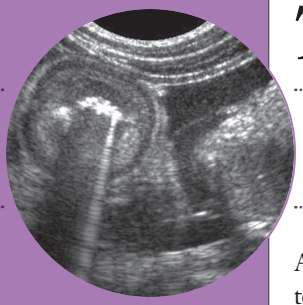
IMAGING ESSENTIALS

Physical Principles of Abdominal Ultrasonography *Part 1: Basics of Ultrasound Transducers & Image Formation*



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Abdominal ultrasonography is a noninvasive technique that provides cross sectional anatomy of the organs of the abdomen based on differences in acoustic impedance.

BASICS OF ULTRASOUND WAVES

Ultrasound (US) is defined as sound waves with frequencies that exceed the normal hearing range (> 20,000 Hz). Using noninvasive, nonionizing waves of sound propagated into tissues, US creates images of structures in the body that have both static (such as the liver) and dynamic (such as the heart or blood flow in the vessels) components.

Two-dimensional US scanning is a real-time event, with updates of the abdominal images averaging 40 frames per second.

FIGURE 1. **Ultrasound machine, with patient adjacent to sonographer, who is adjusting the machine in order to optimize image quality.**

Transduction of US Waves

US waves are produced within the transducer of an US machine (**Figure 1**). The transducer is used to interrogate the area of interest after a coupling gel has been applied to the skin, and typically, the hair in this area is clipped before the gel is applied.

Within the piezoelectric crystals or ceramic of the transducer, energy is converted from electrical to mechanical energy. Piezoelectricity is the electric charge that accumulates in certain solid materials, such as crystals and certain ceramics, in response to applied mechanical stress, which results in short bursts of mechanical energy in the form of US waves.

This *pulse–echo principle* forms the basis for *image acquisition*. The transducer sends US waves into the area of interest approximately 1% of the time and listens for returning echoes 99% of the time. The returning reflected US waves are the basis for *image formation*.

Parameters of US Waves

The US wave can be drawn as a sine wave—a mathematical curve that describes smooth repetitive oscillation—and is described by the following physical parameter equation:

$$c = (f)(l)$$

Speed of sound in the tissue ***(c)*** varies between different tissues but is averaged at 1540 m/sec or 1.54 mm/mcsec.

Frequency ***(f)*** is the number of times (cycles/sec or Hz) the wave oscillates through the complete sine cycle in 1 second; medical US transducers typically have a frequency between 2 and 20 MHz (1×10^6 cycles/sec).

Wavelength *(l)* is the distance (mm or mcm) between the peak heights of 2 subsequent sine waves.

TISSUE INTERACTIONS OF US WAVES

There are 5 basic interactions of US waves with tissues.

1. **Reflection** occurs at acoustic boundaries, which correspond with anatomic boundaries, based on differences in the acoustic impedance of the bordering tissues.
   - The *acoustic impedance* (defined in Rayls or Z) is equal to the physical density of the tissue × the speed of sound in the tissue.
   - There are large differences in acoustic impedance between air (0.0004×10^6 Rayls), soft tissues (1.65×10^6 Rayls), and bone (7.8×10^6 Rayls).
   - These differences result in the reflection of a majority of US waves at acoustic interfaces, such as gas–soft tissue, soft tissue–bone, and gas–bone, and these interactions are best observed at perpendicular interfaces with the transducer.
2. **Refraction** describes the difference between the incident angle of the US wave and the reflected angle, particularly when the interface is not perpendicular to the transmitting transducer.
   - Refracted US waves are not directly transmitted back to the transducer and, therefore, are not "interpreted" by the machine as a returning echo.
   - Refracted US waves can "bounce" around in tissues and ultimately be recorded as a reflected US wave by the transducer. However, the transducer assumes straight out and back; therefore, artifactual information will be placed in the image at depth.
3. **Scatter**, or diffusion of the US beam in many directions, results when small particles (structures in the tissues that are less than the wavelength of the US wave) cause *reflection* and *refraction* of the US beam within the tissues.
   - These reflectors give rise to a characteristic echo signature or pattern for a given organ.
   - *Specular* (linear) and *nonspecular* (nonlinear) reflectors are boundary interactions that determine the definition of specific areas within a given organ and the organ boundaries themselves; for example, hepatic veins within the liver.
4. **Attenuation** is the loss of acoustic energy or number of US waves traveling at depth.
   - The *attenuation coefficient*—expressed in decibels (dB)/cm—is the relative loss of intensity of the US beam per cm of depth traveled.
   - Typically, the attenuation coefficient is 0.5 (dB/cm)/MHz frequency of the transducer, which implies that there is more attenuation of US waves per cm of tissue when using higher frequency transducers compared with lower frequency transducers.
   - This means that higher frequency transducers have better resolution (small wavelength) but decreased penetration in the tissue. The opposite is true for low frequency transducers.
5. **Transmission** describes the fact that some US waves continue to depth and, therefore, have no interaction with tissues or the transducer.

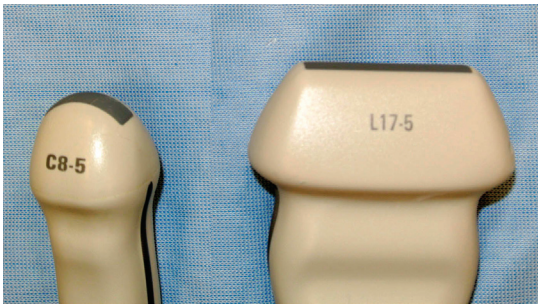

FIGURE 2. **Ultrasound transducers: linear array transducer (**right**) and microconvex-curved array transducer (**left**); these 2 transducers are the most commonly used transducers for the abdomen.**

CONCEPTS PERTAINING TO TRANSDUCERS

The US transducers currently used are called *broad bandwidth* or *multifrequency* transducers. These transducers support movement of the center frequency among a multitude of different frequencies. For example, a transducer with a range between 6 and 10 MHz may allow central frequency placement at 10, 8, and 6 MHz.

Series Highlights

Welcome to our new series of articles on abdominal ultrasonography. The first 3 articles in the series will provide an overview of the basic principles of:

- Image acquisition, artifact creation, and interpretation
- Optimizing the ultrasound image for interpretation (how to *drive* the ultrasound machine).

The next part of the series will review a basic approach to the abdomen, using both lateral and ventral scanning techniques, while the final section will address the basic scanning principles for each organ/system in the abdomen, including the:

- Approach to scanning the given organ
- Review of normal sonographic appearance
- Identification of abnormalities commonly seen during routine ultrasound examination.

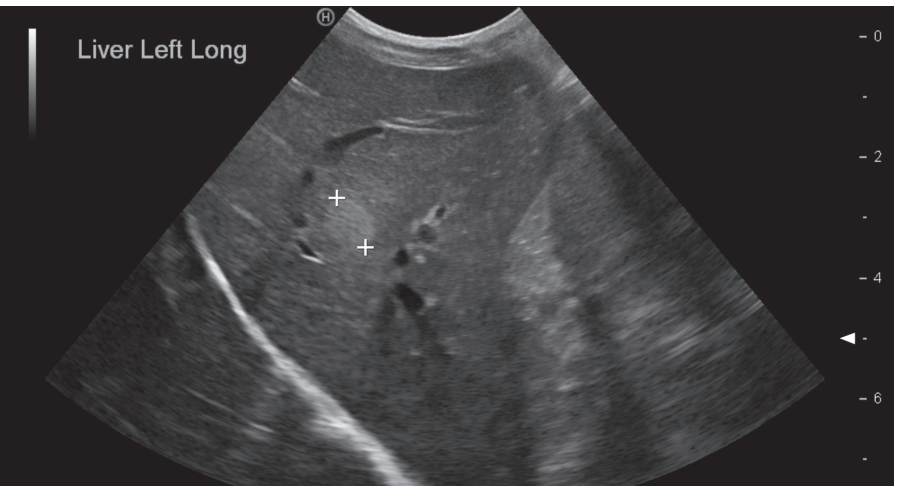

FIGURE 3. **Ultrasound image of the liver: the near field is the area of the image closest to the transducer skin interface, the focal zone (**white triangle**) is the area of best elevational resolution (decreased thickness of the ultrasound beam), and the far field is the area deepest or farthest from the skin/transducer interface.**

Low Versus High Frequencies

As explained in the section about attenuation, higher frequencies result in decreased capability for penetration; however, higher frequencies allow better resolution due to the smaller wavelength of the US waves. Smaller waves and smaller pulses allow for better discrimination between small objects that are a short distance apart on the path of the US beam.

Transducer Crystal Arrays

There are 3 different crystal arrays for US transducers (**Figure 2**, page 35): curved, linear, and microconvex-curved arrays.

Curved, microconvex-curved, and linear array transducers differ in the configuration of their crystals: the crystals in a linear transducer are arranged in a line whereas the crystals in a curved array transducer are arranged in a convex array.

- With a curved or microconvex -curved array, as the US beam travels deeper into tissue, more distance is noted between the lines of US waves going into the tissue, resulting in information gaps (lack of returning echoes) at depth. To fill these gaps at depth, the machine extrapolates and inserts the average gray scale value between the 2 adjacent beams of US waves.
- This effect does not occur with a linear array, in which the lines of crystals are oriented perpendicular to the probe interface.

While discussion of all the physical aspects of US transducers is beyond the scope of this article, further information can be found in the **Suggested Reading** sidebar.

US IMAGE CREATION

US image creation is based on the pulse–echo principle, discussed under **Transduction of US Waves** (page 34). Since the speed of sound in the tissue is known, and the time for an US wave to traverse out and back is known, the distance from the transducer can then be calculated.

Gray Scale Values

Once the number of reflected US waves returned from a given area is calculated, a relative gray scale value is then assigned based on the intensity of the returning signal:

- The higher the number of returning echoes, the brighter (whiter) the area of the image will be; this result is termed *hyperechoic*.
- If there is a relatively small number of returning echoes from a location, then a blacker or darker gray scale value will be assigned and the area termed *hypoechoic* or *anechoic*.

Image Zones & Fields

Each US image has a near field, focal zone, and far field (**Figure 3**):

- The **near field** is the area closest to the skin surface/transducer interface or coupling.
- The **focal zone** is the area where the US beam is thinnest (several mm) and has the best resolution; this zone is marked by small triangles along the right side of the image, typically adjacent to the depth markers (cm).
- The **far field** includes tissues deep to the focal zone. In this area, the beam will start to broaden, diminishing resolution.

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IN SUMMARY

This article has presented the basics of image formation related to the US machine:

1. The transducer contains piezoelectric crystals that deform physically when electrically stimulated, thereby creating an oscillating mechanical pulse that is transmitted into tissues.
2. The US waves interact with tissues and return as reflected echoes that are detected by the probe and then converted back from mechanical energy into an electrical signal.
3. The intensity of the signal is based on the number of US waves reflected, and this intensity is then assigned a relative gray scale value that is depicted on the image.

US = ultrasound

Suggested Reading

Bushberg JT, Siebert JA, Leidholdt EM Jr, Boone JMl. *The Essential Physics of Medical Imaging*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2012.

Kremkau FW. *Sonography: Principles and Instruments*, 9th ed. St. Louis: Elsevier Saunders, 2014.

Nyland TG, Mattoon JS. *Small Animal Diagnostic Ultrasound*, 2nd ed. Philadelphia: Elsevier Saunders, 2002.