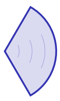
# Medical Physics

A2 Physics ▪ Topic 24

A-Level Physics





## What we will cover



# 1 Ultrasound



## Piezo-electric – two linked effects

A **piezo-electric** 压电 crystal (quartz, PZT) changes shape when a p.d. is put across it, and makes an e.m.f. when its shape is changed.

apply a p.d. → crystal changes shape

squeeze it → an e.m.f. appears

**apply a p.d.**

the crystal vibrates – used to make ultrasound

**squeeze it**

an e.m.f. appears – used to detect ultrasound



## One transducer both sends and listens

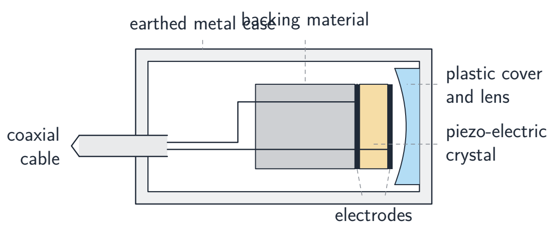
An alternating p.d. (a few MHz) makes the crystal vibrate, sending **longitudinal** 纵波 waves above $20\,\mathrm{kHz}$ ($1$–$10\,\mathrm{MHz}$ for imaging). Returning ultrasound makes it vibrate and produce an e.m.f.

> One transducer switches between sending and listening. **Coupling gel** 耦合剂 pushes out the air – without it almost all the ultrasound would reflect at the skin.



## Inside the transducer

The crystal sits between a damping block (to kill ringing so pulses stay short) and a matching layer (to cut the reflection at the skin).



## Pulse-echo: depth from the time delay

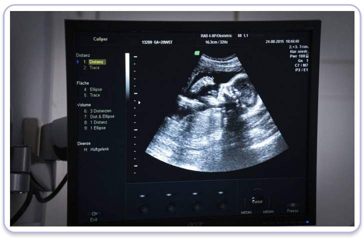
1. send a short pulse
2. at each tissue boundary, part reflects and part goes on
3. detect each echo
4. depth $d = ct/2$ (there and back); amplitude $\Rightarrow$ strength of the reflection

**Echo after $60\,\mu s$; $c = 1500\,\mathrm{m\,s^{-1}}$**

$$d = \frac{ct}{2} = \frac{1500 \times 60 \times 10^{-6}}{2} = 0.045\,\mathrm{m}\ (4.5\,\mathrm{cm})$$



## What the operator sees



A B-scan builds a 2-D image from many pulse-echo lines swept across the body.



## Specific acoustic impedance

$$Z = \rho c$$

Unit $\mathrm{kg\,m^{-2}\,s^{-1}}$. Bone has large $Z$; air has small $Z$; soft tissue is in between. At a boundary the intensity reflection coefficient is

$$\frac{I_R}{I_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

Very different $Z$: almost all reflected (skin/air – hence the gel). Very similar $Z$: the boundary cannot be seen.



## Attenuation – intensity falls exponentially

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

$\mu$ is the **attenuation coefficient** 衰减系数. The same form applies to X-rays.

# 2 X-rays

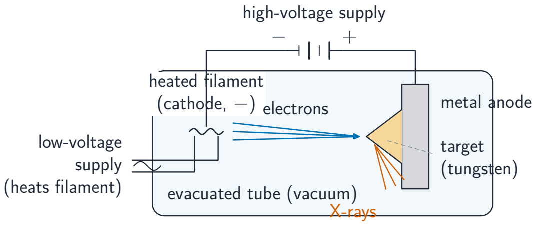


## How an X-ray tube works

1. heated **cathode** 阴极 emits electrons by **thermionic emission** 热电子发射
2. a high p.d. accelerates them across a vacuum to a metal **anode** 阳极 (often tungsten)
3. they slow sharply: most KE becomes heat; a small part is X-ray photons (**Bremsstrahlung** 韧致辐射). Knocking out inner electrons gives **characteristic** 特征 lines.

## The X-ray tube

Most of the electrons' kinetic energy becomes heat; a small part leaves as X-ray photons, so the anode is angled and cooled.






## Minimum wavelength and imaging

The most energy one photon can have is $eV$:

$$hf_{\max} = eV, \qquad \lambda_{\min} = \frac{hc}{eV}$$

Bone (high $Z$) attenuates more and looks lighter; soft tissue looks darker. A **contrast medium** 造影剂 (barium meal) makes soft tissues stand out. Half-value thickness $x_{1/2} = \ln 2/\mu$ halves the intensity.

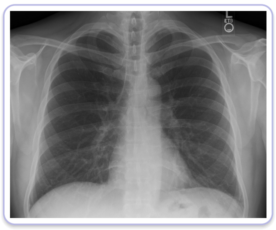
$x = 3.0\,\mathrm{cm}$, $\mu = 40\,\mathrm{m}^{-1}$

$I/I_0 = e^{-40\times 0.030} = e^{-1.2} \approx 0.30$



## Why bone shows white

Dense bone (high $Z$) absorbs strongly and leaves the film unexposed; the air-filled lungs let X-rays through and darken it.





## CT – many angles, then a computer

**Computed tomography** 计算机断层扫描:

1. tube and detectors rotate, imaging one thin slice from many angles
2. a computer combines them into a 2-D cross-section
3. the patient is moved; the next slice is imaged
4. slices stack into a 3-D image

> Overlapping soft tissues that hide each other on a single X-ray are separated by the many-angle reconstruction.

# 3 PET scanning



## A $\beta^+$ tracer, then annihilation

A **tracer** 示踪剂 (often FDG, fluorine-18 on a glucose analogue) is taken up more by active tissue. In PET it is a $\beta^+$ emitter – it gives out a **positron** 正电子. The positron meets an electron and they **annihilate** 湮灭: two photons, opposite directions, each $511\,\mathrm{keV}$ ($= m_e c^2$).

$$2hf = 2m_e c^2$$

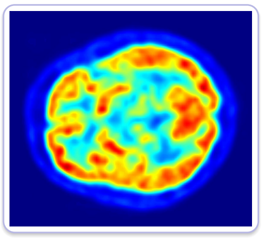
## A coincidence fixes the line

The two photons hit detector rings around the patient. Two simultaneous arrivals (a coincidence) fix the line the annihilation lay on. Many coincidences from many angles build a 3-D map of the tracer – tissues with high metabolic activity.

> Comparing arrival times can refine the position along that line (time-of-flight PET).



## A finished PET image



Warm colours mark where the tracer collected — the most metabolically active tissue.

# 4 Recap



## Topic 24 – key takeaways

1. **Ultrasound**
   piezo; $d = ct/2$; gel; $Z = \rho c$
2. **X-rays**
   $\lambda_{\min} = hc/eV$; $I = I_0 e^{-\mu x}$
3. **CT**
   many angles of one slice, then stack
4. **PET**
   two $511\,\mathrm{keV}$ photons; coincidence line



## Check yourself

1. Why $d = ct/2$, not $ct$?
2. Why put gel between the transducer and the skin?
3. What sets $\lambda_{\min}$ of an X-ray spectrum?
4. Why do PET photons fly in opposite directions?

> **Answers** **1.** there and back **2.** air/skin reflects almost everything **3.** $hf_{\max} = eV$ **4.** momentum conservation (pair at rest)