Ultrasound Physics in Medicine

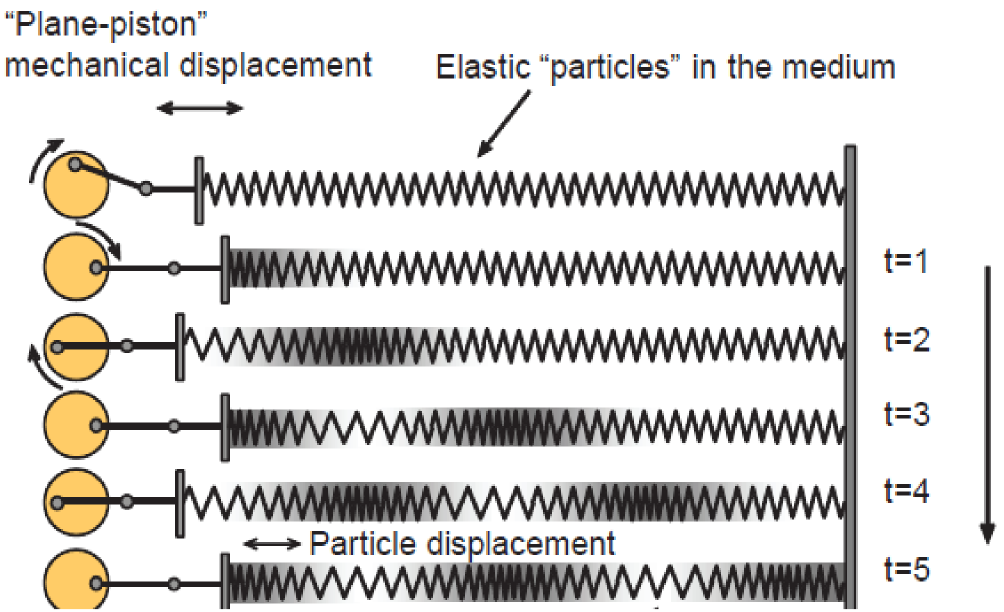
Second Semester /2021

Outlines

- Characteristics of Sound
- Wavelength, Frequency, and Speed
- Interactions of Ultrasound with Matter
- Medical ultrasound
- Medical ultrasound usage

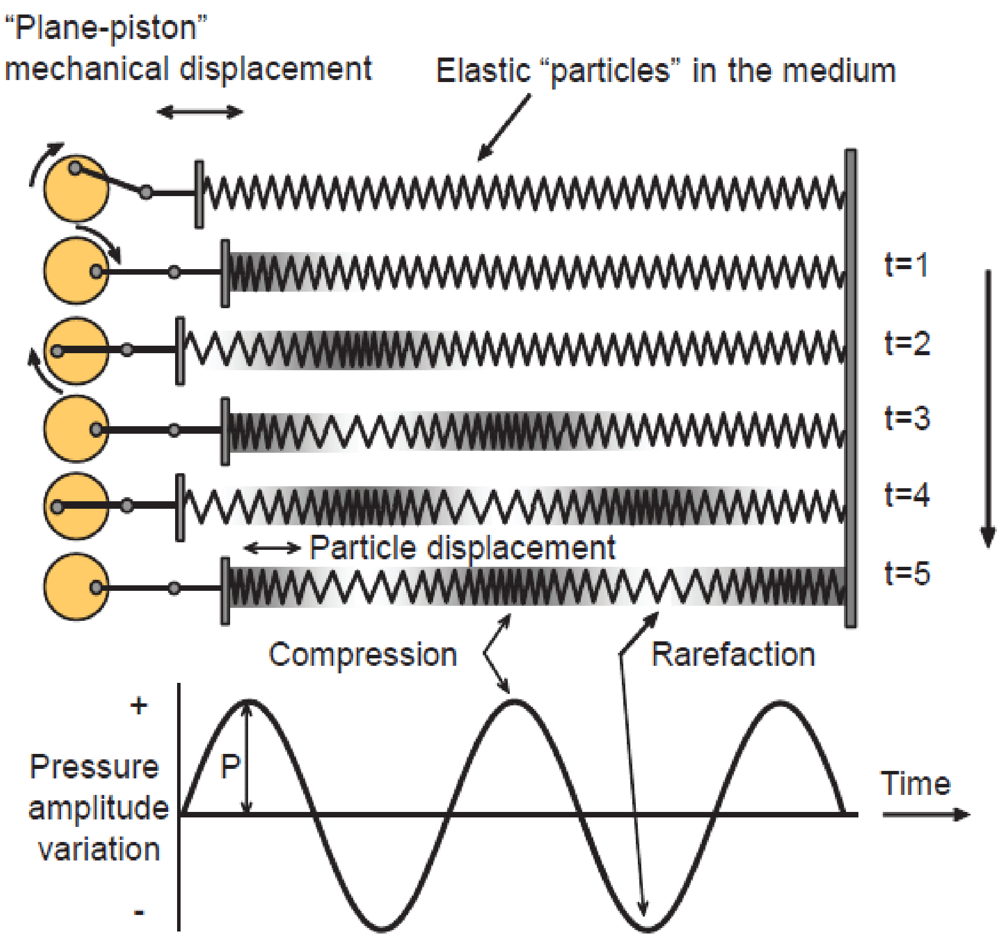
Characteristics of Sound

- Sound is mechanical energy that propagates through a continuous, elastic medium by the compression and rarefaction of "particles" that comprise it.
- A simple model of an elastic medium is that of a spring.
- Compression is caused by a mechanical deformation induced by an external force (such as a plane piston), with a resultant increase in the pressure of the medium.
- Rarefaction occurs following the compression event—as the backward motion of the piston reverses the force,
- the compressed particles transfer their energy to adjacent particles with a subsequent reduction in the local pressure amplitude.



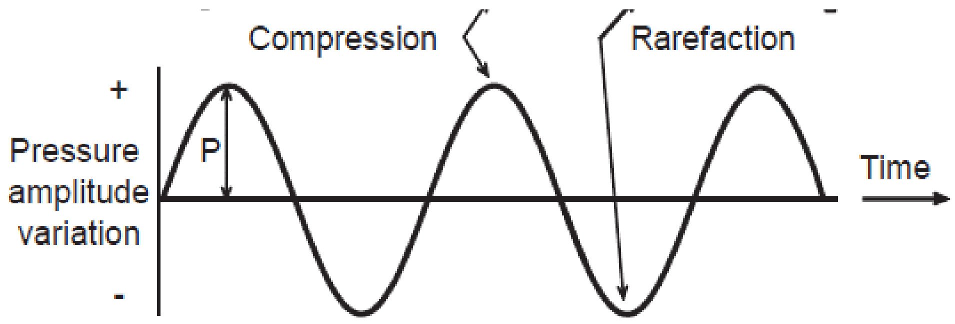
Characteristics of Sound

- Ultrasound energy is generated by a mechanical displacement in compressible medium, which is modeled as an elastic spring.
- Energy propagation is a function of time, resulting in areas of compression and rarefaction with corresponding variations in positive and negative pressure amplitude, P (lower diagram).
- Particles in the medium have only minor displacement as the wave front passes.



Wavelength, Frequency, and Speed

- The wavelength (λ) of the ultrasound energy is the distance (in units of mm or µm) between compressions or rarefactions, or between any two points.
- The frequency (f) is the number of times the wave oscillates through one cycle each second(s).
- Medical ultrasound uses frequencies in the range of 2 to 10 MHz, with specialized ultrasound applications up to 50 MHz.
- The speed of sound (c) is the distance traveled by the wave per unit time and is equal to the wavelength divided by the period.



$$c = \lambda f$$

Wavelength, Frequency, and Speed

TABLE 14-1 DENSITY AND SPEED OF SOUND IN TISSUES AND MATERIALS FOR MEDICAL ULTRASOUND

MATERIAL	DENSITY (kg/m^3)	c (m/s)	c ($mm/\mu s$)
Air	1.2	330	0.33
Lung	300	600	0.60
Fat	924	1,450	1.45
Water	1,000	1,480	1.48
"Soft Tissue"	1,050	1,540	1.54
Kidney	1,041	1,565	1.57
Blood	1,058	1,560	1.56
Liver	1,061	1,555	1.55
Muscle	1,068	1,600	1.60
Skull bone	1,912	4,080	4.08
PZT	7,500	4,000	4.00

EXAMPLE: A 2-MHz beam has a wavelength in soft tissue of

$$\lambda = \frac{c}{f} = \frac{1540\ m/s}{2\ \times 10^6/s} = 770 \times 10^{-6}\ m = 7.7 \times 10^{-4}\ m \times 1000\frac{mm}{m} = 0.77\ mm$$

A 10-MHz ultrasound beam has a corresponding wavelength in soft tissue of

$$= \frac{1540\ m/s}{10 \times 10^6/s} = 154 \times 10^{-6}\ m = 1.54 \times 10^{-4}\ m \times 1000\ \frac{mm}{m} \cong 0.15\ mm$$

Higher frequency sound has shorter wavelength, as shown in Figure 14-3.

EXAMPLE: A 5-MHz beam travels from soft tissue into fat. Calculate the wavelength in each medium, and determine the percent wavelength change.

In soft tissue,

$$\lambda = \frac{c}{f} = \frac{1540\ m/s}{5 \times 10^6/s} = 3.08 \times 10^{-6}\ m \cong 0.31 mm$$

In fat,

$$= \frac{1450\ m/s}{5 \times 10^6/s} = 2.9 \times 10^{-6}\ m \cong 0.29\ mm$$

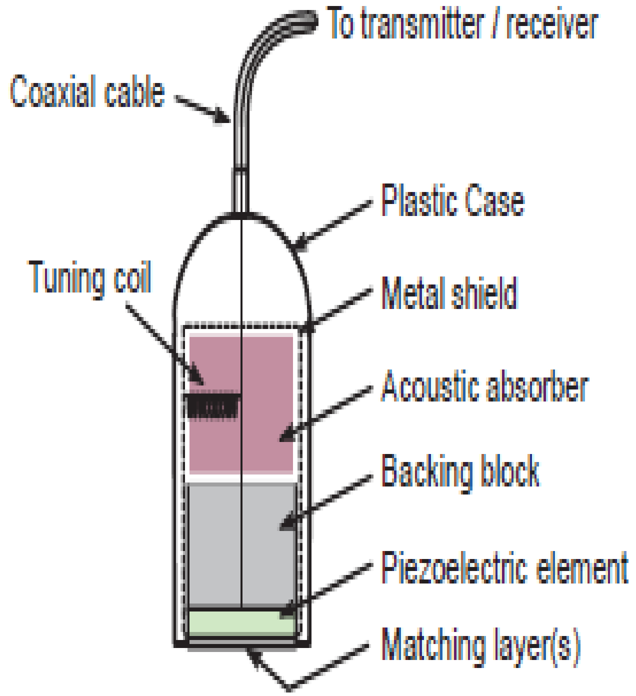
A *decrease* in wavelength of 5.8% occurs in going from soft tissue into fat, due to the differences in the speed of sound. This is depicted in Figure 14-3 for a 5-MHz ultrasound beam.

Interactions of Ultrasound with Matter

- Ultrasound interactions are determined by the acoustic properties of matter.
- As ultrasound energy propagates through a medium, interactions include reflection, refraction, scattering, and absorption.
- Reflection occurs at tissue boundaries where there is a difference in the acoustic impedance of adjacent materials.
- Refraction describes the change in direction of the transmitted ultrasound energy with non-perpendicular incidence.
- Scattering occurs by reflection or refraction, usually by small particles within the tissue medium, causes the beam to diffuse in many directions, and gives rise to the characteristic texture and gray scale in the acoustic image.
- Absorption is the process whereby acoustic energy is converted to heat energy, whereby, sound energy is lost and cannot be recovered.

Interactions of Ultrasound with Matter

- Ultrasound is produced and detected with a transducer, comprised of one or more ceramic elements with electromechanical properties and peripheral components.
- The ceramic element converts electrical energy into mechanical energy to produce ultrasound and mechanical energy into electrical energy for ultrasound detection.
- Over the past several decades, the transducer assembly has evolved considerably in design, function, and capability, from a single-element resonance crystal to a broadband transducer array of hundreds of individual elements.
- A simple single-element, plane-piston source transducer is illustrated in the figure. Major components include the piezoelectric material, matching layer, backing block, acoustic absorber, insulating cover, tuning coil, sensor electrodes, and transducer housing.



Medical ultrasound

- Medical ultrasound is a diagnostic imaging method that uses ultrasound to treat patients.
- It is used in diagnostics to generate images of internal body structures such as tendons, muscles, joints, blood arteries, and internal organs.
- Its goal is often to identify the cause of an illness or to rule out pathology.
- Obstetric ultrasound is the practice of utilizing ultrasound to examine pregnant women, and it was an early development and use of clinical ultrasound.

Medical ultrasound

- Ultrasonic pictures, commonly known as sonograms, are created by inserting ultrasonic pulses into tissue using a probe.
- The ultrasonic pulses reverberate off tissues with varying reflection characteristics and are returned to the probe, where they are recorded and shown as a picture.
- Images of many kinds may be created. A B-mode picture (Brightness) is the most frequent, displaying the acoustic impedance of a two-dimensional cross-section of tissue.
- Other kinds may show blood flow, tissue mobility over time, blood location, the presence of chemicals, tissue stiffness, or the anatomy of a three-dimensional area.

Medical ultrasound

- Ultrasound offers many benefits over other popular medical imaging modalities.
- It offers real-time pictures, is portable, and can be taken to the patient's bedside.
- It is much less expensive than other imaging methods and does not use hazardous ionizing radiation.
- The limitations of its range of view are difficulties imaging tissues hidden by bone and air or gases, and the necessity of a skilled operator, usually with professional training.

Medical ultrasound

- Ultrasound imaging (Ultrasonography) is extensively used in medicine.
- Ultrasound may be used for both diagnostic and therapy.
- Sonography is useful for visualizing soft tissues in the body.
- Higher frequencies (7–18 MHz) are used to scan superficial tissues such as muscle, tendon, testis, breast, thyroid and parathyroid glands, and the newborn brain, which provides greater resolution.
- Deeper tissues, such as the liver and kidney, are scanned at lower frequencies (2–6 MHz), with poorer resolution as a trade-off for deeper tissue penetration.

Medical ultrasound usage

1. Anesthesiology : Ultrasound is often used to help position needles near nerves while administering local anesthetics.
2. Angiology (vascular) : In angiology or vascular medicine, ultrasound is used to diagnose arterial and venous disease.
3. Cardiology (heart) : Echocardiography is an essential tool in cardiology, assisting in evaluation of heart valve function and strength of cardiac muscle contraction.
4. Emergency medicine : ultrasound has many applications in emergency medicine. This includes differentiating cardiac from pulmonary causes of acute breathlessness and differentiating causes of abdominal pain such as gallstones and kidney stones.
5. Gastroenterology/Colorectal surgery : the solid organs of the abdomen such as the pancreas, aorta, inferior vena cava, liver, gall bladder, bile ducts, kidneys, and spleen are imaged. However, sound waves are blocked by gas in the bowel and attenuated to differing degrees by fat, sometimes limiting diagnostic capabilities in this area.

Medical ultrasound usage

6. Gynecology and obstetrics : Ultrasound used examine female pelvic organs and check on the development and presentation of the fetus during pregnancy.
7. Hemodynamics (blood circulation): Blood velocity can be measured in various blood vessels by relatively inexpensive and low risk ultrasound Doppler.
8. Otolaryngology (head and neck):Ultrasound is the preferred imaging modality for thyroid tumors and lesions.
9. Neonatology : Doppler can be used for basic assessment of medical condition of newborn and premature infants.
10. Urinary tract : Ultrasound is routinely used in urology to determine, for example, the amount of fluid retained in a patient's bladder. In a pelvic sonogram, organs of the pelvic region are imaged. This includes the uterus and ovaries or urinary bladder.
11. Kidneys : In nephrology, ultrasonography of the kidneys is essential in the diagnosis and management of kidney-related diseases. The kidneys are easily examined, and most pathological changes in the kidneys are distinguishable with ultrasound.

Risks and side-effects

- Ultrasound imaging is generally considered safe imaging technique.
- Diagnostic ultrasound studies of the fetus are generally considered to be safe during pregnancy. This diagnostic procedure should be performed only when there is a valid medical indication, and the lowest possible ultrasonic exposure setting should be used to gain the necessary diagnostic information under the

"as low as reasonably practicable" principle

- Although there is no evidence ultrasound could be harmful for the fetus, medical authorities typically strongly discourage the promotion, selling, or leasing of ultrasound equipment for making "keepsake fetal videos".

The End