

A common non-invasive medical imaging technique valued for its affordability, portability and minimal safety concerns is ultrasound. It is widely used in gynaecology and many cardiovascular applications.

Ultrasound waves are produced by a transducer as shown in Fig. 8.1. An oscillating voltage is applied to a piezoelectric element formed by a composite of lead zirconate titanate (PZT). The PZT element's thickness oscillates at the same frequency as the applied voltage. Placing the element in contact with a patient's skin transfers the mechanical motion into a pressure wave which is transmitted into the body.

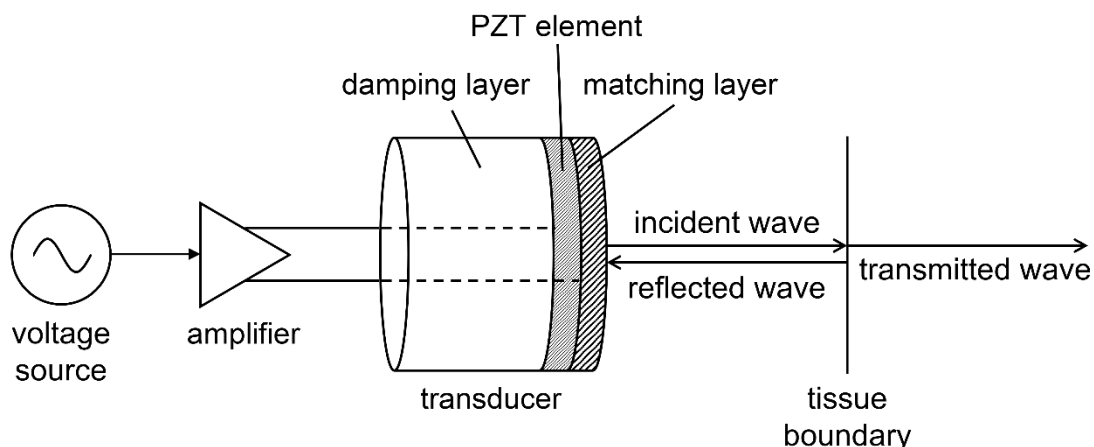


Fig. 8.1

At boundaries between tissues, a certain fraction of the wave energy is reflected back towards the transducer where it is detected to form the ultrasound image. The remainder is transmitted through the boundary deeper into the body.

The propagation of ultrasound energy through the body depends on the characteristic acoustic impedance Z of tissue. Z is determined by the physical properties of the tissue such as its density and compressibility. Table 8.1 shows the acoustic properties for air and some biological tissues.

Table 8.1

	acoustic impedance Z ($10^5 \text{ g cm}^{-2} \text{ s}^{-1}$)	speed of sound v (m s^{-1})	density ρ (kg m^{-3})	compressibility κ ($10^{11} \text{ cm g}^{-1} \text{ s}^2$)
air	0.00043	330	1.3	71 000
bone	7.63	4000	1908	0.328
fat	1.34	1450	925	5.14
brain	1.58	1540	1025	4.11
muscle	1.71	1590	1075	3.68
liver	1.65	1570	1050	3.86
kidney	1.62	1560	1040	3.95

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The following equations relate the transmitted I_t and reflected I_r intensities to the incident intensity I_i at a boundary.

$$\frac{I_t}{I_i} = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}$$

$$\frac{I_r}{I_i} = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2}$$

where Z_1 and Z_2 are the acoustic impedances for the medium before and the medium after the boundary respectively.

As the acoustic impedance of the PZT element Z_{PZT} is large compared to that of skin Z_{skin} , a large amount of energy will be reflected from the patient's skin, preventing effective transmission of ultrasound waves from the transducer into the body. To improve this efficiency, a matching layer is attached to the PZT element. Its acoustic impedance is given by

$$Z_{\text{matching layer}} = \sqrt{Z_{\text{PZT}}Z_{\text{skin}}}$$

The thickness of this matching layer should be one-quarter of the ultrasound wavelength to maximise energy transmission through the layer in both directions.

Finally, to enhance the quality of the ultrasound image, contrast agents like microbubbles are injected into the patient. They are filled with compressible gas and respond to the ultrasound beam by compressing in high pressure regions and expanding in low pressure regions. They absorb energy during the compression and re-radiate them during expansion to produce a strong echo signal returning to the transducer.

- (a) Acoustic impedance Z is related to the density ρ and compressibility κ of tissues by the equation

$$Z = \rho^a \kappa^b$$

where a and b are constants.

By considering the units of Z , ρ and κ , determine the values of a and b .

$$a = \dots\dots\dots$$

$$b = \dots\dots\dots$$

[2]

- (b) (i) Calculate $\frac{I_r}{I_i}$ when the ultrasound beam travels from muscle to bone.

$$\frac{I_r}{I_i} = \dots\dots\dots [2]$$

- (ii) Hence, explain why in the imaging of the heart, the ultrasound must pass in between the ribs.

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- (iii) State the two biological tissues shown in Table 8.1 whose boundary is the hardest to detect by ultrasound.

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- (c) As an ultrasound beam of initial intensity I_0 propagates through tissue, its intensity decreases exponentially. The transmitted intensity I depends on the frequency f of the wave, propagation distance x and the intensity attenuation coefficient μ of the tissue. The relationship is given by the equation:

$$I = I_0 e^{-\mu f x}$$

where μ for soft tissue is $0.23 \text{ cm}^{-1} \text{ MHz}^{-1}$.

- (i) Determine the distance at which the intensity of a 5.0 MHz ultrasound beam will be reduced by half when travelling through soft tissue.

distance = cm [2]

- (ii) Hence, state and explain whether high or low frequency ultrasound waves are used when imaging organs deeper in the body.

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 [2]

- (d) The PZT element in the transducer has an acoustic impedance of $30 \times 10^5 \text{ g cm}^{-2} \text{ s}^{-1}$ while the corresponding value for skin is $1.7 \times 10^5 \text{ g cm}^{-2} \text{ s}^{-1}$.

- (i) Show that only 20% of the energy from the transducer is transmitted into the patient if the PZT element is in direct contact with the patient's skin.

[2]

- (ii) Hence, determine the efficiency in transmitting energy from the PZT element to a patient's skin when a matching layer is used.

efficiency = % [4]

- (iii) For a particular composite material used to make the matching layer, a 5.0 MHz ultrasound beam travels at a speed of 2500 m s^{-1} in it.

Calculate the thickness of the matching layer.

thickness = m [1]

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- (e) Fig. 8.2 shows the change in the shape of a microbubble as an ultrasound pressure wave passes through the tissue in which the microbubble is located.

Sketch the sinusoidal variation with time of pressure at this location.

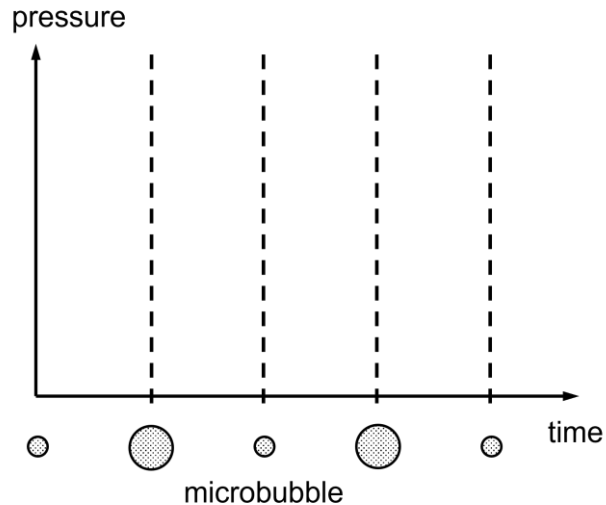


Fig. 8.2

[1]

- (f) Ultrasound is the only imaging technique that is routinely used in pregnancy to assess the health of the foetus. It is preferred over X-rays as it does not involve ionising radiation.

Explain the indirect effect of ionising radiation on living tissues and cells.

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