1

Physics of ultrasound

Basic principles

Nature of ultrasound

Sound = longitudinal, mechanical wave
particles move parallel to direction of travel

Audible sound < 20 kHz
Ultrasound > 20 kHz
Sound cannot travel through a vacuum

Four acoustic variables

Density (g/l)
Pressure (kPa)
Temperature (K)
Particle motion (m)

Compressions: high density/pressure/temperature/motion +
Rarefactions: low density/pressure/temperature/motion
(Fig. 1.1)
Transthoracic echo (TTE) ~ 2–5 MHz
Transoesophageal echo (TOE) ~ 3.5–7 MHz

Sound is described by
Propagation speed (m/s)
Frequency (Hz)
Wavelength (m)

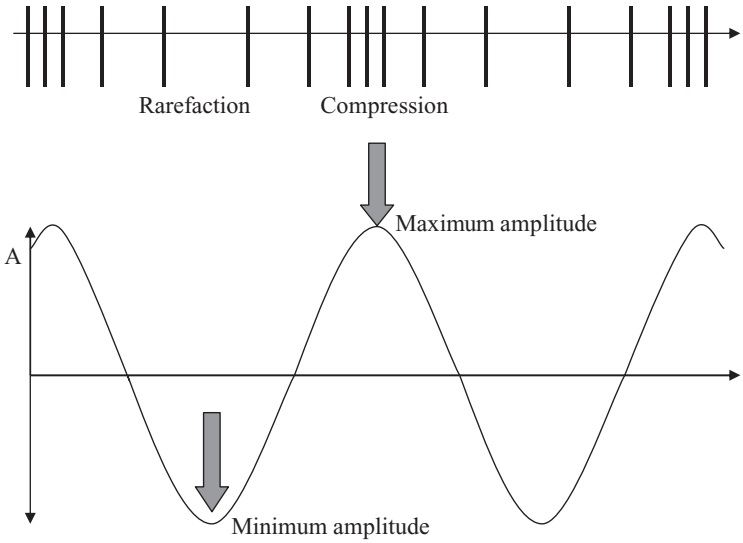


Fig. 1.1

Period (s)
Amplitude (kPa, g/l, K, m, dB)
Power (W)
Intensity (W/cm^2)

Propagation speed (*v* or *c*)

c = speed of sound Units = m/s or mm/μs
Determined by the medium through which the wave travels
Soft tissue (heart) = 1540 m/s = 1.54 mm/μs
Speed affected by density and stiffness of medium
↑density → ↓speed
↑stiffness (= bulk modulus) → ↑speed
Elasticity and compressibility = opposite to stiffness
↑elasticity/compressibility → ↓speed
All sound travels through a specific medium at the same speed (Table 1.1)

Table 1.1 Speed of sound in different media

Tissue	Speed of sound (m/s)
Air	331
Lung	500
Fat	1450
Brain	1541
Liver	1549
Muscle	1585
Bone	>3000

Frequency (f)

f = number of cycles per second Units = Hz
U/S > 20 kHz
Determined by sound source
Affects penetration and axial resolution

Period (T)

T = length of time to complete one cycle Units = s
U/S = 0.1–0.5 μs
Determined by sound source
Reciprocal of frequency $T = 1/f$

Wavelength (λ)

λ = distance occupied by a single cycle Units = m
U/S = 0.1–0.8 mm
Determined by sound source and medium
λ influences axial resolution

Velocity (v), frequency (f) and wavelength (λ) associated by the equation

$$v = f\lambda$$

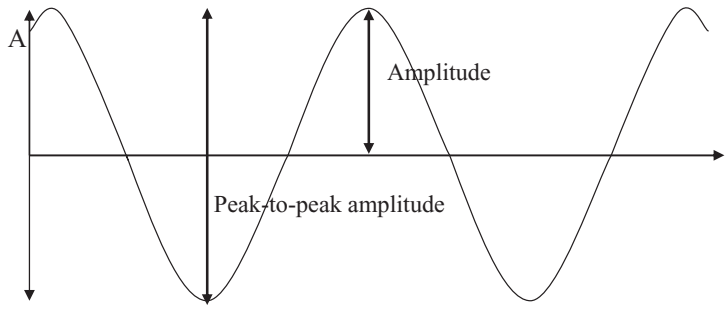


Fig. 1.2

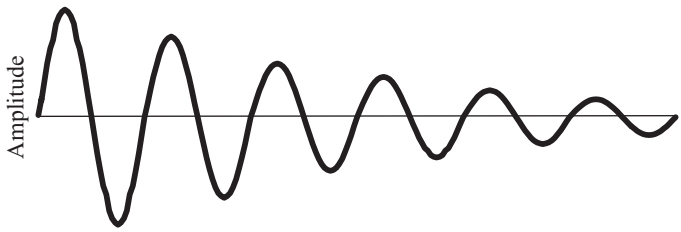


Fig. 1.3

Amplitude (*A*)

A = max. variation in acoustic variable Units = kPa, g/l, K, m, dB,
i.e. difference between mean and max. values
(Fig. 1.2)
Decibel (dB) = logarithmic relative unit of measure of A
i.e. difference between two values
e.g. ↑ by 30 dB = ↑A by 10 × 10 × 10 (×1000)

Determined by sound source
Changed by sonographer
Amplitude decreases as sound wave travels = **attenuation**
(Fig. 1.3)

Power (*P*)

P = rate of work/rate of energy transfer Units = W

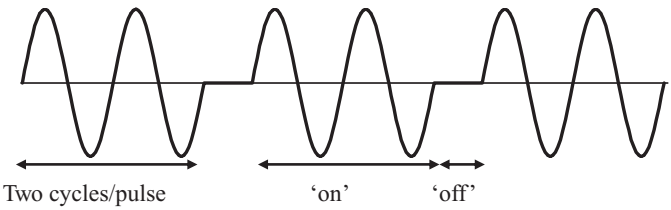


Fig. 1.4

Determined by sound source
Changed by sonographer

$$P = A^2$$

Intensity (*I*)

I = concentration of energy/power in a sound beam
Units = W/cm^2
Determined by sound source
Changed by sonographer
U/S I = 0.1–100 mW/cm^2

$$I = P/\text{area}$$

Pulsed ultrasound

Pulse = collection of cycles travelling together
  individual 'cycles' make up the 'pulse'
  'pulse' moves as one
  'pulse' has beginning and end
Two components:
  'cycle' or 'on' time
  'receive' or 'off' or 'dead' time (Fig. 1.4)
Pulsed U/S described by:
  pulse duration (PD)
  pulse repetition frequency (PRF)
  pulse repetition period (PRP)

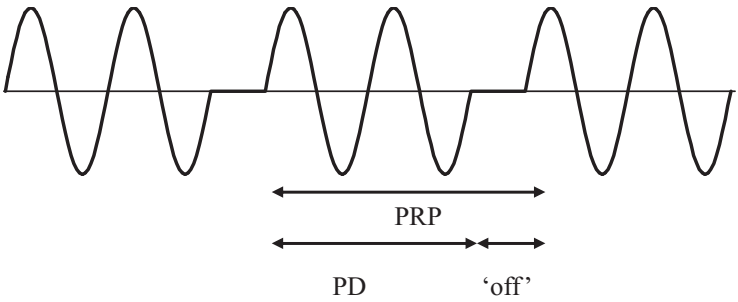


Fig. 1.5

spatial pulse length (SPL)
duty factor (DF)

Pulse duration (PD)

PD = time from start of one pulse to end of pulse Units = s
= 'on' time (Fig. 1.5)
Determined by:
number of cycles in a pulse ('ringing')
period of each cycle
Characteristic of transducer/not changed by sonographer
TOE PD = 0.5–3 μs

PD = number of cycles × T PD = number of cycles/f

Pulse repetition frequency (PRF)

PRF = number of pulses per second Units = Hz
(Number of cycles per pulse *not* relevant)
Determined by sound source
Changed by sonographer by changing image depth

As image depth increases → PRF↓
Sonographer ↑'dead' time by ↑image depth = ↓PRF
TOE PRF = 1–10 kHz

PRF(kHz) = 75/depth (cm)

Pulse repetition period (PRP)

PRP = time from start of one pulse to start of next pulse
Units = s
PRP = 'on' time (PD) + 'off' time (Fig. 1.5)
Changed by sonographer by changing 'off' time
TOE PRP = 0.1–1 ms

$$\text{PRP } (\mu\text{s}) = 13 \times \text{depth (cm)}$$

Spatial pulse length (SPL)

SPL = length in distance occupied by one pulse Units = m
Determined by sound source and medium
Cannot be changed by sonographer
TOE SPL = 0.1–1 mm
Determines axial resolution
i.e. short SPL → better axial resolution

$$\text{SPL} = \text{number of cycles} \times \lambda$$

Duty factor (DF)

DF = percentage of 'on' time compared to PRP Units = %
Changed by sonographer by changing 'off' time
TOE DF = 0.1–1% (i.e. lots of 'off'/listening time)

$$\text{DF} = \text{PD}/\text{PRP}$$

↑DF by:
  ↑PRF (more pulses/s)
  ↑PD (by changing transducer)
↓DF by:
  ↑PRP (by ↑'off' time)
  ↑image depth
DF = 100% = continuous wave (CW) U/S
DF = 0% = machine off

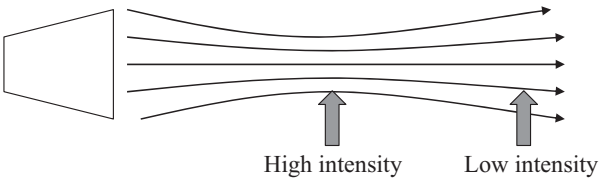


Fig. 1.6

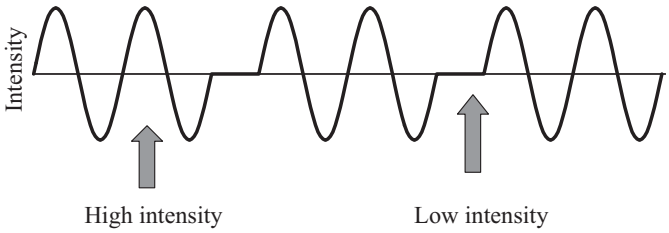


Fig. 1.7

Properties of ultrasound

Intensity (*I*)

Described by:

(1) Spatial – U/S beam has different *I* at different locations (Fig. 1.6)
Peak I = spatial peak (SP)
Average I = spatial average (SA)

(2) Temporal – U/S beam has different *I* at different points in time (Fig. 1.7)
Peak I = temporal peak (TP), i.e. 'on' time
Average I = temporal average (TA), i.e. average of 'on' and 'off'
For CW: TP = TA

(3) Pulse – U/S beam has average *I* for duration of pulse ('on')
= pulse average (PA)

Highest I	SPTP
↓	SPPA
	SPTA
	SATP
	SAPA
Lowest I	SATA

SPTA relevant to tissue heating
For CW: SPTP = SPTA and SATP = SATA
When PW and CW have same SPTP/SATP
  CW has higher SPTA/SATA
PA > TA for PW

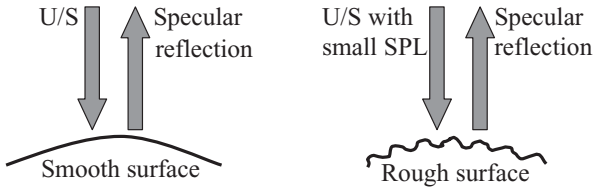
Beam uniformity ratio (BUR)

BUR = SP/SA factor
No units
Scale 1–∞ (infinity)
Describes the spread of sound beam in space
TOE BUR = 5–50

Attenuation

Decrease in A/P/I as sound wave travels (Fig. 1.3)
Units = −dB
In soft tissue: ↑f → ↑attenuation
Three components:
(1) absorption:
  energy transferred to cell in tissue by conversion to other form of energy
  sound → heat/vibration
(2) reflection:
  energy returned to source when it strikes a boundary between two media

(i) Specular reflections



(ii) Scatter

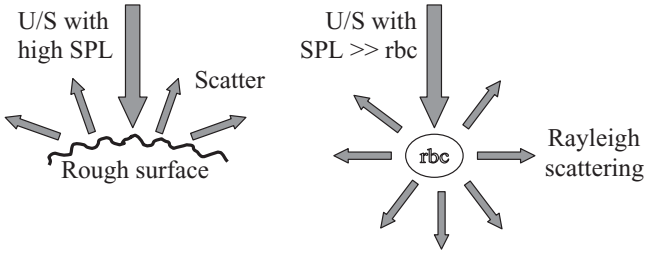


Fig. 1.8

(3) scatter:
sound beam hits rough surface → sound wave redirected in several directions

Rayleigh scattering = when reflector << SPL (e.g. red blood cells)
→ scattering equal in all directions
(Fig. 1.8)
Attenuation coefficient (AC)
Units = −dB/cm
In soft tissue: ↑f → ↑AC

$$AC = 0.5 \times f \text{ (MHz)}$$

Total attenuation = AC × path length (cm)
↑AC in: bone (absorption and reflection)
air/lung (scatter)