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)
Transoesophageal Echocardiography

Fig. 1.1

Period (s)
Amplitude (kPa, g/l, K, m, dB)
Power (W)
Intensity (W/cm²)

Propagation speed (\( v \) or \( c \))
\[ c = \text{speed of sound} \quad \text{Units} = \text{m/s or mm/µs} \]
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

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Speed of sound (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>331</td>
</tr>
<tr>
<td>Lung</td>
<td>500</td>
</tr>
<tr>
<td>Fat</td>
<td>1450</td>
</tr>
<tr>
<td>Brain</td>
<td>1541</td>
</tr>
<tr>
<td>Liver</td>
<td>1549</td>
</tr>
<tr>
<td>Muscle</td>
<td>1585</td>
</tr>
<tr>
<td>Bone</td>
<td>&gt;3000</td>
</tr>
</tbody>
</table>

Frequency (f)

\[ f = \text{number of cycles per second} \quad \text{Units} = \text{Hz}\]

U/S > 20 kHz

Determined by sound source

Affects penetration and axial resolution

Period (T)

\[ T = \text{length of time to complete one cycle} \quad \text{Units} = \text{s}\]

U/S = 0.1–0.5 µs

Determined by sound source

Reciprocal of frequency \( T = 1/f \)

Wavelength (λ)

\[ \lambda = \text{distance occupied by a single cycle} \quad \text{Units} = \text{m}\]

U/S = 0.1–0.8 mm

Determined by sound source and medium

\( \lambda \) influences axial resolution

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

\[ v = f\lambda \]
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**Amplitude**

\[ A = \text{max. variation in acoustic variable} \]

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. \( \uparrow \text{ by 30 dB} = \uparrow A \text{ by } 10 \times 10 \times 10 (\times 1000) \)

Determined by sound source

Changed by sonographer

Amplitude decreases as sound wave travels = **attenuation** (Fig. 1.3)

**Power** (\( P \))

\[ P = \text{rate of work/rate of energy transfer} \]

Units = W
Two cycles/pulse ‘on’ ‘off’

**Fig. 1.4**

Determined by sound source
Changed by sonographer

\[ P = A^2 \]

**Intensity (I)**

\[ I = \text{concentration of energy/power in a sound beam} \]

Units = W/cm\(^2\)

Determined by sound source
Changed by sonographer

U/S \[ I = 0.1–100 \text{ mW/cm}^2 \]

\[ I = P/\text{area} \]

**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)
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**Fig. 1.5**

- spatial pulse length (SPL)
- duty factor (DF)

**Pulse duration (PD)**

\[
PD = \text{time from start of one pulse to end of pulse} \quad \text{Units} \quad s
\]

- = ‘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 \quad PD = 0.5–3 \mu s

\[
PD = \text{number of cycles} \times T \quad PD = \text{number of cycles}/f
\]

**Pulse repetition frequency (PRF)**

\[
\text{PRF} = \text{number of pulses per second} \quad \text{Units} \quad \text{Hz}
\]

(Number of cycles per pulse not relevant)

Determined by sound source

Changed by sonographer by changing image depth

As image depth increases \(\rightarrow\) PRF↓

Sonographer ↑‘dead’ time by ↑image depth \(\rightarrow\) ↓PRF

TOE \quad \text{PRF} = 1–10 kHz

\[
\text{PRF(kHz)} = 75/\text{depth (cm)}
\]
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

\[\text{PRP (µs)} = 13 \times \text{depth (cm)}\]

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)

\[\text{DF} = \text{PD/PRP}\]

↑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
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)
Physics of ultrasound

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
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(i) Specular reflections

U/S Specular reflection
Smooth surface

U/S with small SPL Specular reflection
Rough surface

(ii) Scatter

U/S with high SPL Scatter
Rough surface

U/S with SPL >> rbc Rayleigh scattering

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: \( f \rightarrow AC \)

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

Total attenuation = \( AC \times \text{path length (cm)} \)

↑AC in: bone (absorption and reflection)
    air/lung (scatter)