ : 1 \]
The concept to be conveyed in this slide is the concept of the angle interrogation, in this case more mathematically -- to show what happens when we deviate from parallel angle (0 degrees); a 20° deviation will result in approximately 6% error, conventionally the “maximum” allowed in clinical echocardiography. A perpendicular interrogation will result in “no flow”.

\[ V = \frac{F_d \cdot c}{2 \cdot f_o \cdot \cos \theta} \]

\[ \cos 0^\circ : 1 \]
\[ \cos 20^\circ \approx 0.94 \text{ (6% error)} \]
The concept to be conveyed in this slide is the concept of the angle interrogation, in this case more mathematically – to show what happens when we deviate from parallel angle (0 degrees). A 20° deviation will result in approximately 6% error, conventionally the “maximum” allowed in clinical echocardiography. A perpendicular interrogation will result in “no flow.”
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is the color Doppler velocity map and how to know in which direction flow of blood is. Key to explain that it is important to look at the individual map each time we scan, as the velocity map can be reversed in such a way that blue will be towards and red away from the probe.
The concept to be conveyed in this slide is examples of the concept discussed in previous slide.
The concept to be conveyed in this slide is examples of the concept discussed in previous slide.
The concept to be conveyed in this slide is examples of the concept discussed in previous slide.
The concept to be conveyed in this slide is examples of valvular leaks and how they look in "real life" with explanation on how we look at the flow of blood in during the cardiac cycle and assess valvular leaks. In upper left: this is TEE example of mitral regurgitation; LA is at the top, LV is at bottom and we look at the directionality of blood, in this case blood coming toward the probe -- MR. Upper right: apical 3-chamber view showing AI and at bottom; apical 4-ch view showing severe MR.
The concept to be conveyed in this slide is examples of valvular leaks and how they look in "real life" with explanation on how we look at the flow of blood in during the cardiac cycle and assess valvular leaks. In upper left: this is TEE example of mitral regurgitation; LA is at the top, LV is at bottom and we look at the directionality of blood, in this case blood coming toward the probe -- MR. Upper right: apical 3-chamber view showing AI and at bottom; apical 4-ch view showing severe MR.
The concept to be conveyed in this slide is examples of valvular leaks and how they look in "real life" with explanation on how we look at the flow of blood in during the cardiac cycle and assess valvular leaks. In upper left: this is TEE example of mitral regurgitation; LA is at the top, LV is at bottom and we look at the directionality of blood, in this case blood coming toward the probe -- MR. Upper right: apical 3-chamber view showing AI and at bottom; apical 4-ch view showing severe MR.
The concept to be conveyed in this slide is examples of valvular leaks and how they look in “real life” with explanation on how we look at the flow of blood in during the cardiac cycle and assess valvular leaks. In upper left: this is TEE example of mitral regurgitation; LA is at the top, LV is at bottom and we look at the directionality of blood, in this case blood coming toward the probe — MR. Upper right: apical 3-chamber view showing AI and at bottom; apical 4-ch view showing severe MR.
The concept to be conveyed in this slide is examples of valvular leaks and how they look in "real life" with explanation on how we look at the flow of blood in during the cardiac cycle and assess valvular leaks. In upper left: this is TEE example of mitral regurgitation; LA is at the top, LV is at bottom and we look at the directionality of blood, in this case blood coming toward the probe – MR. Upper right: apical 3-chamber view showing AI and at bottom; apical 4-ch view showing severe MR.
The concept to be conveyed in this slide is the principle of CW Doppler.
The concept to be conveyed in this slide is the principle of CW Doppler.
The concept to be conveyed in this slide is the principle of CW Doppler
Continuous wave Doppler

- **ADVANTAGE** - able to measure high blood velocities accurately

- **DISADVANTAGE** - receives reflection from every moving RBC → no depth discrimination
The concept to be conveyed in this slide is to explain how we interrogate the TV with CW Doppler.
The concept to be conveyed in this slide is to explain how we interrogate the TV with CW Doppler.
The concept to be conveyed in this slide is to explain how we interrogate the TV with CW Doppler.
The concept to be conveyed in this slide is to show the spectral display seen with CW Doppler — full all throughout.
The concept to be conveyed in this slide is the principle of PW Doppler.
The concept to be conveyed in this slide is the principle of PW Doppler.
The concept to be conveyed in this slide is the principle of PW Doppler.
pulse wave Doppler

- **ADVANTAGE** - able to measure along small segment of beam, known as “sample volume”

- **DISADVANTAGE** - difficulty with measuring high velocity blood flow

www.echoincontext.com/doppler01.pdf
The concept to be conveyed in this slide is to explain how we obtain PW Doppler, here in the LVOT.
The concept to be conveyed in this slide is to explain how we obtain PW Doppler, here in the LVOT.
The concept to be conveyed in this slide is to explain how we obtain PW Doppler, here in the LVOT.
The concept to be conveyed in this slide is to show the spectral display seen with PW Doppler – full at the edges, but "hollow" in the middle, which is a characteristic of laminar flow.
The concept to be conveyed in this slide is to compare the two Doppler modalities and how their spectral displays are seen.
The concept to be conveyed in this slide is to compare the two Doppler modalities and how their spectral displays are seen.
CW Doppler compared with PW doppler

CW receiving flow information from all portions of ultrasound beam

PW receiving flow information only from “sample volume”

The concept to be conveyed in this slide is to compare the two Doppler modalities and how their spectral displays are seen.
Measurement of Cardiac Output

- Based on the continuity equation
- Any cardiac structure can be used to calculate cardiac output (MV, TV, AV, pulmonary artery)
- LVOT is most commonly used:
  - Predicted geometry
  - Ease of measurement
- LVOT is assumed to be a cylinder (easy to calculate cylinder volume)

CO measures are based on the continuity equation, which states that in the absence of valve dysfunction or shunting, blood flow is equal to the forward flow across each of the cardiac valves. For a given valve, this assumption will be invalid if there is significant regurgitation or if valve flow reflects the augmented flow of a shunt lesion. Although theoretically any cardiac structure can be used to calculate CO, practically the LVOT is used due to its circular and relatively fixed geometry and ease of imaging. The aortic valve or RVOT can also be used, although less commonly. The MV and TV have complex dynamic orifices geometry, which make them less desirable.
Measurement of Cardiac Output

CO = SV x HR

• SV = Cylinder Volume = CSA x height
  - CSA = πr^2 = π(D/2)^2
  - Height = calculated from the velocity-time integral (VTI) measured at the LVOT
• SV = CSA x VTI
velocity time integral (VTI)
velocity time integral (VTI)

\[ \int \text{Velocity} = \text{distance} \]

VTI represents the sum of instantaneous velocities during one ejection phase of the cardiac cycle.
cardiac output – principle

Stroke Volume (cc) = Stroke Distance \times CSA

\[
\text{Stroke Distance (cm)} = \frac{V_x t}{\int V dt}
\]
CARDIAC OUTPUT – PRINCIPLE

The image shows an ultrasound image of a heart. The principle of cardiac output involves measuring the volume of blood pumped out by the heart per minute. This is crucial in critical care settings for assessing cardiac function and monitoring patient health.
CARDIAC OUTPUT – PRINCIPLE
CSA determination often leads to the greatest source of error. When using any diameter for CSA determination, any error in measurement will be squared. This translates to a 20% error in calculation of CO for each 2 mm error when measuring a 2 cm diameter. Studies have shown that while the Doppler velocity curves can be recorded consistently with little inter-observer measurement variability (2-5%), the variability in 2D LVOT diameter measurements for CSA is significantly greater (8-12%). The Doppler signal is assumed to have been recorded at a parallel or near parallel intercept angle to blood flow. Deviations of up to 20° in intercept angle are acceptable since only a 6% error in measurement is introduced.

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.
1. parasternal long axis view

- Zoom in on LVOT
- Measure LVOT diameter in Systole
- Error will be squared \((r)^2\)

CSA determination often leads to the greatest source of error. When using any diameter for CSA determination, any error in measurement will be squared. This translates to a 20% error in calculation of CO for each 2 mm error when measuring a 2 cm diameter. Studies have shown that while the Doppler velocity curves can be recorded consistently with little inter-observer measurement variability (2-5%), the variability in 2D LVOT diameter measurements for CSA is significantly greater (8-12%). The Doppler signal is assumed to have been recorded at a parallel or near parallel intercept angle to blood flow. Deviations of up to 20 in intercept angle are acceptable since only a 6% error in measurement is introduced.

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.
2. Apical 5-chamber view

1. Place PW sample volume in LVOT
2. Press PW Doppler button
2. Apical 5-chamber view

1. Place PW sample volume in LVOT
2. Press PW Doppler button
2. Apical 5-chamber view

1. Place PW sample volume in LVOT
2. Press PW Doppler button
3. Apical 5-chamber view: trace spectral display
3. Apical 5-chamber view: trace spectral display
stroke volume accuracy

Depends on..

\[
\cos (\text{angle up to 20deg}) \rightarrow 6\% \text{ error; up to 60deg} \rightarrow 50\% \text{ underestimation of flow velocity}
\]

Only issue if using CW across AS valve. Since flow turbulent in DISTAL to AS. o/w using PW w/ sample volume at LVOT → Look for AV click AFTER VTI CURVE to indicate proximity to AV.
stroke volume accuracy

**Depends on..**

✧ **Accurate LVOT**
  
  → *Every mm counts...*

✧ **Doppler parallel to flow**

  → \( \cos (0^\circ) = 1 \sim 0\% \text{ error} \)

  → \( \cos (20^\circ) = 0.94 \sim 6\% \text{ error} \)

---

Cos (angle up to 20deg) → 6% error; up to 60deg → 50% underestimation of flow velocity

Only issue if using CW across AS valve. Since flow turbulent DISTAL to AS. o/w using PW w/ sample volume at LVOT → Look for AV click AFTER VTI CURVE to indicate proximity to AV.
stroke volume accuracy

Depends on..

✦ Accurate LVOT
   — Every mm counts…

✦ Doppler parallel to flow
   — \( \cos (0°) = 1 \sim 0\% \text{ error} \)
   — \( \cos (20°) = 0.94 \sim 6\% \text{ error} \)

✦ Regular Rhythm
   ... Afib leads to different VTI and thus SV’s

✦ Laminar flow
   ... Distal turbulence in Aortic Stenosis

Cos (angle up to 20deg) \( \sim 6\% \text{ error} \); up to 60deg \( \sim 50\% \text{ underestimation of flow velocity} \)

Only issue if using CW across AS valve. Since flow turbulent DISTAL to AS. o/w using PW w/ sample volume at LVOT \( \to \) Look for AV click AFTER VTI CURVE to indicate proximity to AV.
Questions?