UNDERSTANDING AND TEACHING ULTRASOUND PHYSICS

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ABSTRACT

For sonography students and residents, ultrasound physics can be intimating and seemingly remote from their clinical responsibilities. This is primarily because of the difficulty in translating textbook physics concepts into their clinical practice. Although this may be a challenge in any discipline, in ultrasound physics it is compounded by the fact that what is seen, or measured, on the scanner is not always consistent with what is expected based on basic principles. The confusion between expectation and observation is usually artifact or results from a particularly clever implementation of technology. Demystifying the physics not only helps the student develop an intuition on how the scanner creates an image; it also gives them a greater appreciation of imaging as a science.

This course is designed to assist physicists in teaching ultrasound physics concepts to non-physics personnel (residents, sonographers, graduate students, etc.). Several demonstrations and exercises are reviewed which emphasize the clinical implications of various scan parameter settings, including: power, gain, dynamic range, time-gain compensation, field-of-view, displayed depth, postprocessing, zoom (magnification). The effect of these parameters on resolution (axial and lateral), frame rate, depth of penetration, blood flow velocity, and overall image appearance are discussed where appropriate. Doppler ultrasound physics measurements are introduced and briefly discussed. Introductory physics concepts are provided along with sample data and images. Additionally, an explanation of possible discrepancies between measured and "theoretical" results are presented.

Although the target audience of this session is physicists who have teaching responsibilities, the material provides an excellent review, with examples, of the effect of various scan parameters on image appearance. Additionally, the experiments and demonstrations reviewed in this course illustrate many important relationships between ultrasound imager scan parameters and image or measurement quality. Anyone with an interest in clinical ultrasound imaging would benefit from this session.

INTRODUCTION

There are ten clinical ultrasound physics demonstrations discussed in this course, participants are introduced to procedures used to demonstrate and explore the physics associated with these demonstrations. Additional information and details regarding the ten demonstrations reviewed and an additional ten ultrasound physics demonstrations (not reviewed in this course) are provided in the following reference: *Clinical Ultrasound Physics: A Workbook for Physicists, Residents, and Students*, Published for the AAPM by Medical Physics Publishing, July 2001. The equipment needed to perform all the demonstrations is available in any clinical ultrasound environment. However, some of the concepts are best illustrated with quantitative measurements. Therefore, I suggest using an ultrasound quality assurance (QA) phantom that contains resolution targets for these demonstrations. Phantoms with a speed of sound of 1540 m/s are recommended when acquiring quantitative data. Any other phantoms may be used for demonstrative purposes but may not give the same results as the recommended phantoms. A brief description of the demonstrations discussed in the course follows.

FRAME RATE AND MAXIMUM IMAGING DEPTH

The scope and purpose of this test is to investigate real-time image frame rate and its relationship with maximum imaging depth. This experiment can be done with the transducer in its holder. However, students may be more interested if a phantom or some other object is scanned.

Frame Rate and Maximum Imaging Depth Procedures

1. Step through the maximum imaging depth choices available on a clinical ultrasound unit using a low frequency transducer. Record the frame rate at each step as the maximum imaging depth is increased. (Note that some scanners express the frame rate as Hz, which implies frames/s.)
2. Plot the data on a graph of frame rate versus maximum imaging depth.

FRAME RATE AND NUMBER OF FOCAL ZONES

The scope and purpose of this test is to investigate real-time image frame rate and its relationship with the number of focal, or transmit zones. This experiment can be done with the transducer in its holder. However, students may be more interested if a phantom or some other object is scanned.

Frame Rate and Number of Focal Zones Procedures

1. Step through the number of focal zones available (keep the maximum imaging depth constant). Record the frame rate at each step as the number of focal zones increases.
2. Plot the data on a graph of frame rate versus number of focal zones.

AXIAL RESOLUTION

The scope and purpose of this test is to investigate the relationship between imaging depth and axial resolution. The relationship between frequency and spatial resolution is also demonstrated.

Axial Resolution Procedures

Option 1

1. Using a tissue-mimicking phantom, determine the axial resolution for several different depths within the phantom. (Note: Do not change the focal zone between measurements.) If a phantom with fiber resolution targets is used, the axial resolution measurement may only be possible at two or three depths. Axial resolution can be determined using a single fiber by measuring the axial extent of the fiber image using the scanner's electronic calipers or computer-assisted methods.
2. Using a multiHertz transducer or several similar transducers of different frequencies, measure the axial resolution at a single depth. Repeat the measurement using several different transmit frequencies.

Option 2

1. On a clinical image, note the change in the detail (in the axial direction) with depth. The degradation of axial resolution as a function of depth is most readily apparent when comparing a proximal portion of the image to the most distal portion.

2. On a clinical image, note the change in the detail or edge sharpness (in the axial direction) as the frequency is changed. Your attention should be focused on a small portion of the image that contains small objects or well-defined organ boundaries.

LATERAL RESOLUTION

The scope and purpose of this test is to investigate the relationship between imaging depth and lateral resolution. The relationship between frequency and spatial resolution is also demonstrated.

Lateral Resolution Procedures

Option 1

1. Using a tissue-mimicking phantom, determine the lateral resolution for several different depths within the phantom. Lateral resolution can be determined using a single fiber by measuring the width of the fiber image using the scanner's electronic calipers or computer-assisted methods.
2. Plot the lateral resolution data versus depth.
3. Using a multiHertz transducer or several similar transducers of different frequencies, measure the lateral resolution at a single depth. Repeat the measurement using several different transmit frequencies.
4. Plot the lateral resolution versus frequency at a given depth.
5. Note the lateral resolution at a single depth as the focal zone is placed above, below, and at the depth of interest.

Option 2

1. On a clinical image, note the change in the detail or edge sharpness (in the lateral direction) with depth. The degradation of lateral resolution as a function of depth is most readily apparent when comparing the region at the focal depth to a region beyond the focal depth.
2. On a clinical image, note the change in the detail or edge sharpness (in the lateral direction) as the frequency is changed. Your attention should be focused on a small portion of the image that contains small objects or well-defined organ boundaries.
3. On a clinical image, note the change in the detail or edge sharpness (in the lateral direction) at a single depth as the focal zone is placed above, below, and at the depth of interest.

FREQUENCY AND DEPTH OF PENETRATION

The scope and purpose of this test is to investigate the relationship between depth of penetration with respect to transducer frequency.

Frequency and Depth of Penetration Procedures

Option 1

1. Using a tissue-mimicking phantom determine the maximum depth of penetration for a low frequency transducer. The depth of penetration is defined as the depth at which the noise, or speckle, in the image is comparable to the electronic noise (electronic noise is different on each frame and therefore appears to move on the display). Thus, the depth where the background no longer moves is the depth of maximum penetration. Note that many ultrasound systems limit the maximum displayed depth according to the expected depth of penetration. If this is the case, record the depth of penetration as being equal to the maximum displayed depth.
2. Record the result. Repeat the measurement using higher frequencies.
3. Plot the data on a graph of frequency versus depth of penetration.

Option 2

1. Obtain several clinical images that were acquired using a range of frequencies. Ideally, the clinical images should all be from the same patient, but this is typically not practical.
2. Note the differences in the depth of penetration for each transmitted frequency. Note that many ultrasound systems limit the maximum depth according to the expected depth of penetration. If this is the case, record the depth of penetration as being equal to the maximum imaging depth.

OPERATOR-CONTROLLED VARIABLES: TRANSMIT POWER AND GAIN

The scope and purpose of this test is to investigate the relationship between image quality and changes in several operator-adjustable variables, including transmit power and gain. Acoustic output, or power, is the total energy transmitted summed over the entire cross-sectional area of the ultrasound beam per unit time. Increasing the transmit power will increase the amplitude of the voltage pulses across the crystals. The stronger voltage pulses will produce higher amplitude transmitted waves that, in turn, will yield higher amplitude echoes. Advantages of using a high power setting are improved signal-to-noise ratios and better penetration. A disadvantage of using a high power setting is the increased potential for biological effects. The gain amplifies the signals from the returning echoes for display. Gain is analogous to the volume control on a radio. Increasing the volume on a radio increases the loudness of the broadcast. However, if a station is not being received adequately, increasing the volume simply makes the static noise louder. In other words, the gain or volume control cannot discriminate between signal and noise. Every electronic signal that passes through the gain circuitry is amplified, regardless of whether it is image data, speckle, or electronic noise.

Operator-Controlled Variables Procedures

Note: The following demonstrations are best performed using a clinical image. If obtaining a set of clinical images with a range of a particular scan parameters is not possible, a phantom can be used. A phantom with objects having a variety of object-contrasts is recommended, but not essential.

On a real-time image, note the change in the appearance of the image as the various operator-controlled parameters are varied. Try to subjectively describe the change in the appearance of the image, including changes in spatial and temporal resolution, contrast, noise (electronic), speckle, and depth of penetration. All other scan parameters should remain constant.

DOPPLER DEMONSTRATIONS

Three parameters are varied to investigate their influence on a Doppler ultrasound measurement, they are: gate angle, gate size, and gate position.

Gate Angle

Any discussion on Doppler ultrasound typically begins with the Doppler Equation, which is written as

$$Frequency\ Shift = \frac{2\, f_{sent}\ v_{blood}}{v_{sound}} \cos\theta$$

where the terms are:

f_{sent} = The frequency of the transmitted ultrasound
v_{blood} = The velocity of the blood
v_{sound} = The velocity of sound in the medium
θ = The angle between the scan line and the direction of moving blood.

However, most people do not appreciate that the scanner does not use this form of the equation. The scanner measures the frequency shift, it “knows” the velocity of sound in the medium and the frequency of the transmitted ultrasound, and it solves for the velocity of blood, such as,

$$v_{blood} = \frac{(Frequency\ Shift)\ v_{sound}}{2\ f_{sent} \cos\ \theta}$$

Noting this equation, the only variable that the scanner does not know or measure is the angle term. The operator provides the angle term, typically by a graphical indicator displayed over a duplex image. The angle supplied by the operator has a direct influence on the measured blood velocity and is a common source of error in this measurement. The magnitude of any error introduced is compounded by the cosine function. If the actual Doppler angle is small, a slight deviation in the supplied angle will result in only a slight error. However, if the actual Doppler angle is large, even a small deviation can result in a large error. Therefore, angles greater than 60 degrees are discouraged.

Gate Size

The size of the Doppler gate determines the size of the sample volume (in the axial direction). The hemodynamics of blood in vessels can be quite complex and factors such as vessel tortuousity, vessel size, pressure differences, pulsatility, disease state, and other variables all must be considered when determining flow states. The Doppler gate size determines how much of the flow throughout a vessel cross-section will contribute to the Doppler measurement. For example, if the flow profile within a vessel is parabolic, the velocity of the moving red blood cells will be greatest in the center of the vessel and lowest near the vessel wall. If a small gate size is positioned in the center of the vessel, only the high-velocity blood cells will contribute to the Doppler signal. If the gate is made sufficiently large to encompass the entire vessel cross section, the range of measured velocities will be much greater, including the high velocities from the center, the very low velocities near the wall, and all velocities in-between.

Gate Position

Similar to the Doppler gate size, the gate position influences which velocity components of the flow will be measured. Placing the gate in the center of the vessel will include the highest-velocity components whereas placing the gate at the vessel wall will consider the lowest-velocity components (assuming parabolic flow for both cases).

Doppler Demonstration Procedures

Note: The following demonstrations are best performed using a clinical image. If obtaining a set of clinical images with a range of particular scan parameters is not possible, a Doppler phantom can be used. If your institution does not own a Doppler phantom, you may wish to rent one or construct your own. A simple gravity-driven flow system is adequate to explore the relationships between Doppler measurements and scan parameters.

Gate (Sample Volume) Angle

1. Perform a Doppler measurement on a vessel and freeze the image. Change the gate angle in steps of approximately 5 degrees, noting the measured blood velocity at each angle. Use a minimum of three different gate angles.

Gate (Sample Volume) Size

1. Perform a Doppler measurement on a vessel with the gate size set small enough to measure flow only within the center of the vessel. Note the measured blood velocity and spectral trace.
2. Increase the gate size such that the sample volume contains approximately 50% of the vessel and repeat the measurement (attempt to keep the Doppler angle constant).
3. Repeat the measurement using a gate size that encompasses the entire vessel.

Gate (Sample Volume) Position

1. Perform a Doppler measurement on a vessel with the gate size set small enough to measure flow only within the center of the vessel. Note the measured blood velocity and spectral trace.
2. Move the gate halfway to the vessel wall and repeat the measurement. Make sure not to change the gate size or Doppler angle. Note the measured blood velocity and spectral trace.
2. Position the gate such that it is adjacent to a vessel wall. Perform a Doppler measurement and note the measured blood velocity and spectral trace.