Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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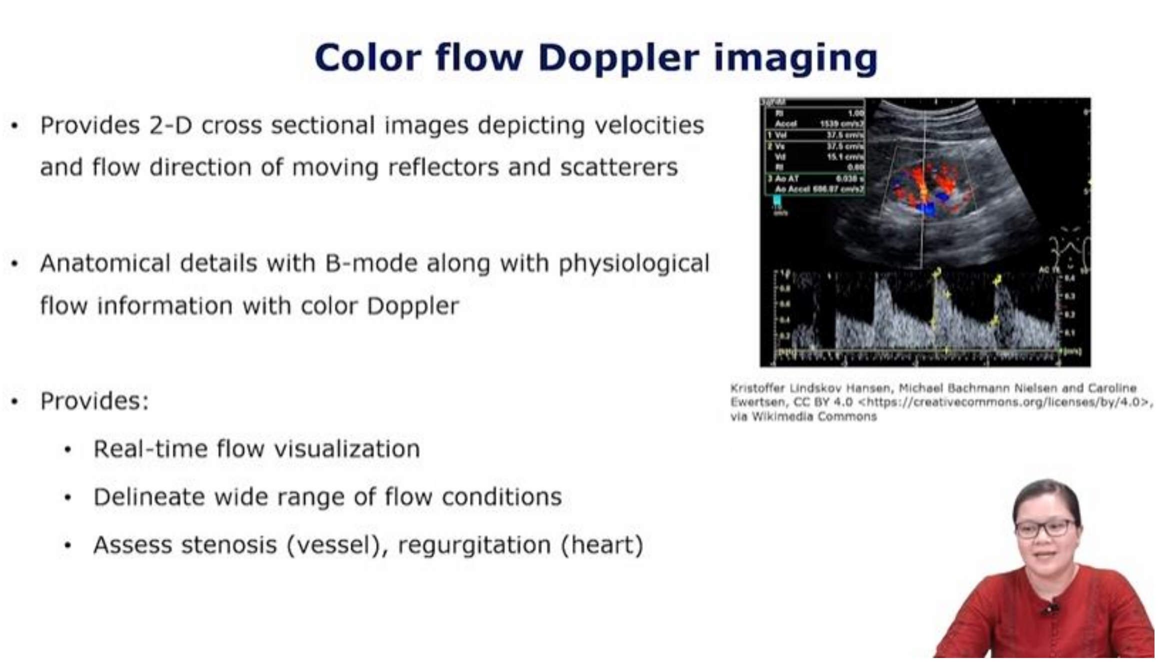
Lecture: 43

Color and Power Doppler Ultrasound

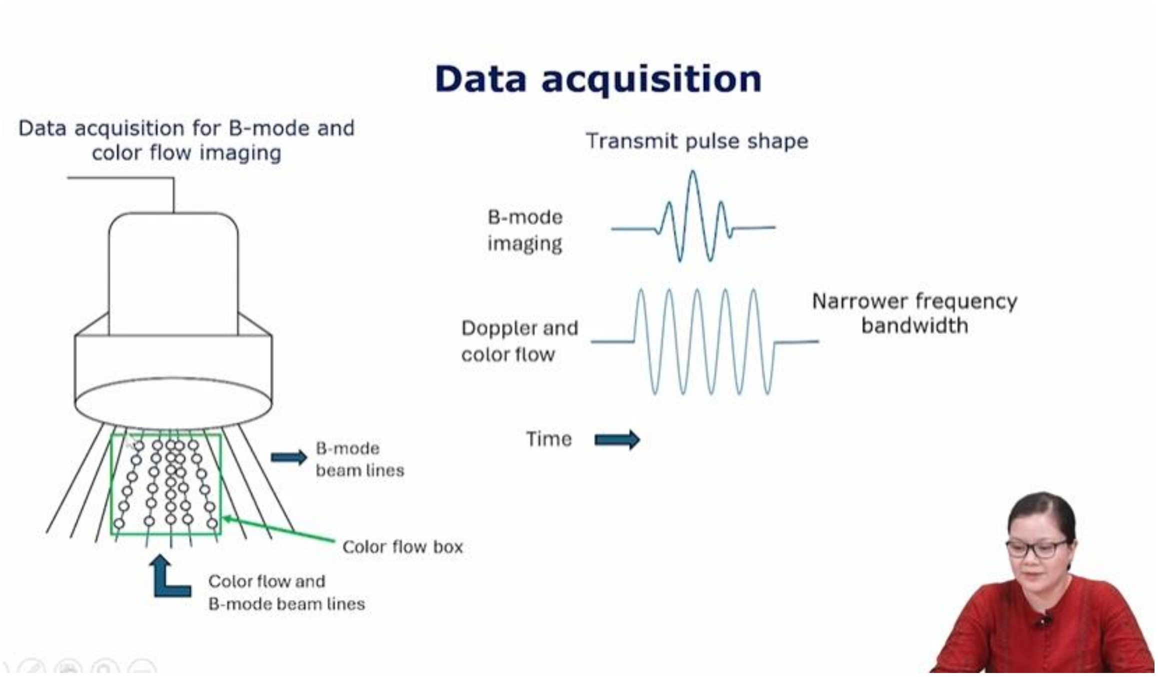
Hello. Welcome to today's lecture on color and power mode Doppler. So in previous lectures, we had discussed the Doppler principle as well as the pulsed Doppler and continuous wave Doppler modes. We also talked about how to do spectral Doppler. So in this lecture, we will continue and talk about the color and power Doppler modes that are frequently used in the clinic.

Now what is color flow Doppler imaging? So this provides a 2D cross-sectional image depicting the velocities and flow direction of moving reflectors and scatterers inside a vascular system. Here you can see that this is an example of a color flow Doppler image, wherein in the bottom you have a spectral Doppler display, you see that B mode image is overlaid with a color map, and this color map corresponds to color Doppler.



What's nice about this mode is that it can be duplexed with B-mode. And so you can have the advantage of getting the anatomical details with B-mode, as well as getting the physiological flow information with color doppler. Also, it provides real-time flow visualization, and it can help delineate a wide range of flow conditions, including those of diseases such as when you have stenosis in a vessel or a narrowing of the arteries. You can also use it to assess regurgitation or backflow in the chambers of the heart.

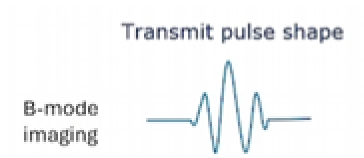
In terms of acquiring the data, the data acquisition schematic looks like this, wherein you have B-mode lines coming out of the transducer.



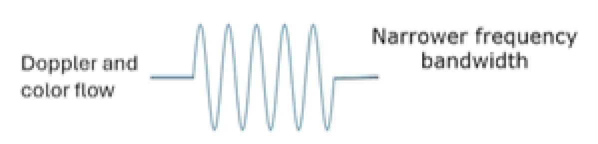
The B-mode lines are situated in various lateral locations to look into a region of interest. And within a region of interest, you can also select a region wherein you will calculate the color flow Doppler signal or the blood velocities with the direction. The green box here, is called the color flow box, which one can indicate in the Doppler display.

And here you have your B-mode lines as well as what's called the color flow packets indicated by the circles inside the color flow box, which we will discuss further in the next few slides. These are technically windows of the color Doppler signal that you will look into, at different depth locations in the region of interest.

So looking at what the transmit pulse shapes are, and how they are different between B-mode and Doppler. So in B-mode, you would recall that the pulse is typically two or three cycles. It might look something like this.

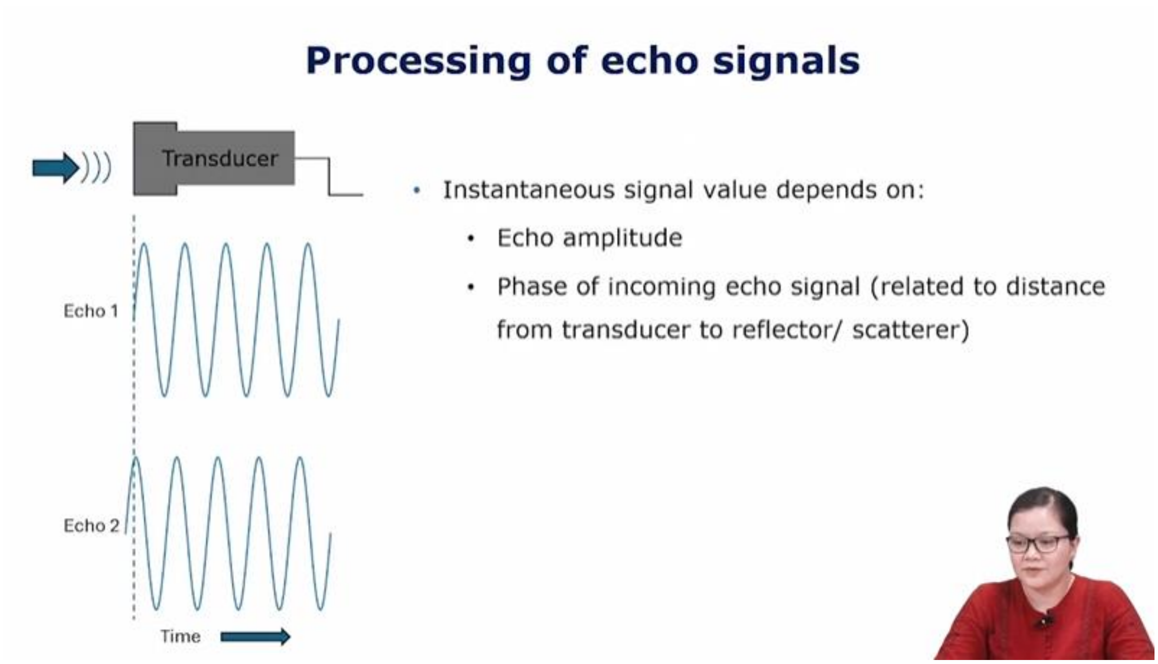


And in color Doppler, you can see that the number of cycles is much more, typically on the orders of 5 to 10 cycles.



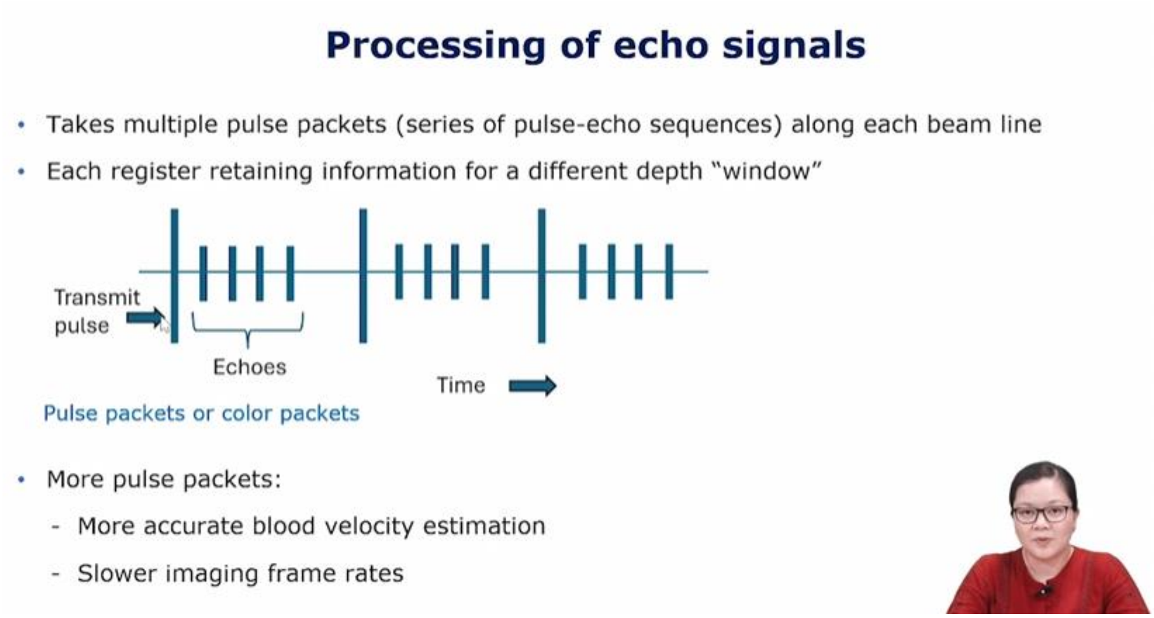
And the longer the cycle means that the bandwidth of the signal will be narrower. So in this case, the Doppler and color flow pulse signals typically have narrower frequency bandwidth. And this is useful to have good resolution in your color flow Doppler images.

When we talk about processing of the echo signals for Doppler, so here's just the schematic of your echoes coming into the transducer.



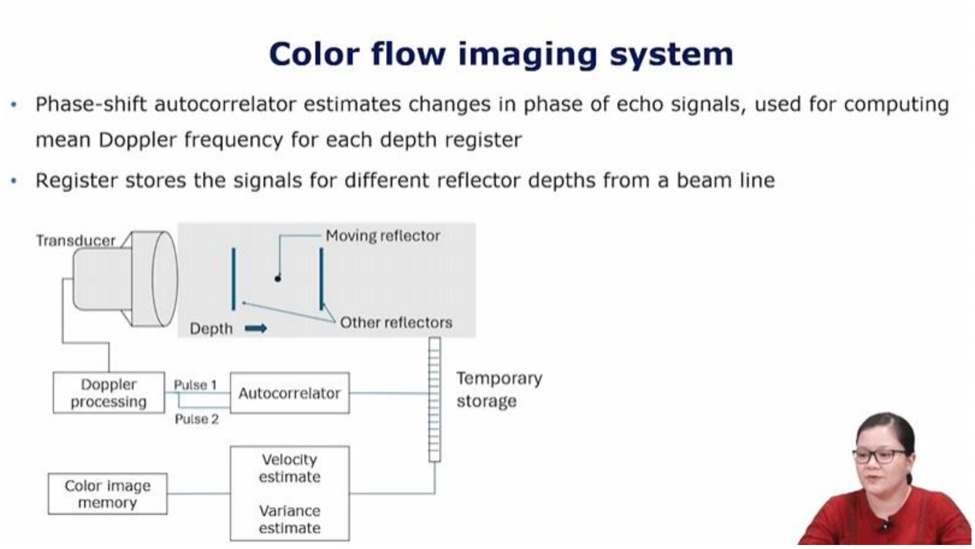
So for instance, here you have an echo signal from a particular reflector, and then a second echo signal that is shifted in time, marked as Echo2. So in this case, the signals are phase shifted. And when you are computing the Doppler echo signal values, what's also important is the phase of the incoming echoes, because that also relates to the depth or the distance at which the reflector is, from the transducer. What's also important is the echo amplitudes, and that will be useful for assessing the intensity of the blood flow display in color flow Doppler.

The way color flow doppler works is that first you transmit a pulse and then you would collect echoes from different pulse packets, and each pulse packet is one pulse echo sequence. And within this pulse packet, the echoes will be saved into a register which retains information for a different window at a particular depth.



So you can imagine that a transmit signal is being sent to a particular lateral location and it's going through a function of depth and the echoes are being received at each individual depths. And this pulse echo sequence is happening in order to be able to assess the flow or the velocity of the scatterers inside that region of interest. And the more pulse packets there are, that means there are more accurate blood velocity estimation. However, to get an entire color flow image, it will take some time to form the image based on this pulse echo sequences. Therefore, if you have more pulse packets, then it might result in slower imaging frame rates. So there is a trade-off with Color Doppler and the imaging frame rates.

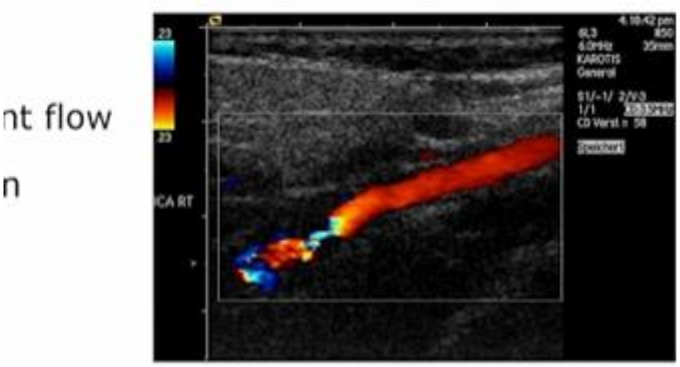
Now this is just looking into the color flow imaging system.



We have the transducer and it is emitting the transmit ultrasound signals. It's going to interact with the reflector. The reflector will then send the ultrasound signal back, and there will be an echo signal. Then, that echo signal will be received by the transducer, and then Doppler processing will happen in terms of looking into the echo from the first pulse and then the echo from the second pulse. Then the signals will then go into an autocorrelator, which is a phase shift autocorrelator that estimates the changes in the phase between echo signals. And this is useful for computing the mean Doppler frequency and the velocity at each depth within that axial location. So then the signals get saved into a temporary storage unit.

Afterwards, within that temporary storage unit, we can map the velocities as well as the variance estimates for detecting the presence of turbulence in blood flow. So the velocity, of course, is important, but the variance estimate is equally important. Variance will also give you an indication of how much differences or variations there are, within a region of interest.

So if you look at this image on the right, we have a blood vessel, but afterwards it reaches a location in the tissue where you can find multiple colors and large variations in the velocity estimate. And what one can do is you can estimate the variance of these blood velocities at the location with mixing of colors, and that can give you an indication of how much turbulence there is here.



And that's useful for assessing certain diseases within that region. After these estimates, then it saves into the color image memory, which will then be used to map your color Doppler display.

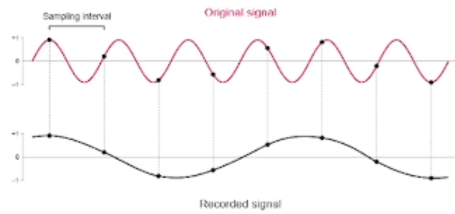
So now let's talk about the properties of color displays. There are certain image properties that are based on the psychophysical perception of color. One of those properties is called hue, and that's typically related to the wavelength of the visible light. So in a color Doppler image, the map is typically based on a red hue, which means that the reflector is flowing towards the transducer. So if you can see the color map here, this is a color Doppler map, overlaid onto a B-mode image.

- Image properties related to psychophysical perception of color:
  - **Hue:** related to wavelength of visible light
  - RED HUE: flow moving towards the transducer
  - BLUE HUE: moving away from the probe
  - **Intensity:** measure of brightness; indicate flow rate (e.g., dull red to bright red)

Here, red to bright red means that the flow is moving towards the transducer and the brighter intensity of that red means that the reflector is moving faster. In contrast, if the scatterer or reflector is moving away from the transducer, then there will be a blue hue in the color Doppler display. So you can see the color map, you have from blue to even brighter blue. That corresponds to the reflector moving further away from the transducer, and the brighter the blue, means that it's moving faster away from the transducer. So the intensity also matters when I talk about the measure of the brightness of that hue, and that indicates the flow rate.

There is one component that is very important in terms of adjusting your Doppler display. Let's talk about the concept of aliasing. So you might remember from your signal processing class wherein if you have a signal and you sample it at certain intervals, depending on how often you sample it or basically the sampling rate, your sampled signal may or may not accurately represent your original signal. If you are recording the signal using a digital device, and if you sample it enough, then the recorded signal will be similar to the original signal. But if you sample it too low, then the signal will have a lower frequency component. So basically, the sampling rate of the system does matter when you're talking about color Doppler and being able to avoid this aliasing artifact.

- Limit on pulse repetition frequency (PRF) in pulsed and color Doppler ultrasound systems, limiting sampling rate
- Insufficient sampling rate results in artifactual lower-frequency components in the spectrum

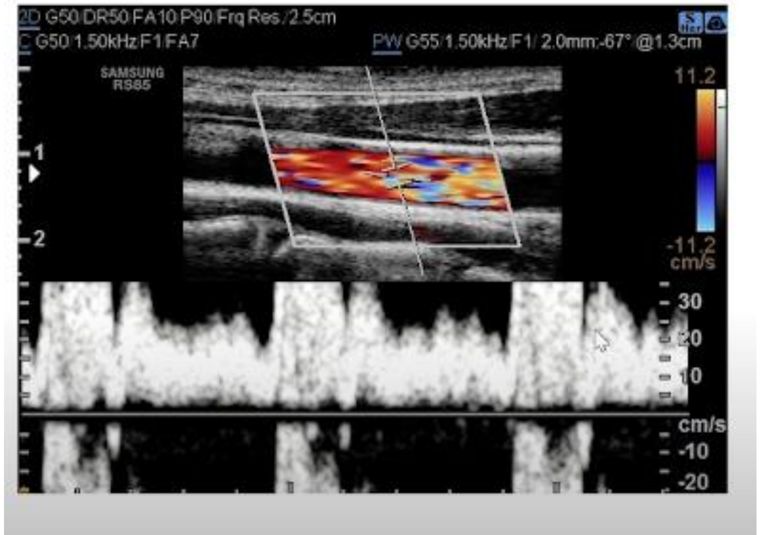


Laurens R. Krol, CC0, via Wikimedia Commons,
https://commons.wikimedia.org/wiki/File:Signal_aliasing_demonstration.svg

- Factors that can cause aliasing:
  - Higher blood velocities
  - Increasing depth of region of interest, causing range ambiguity
  - Inappropriate Doppler angle
  - Large sampling volume

There is a limit on the pulse repetition frequencies in these pulse and color Doppler systems, which limits the sampling rate. And as you can see here, if there's aliasing, then lower frequency components are developed. Several factors that can cause this is, if you have really high velocities in your blood flow and your pulse-repetition frequency is not enough to capture those high velocities, and also, if there is an increasing depth in the region of interest, that can cause some range ambiguity. In a previous lecture, we talked about range ambiguity in terms of an imaging artifact. Also, if the operator dials an inappropriate Doppler angle, that can also affect the Doppler frequencies that's being measured, and then consequently the blood velocity. And if you have a large sample volume, let's say you sample a really large vessel, and you have a range of Doppler frequencies ranging from low towards the sides of the vessel and going really high towards the middle. So if you're trying to capture all that range of Doppler frequencies, then it might also be that the frame rates will not be adjusted properly. So one should keep in mind the aliasing phenomenon, and we'll discuss a way that you can remove or eliminate this aliasing phenomenon.

This is an example of an aliasing artifact, where I show a color Doppler image, and below is the spectral Doppler. What you can see in the spectral Doppler display is that you have this wrap around phenomenon.



Case courtesy of Bálint Botz, Radiopaedia.org, rID: 64786

So the horizontal line with zero velocity is the baseline of the spectral Doppler. The higher velocities are because of higher Doppler frequencies. and then the lower velocities are because of lower Doppler frequencies. The bottom part of the spectrum indicates that the flow is moving away from the transducer, and the top part, is indicating that the flow is moving towards the transducer. So when the flow is moving away, then you get these negative velocities. When the flow is moving closer to the transducer, then you get positive velocities. If aliasing happens, then you get this wrap around phenomenon, where it appears that the high velocity reflectors are actually being read as lower velocities. It appears as if both high and low velocity components are present simultaneously. So these components of the spectrum that are in the low velocities are because of aliasing of the high frequency parts of the signal right here. In the color Doppler display, what you can actually see is a mixture of blue and red hue in the intermediate parts as well. So typically a healthy vessel would have either a red or a blue hue depending on the direction of flow. And if you find that there is a region where there's a mixture of red and blue hue, that means there's some turbulence in there or it's because of some inconsistent PRF or very low PRF due to this aliasing artifact.

Now, what is the maximum velocity that you can detect with pulse Doppler? So there's a very simple criterion that one has to follow to avoid aliasing. So you must have remembered the Nyquist sampling theorem. In Doppler, if the pulse repetition frequency is at least twice that of the Doppler frequency, then you can avoid aliasing. So let's look at how we can calculate that maximum velocity to avoid this aliasing. So here, v_{max} is the maximum reflective velocity. PRF_{max} is the maximum PRF from a sample volume at a certain depth. So this is within your smaller windows along the axial depths of your region of interest. So then to avoid aliasing, in this case, let's assume a Doppler angle of zero, meaning that the flow is moving directly towards the transducer. So if the Doppler angle is zero, then you'll get the maximum velocity when the reflector is moving directly towards the transducer. So the maximum pulse repetition frequency should be at least two times the Doppler frequency.

- Avoid aliasing: $PRF \geq 2f_D$ (must be above Nyquist sampling rate)
- Let v_{max} → maximum reflector velocity
- PRF_{max} → maximum PRF from sample volume at a specific depth

- Then, to avoid aliasing (assuming Doppler angle $\theta = 0^o$, $\cos(\theta) = 1$):

$$PRF_{max} = 2f_D = \frac{4f_o v_{max}}{c}$$

$$v_{max} = \frac{c\ PRF_{max}}{4f_o} = \frac{c^2}{8f_o d}$$

And if you plug in the Doppler equation into this, the cosine term is gone because if you assume a Doppler angle of zero, then cosine is just one. So v_{max} becomes,

$$v_{max} = \frac{cPRF_{max}}{4f_0} = \frac{c^2}{8f_0 d}$$

Where, d is the depth of the location. And the v_{max} will vary depending on where you are actually in that beam line.

Now let's look at an example of how we can use this expression to be able to compute the maximum detectable blood velocity. So we asked the question, what is the maximum detectable blood velocity if the ultrasound operating frequency is 4 MHz? So this is our transmit frequency, and the vessel of interest is at 5 cm depth, 5 cm away from the transducer.

- What is the maximum detectable blood velocity if the ultrasound operating frequency is 4 MHz and the vessel of interest is at 5 cm depth?

When we compute, by assuming that the speed of sound is 1540 m/s, we get 1.48 m/s. Typically, when we talk about blood flow velocities in the body, it's in terms of cm/s. So in this case, our maximum velocity is 148 cm/s.

Solution:

- Assume 1540 m/s as speed of sound $\qquad v_{max} = \dfrac{c^2}{8 f_o d}$

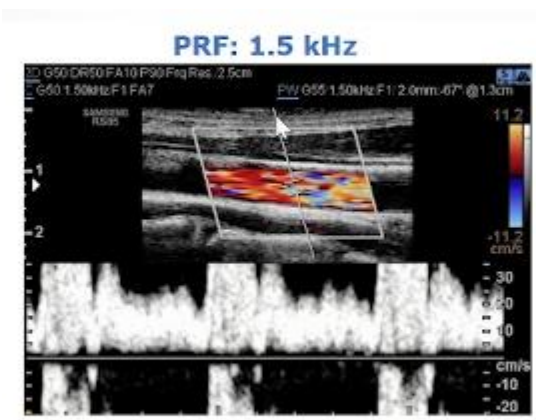
$$v_{max} = \frac{\left(1540\,\frac{m}{s}\right)^2}{8 \times 4 \times 10^6 \left(\frac{1}{s}\right) \times\ 0.05\,m} = 1.48\,\frac{m}{s} = \boxed{148\,\frac{cm}{s}}$$

- If the vessel was deeper than 5 cm, maximum detectable velocity would decrease

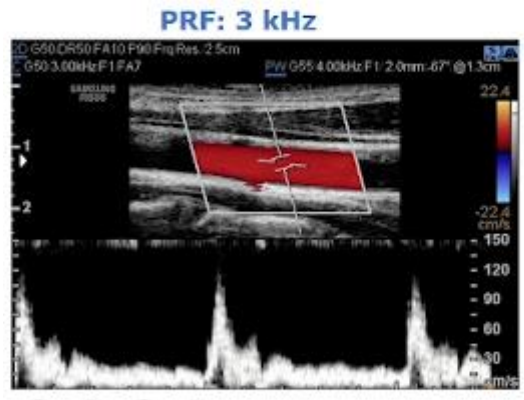
So if the vessel was deeper than five centimeters, then the maximum detectable velocity would decrease, as you can see based on this inverse relationship between the maximum velocity and the depth. So the deeper you are, the smaller the maximum velocity will be and vice versa.

So these can happen anywhere in the body, for example, if you image in the heart, the blood flow can be in various directions. So depending on your image field of view, this Doppler angle can even go into zero degrees.

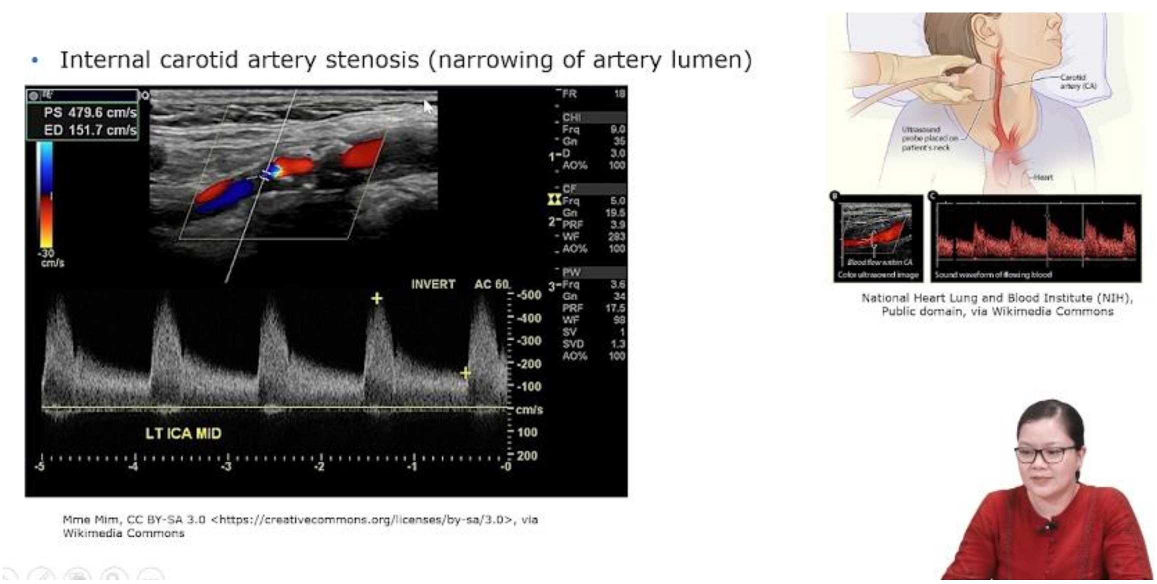
Now, how do we eliminate aliasing? So there's one way that's typically used and it's by increasing your pulse repetition frequency. So what I'm showing here are some examples. So here the color Doppler ultrasound was being done at a pulse repetition frequency of 1.5 kHz here.



And you can see by the spectral Doppler display, there's a wrap around in the spectrum. And this implies aliasing, as well as a mixing of blue and red. So this is also an indication of aliasing. And so what you can do is that if you increase the PRF to 3 kHz, means you will be able to sample faster, then you can get more of that higher frequency components. Then you can see that the flow through this vessel is very smooth, just red. And in the Doppler spectrum you can see that the y-axis shows only positive velocity components.

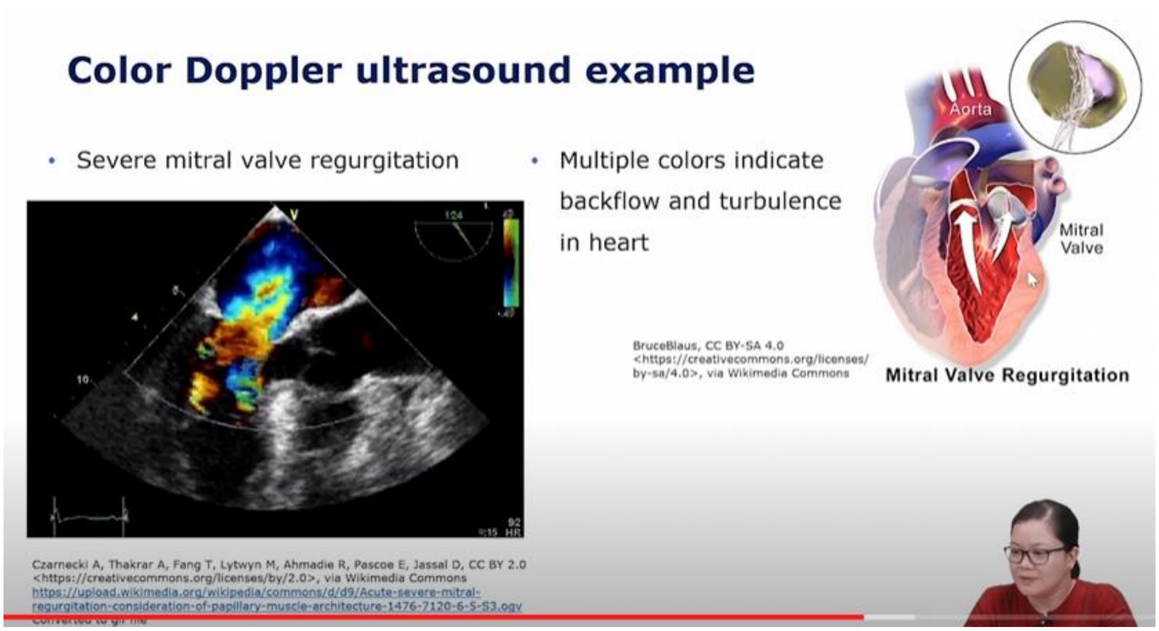


Now let's talk about some examples where color Doppler is frequently used in the clinic. So an example that I showed here is the internal carotid artery stenosis. So stenosis is the narrowing of the artery lumen due to some obstruction in the artery, like a plaque, for instance. So in the clinic, this procedure is important to be able to gauge how much blood flow is going into the brain. Because your carotid artery is actually one of the main vessels that will move blood from your heart to your brain, and if that gets blocked, then a person can experience what's called a stroke, lack of blood flow to the brain. Here what we see is that this is the carotid artery right here, and you can see that there's red and also some blue hue in this image.



What this is indicating is that there could be some sort of stenosis that's causing turbulence. And that turbulence can have mixing effects at the other end of the stenosis. Therefore, what color Doppler shows is a reversal of flow as well as a forward motion of the flow. You can also see in the spectral Doppler that there's some negative flow components indicating flow reversal as well in addition to the positive flow. So this is just one example.

Another example is looking into the heart, to see if there are any flow defects in the heart. The heart is a very special organ and very important, making sure that blood moves through the chambers of the heart in the proper directions. Heart has valves between the chambers, to make sure that blood flows only in one direction. Now, if there is a defect in any of these valves, then there could be a backflow into the other chambers of the heart. And that can cause issues with trying to oxygenate other parts of the body. So one example here is a mitral valve, one of the valves that are in your heart, and it's related to blood flow going from your left atrium to the left ventricle. And this left ventricle is the part of the heart that is useful for ejecting blood through the rest of your body.

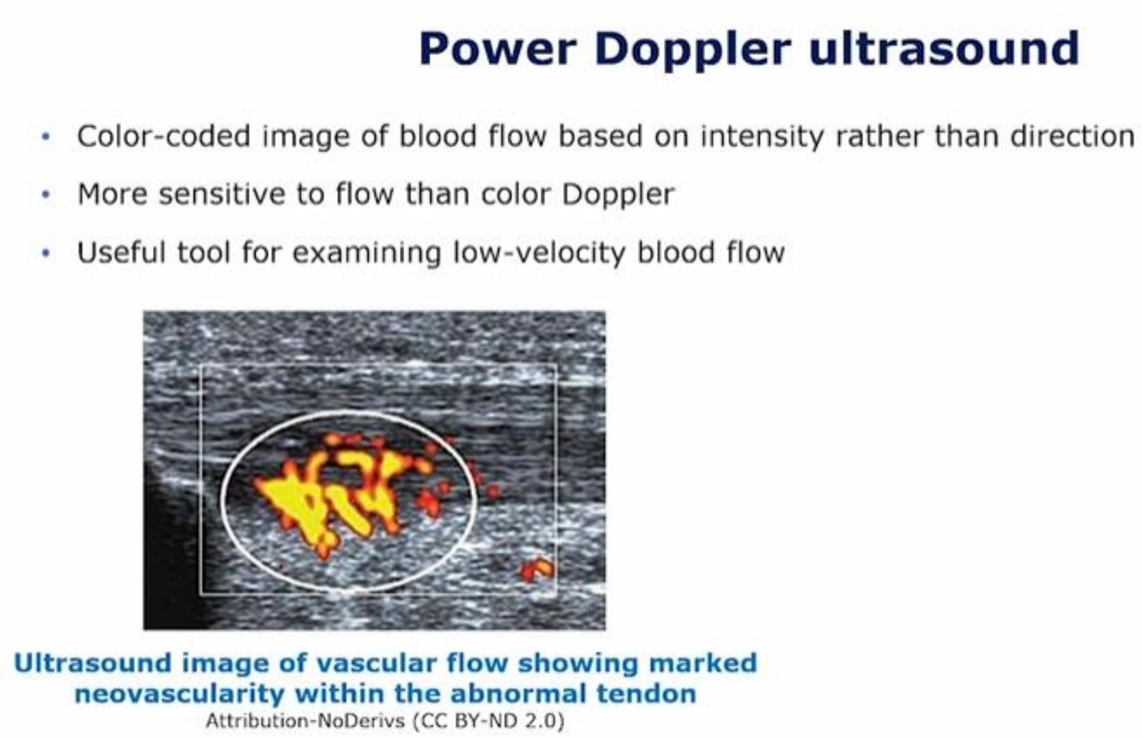


Now, if there is some backflow through this mitral valve, then it means that not all the blood that is needed can go to the rest of your body. So here is just an example of a heart ultrasound or echocardiography. Now we might have talked about this term earlier. So echocardiography is a common ultrasound procedure of imaging the heart. So what you are seeing here, are the heart chambers. One of them is the atria and the other is the ventricles. And you can see that this mitral valve, one of these heart valves, are not functioning properly because looking at the color map, you see red blue hue that are mixing around inside the heart chambers. So this is an indication that there could be some flow reversal or backflow through the mitral valve and that is not good for the heart.

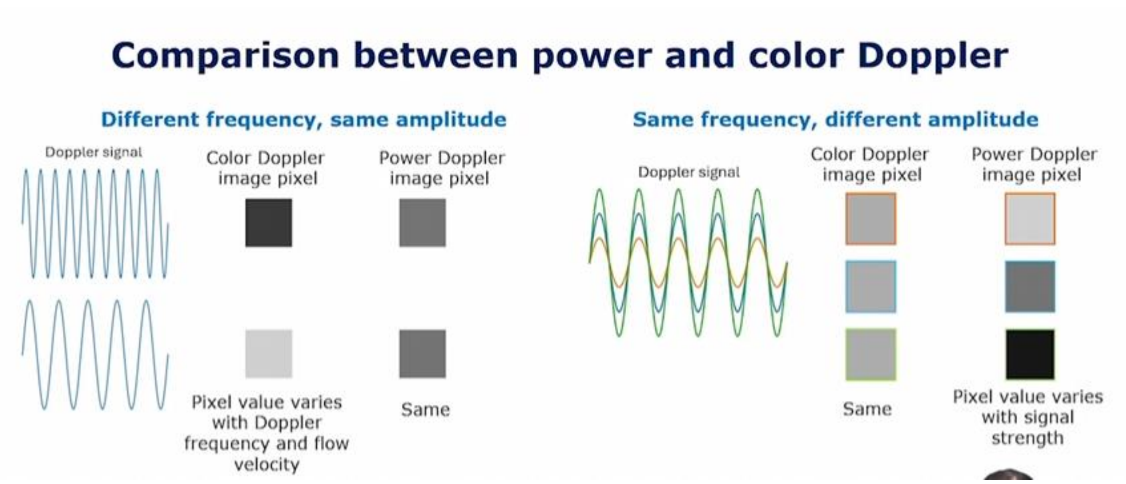
Another common example is in fetal ultrasound. Now this is a B-mode image overlaid with a color Doppler of a fetus at several weeks old.

You cannot delineate at this point, the full picture of the baby because the baby is very, very small at this point. But what color doppler is useful for is for looking into blood flow in that heart. Now you can see that as the heart is beating, of course you see motion around the placenta, but also some changes in the blood flow in the heart. indicating that the heart is developing properly.

Now let us explain what power Doppler is. So it's a color-coded image of blood flow based on intensity rather than direction. So if you recall, color Doppler can map the velocity as well as the direction of blood flow and for power Doppler, what it maps is the intensity of that blood flow or the energy that's coming out from that Doppler signal. It's considered more sensitive to flow than the color Doppler, and it's also a useful tool for examining low blood flow velocity. So here's just an example of a power Doppler image. Now, there's only one type of color map here, or a heat map like this, where it goes from orange to really bright orange and yellow. Yellow meaning higher intensity, so more brighter hue, indicating that there is more blood flow in that region.



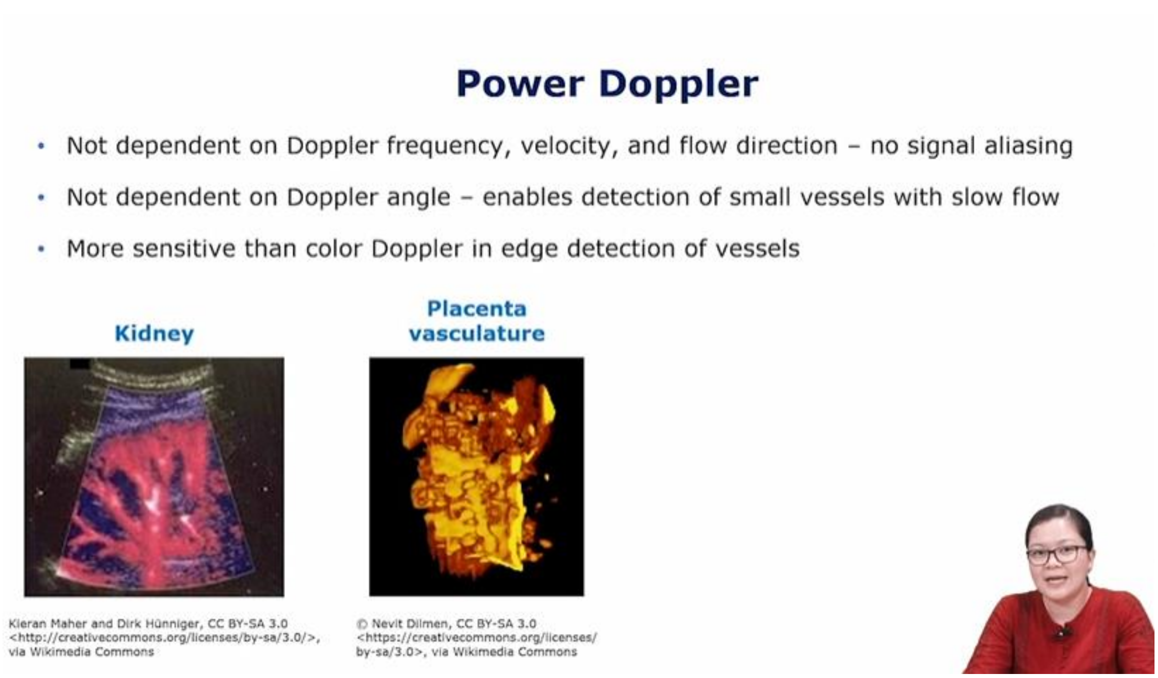
Now here's a comparison between power and color Doppler. So on the left here, we're going to compare between Doppler signals of different frequencies and how they impact the color pixels in a color Doppler, as well as the image pixel in a power Doppler. So here in the left is a case where you have a higher frequency Doppler signal and a lower frequency Doppler signal. And you can see that color Doppler is mapped based on the differences in the frequencies of the Doppler signal. And that can lead to differences in the flow velocity.



So you can see the intensities of the image will change. But in terms of power Doppler, since the signals have same amplitude, despite differences in frequencies, won't show any change in the image pixels. Here, also because of the same amplitude, there is no change.

But in the case shown in right,, where you have a single Doppler frequency with different amplitudes of the signal. The pixel intensity in color Doppler will be the same for the yellow, blue and the green signals, despite their amplitude differences. Whereas in power Doppler, because these signals have different amplitudes so the power doppler image pixel values will vary. It will read that the signal has different strengths here. So in Power Doppler, you will be able to identify those differences in the strengths. So, power Doppler is not dependent on the Doppler frequency or the velocity and the flow direction, whereas color Doppler is dependent on them.

So, in power Doppler, aliasing is not a confounding factor. There's no signal aliasing because the Doppler frequency is not taken into account in power Doppler images. There's also no dependence on the Doppler angle. And what this enables is detection of small vessels with really, really slow flows. So what it looks at is more sensitive than color Doppler in detection of the edges of the vessels.



So here's just an example of a power Doppler of a kidney. You can see that the color map is based on different intensities of red hue, where your brighter red indicates that there is higher energy flow. Here's just another example of where the power Doppler technology has gone. So you can even look into the vasculature of a placenta, and you can map in 3D nowadays. So it's very useful for looking at low flow velocities, but a limitation of power

Doppler is that it doesn't give you the velocity as well as the flow direction. So these are disadvantages, but it's widely used for looking into slow flow velocities.

So I hope this gives you a good overview of color and power Doppler. We've talked about the Doppler imaging system, what the color displays are outputting. We talked about the aliasing artifact and how to eliminate aliasing by increasing the PRF. We also looked into some clinical applications of both power and color Doppler. So with this, hope you enjoyed the lecture and we'll see you again. Thank you.