Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

Course Instructor: Prof. Karla P Mercado-Shekhar

Department of Electronic Systems Engineering

Indian Institute of Science, Bangalore

Lecture – 42

Hello, welcome to today's lecture. In a previous lecture, I introduced the Doppler imaging modes and briefly explained the different modes that are available in ultrasound systems. In this lecture, we will dive deeper into Doppler ultrasound, understanding the physics behind it, as well as the different parameters that define the Doppler frequency shift.

We know that Doppler ultrasound is a non-invasive test to measure blood flow through blood vessels. It can help us diagnose blood clots, heart valve defects, a blocked artery (called an arterial occlusion), as well as arterial stenosis.

There are several types of Doppler. One is continuous Doppler, which we briefly discussed earlier. Then, there is pulse wave Doppler, color Doppler, and power Doppler.

The Doppler effect occurs when a relative motion exists between a wave source and a wave receiver. It was defined by Christian Andreas Doppler back in the early 1800s, and this Doppler effect has been incorporated into medical ultrasound to assess blood flow velocities. Doppler ultrasound is based on a shift of ultrasound frequency caused by a moving reflector. If you see in this schematic, we have our transducer in a stationary phase. If you have a stationary reflector, the signal you transmit will have the same frequency as the signal that is reflected from that stationary reflector.

Now, if that reflector is moving towards the transducer, the frequency of the sound received by the transducer will be higher than the transmitted ultrasound signal. If the reflector is moving away from the transducer, the frequency received by the transducer will be lower than the transmitted signal. What are the reflectors in your body? In blood vessels, the main reflectors are the red blood cells or blood cells in general. The blood cells will scatter ultrasound, and these cells are much smaller than the ultrasound wavelength. In scattering physics, we talked about the wavelength times the diameter of the scatterer, so K*a.

This is a being the radius. So K*a, if it's much less than one, this scatterer is considered a Rayleigh scatterer. Red blood cells in the body are considered Rayleigh scatterers. Now, the Doppler frequency shift is defined as twice that of the frequency of the incident beam, the velocity of the blood flow (in this case, the red blood cell velocity), the cosine of the Doppler angle, as well as the speed of sound (in this case, the longitudinal sound speed).

$$f_D = (2\times f_i \times v\times \cos(\theta))/c$$

f_i : frequency of incident beam

v: blood flow (red blood cell) velocity

c: speed of sound

θ: angle between the direction of the incident beam and blood flow (Doppler angle)

If we look at this schematic, the transducer is sending an ultrasound of our initial frequency, f_i .

In this schematic, the blood flow is towards the right, away from the transducer. In this case, the reflected signal will have a lower frequency, denoted by f_r. The Doppler angle is denoted by θ. This also affects the Doppler frequency shift that will be measured. If you rearrange this equation, the blood velocity can be calculated as follows:

$$v = (f_D \times c)/(2\times f_i \times \cos(\theta))$$

It equals the Doppler shift frequency times the sound speed, all divided by two times the frequency of the incident beam times the cosine of the Doppler angle. This is what is calculated in Doppler ultrasound systems to assess blood flow.

The Doppler frequency depends on several factors. It's proportional to the blood velocity. So, if the velocity of the blood doubles, then the Doppler frequency shift will double. Similarly, if the blood velocity decreases or is halved, then the Doppler shift frequency will also decrease by half. The ultrasound frequency of the incident beam also affects it. In the equation, the Doppler shift frequency is proportional to the frequency of the incident beam.

So, if the incident beam has a frequency of 10 MHz, then the Doppler frequency shift would be twice that of the Doppler frequency shift if the incident beam is at 5 MHz. Similarly, if the incident frequency is halved, then the Doppler shift frequency will also decrease by half. So, this proportionality exists. The third parameter that affects the Doppler shift frequency is the Doppler angle. I show a situation here where we have the incident frequency beam as 5 MHz, the speed of sound as 1540 m/s, and the blood velocity as 1 m/s.

Blood is flowing in this vessel at 1 m/s. As I change the Doppler angle, we see different Doppler shifts. At a zero-degree Doppler angle, you would get a Doppler shift frequency of 6.5 kHz. If the angle increases to 30 degrees, the Doppler shift frequency would be 5.6 kHz. At 60 degrees, it would decrease to 3.3 kHz. So, as we increase the Doppler angle, the Doppler shift frequency decreases.

It's important to set the Doppler angle correctly in your system. Also, if the Doppler angle is 90 degrees, meaning the transducer is directly perpendicular to the blood vessel, the Doppler shift frequency will be zero. This is because of the cosine function. Here I plot the cosine of the Doppler angle from 0 to 180 degrees. As you can see, as we increase the Doppler angle from 0 to 90 degrees, the cosine decreases from 1 all the way down to 0. If we increase the Doppler angle beyond 90 degrees, the cosine becomes negative.

In a Doppler image, the positive cosine angle for flow towards the transducer is indicated by angles less than 90 degrees. If you move perpendicular to the transducer, you won't see any Doppler shift. If the cosine is negative, it indicates the flow is away from the transducer.

In this case, the frequency of the reflected sound is much lower than the incident beam. This is important to note. In practice, what is typically done in clinics is to keep the Doppler angle between 30 and 60 degrees for optimal estimates of the Doppler shift frequency.

Now, let's go through an example problem:

Suppose the frequency of the incident beam is 2 MHz, and the blood flow velocity is 5 cm/s.What is the Doppler shift frequency?

Here, let's assume the Doppler angle is set at 30 degrees and the speed of sound in the blood is 1540 m/s. If you substitute these values into the Doppler shift frequency formula:

$f_D = (2 \times f_i \times v \times \cos(\theta))/c$

$f_D = [2 \times (2 \times 10^6 \text{ Hz}) \times (0.05 \text{ m/s}) \times \cos(30°)] / 1540 \text{ m/s}$

$f_D = 112.5 \text{ Hz}$

This is in the audible frequency range. If you have experienced Doppler imaging before, you may have noticed an audible sound coming from the Doppler system that reflects the frequency shifts based on the amplitude of the sound. Adding the Doppler shift frequency to the incident frequency, the reflected frequency f_r = 2.0001125 MHz So, you can see the Doppler shift frequency is much smaller compared to the incident or reflected frequency of the ultrasound beam.

Here is an example of a Doppler ultrasound display. This is a B-mode image of a vessel, the inferior vena cava. This is the large blood vessel that brings blood from the lower half of the body to the heart. In a B-mode image, blood vessels are typically hypoechoic compared to the surrounding tissues.

By anatomy, we can identify this as the inferior vena cava. You would set the line of the Doppler signal along this region, focusing on the inferior vena cava. You would notice a small gate with a cursor at an angle similar to the vessel's direction. This is the angle cursor, used by sonographers to input the flow angle by adjusting this cursor.

So, they would typically align this cursor parallel to the blood vessel's geometry right here. Whatever is inputted by the operator will help compute the Doppler angle, which is calculated by the instrument. There can be several mistakes in specifying this flow angle, and these can result in errors in the velocity estimates. For instance, for small Doppler angles of 0° to 40°, a 5° error in this flow angle can lead to less than a 10% velocity error. But for larger Doppler angles, a 5° error can lead to nearly a 100% velocity error.

It is, therefore, very important to be properly trained in how to set these Doppler angles correctly. Now, let's talk about two Doppler modes commonly used in ultrasound. First, we'll discuss Continuous Wave Doppler (CW Doppler). In this mode, there are two crystals or piezoelectric elements in the transducer that continuously transmit and receive the echo signals from the blood. We also have Pulse Wave Doppler, where one crystal produces short bursts of ultrasound. I will discuss the principles behind each system, as well as the advantages and disadvantages. Both Doppler modes are frequently used in clinical ultrasound.

The Continuous Wave Doppler system is the simplest and least expensive of the Doppler devices. It includes a continuous wave function generator, an oscillator, which sends a signal to the transducer. One of the transducer elements transmits the signal to the tissue, and the echoes received from the blood are picked up by another piezoelectric element.

Here's an example of what a transmitted waveform looks like. Depending on the direction of blood flow, the received wave will have a frequency that is either higher or lower than the transmitted wave. In this case, the received wave has a higher frequency, meaning that the reflectors (red blood cells) are moving towards the transducer. After the signal is received by the piezoelectric element, it is amplified by an amplifier circuit. The signal then goes into a demodulator circuit.

In the demodulator, the reference signal and the echo signals received by the transducer are multiplied together. Here's an example of the product of the reference and echo signals. As you may recall from mathematics, multiplying two sine waves creates a difference and a sum signal. The difference signal corresponds to the Doppler frequency signal, which we are interested in. After passing through the demodulator, a wall filter is applied to remove low-frequency Doppler signals from slow-moving reflectors like the vessel walls.

Here is an example of what a Doppler signal looks like. It's also important to understand how to choose the appropriate Doppler ultrasound frequency. There is a trade-off between resolution and penetration depth. Higher-frequency ultrasound is desired for high resolution, but adequate penetration of the ultrasound beam through the tissue is necessary, and penetration decreases as frequency increases. The source of Doppler signals is the red blood cells, which are Rayleigh scatterers.

We also remember from a previous lecture that the backscattered intensity from these Rayleigh scatterers is proportional to the fourth power of the frequency. Using high frequencies increases the intensity of the echo signals scattered from the blood. However, as frequency increases, ultrasound attenuation also increases. Therefore, the choice of ultrasound frequency depends on the depth of the vessel and attenuation. For small, superficial vessels, ultrasound frequencies of 8 to 10 MHz are typically used.

For greater depths and tissues with more attenuation, frequencies as low as 2 MHz may be used. Now, let's discuss the advantages and disadvantages of each technique. The advantage of Continuous Wave Doppler is that it can accurately display flow without aliasing. A disadvantage is that because you are using continuous wave signals, there is no time delay information, making it difficult to determine the exact range location of what you're imaging.

The advantage of Pulse Wave Doppler is that it uses shorter cycles, allowing for better range resolution. The time delay information helps locate the scatterers. A disadvantage is that you are unable to measure high velocities due to aliasing.

Now, let's focus on the Pulse Doppler system. We first select Doppler signals from specific depths using a range gate. Here's a schematic of a Pulse Doppler system, where a transmitted signal is sent to the transducer, and the same piezoelectric element receives the echoes from the scatterers in the blood. The received signal is then amplified to enhance its amplitude.

Some instruments allow the operator to vary the pulse duration, which can alter sensitivity. More cycles can improve imaging sensitivity but at the expense of more ultrasound exposure to the patient and reduced axial resolution. The number of cycles can be adjusted depending on the application. Once the signal is amplified, it is sent to the demodulator. The output from the demodulator depends on both the amplitude of the echoes from the blood reflectors and the phase of the echo signals. The phase is important because it helps incorporate the distance of the scatterers.

The range gate isolates the signal from the desired depth, which is selected by the operator. That signal is then sent to a sample-and-hold unit, which temporarily stores the received signal until the next transmit pulse is sent. This process allows for pulse-echo imaging in Pulse Doppler. Afterward, the signal goes through a wall filter again to remove low-frequency Doppler signals from slow-moving structures such as the vessel walls.

When we talk about which region of the blood vessel we're imaging, we refer to the "sample volume." The sample volume is the region from which signals are selected. Here's a schematic of a transducer and the ultrasound beam. Typically, a focused beam is used. The cross-sectional area of the sample volume is determined by the ultrasound beam width along the scan plane and the beam width perpendicular to the scan plane. A tightly focused ultrasound beam has a narrower beam area, resulting in a smaller sample volume. The axial length of the sample volume is determined by the pulse duration or the number of cycles in the wave.

It is also determined by the gate size selected by the user. If you have a narrow gate, you will be imaging a narrower range of velocities. If you have a larger gate, you will be looking at a larger range of velocities in the blood. Now, let's talk about the types of flow present in blood vessels. Here is a schematic of three different flow profiles that could occur.

You have laminar parabolic flow here, where the highest blood velocity is typically at the center of the vessel lumen. As the scatterer moves toward the blood vessel wall, the velocity of that scatterer will drop to nearly zero. In this laminar flow profile, you have a smooth flow with a range of velocities, from slow to moderately fast, without any abrupt discontinuities.

These discontinuities can be caused by obstructions or turns in the vascular system. What I'm showing here is another example of a flow profile called blunt flow. This typically occurs in larger vessels, such as the large arteries in the arterial system. The actual velocity profile across any vessel depends on the diameter of the vessel, the mechanical properties of the blood, and the flow velocity. In this example, if you have an obstruction in the vessel, it changes the internal diameter of the lumen, narrowing it.

As the blood flow moves from left to right, it hits this region, causing turbulence. The flow becomes disturbed, and this can be detected by Doppler ultrasound. The number of different Doppler frequencies depends on the distribution of velocities in the vessel.

If you have laminar flow, there will be a narrow distribution of velocities. If you have turbulent flow, you can imagine many different scatterers moving in various directions and at various speeds, leading to a broader distribution of velocities in the vessel. This also depends on the transducer beam width. If you have a smaller transducer beam width, you are looking into a smaller region of the vessel. Within that smaller region, you will have a narrower velocity profile compared to a larger transducer beam width. The size of the sample volume also matters, especially for pulse Doppler. When we talk about Doppler spectral analysis, it refers to a quantitative analysis showing the distribution of Doppler frequencies.

In spectral analysis, a complex ultrasound signal is broken down into simpler frequency components. The complex signal typically passes through a fast Fourier transform analyzer, which bins the signal into these simpler frequency components. Here's a schematic of a Doppler spectrum. On the y-axis, we have the velocities, which are binned according to the velocities present in the blood vessel. Each pixel represents the magnitude of the velocity.

This color scale shows how the signal is binned. For example, here we have five bins corresponding to specific velocities in the blood: 60, 65, 70, 75, and 80. If you see a darker pixel, it means many scatterers are moving at 70 cm/s in that region. Other scatterers are moving at different velocities. The Doppler spectrum shows the distribution of the Doppler shift frequencies present in the blood.

It means there are various scatterers experiencing different Doppler frequencies in the blood vessels. When looking at the Doppler display, you can see the Doppler spectrum at the bottom of the image. The y-axis shows velocity, which can be calculated from the Doppler shift frequencies. The white signal isn't a single line or curve, but a distribution of pixels within each time frame.

This distribution is a function of time. Here's an example of how the Doppler spectrum looks under different flow conditions. If you have laminar flow and place the range gate at the center of the lumen, and if the range gate is narrow, you'll get a Doppler spectrum with a narrow distribution. In the case of an obstruction, turbulent flow will cause a broader Doppler spectrum. If stenosis (narrowing of the artery) occurs, as blood moves from a larger to a narrower part of the vessel, the velocity increases.

This increased velocity causes turbulence at the output of the stenotic region, leading to swirling and mixing. In the Doppler spectrum, this appears as a broad distribution of Doppler frequencies. You can see spectral broadening here. Clinicians use the Doppler spectrum to identify turbulent flow and pinpoint areas of arterial obstruction, such as those caused by atherosclerosis, plaques, or blood clots.

Besides looking at the spectrum, quantitative parameters can also be derived. These provide data on the relative resistance of flow in the vascular network, which is useful for diagnosing diseases such as hypertension or blood clots.

One example of a quantitative parameter is the pulsatility index (PI):

$$PI = (max - min) / ave$$

PI: Represents the Pulsatility Index.

max: Indicates the peak systolic velocity.

min: Represents the minimum diastolic velocity.

ave: Stands for the average flow during the cardiac cycle.

Another quantitative parameter is the resistivity index (RI), which is simpler than the pulsatility index.

$$RI = (max - min) / max$$

It looks at the maximum velocity during peak systole and the minimum diastolic velocity during the cardiac cycle.

These two metrics are widely used, and in Doppler imaging systems, you will see these metric values displayed on the monitor. We have discussed the Doppler effect, the parameters affecting Doppler frequency estimates, Continuous Wave and Pulse Wave Doppler, as well as how spectral analysis is performed and the quantitative parameters that can be derived from it. In the next lecture, we will continue our discussion on Doppler ultrasound.