Ultrasound in Anesthesia: Applying Scientific Principles to Clinical Practice

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The use of ultrasound as an adjunct to invasive anesthesia procedures is becoming commonplace. The US Agency for Health Care Quality and the United Kingdom National Institute for Clinical Excellence have identified the role of ultrasound in improving patient safety. Numerous studies have demonstrated the benefits of ultrasound, yet there have also been articles inferring it may not offer additional benefits to traditional landmark techniques. The major disadvantage often cited is that success is user-dependent, and using ultrasound is a unique skill that requires training and experience to become proficient.

Modern ultrasound systems incorporate 2 sound technologies to provide users with specific information about what is being viewed. Brightness mode imaging and pulsed-wave Doppler can be combined to reduce potential complications associated with central venous access and regional anesthesia. Human tissue is also an important factor in ultrasound imaging. The different densities of soft tissues, bone, fluid, and air all interact with sound, creating distinctive images that can aid and potentially hinder accuracy. Comprehension of basic ultrasound principles and how it is affected by tissue will enable anesthetists to better understand what is being seen and reduce the potential for errors.

Keywords: Attenuation, Doppler, frequency, propagation velocity, ultrasound.

Objectives
At the completion of this course the reader should be able to:
1. State why higher frequency ultrasound is preferred for superficial invasive procedures such as central venous catheter insertion or interscalene blocks.
2. Explain how Doppler can augment brightness mode (B-mode) imaging to reduce potential complications during central venous catheter insertion.
3. Describe the factors that determine reflection, refraction, scattering, and, ultimately, attenuation.
4. Articulate the difference between specular and diffuse reflectors and how each would appear on a B-mode image.
5. Recognize how improper transducer orientation can affect the B-mode image and cause potential complications during ultrasound-assisted invasive procedures.

Introduction
The incorporation of ultrasonography as an adjunct to invasive anesthesia procedures has been intended to reduce potential complications such as pneumothorax and peripheral nerve injury. Ultrasonography provides anesthetists with numerous advantages, most notably, real-time imaging of anatomic structures beneath the skin previously not visualized. Advances in ultrasound technology have made it appear as a simple bedside modality requiring little expertise. However, the principles required in its application can be complicated and confusing if not fully understood. Ultrasound systems used today incorporate several sound applications that provide users with specific information about what is being imaged. Brightness mode (B-mode) imaging and pulsed-wave Doppler provide practitioners with valuable information to accurately evaluate most anatomic areas in the body. When used properly, ultrasound can reduce or eliminate the complications associated with central venous access such as pneumothorax, inadvertent carotid puncture, and multiple insertion attempts and complications associated with regional anesthesia such as intravascular injection and direct nerve injury.

Tissue properties are also an important component in
Figure 1. Anatomy of a Sound Wave
Sound is a mechanical, longitudinal wave, meaning that particles are displaced parallel to the direction that the wave is traveling.

**Table 1. Glossary**

- **Amplitude**: maximum increase or decrease in pressure due to the presence of sound; often referred to as the “height” of the wave
- **Anechoic**: unable to generate echoes
- **Attenuation**: decrease in amplitude or intensity of a sound wave as it travels through a medium
- **B-mode (brightness mode)**: a sound application in which returning sound echoes cause a brightening spot on the screen to create an image based on the strength and time at which the echo is received; the greater the intensity of the echo, the brighter the spot
- **Color flow**: real-time, 2-dimensional flow direction information that is superimposed on a gray-scale image using color to depict positive and negative Doppler shifts
- **Compressions**: areas of high pressure in a medium created by a vibrating source
- **Cross-sectional view**: also called short-axis view; creating an ultrasound image of tissue in which the axis of the sound beam is perpendicular to anatomical structures, such as blood vessels and nerves
- **Cycle**: the complete variation of a wave from one compression to the next
- **Density**: the mass of a substance divided by its volume
- **Doppler shift**: the reflected frequency minus the incident frequency; a change in frequency because of motion
- **Far zone (Fraunhofer zone)**: the section of the sound beam that diverges as the distance from the transducer increases
- **Focal zone**: the section of the sound beam where it is at its minimum diameter and density; image resolution best in this region
- **Frequency**: the number of cycles that occur per second
- **Hertz (Hz)**: the unit of measure for frequency, 1 cycle per second; diagnostic ultrasound uses frequencies greater than 2 MHz or 2 million cycles per second
- **Hyperchoic**: strong echoes
- **Hypochoic**: weak echoes
- **Impedance (acoustic)**: the density of a medium multiplied by its propagation velocity
- **Incident wave**: a sound wave that originates from a transducer or other vibrating source
- **Linear array transducer**: a transducer in which rectangular crystals are aligned in a row
- **Longitudinal view**: also called long-axis view; creating an ultrasound image of tissue in which the axis of the sound beam is parallel to anatomical structures, such as blood vessels and nerves
- **Longitudinal wave**: a wave that displaces particles parallel to its direction of its travel
- **Medium**: any substance in which sound will travel
- **Near zone (Fresnel zone)**: the section of the sound beam in which the diameter decreases as the distance from the transducer increases
- **Piezoelectric effect**: the conversion of electrical energy to mechanical energy and vice versa
- **Propagation velocity**: the speed at which sound travels through a medium
- **Pulse-echo**: ultrasound imaging in which reflected sound pulses are used to produce an image
- **Rarefactions**: areas of low pressure in a medium created by a vibrating source
- **Reflected wave**: an echo; the portion of a sound wave returned from a boundary between 2 media
- **Refraction**: a type of reflection that occurs when a sound wave strikes the boundary of 2 tissues at an oblique angle
- **Scattering**: diffusion or redirection of sound in multiple directions; usually occurs when the sound wave is larger than the object it comes in contact with, such as red blood cells
- **Shadowing**: reduced reflections from an object that lie behind strongly reflecting or attenuating tissues
- **Specular reflection**: a reflection that occurs between tissues with a smooth boundary, such as bone and fascia
- **Transducer**: a device that converts one form of energy into another
- **Wavelength**: the distance over which a cycle repeats itself at any instant of time
determining an ultrasound image. The different densities characteristic of muscle, fat, organs, nerves, fluid, air, and bone interact with sound differently, creating distinctive patterns that can aid an anesthetist in analyzing what is being seen. Comprehension of tissue-sound interaction allows users to distinguish anatomic structures and optimize the image, thus minimizing complications.

Principles of Sound

Sound is created when a vibrating source comes in contact with a medium causing it to vibrate, as is the case when vocal cords vibrate against air. In this example, the vocal cords are the source, and air is the medium. The mechanical energy generated from the vibrations travels in a longitudinal wave through the medium, generating cyclical areas of high and low pressure, known as compressions and rarefactions (Figure 1). Table 1 provides a list of common ultrasound terms. The area beginning at one compression to the next is called a cycle. The distance over which the cycle repeats itself at any instant of time is known as the wavelength. It is defined by the following equation:

$$\lambda = \frac{c}{f}$$

Where \(\lambda\) is the wavelength, \(f\) is the frequency, and \(c\) is the speed of sound.\(^1\) Frequency is the number of cycles that occur per second and is measured in Hertz (Hz). In ultrasound imaging, the speed of sound in human tissue is a constant value and will be discussed in greater detail later. Amplitude (\(A\)) is the maximum increase (or decrease) in pressure due to the presence of sound.\(^1\) It is often described as the “height” of the wave and has no relationship to the wavelength or frequency.

Ultrasound is considered the frequencies that exceed the limits of human hearing, or 20 kHz.\(^2\) Modern ultrasound systems typically use frequencies between 2 and 10 MHz.\(^3\) Frequency is an important factor in ultrasound imaging. Higher frequencies (\(\geq 7\) MHz) offer better image resolution at shallow depths. A higher frequency transducer would be used to create the best image of the...
brachial plexus when performing an interscalene block. Lower frequencies allow for imaging at greater depths, but with poorer resolution (Figure 2).

Ultrasound used for vascular access and regional anesthesia to create images of structures within the body uses what is known as a pulse-echo technique. The transducer emits brief impulses of energy at a fixed rate and then “listens” between the pulses for returning echoes created by the different tissue densities in the body. Sound waves are transmitted by numerous crystals aligned in succession along the face of the transducer, creating the rectangular image seen on the screen. This differs from a sector transducer, as used for transesophageal echocardiography, in which 1 crystal emits many impulses in a fanning motion to create the familiar pie-shaped image. The echoes created by the interaction between sound and motion to create the familiar pie-shaped image. The echoes created by the interaction between sound and various tissues are sent back to the transducer and converted into electrical energy, which is then analyzed to create an image. Based on the time and strength of the returning echoes, a microprocessor within the ultrasound system assigns each echo a position and color in a gray scale, ultimately forming the B-mode image.¹

Modern ultrasound is commonly referred to as real-time imaging because the devices have the ability to rapidly display B-mode images so that any motion that occurs is visualized as it happens. These systems have the ability to display between 15 and 50 images per second. To produce the effect of continuous movement, at least 16 frames per second must to be displayed.²

**The Doppler Effect**

No discussion of sound would be complete without revisiting the Doppler effect. First described by the Austrian, Christian Doppler, in 1842, it explains how the frequency of a wave is perceived to change relative to movement. The central premise of the Doppler effect is that a change in frequency of a detected wave occurs when either the source or detector is moving.¹ The perceived change in pitch of an ambulance siren by a bystander is a familiar example of the Doppler effect. It is also used every day in weather tracking and police radar detection systems. In diagnostic ultrasound, Doppler is used to detect and measure blood flow, not to create an image. When a Doppler ultrasound device is placed over a blood vessel so that the flow of blood is directed toward the transducer, the reflected wave will have a higher frequency than the incident, or originating, signal. This observation is known as a positive Doppler shift. Conversely, if the flow of blood is moving away in relation to the transducer, a lower frequency wave will be reflected and a negative Doppler shift will occur. The angle between the receiver and the transmitter has an important role in determining the amount of shift. Doppler shifts calculated by an ultrasound system use the cosine of the angle between the axis of the ultrasound beam and the direction of flow. Maximum Doppler shift occurs at 0° (cosine of 0° = 1) when flow is directly toward or away from the transducer.⁴ When flow is perpendicular to the ultrasound beam, no shift is detected (cosine of 90° = 0).⁴ Color-flow Doppler technology used in ultrasound systems enables practitioners to determine the direction of flow by applying color to the blood based on its flow in relation to the transducer. Contrary to what has been written in some texts, the red and blue shades used in color-flow Doppler do not represent arterial and venous flow, respectively (Figure 3).

**Tissue Properties**

Sound travels at different speeds through different media. This phenomenon is known as propagation velocity. In diagnostic ultrasound, human tissue is the medium in which sound travels. The standardized propagation velocity of sound through tissue is approximately 1,540 m/s,⁵ which is derived by averaging the different velocities of soft tissues in the body (Table 2). By comparison, the propagation velocity of air is quite slow, 440 m/s, and in bone, it can be as high as 5,000 m/s.⁶ The basis of diagnostic ultrasound is the pulse-echo technique in which small bursts of sound are transmitted into the tissue, and the reflected echoes are then measured. By knowing the velocity at which sound travels through tissue, the depth at which the echo occurs can be determined. This depth can be calculated as 2s = v × t, where 2s is the distance between the transducer and the reflector, v is the velocity of sound in tissue, and t is the elapsed time.⁴

The impedance (Z) of tissue describes its stiffness, or resistance against the propagation of sound. It is equal to density (p) multiplied by propagation velocity (v),⁷ where Z = p × v. The differences in impedance along boundaries result in reflection, refraction, scattering, and, ultimately, attenuation (Figure 4). On ultrasound, these properties determine the varying shades of the gray scale that form the image (Figure 5).

Table 2. Propagation Velocities of Different Media

<table>
<thead>
<tr>
<th>Medium</th>
<th>Propagation velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>331</td>
</tr>
<tr>
<td>Brain</td>
<td>1,541</td>
</tr>
<tr>
<td>Kidney</td>
<td>1,561</td>
</tr>
<tr>
<td>Liver</td>
<td>1,549</td>
</tr>
<tr>
<td>Muscle</td>
<td>1,585</td>
</tr>
<tr>
<td>Fat</td>
<td>1,450</td>
</tr>
<tr>
<td>Soft tissue (average)</td>
<td>1,540</td>
</tr>
<tr>
<td>Bone (different densities)⁴</td>
<td>3,000 - 5,000</td>
</tr>
</tbody>
</table>

Reflection of ultrasound beams forms the basis for all diagnostic imaging.¹ Reflection occurs when a sound
wave contacts tissues with different densities (acoustic impedances), with part of the beam reflected back and part continuing through the tissue. The amount of reflection of the incidence beam is proportional to the difference of the impedance between the 2 tissues. 

- **Reflection** occurs when an ultrasound beam contacts tissues with different acoustic impedances, with part of the beam reflected back to the transducer, and part continues through the tissue. The amount of reflection of the incidence beam is proportional to the difference of the impedance between the 2 tissues.

- **Refraction** occurs when sound strikes the boundary of 2 surfaces with different acoustic impedances at an oblique angle and the reflection does not return directly back to the transducer. The amount of refraction for the transmitted beam is determined by the angle at which the incident beam strikes the 2 boundaries and the difference in propagation velocity between the 2 tissues.

- **Scattering** occurs at interfaces involving structures with smaller dimensions such as red blood cells than the ultrasound beam resulting in a uniform distribution of echoes.

- **Attenuation** is the decreasing intensity of a sound beam as it passes through a medium. In diagnostic ultrasound, it is the result of energy absorption of the tissue and a reflection and scatter that occur between the boundaries of media of 2 different densities.
The transducer is the link between an anesthetist and a patient (Figure 7). All transducers require several key components to generate an image. Crystals located in the transducer use the piezoelectric effect to create sound. The piezoelectric principle enables the crystals to convert the electrical voltage sent from the ultrasound system into mechanical energy so it can be safely introduced into the body. Crystals also receive echoes returned to the transducer and convert them into electrical energy that is processed by a microcomputer to create an image. Linear array transducers, like those commonly used for regional anesthesia and central venous access, contain as many as 120 individual ceramic crystals aligned side by side along the face of the transducer. The thickness of the piezoelectric crystals determines the inherent frequency of the transducer, which directly impacts the depth of the near (Fresnel), focus, and far (Fraunhofer) zones.

Resolution describes the smallest possible distance between 2 points that allows them to be discriminated. Resolution is best in the focal zone, where the ultrasound beams are the narrowest, and separates the near and far zones. Lateral resolution, the ability of the ultrasound system to display 2 side-by-side objects as separate structures, is best in the focal zone. Lateral resolution depends on the distance between the individual crystals within the transducer rather than on the distance between the objects being viewed. Resolution diminishes in the far zone as the waves begin to diverge and are attenuated by tissue. Axial resolution relates to the ability of the ultrasound system to differentiate objects in line with the axis of the sound wave. It is dependent on the length of the sound impulse on the ultrasound frequency. A backing layer located behind the crystals dampens the generated pulse, reducing the amount of scatter, and improves axial resolution.

Clinical Considerations
Transducer orientation is an important but rarely discussed topic in ultrasound-assisted anesthesia procedures. Proper placement of the transducer in relation to patient position is vital to determining an accurate image (Figure 9). A common practice is to place the desired object (blood vessel or nerve) in the center of the image. However, this practice can also be problematic when the probe is not oriented properly because any adjustments required in needle position will appear to be the opposite of what is intended (Figure 10). To ensure accurate and consistent transducer orientation, the transducer should be held so that the external notch is facing the patient’s anatomic right in a cross-sectional view or toward the head in a longitudinal view. When done consistently, an anesthetist can not only predict where needle insertion will be displayed in the B-mode image, but also anticipate the direction of any adjustments that may be required during the procedure.
Alternating current from the ultrasound system is converted to mechanical energy by piezoelectric crystals. The backing layer dampens the vibrations of the generated pulse, decreasing its duration. This dampening improves the axial resolution. The matching layer is used to decrease the acoustic impedance between the air and skin. Coupling gel further decreases the impedance and allows for easy transmission of sound into the skin.

Axial resolution (A) and lateral resolution (B) are best in the focal zone, the region of the sound beam where it is at its minimum diameter and maximum density. The depth of the focal zone varies with the frequency, which is determined by the thickness of the crystals within the transducer.
Consistent and accurate transducer orientation is fundamental to reducing potential complications during central venous catheter insertion and regional anesthesia. Anesthetists must have an understanding of the basic principles related to the creation of an image with sound and the ability of Doppler to detect the direction and velocity of flow. Although not frequently addressed, proper transducer orientation is also fundamental in creating accurate and consistent pictures and can often be the difference.
between success and failure. The different characteristics of tissues in the body create distinctive patterns based on their impedance to sound and propagation velocity. Practitioners must accurately incorporate all of this information to ensure the best possible outcome.

REFERENCES

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