In Clinical Practice

Dmitriy Kireyev
Judy Hung *Editors*

Cardiac Imaging in Clinical Practice

Springer

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Contents

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Chapter 1
Basics of Ultrasound Physics

Dmitriy Kireyev and Judy Hung

Ultrasound – Refers to sound waves with frequencies higher than 20 kHz, which is higher than the frequencies perceptible to the human ear.

Ultrasound waves travel at a speed of approximately 1540 m/s in soft tissue such as muscle.

- Sound of different frequencies travels through the same media at same speed.
- High frequency sound has lower penetration.
- The higher the frequency, the smaller the object that reflects sound without scattering.
- $C = \lambda \upsilon$, where c – speed of sound λ – wavelength, υ – frequency
- Speed in media is proportional to density and elasticity (which is proportional to temperature). Thus sound travels faster in soft tissue than air and faster in metal than soft tissue.
- Ultrasound waves can reflect and refract when they are interacting borders between different media (Fig. 1.1)

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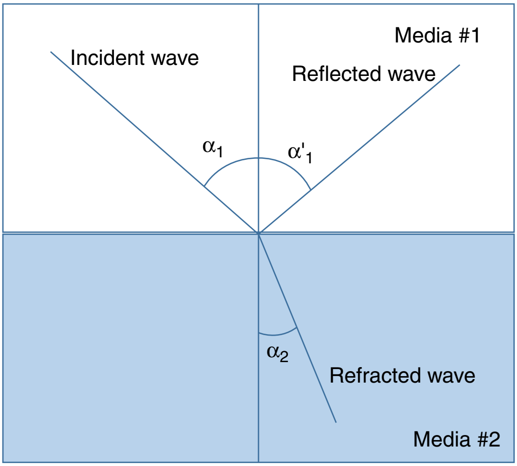

FIGURE 1.1 Ultrasound waves both reflect and refract when they come to border between two media with different physical properties

Transducer can be focused only in near field

$L_n = r^2/\lambda = r^2\upsilon/c$, Where Ln – length of near field, λ – wavelength, υ – frequency, r – radius of the transducer, c- speed of sound in media

Sin α = 0.61/r – divergence of beam in the far field

Snell's law: calculates angle of refraction

$\text{Sin}\alpha_1 / \text{Sin}\alpha_2 = V_1 / V_2 = n_2 / n_1$ where n is index of refraction

Spatial Resolution: refers to the smallest distance in which 2 points can be distinguished as separate. There are two types of spatial resolution; axial and lateral (Fig. 1.2).

- Axial resolution: refers to ability to resolve 2 points in the direction of the ultrasound beam (axial direction or depth); proportional to λ, υ, and duration of transmitted pulse. Typical axial resolution for cardiac ultrasound is
- Lateral resolution: refers to ability to resolve 2 points in a perpendicular plane from the ultrasound beam (along the sides of the beam); proportional to beam width

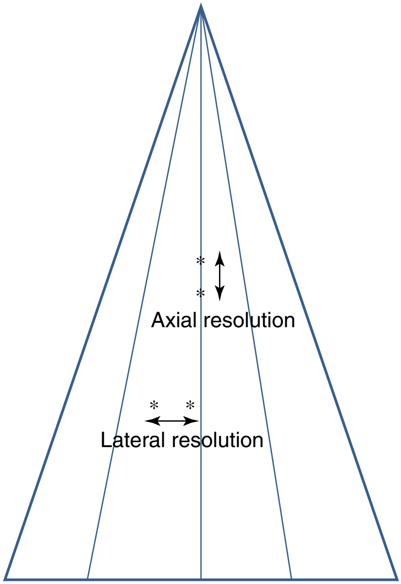

FIGURE 1.2 Definition of axial and lateral resolution

Temporal Resolution: refers to ability to resolve 2 points that has moved over time; is quantified as the frame rate; frame rates can be improved by narrowing imaging sector, decreasing depth, and decreasing line density

Absorption: refers to when sound amplitude is weakened due to inner friction (viscosity)

– Energy transferred to heat
– Scattering occurs at all the interfaces

Attenuation refers to decrease in sound amplitude from reflection of sound wave

– Attenuation increases as frequency of sound wave increases (can reflect off smaller interfaces)

Half value level – distance sound travels before intensity goes to 50 %

In tissue attenuation is 1 dB/cm/MHz

Transducer

Transducers contain piezoelectric elements which are made of metallic crystals that can transfer sound waves to electric signals and vice versa. These physical elements are responsible for the mechanoelectric transduction of ultrasound to electric data.

Diagram Basic Elements in an Ultrasound Probe (Fig. 1.3)

1. Piezoelectric element. It is responsible for generating pulses and receiving the ultrasound signals
2. Marching layers. Due to significant impedance differences between the transducer and the human body a significant amount of reflection can occur at the interface between the two (this is also a reason why we use gel to eliminate the air between the probe and the body). These layers increase

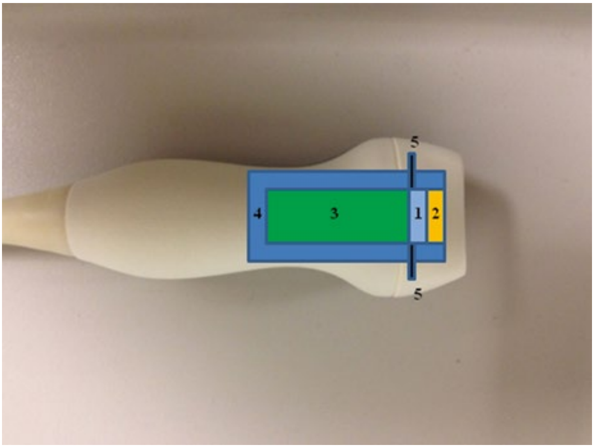

FIGURE 1.3 Diagram of basic components in ultrasound transducer. Please review text for more details

the acoustic power, sensitivity and axial resolution. The thickness of each layer is ¼ of transducer basic frequency to minimize internal reverberations within the probe.

3. Dampening material. It dampens the vibration of the piezoelectric element allowing to limit output time (thus improving range resolution) and absorbing the waves released from the back end of the transducer
4. Shielding material which limits the effect of outside vibrations on a piezoelectric element
5. Electrical connections – they both provide initial energy to excite the piezoelectric element and transmit back to the machine the electric signal which is generated by the piezoelectric element upon encountering reflected ultrasound waves

Transducer Frequency

– Determined by thickness of piezoelectric element
– Shock-excitation of a piezoelectric crystal results in transmission of sound energy from both front and back faces of crystal
– When thickness of element is ½ λ, the reflected and transmitted stresses at each surface reinforce each other and transducer resonates at maximum displacement amplitude –this is referred to as fundamental resonant frequency of the transducer
– when thickness is λ, the stresses at each surface are opposite – then displacement amplitude is minimal
– the thickness of piezoelectric element is inversely proportional to frequency generated (thickness proportional to λ proportional to c/υ)

Transducer Damping

– Piezoelectric elements used in transducers have long response to excitation – long ultrasound pulse

- Damping material is placed behind transducer to decrease length of ringing. This material also absorbs sound energy emitted from the back of the transducer
- High degree of damping decreases both pulse duration and sensitivity
- Impedance matching layers:
  - acoustic impedance of transducer is 25 times higher than that of human body.
  - acoustic impedance difference can cause 96 % reflective loss at transducer-skin interface.
  - Impedance matching layers increase power input, sensitivity, bandwidth and axial resolution.

Transducer Frequency

- Increases in frequency improve resolution but also decrease penetration into structures.
- Typical transducer frequencies are 2.0–2.5 mHz (in adults), 3.5 MHz (in children), and 5–12 MHz (in neonates and young children).

Doppler Basics

Doppler effect is a change of frequency of sound for an observer as his or her position changes relative to the source. (Do you remember how the sound of fire truck changes when it comes first towards you and then drives away?)

$$\upsilon = \upsilon \text{ initial}\left(\frac{c + V\ receiver}{c + V\ transducer}\right)$$

Where **υ** is frequency, **c** is the speed of sound in particular media and **V** is velocity

The ultrasound transducer emits an ultrasound wave which upon reaching target is reflected back to transducer. The change in frequency allows the machine to determine the speed of moving object.