CIHR Strategic Training Program in Vascular Research

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VASCPROG 560

Vascular Imaging Techniques

Module 5 *DOPPLER IMAGING*

CIHR Strategic Training Program
In Vascular Research

Navigation through this Module

- This module was generated using Microsoft PowerPoint and then converted to Adobe Acrobat. You will need Adobe Acrobat Reader to view the content. Different web browsers may display WebCT content differently. Please contact Jackie Williams at the email address below if you experience difficulties viewing any module.

- Instead of a course textbook, all the modules contain links to excellent information that can be found on the internet. It is important that you visit these links to get more background on the topics. These also may be printed out to read in more detail later, or to be saved for future reference.

- If you have any difficulty in accessing any of the links within these modules please send an email to jwilliams@robarts.ca. Sometimes the sources of the links change and adjustments will be made to correct this.

- When you have finished the module, please go to the Module 5 Quiz under the Quizzes icon on the Course Home Page.

Credits

Information in this module was based on lecture notes given by Robarts Scientists as part of the coursework in the Department of Biomedical Engineering at the University of Western Ontario, and from material from the following sources:

C. M. Rumack, S.R. Wilson & J.W. Charbonneau (Eds). Diagnostic Ultrasound, Vol 1, 2nd edition. Mosby 1998. Chapter 1, The Physics of Ultrasound, Christopher R.B. Merritt, MD.

W. Huda & R. Slone. Review of Radiologic Physics, 2nd edition. Lippincott Williams & Wilkins. 2003. Chapter 11 – Ultrasound pp. 173-191.

Navin C. Nanda (Ed.) Textbook of Color Doppler Echocardiography. Lea & Febiger, Philadelphia; 1989.

Jackie Williams wrote some of the course content and organized the module in its present format for WebCT.

I wish to thank Dr. Donal B. Downey, Interventional Radiologist at London Health Sciences Centre, London, Ontario, for his input into this module.

Additional Resources

For those students who are interested in more detailed information on Doppler ultrasound, there is a series of excellent, in depth articles by Joseph A. Kisslo, MD and David B. Adams, RDCS to be found at the following web links:

Principles of Doppler Echocardiography and The Doppler Examination #1

Doppler Evaluation of Valvular Regurgitation #2

Doppler Evaluation of Vascular Stenosis #3

Doppler Color Flow Imaging #4

Objectives

After completing this module, the student should be able to:

- Briefly describe real-time B-mode, and continuous and pulsed Doppler modes).
- Understand how the velocity of blood is calculated by using the Doppler shift of ultrasound.
- Describe how pulsed Doppler can be used to obtain flow velocities from a specific depth in tissue.
- Describe the Nyquist limit and aliasing.
- Describe the differences between colour flow and power mode Doppler imaging.
- Briefly describe duplex scanners, colour Doppler flow imaging, and spectral analysis of Doppler velocity signals.
- Understand gain control on the instrumentation panel.
- Describe how different artifacts arise in Doppler imaging.

The Uses of Doppler Ultrasound

Different forms of Doppler ultrasound are used to:

- Help detect blood clots and blocked or narrowed blood vessels in almost any part of the body, especially in the neck, arms, and legs. Blocked or narrowed arteries of the neck can cause dizziness, loss of vision, paralysis, weakness, or numbness. Blood clots in the deep veins of the leg can cause leg pain and swelling and can increase a person's risk of pulmonary embolism.
- Evaluate leg pain that may be caused by intermittent claudication, a condition caused by atherosclerosis of the lower extremities.
- Determine the presence, amount, and location of arterial plaque. Plaque in the carotid arteries can reduce blood flow to the brain and may increase the risk of stroke.
- Evaluate blood flow after a stroke or other condition that might be caused by a problem with blood flow. Evaluation of a stroke can be done through a technique called transcranial Doppler (TCD) ultrasound.
- Map veins that may be used for blood vessel grafts. It can also evaluate the condition of grafts used to bypass blockage in an arm or leg.
- Determine the amount of blood flow to a transplanted kidney or liver.
- Monitor the flow of blood following blood vessel surgery.

Doppler Ultrasound and the Doppler Effect

Doppler ultrasound involves a group of ultrasound techniques that use the Doppler effect to image blood flow velocity.

The Doppler Effect

The Doppler effect was named after Johann Christian Doppler (1803–1853), an Austrian mathematician and physicist, who theorized that sound waves from a moving source would be closer together as the sound came closer, and further apart as the sound went further away. Closer-spaced waves would have a higher pitch, and waves further apart would have a lower pitch.

The Doppler effect is applicable to any kind of wave, whether electromagnetic (e.g. light) or mechanical (e.g. ultrasound).

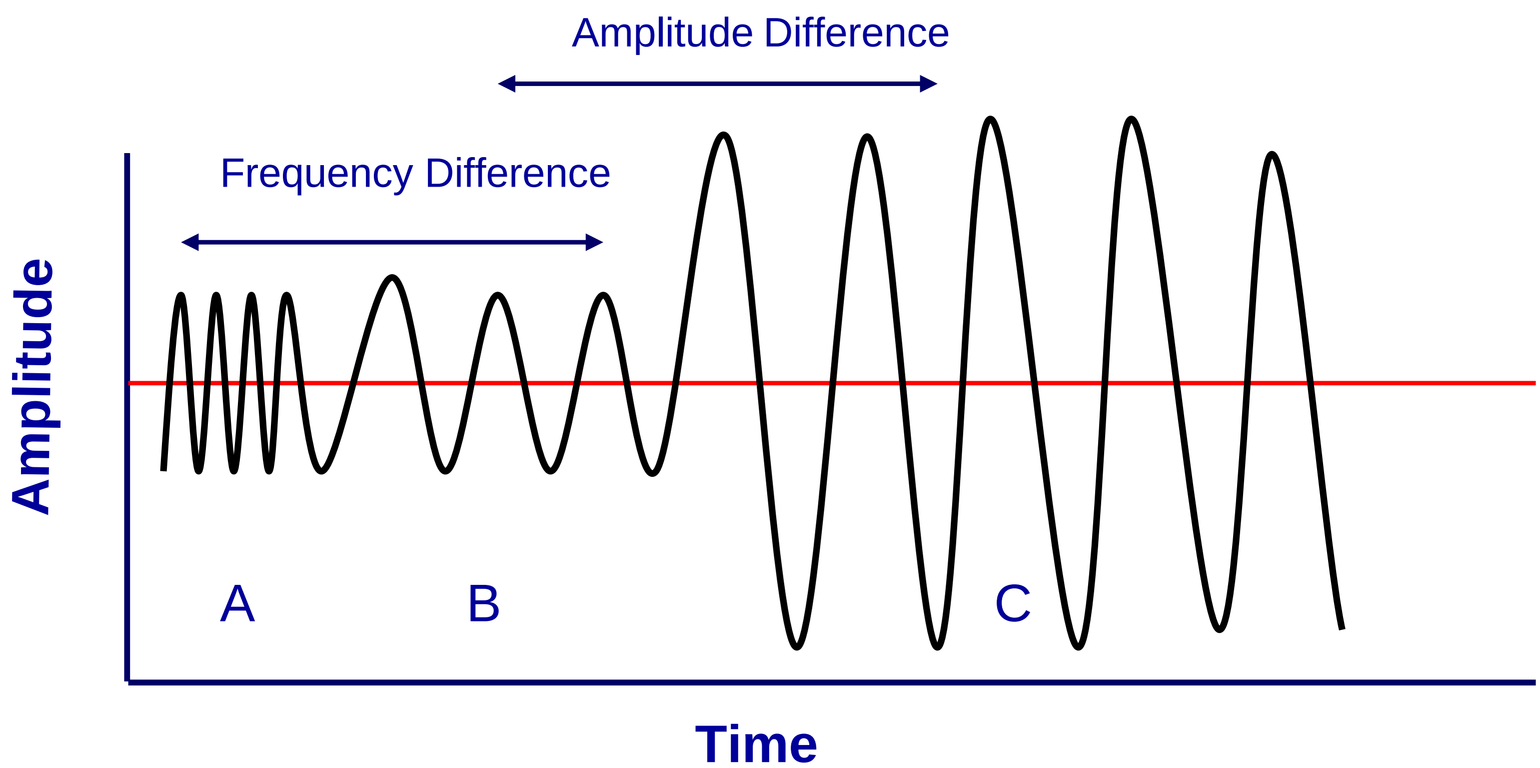
If you need a refresher on how the Doppler effect works, the following website demonstrates the phenomenon using animation:

The Doppler Effect

We will begin by describing how the Doppler effect works when applied in medical ultrasound, and then will describe the different Doppler techniques that are used in medicine.

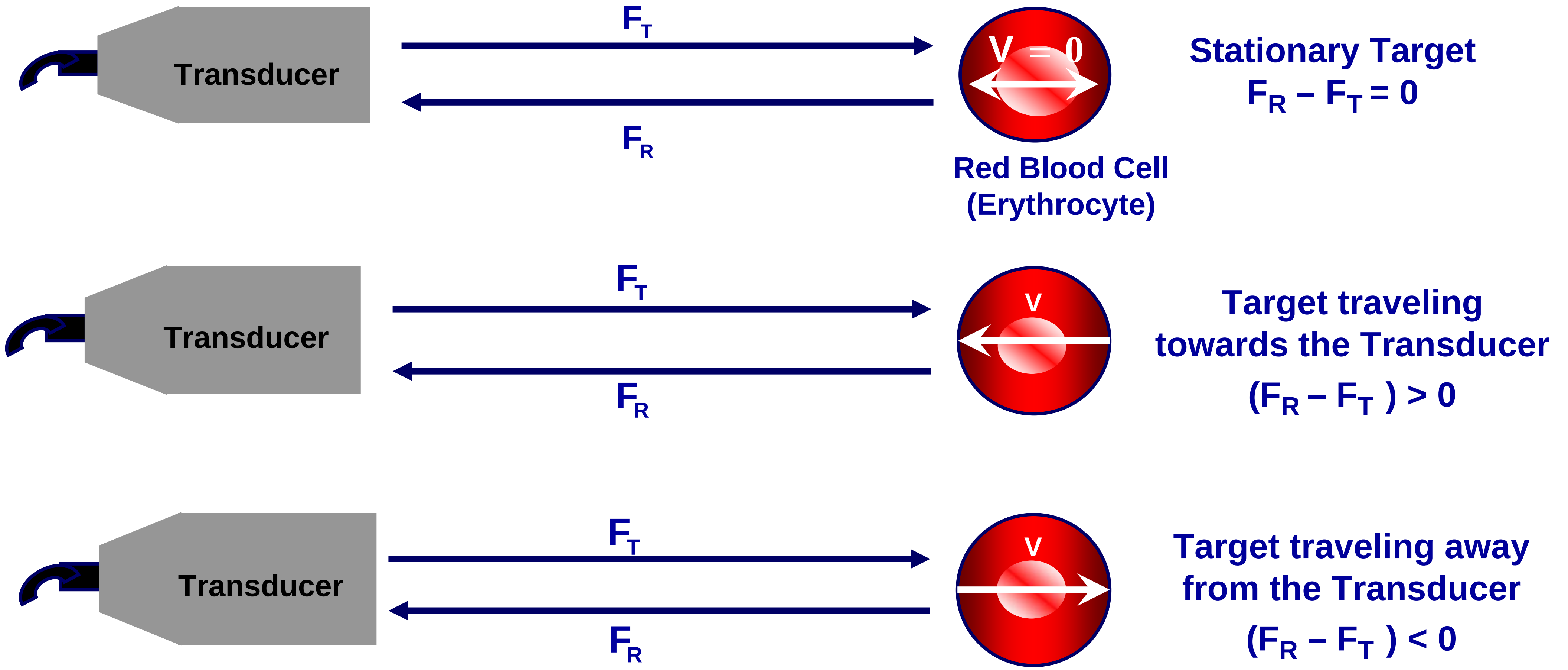
In ultrasound, the Doppler effect is used to measure blood flow velocity. The reflector in this case is the red blood cell. Ultrasound reflected from red blood cells will change in frequency according to the blood flow velocity. When the direction of blood flow is towards the Doppler transducer, the echoes from blood reflected back to the transducer will have a higher frequency than the one emitted from the transducer. When the direction is away from the transducer, the echoes will have a lower frequency than those emitted. The difference in frequency between transmitted and received echoes is called the Doppler frequency shift, and this shift in frequency is proportional to the blood flow velocity.

Doppler Ultrasound



This diagram shows the frequency differences that form the basis of Doppler ultrasound. The back scattered ultrasound signal contains amplitude, phase and frequency information. Signals B and C differ in amplitude but have the same frequency. Signals A and B have different frequencies, but the same amplitude. It is the **frequency differences** that are the basis of Doppler ultrasound.

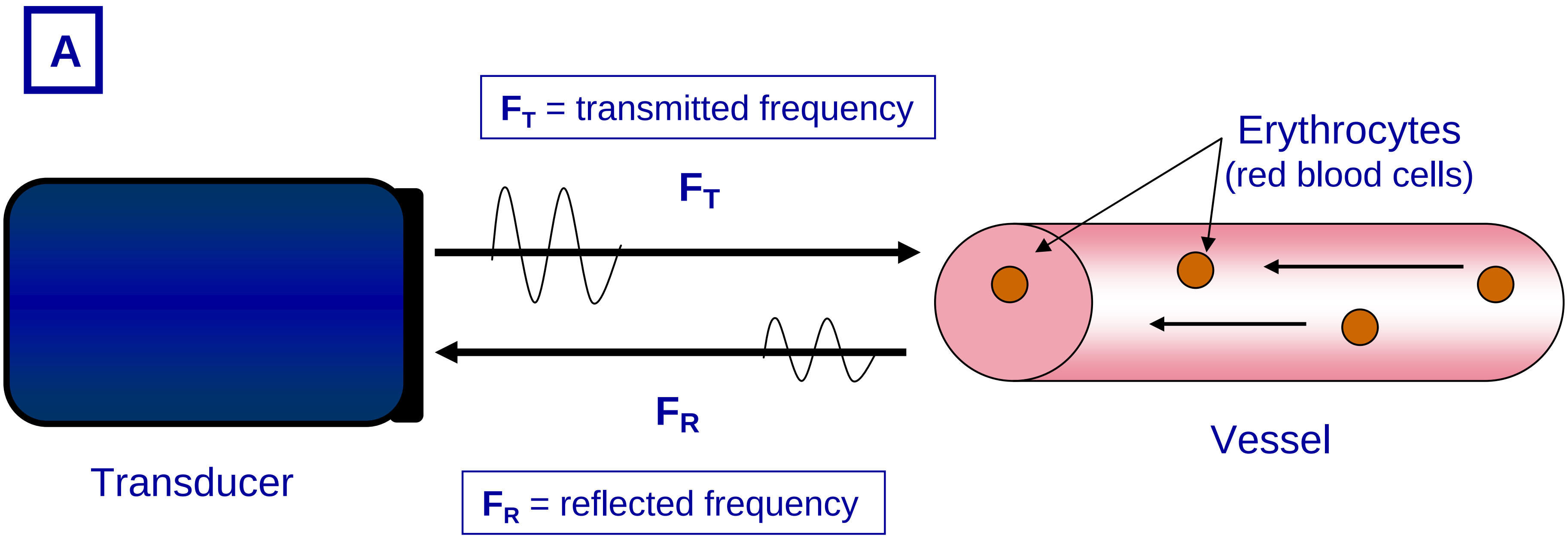
Doppler Effect



If the target is stationary then the reflected ultrasound has the same frequency as the transmitted sound, so there is no difference between the transmitted (F_T) and the reflected (F_R) frequencies. When the target is moving there is a change in the frequency of the sound scattered by the target interface. The change in frequency is directly proportional to the velocity of the moving target and can be calculated using the Doppler equation (see over page).

The Doppler Equation

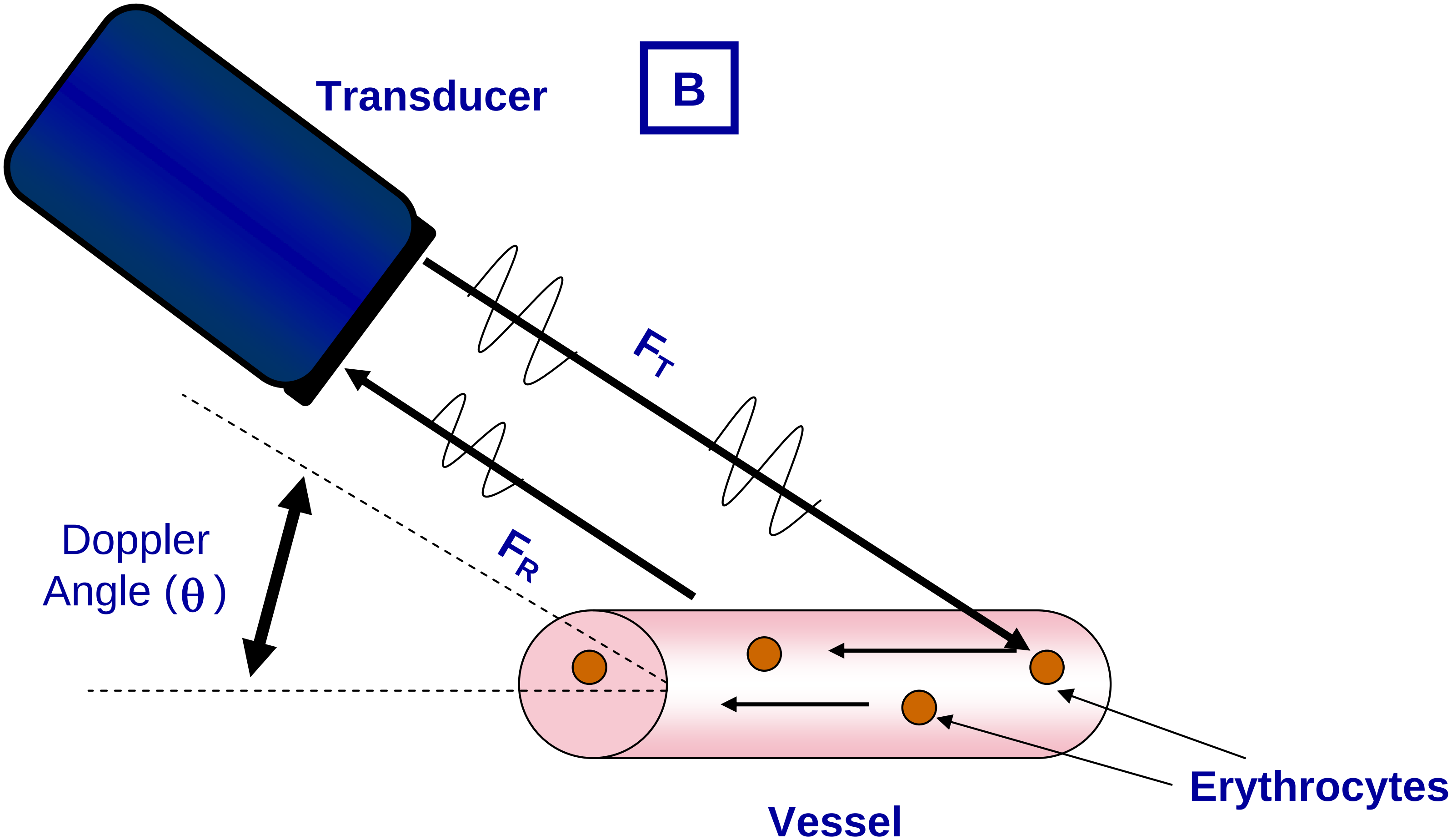
The Doppler Equation describes the relationship of the Doppler frequency shift to target velocity. The frequency difference is equal to the reflected frequency (F_R) minus the originating frequency (F_T). If the resulting frequency is higher, then there is a positive Doppler shift and the object is moving toward the transducer, but if the resulting frequency is lower, there is a negative Doppler shift and it is moving away from the transducer. In its simplest form it would be calculated as if the ultrasound was parallel to the target's direction, as shown in diagram **A** below.



However, this would be a rare occurrence in clinical practice, because the transducer is rarely pointed head on to a blood vessel. In real life, the ultrasound waves would approach the target at an angle, called the Doppler angle (θ). On the following page, diagram **B** shows the Doppler equation used in general clinical situations, which includes the Doppler angle.

Continued

The Doppler Angle



The ultrasound beam usually approaches the moving target at an angle called the ***Doppler angle* (θ)**. This reduces the frequency shift in proportion to the cosine of this angle. If this angle is known then the flow velocity can be calculated. The equation used is:

$$\Delta F = (F_R - F_T) = \frac{2F_T V \cos\theta}{C}$$

(See over page for description)

Continued

The Doppler Equation

The Doppler Equation

$$\Delta F = (F_R - F_T) = \frac{2F_T V \cos\theta}{C}$$

Where:

ΔF ≡ Doppler shift frequency (the difference between the transmitted and received frequencies)

F_T ≡ transmitted frequency

F_R ≡ reflected frequency

V ≡ velocity of the blood flow towards the transducer

C ≡ velocity of sound in tissue

θ ≡ the angle between the sound beam and the direction of moving blood

The Doppler Angle

- The Doppler angle (θ) is also known as the angle of insonation. It is estimated by the sonographer by a process known as angle correction, which involves aligning an indicator on the duplex image along the longitudinal axis of the vessel.

- There are a few considerations that affect the performance of a Doppler examination that are inherent in the Doppler equation, which are:

  - The cosine of 90° is zero, so if the ultrasound beam is perpendicular to the direction of blood flow, there will be no Doppler shift and it will appear as if there is no flow in the vessel.

  - Appropriate estimation of the angle of insonation, or angle correction, is essential for the accurate determination of Doppler shift and blood flow velocity. The angle of insonation should also be less than 60° at all times, since the cosine function has a steeper curve above this angle, and errors in angle correction will be magnified.

Doppler Signal Processing and Display

As ultrasound developed different modes to display information from tissue interfaces (A-mode, B-Mode etc.), so did different Doppler ultrasound techniques develop, each with its own strengths and weaknesses. All Doppler techniques display flow information, but some are optimized to display certain characteristics of blood flow.

For example, conventional Doppler imaging produces a wave form that can be used to calculate the actual flow rate in a vessel, whereas colour flow Doppler displays the same information by superimposing the image of moving blood in colour on the usual real time image.

The colour flow immediately draws the operator's attention to areas of high flow or disturbed flow, which can then be examined more thoroughly and quantitatively with conventional Doppler imaging.

In the following pages the different techniques will be described in more detail.

Doppler frequency shifts in most clinical situations are audible to the human ear and flow characteristics can be identified by sound alone to a trained ear, but they are usually displayed on a screen as a frequency spectrum of the returning signal over time.

These frequencies are analyzed using spectral analysis, which separates the signal into individual components and assigns a relative importance. Fast Fourier transformation (which does not need to be understood for this course) is the most popular method of spectral analysis.

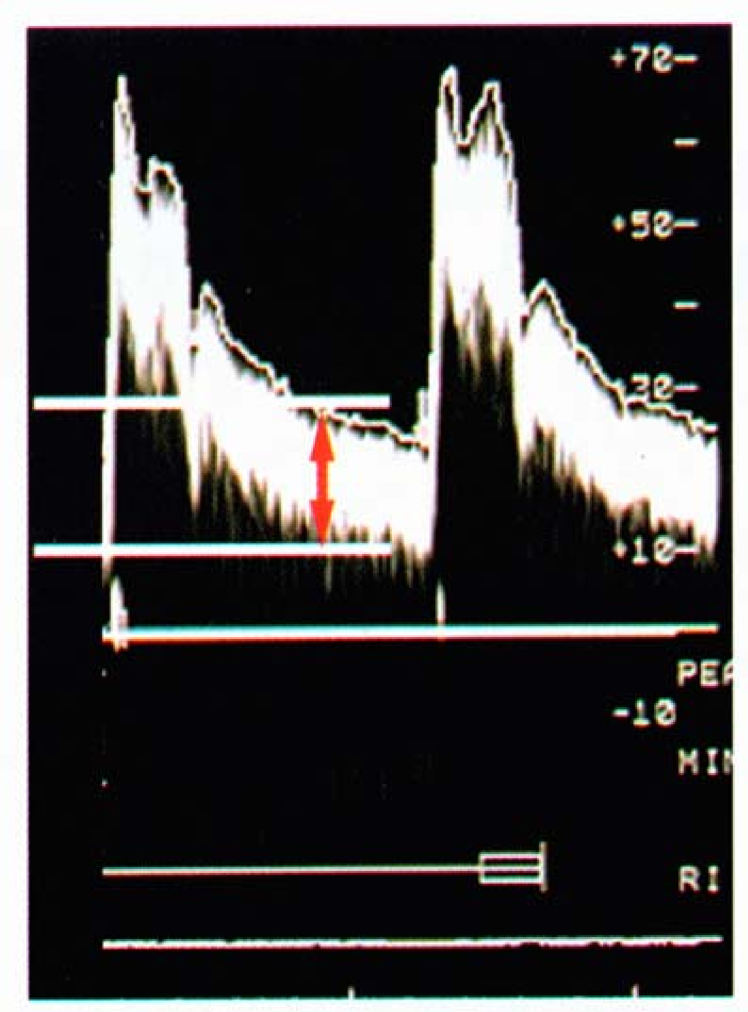
Continued

Doppler Frequency Spectrum

The figure on the right shows changes in the flow velocity and direction in the cardiac cycle by deflections in the waveform above and below the baseline. The height of the waveform indicates the velocity while time is measured along the horizontal axis. So with each contraction of the heart the blood flow increases speed initially and then slows until the next pulse.

Spectral broadening results when there are a mixture of different velocities in the sample at any one time. This is shown by the red arrow, which shows a shaded area below the peak velocity value.

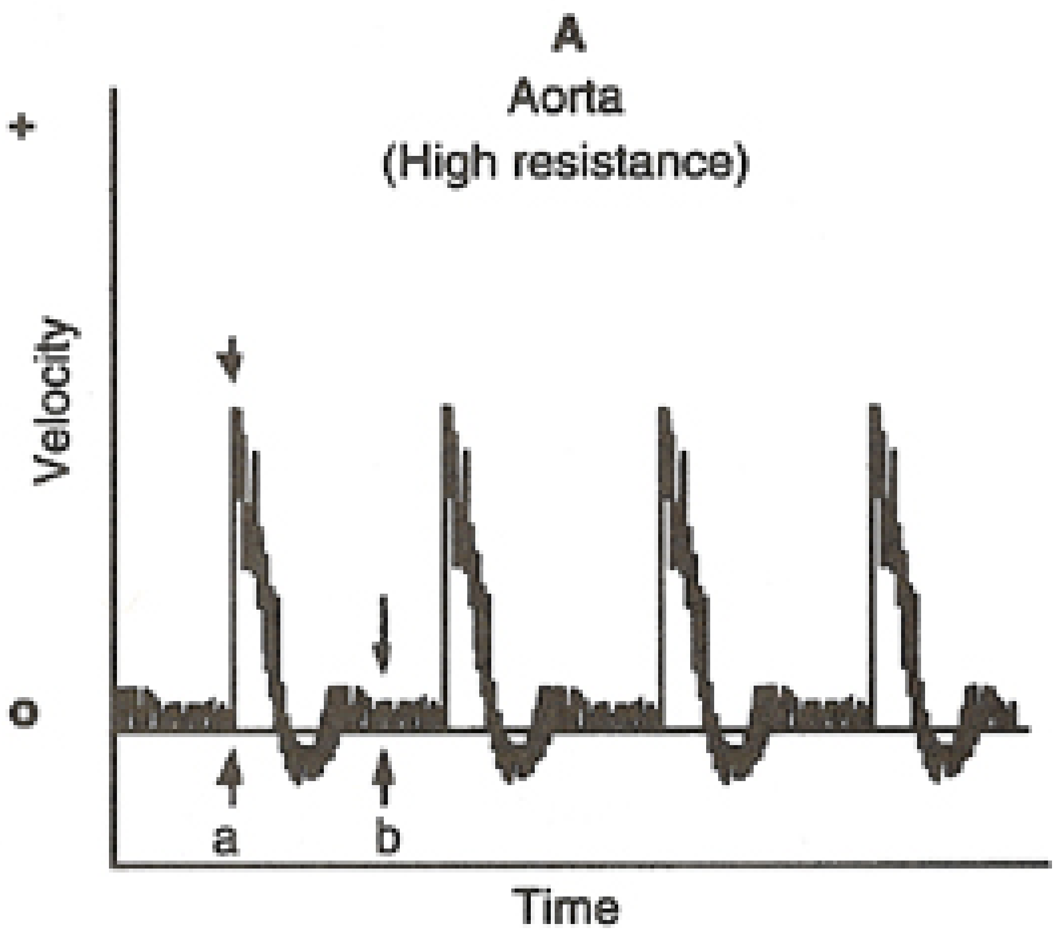
There are two main types of Doppler ultrasound transducers: Continuous Wave (CW Doppler) and Pulsed Wave Doppler.



Doppler Frequency Spectrum Display

Doppler Waveforms – High Resistance Vessel

Doppler waveforms are tracings of the relationship of the velocity of the blood flowing in a vessel over time. The velocity is determined from the Doppler shift frequency. The tracing below is of a high-resistance arterial vessel, which shows a rapid fall in velocity following systole (in the diagram, **a** is systole and **b** is diastole).



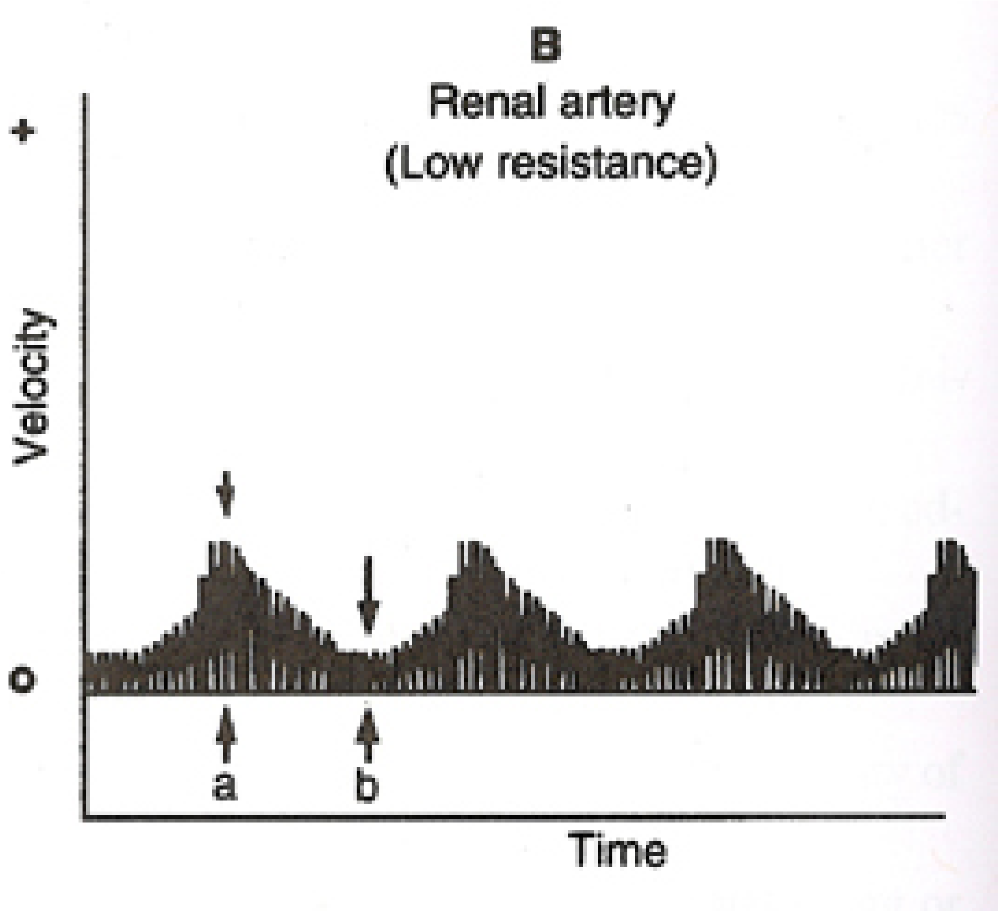
- “a” (systole) is the maximum amplitude representing the peak velocity
- “b” (diastole) is the slowest forward flow
- The resistive index is (a - b)/a
- The higher the resistance, the higher the resistive index
- Negative velocity represents flow away from the transducer, as can be seen where the waveform falls below the axis between systole and diastole (continued over page)

Image and information on this page are from W. Huda & R. Slone. Review of Radiologic Physics, 2nd edition. Lippincott Williams & Wilkins. 2003. Used with permission.

Doppler Waveforms – Low Resistance - Artery

The characteristic normal arterial waveform has a high velocity forward flow component during systole (ventricular contraction), followed by a brief reversal of flow in early diastole, due to peripheral resistance (see previous page), ending with a low velocity forward flow phase in late diastole, caused by the recoil of the vessel wall.

A low-resistance artery, such as the renal artery, shows some flow during diastole.



"a" (systole) is the maximum amplitude representing the peak velocity

"b" (diastole) is the slowest forward flow

Image and information on this page are from W. Huda & R. Slone. Review of Radiologic Physics, 2nd edition. Lippincott Williams & Wilkins. 2003. Used with permission.

Doppler Waveforms – Low Resistance - Vein

A low-resistance vein, such as the renal vein, shows that typically, veins have low velocity and low resistance.

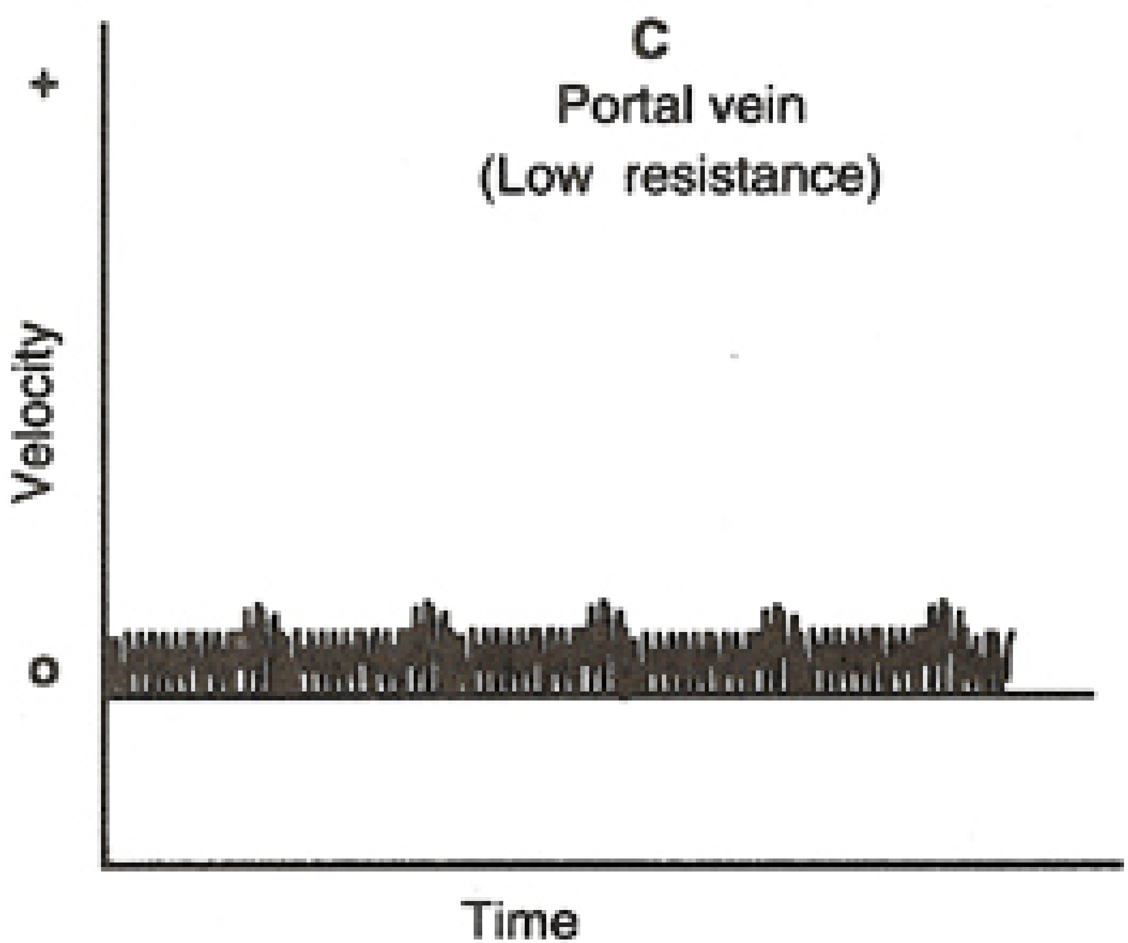
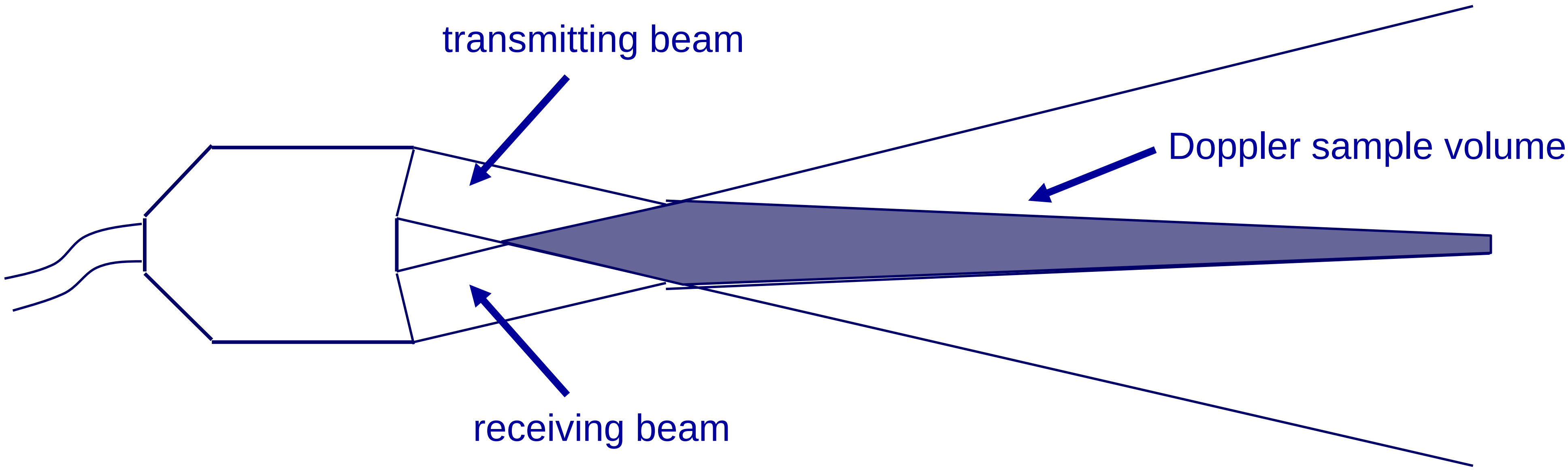


Image and information on this page are from W. Huda & R. Slone. Review of Radiologic Physics, 2nd edition. Lippincott Williams & Wilkins. 2003. Used with permission.

Continuous Wave Doppler (CW Doppler)

The simplest Doppler devices use continuous wave (CW Doppler), rather than the pulsed wave used in more complex devices. CW Doppler uses two transducers (or a dual element transducer) that transmit and receive ultrasound continuously. The transmit and receive beams overlap in a Doppler sample volume some distance from the transducer face, as shown in the diagram below.



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Continuous Wave Doppler (CW Doppler)

The region over which Doppler information can be acquired (Doppler sample volume) is the region of transmitting and receiving beam overlap (shaded region). Because there is continuous transducer transmission and reception, echoes from all depths within the area arrive at the transducer simultaneously.

So although CW Doppler can determine the direction of flow, it cannot discriminate the different depths where the motion originates. The usefulness of CW Doppler devices is limited, but they are used clinically to confirm blood flow in superficial vessels, as they are good at detecting low velocities. As they are easily portable, this can be done at the bedside or in the operating room. Most other clinical applications require pulsed wave Doppler.

If you are interested in a mathematical description of CW Doppler, try:
Continuous Wave Doppler Ultrasound

Pulsed Wave Doppler (PW Doppler)

Pulsed wave Doppler (PW Doppler) uses a single-element transducer that emits brief pulses of ultrasound energy. The time interval between transmitting and then receiving the echoing sound can be used to calculate the depth from where the echo arises.

The Doppler sample volume can be chosen as to shape, depth, and position in sampling the flow data. For example, the depth is chosen by processing only the signals that return to the transducer in a stipulated time.

For this technique, the ultrasound system transmits a short pulse. The receiver is opened to detect the returning echoes only after a controlled delay, and only for a specific duration. This time-based gating of the receiving channel allows the definition of a fixed measuring distance which is often referred to as the Sample volume or Doppler gate.

Then the next ultrasound wave is transmitted. The number of pulses transmitted by the system within a second is referred to as the pulse repetition frequency (PRF). The upper PRF limit is given by the time interval required for the echoes to arrive from a sample volume located at a certain depth. The greater the sample-volume depth, the longer the time before the echoes are returned, and the longer the delay between pulse transmission. The greater the sample-volume depth, the lower will be the maximum PRF setting.

Errors in the accuracy of the information arise if the velocities exceed a certain speed. The highest velocity accurately measured is called the Nyquist limit. Beyond this limit, the errors that occur are referred to as *aliasing*.

The Nyquist Limit and Aliasing

PW Doppler gives an accurate measure of the blood flow at a specific area and allows the detection of both velocity and direction. The reception of the returning signals is timed, and shows flows at specific depths.

Errors in the accuracy of the information arise if the velocities exceed a certain speed. The highest velocity accurately measured is called the Nyquist limit.

The Nyquist limit states that the **sampling frequency** must be *greater than twice* the highest frequency of the input signal in order to be able to reconstruct the original perfectly from the sampled version. Once the sample is below that limit, not only is the signal inaccurate, but the resulting data contains artifacts. This type of artifact is called "aliasing".

The Nyquist limit (named after Harry Nyquist, a Swedish/American scientist) is defined as being half the Pulse Repetition Frequency (PRF - the number of pulses per second.) If the velocity of blood flow exceeds the Nyquist limit, the direction and velocity are inaccurately displayed and, in fact, appear to change direction. Colour flow Doppler actually capitalizes on this effect allowing the detection of flow disturbances from laminar to turbulent flow. Laminar and turbulent flows are explained in more detail in Module 7 – Vascular Hemodynamics.

There is a java applet that demonstrates the Nyquist limit and aliasing at:

The Nyquist Limit and Aliasing

Just click on one of the Java selections in the left hand sidebar to display the applet. The instructions are given in the main frame.

Duplex Scanning

PW Doppler is usually combined with a 2D, real-time, B-mode scanner, to form what is known as a Duplex Scanner.

The term duplex scanning was first coined by F.E. Barber et al. in 1974, when they described how they had combined B-mode ultrasound with pulsed wave Doppler. Using a multi-gated system, the Doppler signals produced a two-dimensional image. The bright areas on the monitor showed blood flow, and the Doppler image was superimposed on the B-mode image producing a "duplex image".

The B-mode image allows the position of the Doppler sample volume to be precisely controlled and monitored. The imaging and the Doppler cannot be done simultaneously, but electronic scanning can switch quickly back and forth between the two.

Arteriography was considered the gold standard for detecting stenoses in the vasculature, such as in the renal artery, but in recent years, duplex ultrasound scanning of such arteries has been found to be an ideal screening test because it is noninvasive and can predict the presence or absence of arterial stenosis with a high degree of accuracy.

Although arteriography allows direct visualization of arteries, it is invasive, expensive, and does not adequately assess the functional significance of arterial lesions.

Colour Flow Doppler Imaging

- This is the most common Doppler application to be used clinically. In colour flow Doppler imaging systems, the velocity of the flow is displayed in the image as a colour flow map by colour encoding the Doppler frequency shift.

- This is achieved by calculating the average frequency shift from each pixel in an entire image. The frequency shift is color-encoded depending on the velocity and direction of flow relative to the transducer and then is superimposed on the B-Mode anatomic gray-scale image.

- Variations in blood flow are assigned different colours. The colour reflects the blood flow velocity and the insonation angle. For example, blood flowing towards the transducer can be given a red hue and can be displayed above the baseline of the duplex spectral tracing. Fast flow can be assigned a lighter hue, and slow flow with a deeper.

- Steeper angles relative to the transducer have deeper hues, while shallow Doppler angles have lighter hues. Insonation perpendicular to the vessel (90°) results in color signal void as there is no Doppler shift (cos 90° = 0).

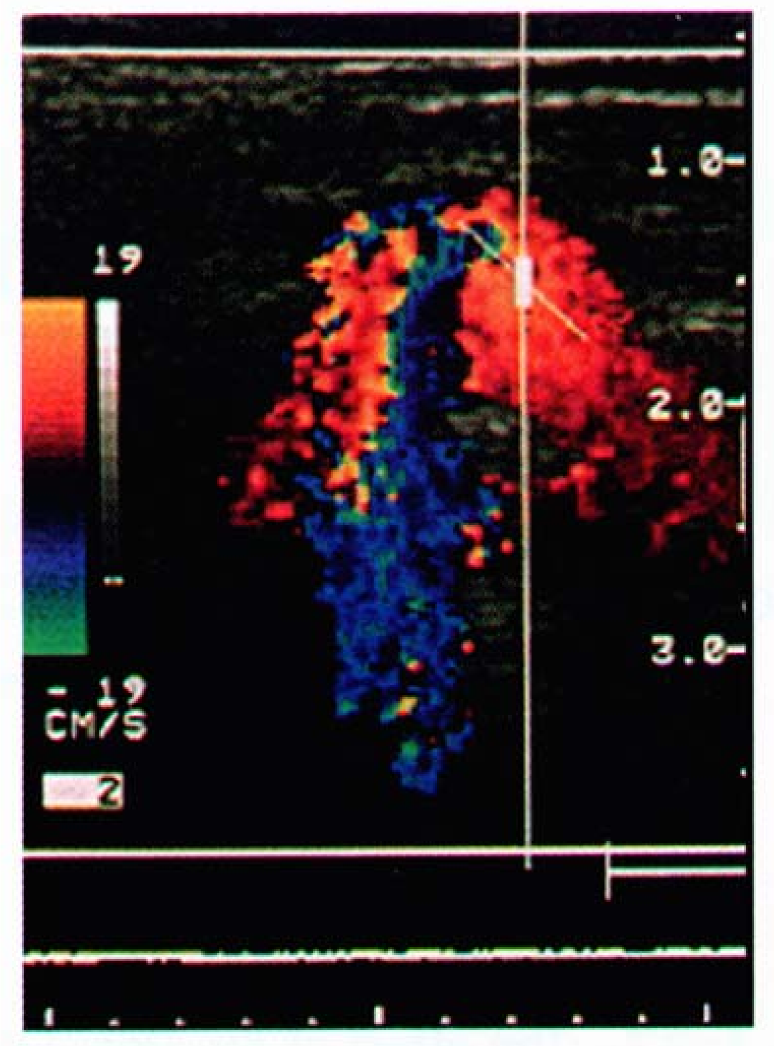
- Colour Flow Doppler shows the position and orientation of the vessels in question, and the flow information can show areas of turbulent flow, which could point towards stenosis or abnormalities in the vessel walls. The contrast of flow within the vessels allow quite small vessels to be visualized that would be impossible using other imaging methods.

- If you would like more information on Colour Flow Doppler there is an excellent article at the following link:

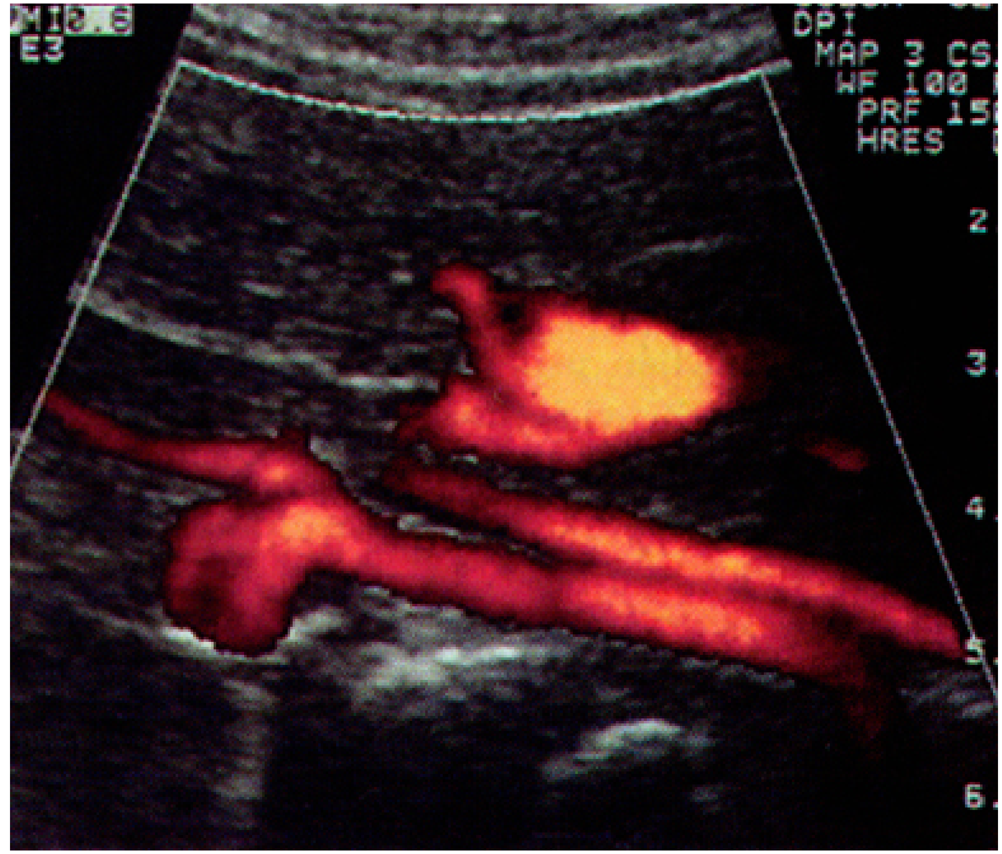
  Doppler Color Flow Imaging

continued

Colour Flow Doppler Imaging



Colour Flow Doppler Imaging



Power mode Doppler (see next page)

Images from C. M. Rumack, S.R. Wilson & J.W. Charbonneau (Eds). Diagnostic Ultrasound, Vol 1, 2nd edition. Mosby 1998. Chapter 1, The Physics of Ultrasound, Christopher R.B. Merritt, MD

Power Doppler

- Power Doppler uses the returning Doppler signal strength (amplitude) only, to estimate the power of the Doppler signal. This is displayed as a colour map to show the distribution of the amplitude.

- Power Doppler is up to five times more sensitive at detecting blood flow than color Doppler. Power Doppler can obtain some images that are difficult or impossible to obtain using standard color Doppler.

- Power Doppler is most commonly used to evaluate blood flow through vessels within solid organs. Blood flow in individual blood vessels is usually evaluated by combining colour Doppler with duplex Doppler. The combination of colour Doppler and duplex Doppler provides better information on the direction and speed of blood flow than when either technique is used alone.

- Power Doppler does not give the flow direction or the velocity, but it is more sensitive to detecting small amounts of flow, as noise in the image is reduced.

- Unlike colour flow Doppler, where noise can appear as a colour in the image, noise in Power Doppler mode blends into the background and does not interfere with the image.

- Aliasing artifacts do not occur in Power Doppler.

- 3-dimensional Power Doppler is also possible.

Instrumentation Controls

Gain Control

When sounds (echoes) are coming from a distance their amplitude (sound level) is lower. Gain control uses several manually operated controls to manipulate the echo intensities from various depths, and displays them on the monitor.

- ***Coarse gain control*** regulates echo amplitudes from all depths equally.
- ***Time gain control*** (TGC) provides an increasing amplification of the echoes with increasing depth to create a uniform grey-scale appearance throughout the image.
- ***Eject control*** selectively rejects echo amplitudes below a certain threshold to enhance the clarity of the stronger echoes.
- ***Near gain control*** diminishes strong superficial echoes. The delay control regulates the depth at which the TGC starts; the far gain control is used to enhance all distant echoes; and the enhancement control may be used to selectively enhance echoes from a specific depth range.

Artifacts in Doppler Imaging

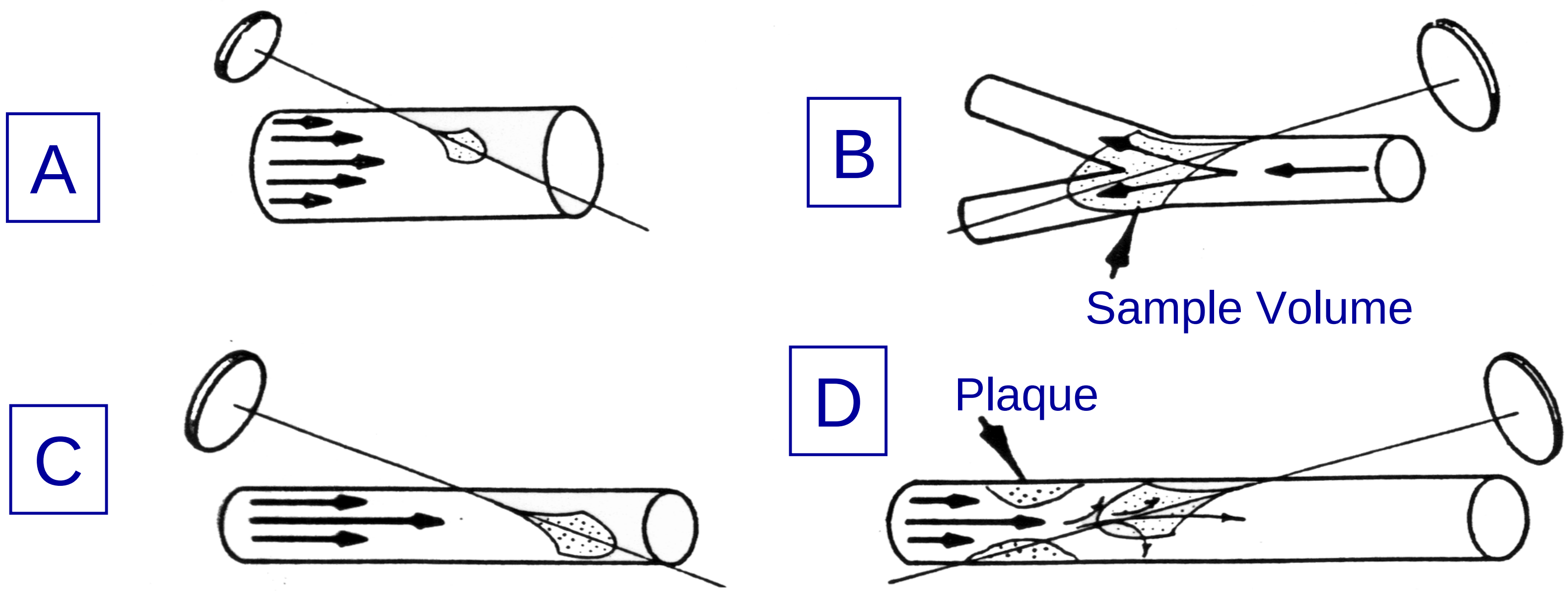
An artifact is a misrepresentation of the anatomy or physiology even though the instrumentation is working normally. The recognition and interpretation of artifacts is a very complex process, and only a few Doppler artifacts are described here to give an idea of the scope of the problem. Although Doppler imaging suffers from the same types of artifacts as B-mode imaging, there are a number of extra problems associated with Doppler of which it is important to be aware. These have to do with the detection and display of the frequency information of moving targets.

The most common sources of artifacts are:

- **Aliasing** (described earlier in the module)
- **Spectral Broadening** – this is the result of a mixture of different velocities in a sample volume (some examples are shown on the following page).
- **Doppler Frequency**
- **Doppler Angle**
- **Sample Volume Size**
- **Wall Filters**

Sources of Doppler Spectral Broadening

- Blood flow in vessels does not flow at uniform velocities. Flow close to the inside vessel wall is slower than flow in the middle of the vessel. Spectral broadening is shown on a previous page, where a large number of different frequencies exist at a particular moment in time. Depending on the sample, this can cause an artifact in the spectral display.



A: Spectral broadening from sampling the gradient at the edge of a flow velocity pattern.

B: Broadening from complex flow divisions within the sample volume.

C: Broadening from high-velocity flows intercepting a small sample volume, creating a modulated Doppler signal.

D: Broadening from disturbed or turbulent flow caused by disease.

Artifacts - Doppler Frequency and Angle

Doppler Frequency

The Doppler signal is reflected off the moving erythrocytes within the vasculature, but they are weak reflectors and tend to scatter the ultrasound beam. For this reason, Doppler systems typically run at lower frequencies than B-mode ultrasound. Although higher transducer frequencies increase Doppler sensitivity, they also increase attenuation, resulting in lower penetration into the tissues.

Operators must estimate the optimal Doppler frequency, depending on the distance of the vessels to the skin surface to balance the sensitivity and the level of penetration. If this is done inappropriately then artifacts will occur.

Doppler Angle

Doppler instrumentation estimates flow velocity accurately only as long as the Doppler angle is correctly measured. This is even more the case if the Doppler angle exceeds 60º.

Appropriate estimation of the angle of insonation is essential for the accurate determination of Doppler shift and blood flow velocity. To minimize this type of artifact the angle of insonation should also be less than 60° at all times, since the cosine function has a steeper curve above this angle, and errors in angle correction will be magnified.

Continued

Artifacts – Sample Volume Size & Wall Filters

- **Sample Volume Size**

  Using Doppler instruments, motion is detected not only from blood flow in vessels, but also from adjacent structures, such as the vessel walls. The operator controls the length of the Doppler sample volume on pulsed wave systems to exclude the unwanted signals from as near the vessel walls as possible.

- **Wall Filters**

  The Wall Filter is a necessary device that eliminates low frequency signals from the Doppler spectrum trace, which are usually produced by low velocity structures such as vessel walls. Wall filters are designed to be High-Pass Filters that remove low frequencies, which fall below a certain frequency cutoff point. The Wall Filter setting is variable and can be adjusted by the user.

  However, artifacts can arise because an inappropriate setting on the wall filter eliminates genuine signals from low velocity blood flow. This particularly affects low velocity venous or diastolic flow and leads to errors in the calculation of the systolic-diastolic ratio or the resistive index.

  To prevent these artifacts, the wall filter should be set to the lowest practical level.