Ultrasound Imaging

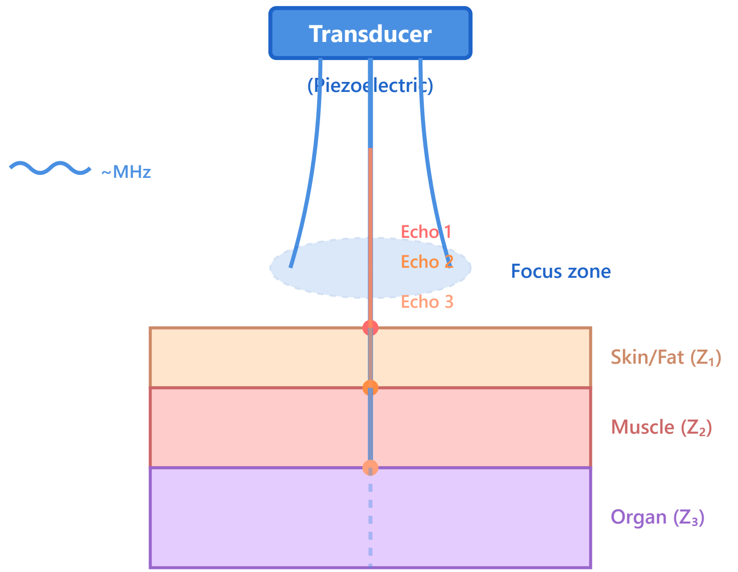
Piezoelectric transducers
Convert electrical to acoustic energy

Acoustic impedance
Tissue resistance to sound propagation

Reflection and refraction
Interface properties determine echoes

Beamforming
Focusing and steering ultrasound beam

Harmonic imaging
Higher frequencies improve resolution



Acoustic Impedance

$Z = \rho \times c$

ρ = density, c = sound speed

Reflection Coefficient

$R = (Z_2 - Z_1)^2 / (Z_2 + Z_1)^2$

Larger ΔZ → Stronger echo

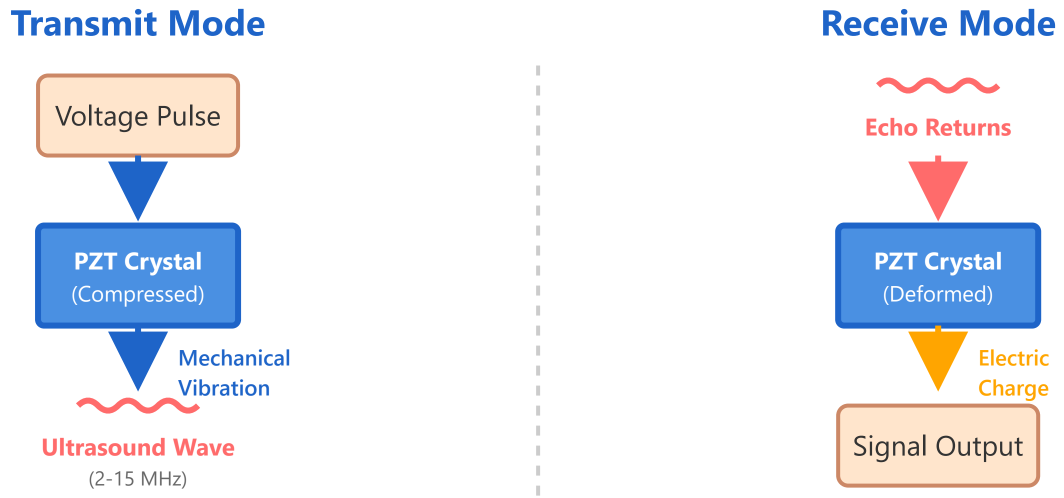
1. Piezoelectric Transducers

Principle of Operation

Piezoelectric transducers are the heart of ultrasound imaging systems. They exploit the piezoelectric effect, where certain crystalline materials generate an electric charge when mechanically stressed, and conversely, deform when an electric field is applied. This bidirectional conversion enables both the transmission and reception of ultrasound waves.

Key Components

- **Piezoelectric element:** Typically made from lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF), this crystal converts electrical energy to mechanical vibrations (transmit mode) and mechanical vibrations to electrical signals (receive mode).
- **Matching layer:** Reduces acoustic impedance mismatch between the transducer and tissue, maximizing energy transfer efficiency.
- **Backing material:** Dampens vibrations to produce short pulses, improving axial resolution.
- **Electrodes:** Apply voltage for transmission and collect charges during reception.



Clinical Significance

The frequency of the transducer determines imaging depth and resolution. Higher frequencies (7-15 MHz) provide excellent resolution but limited penetration, ideal for superficial structures. Lower frequencies (2-5 MHz) penetrate deeper but sacrifice resolution, suitable for abdominal and cardiac imaging.

2. Acoustic Impedance

Definition and Importance

Acoustic impedance (Z) is a fundamental property that describes how much resistance a material offers to the propagation of sound waves. It is the product of the material's density (ρ) and the speed of sound through that material (c). This property is crucial in ultrasound imaging because differences in acoustic impedance between tissues determine the strength of reflected echoes.

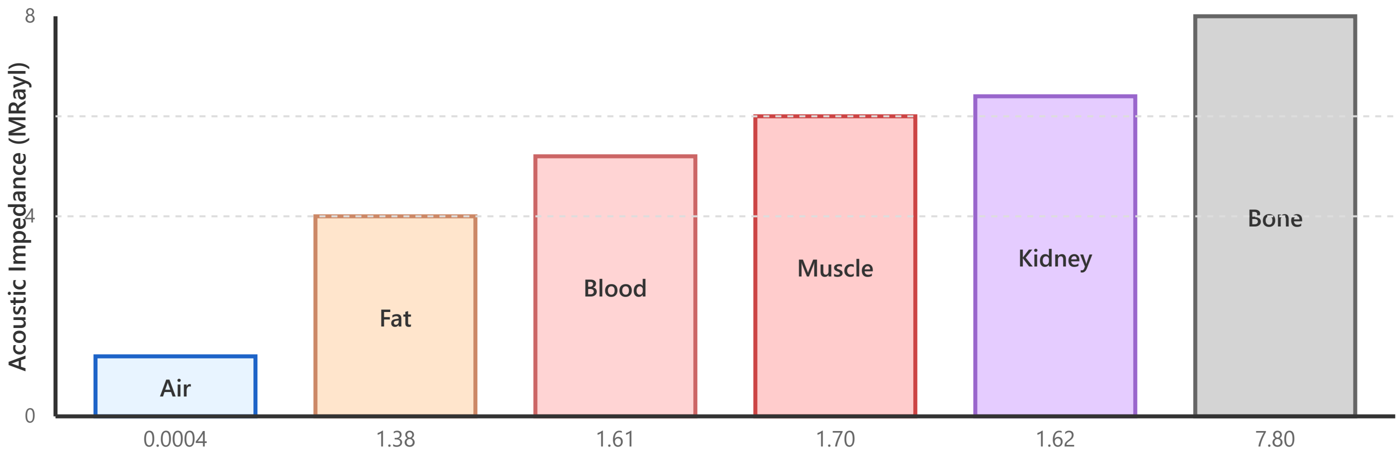
$$Z = \rho \times c$$

where ρ is density (kg/m^3) and c is sound velocity (m/s)
Unit: Rayl (1 Rayl = 1 $kg \cdot m^{-2} \cdot s^{-1}$)

Acoustic Impedance Values

Different tissues have characteristic impedance values:

Acoustic Impedance Comparison



Clinical Impact

Large impedance mismatches create strong reflections. For example, the air-tissue interface reflects nearly 100% of ultrasound energy, which is why gel is essential to eliminate air gaps. The bone-soft tissue interface also creates strong reflections, causing acoustic shadowing behind bones.

3. Reflection and Refraction

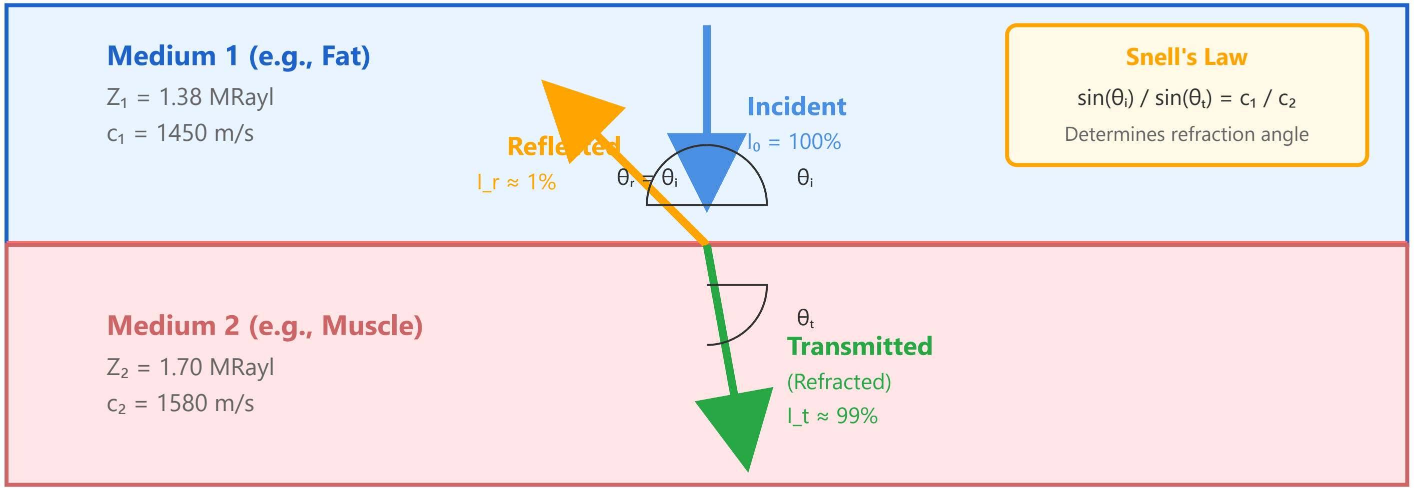
Reflection Coefficient

When an ultrasound wave encounters an interface between two materials with different acoustic impedances, part of the wave is reflected back (echo) and part continues forward (transmitted). The reflection coefficient (R) quantifies the fraction of intensity reflected at the interface.

$$R = [(Z_2 - Z_1) / (Z_2 + Z_1)]^2$$

Intensity Reflection Coefficient ($0 \leq R \leq 1$)
Larger impedance difference → Stronger reflection

Reflection and Refraction at Tissue Interface



Types of Reflection

- **Specular reflection:** Occurs at large, smooth interfaces (e.g., diaphragm, vessel walls). Produces strong echoes when the beam is perpendicular to the interface.
- **Diffuse reflection (scattering):** Occurs when the interface is rough or when structures are smaller than the wavelength. Creates the characteristic tissue texture in images.

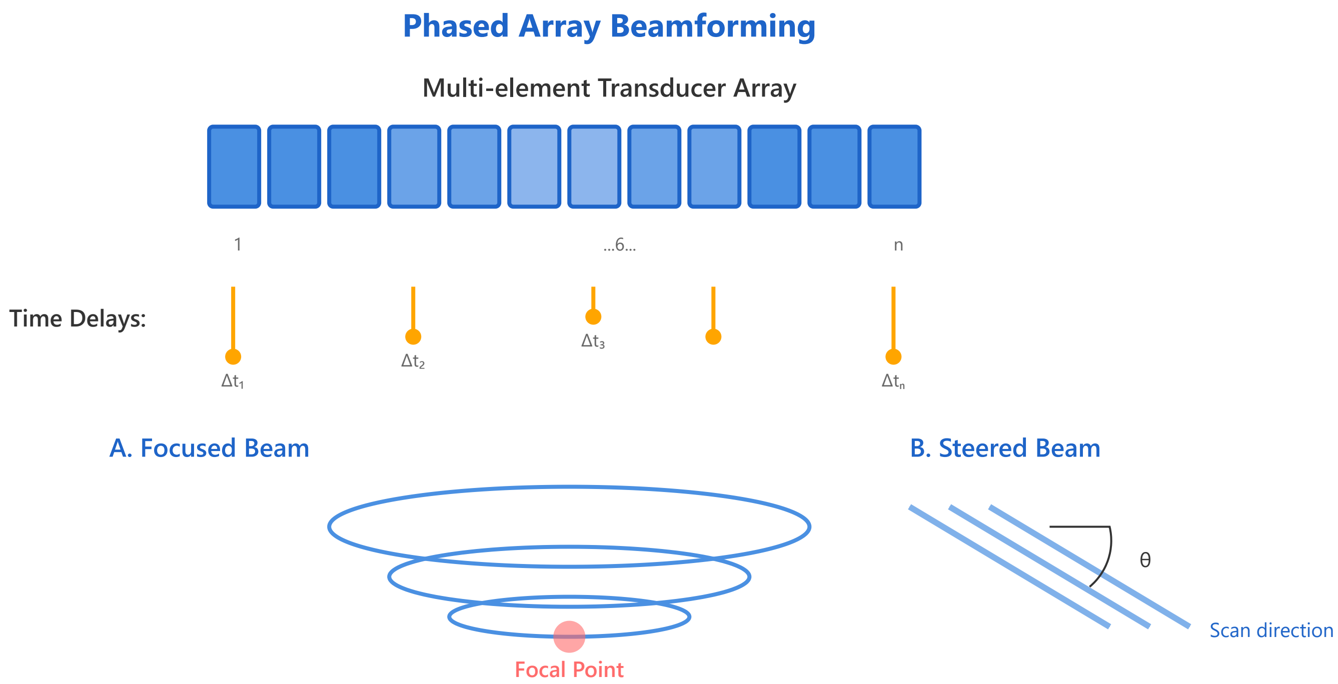
Practical Considerations

Refraction can cause image artifacts, particularly when imaging through curved surfaces or oblique angles. Speed of sound variations between tissues can lead to geometric distortion and misregistration of structures. Proper probe angulation and understanding of tissue interfaces help minimize these artifacts.

4. Beamforming

Concept and Purpose

Beamforming is the process of electronically focusing and steering the ultrasound beam to improve image quality and enable scanning without mechanical probe movement. Modern array transducers contain multiple piezoelectric elements (64-256 or more) that can be controlled independently to shape and direct the acoustic beam.



Beamforming Techniques

- **Transmit focusing:** Elements fire with precise time delays to make waves converge at a desired focal depth, improving lateral resolution at that depth.
- **Dynamic receive focusing:** Continuously adjusts receive delays as echoes return from different depths, maintaining optimal focus throughout the image.

- **Electronic steering:** Sequential firing patterns direct the beam to different angles without moving the probe, enabling sector scanning.
- **Parallel beamforming:** Modern systems can process multiple receive beams simultaneously, dramatically increasing frame rates.

Advanced Applications

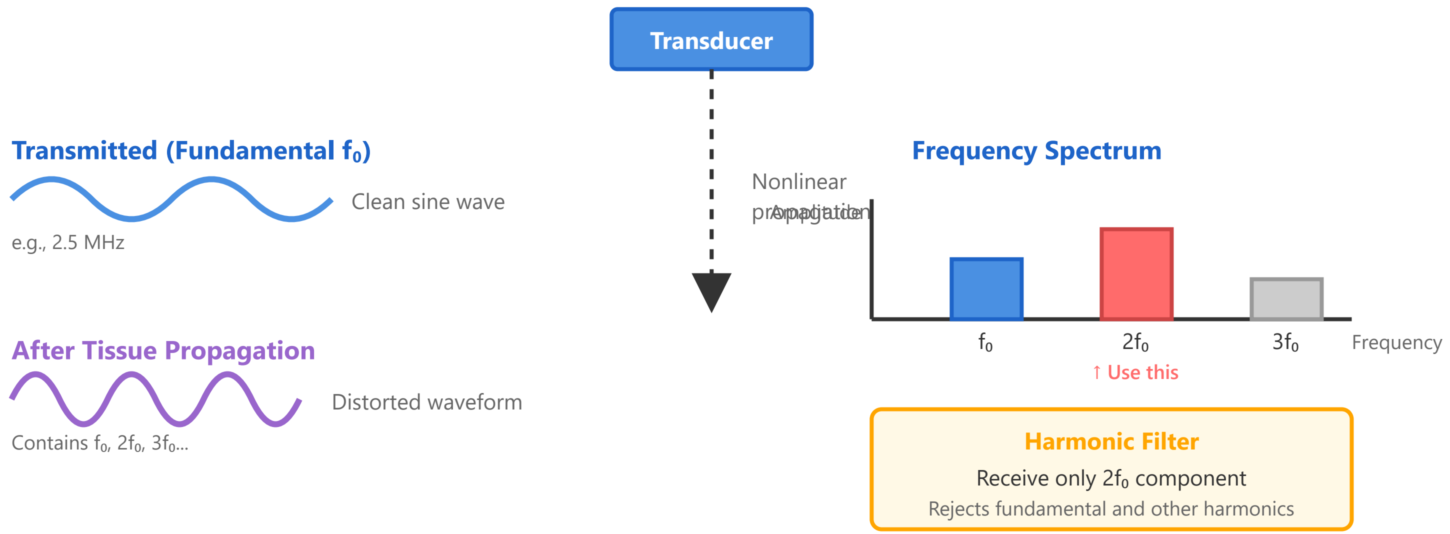
Adaptive beamforming algorithms can correct for phase aberrations caused by tissue inhomogeneities. Synthetic aperture techniques combine data from multiple transmit events to synthesize larger effective apertures. These advances enable improved penetration, resolution, and contrast in challenging imaging scenarios.

5. Harmonic Imaging

Physical Basis

Harmonic imaging exploits the nonlinear propagation of ultrasound through tissue. As ultrasound waves travel through tissue, the peaks of the waveform propagate slightly faster than the troughs due to pressure-dependent sound velocity. This nonlinear distortion generates harmonic frequencies—integer multiples of the transmitted fundamental frequency. By receiving only the second harmonic ($2f_0$), image quality can be significantly improved.

Harmonic Generation and Detection



Advantages of Harmonic Imaging

- **Reduced clutter:** Harmonics are generated primarily in tissue, not in superficial layers, reducing near-field artifacts and reverberation.
- **Improved contrast resolution:** Better discrimination between different tissue types and improved border definition.
- **Enhanced lateral resolution:** Narrower beam width at harmonic frequencies improves spatial resolution.

- **Reduced side lobe artifacts:** Side lobes of the transmit beam contribute less to harmonic generation.

Clinical Applications

Harmonic imaging has become standard in cardiac ultrasound for improved endocardial border definition. Tissue harmonic imaging (THI) is routinely used in abdominal scanning to reduce artifacts from body wall and improve visualization of deep structures. Contrast harmonic imaging exploits the strong nonlinear response of microbubble contrast agents for perfusion assessment and lesion characterization.

Resolution Trade-off

Axial resolution $\approx \lambda/2 = c/(2f)$

Higher harmonic frequency ($2f_0$) → Better resolution

But: Higher frequency → Increased attenuation → Reduced penetration