超音波影像
Ultrasonography

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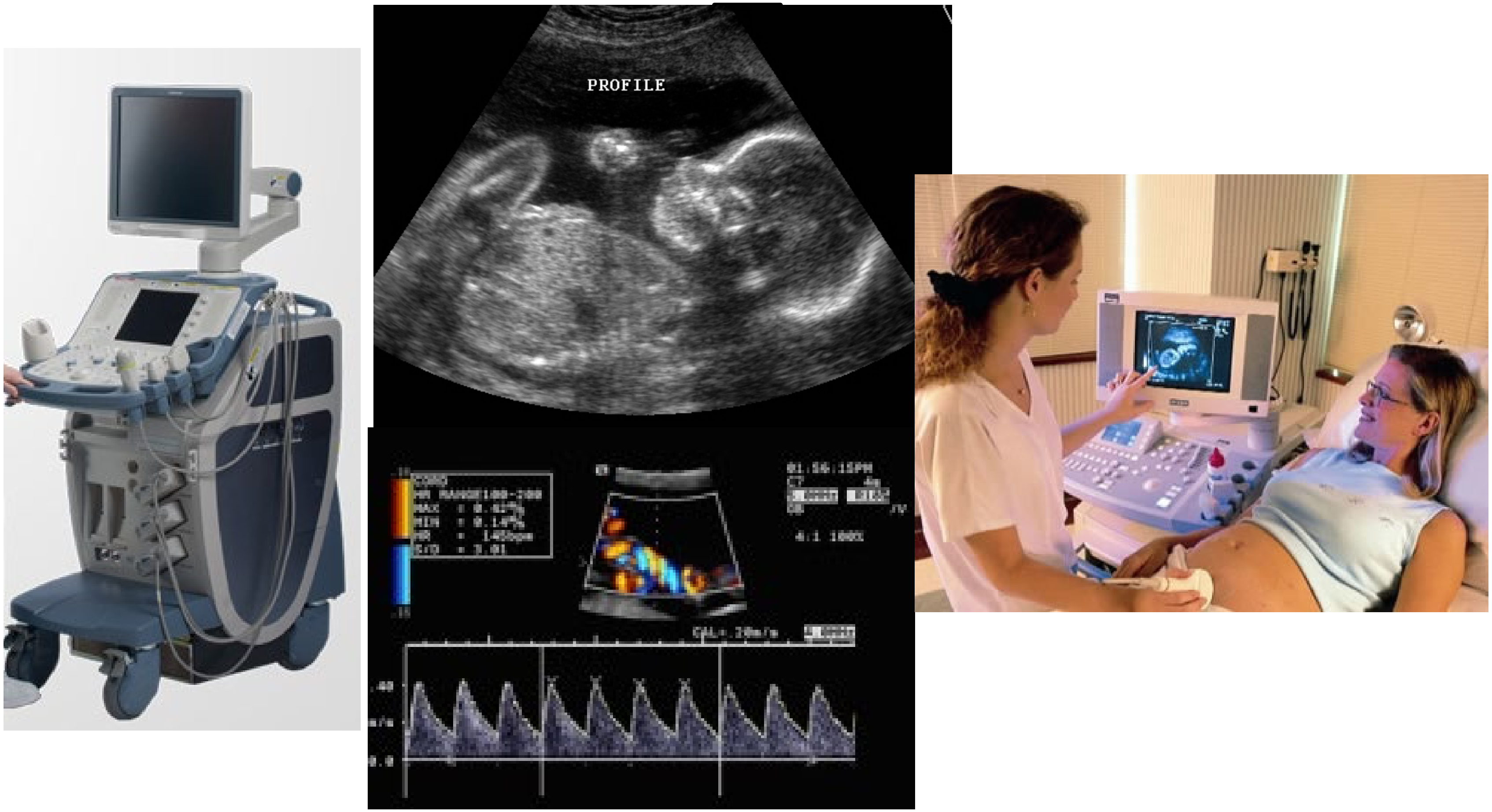
中山電機系

典型超音波系統與影像



What is Ultrasound?

Ultra-sound
超　音波

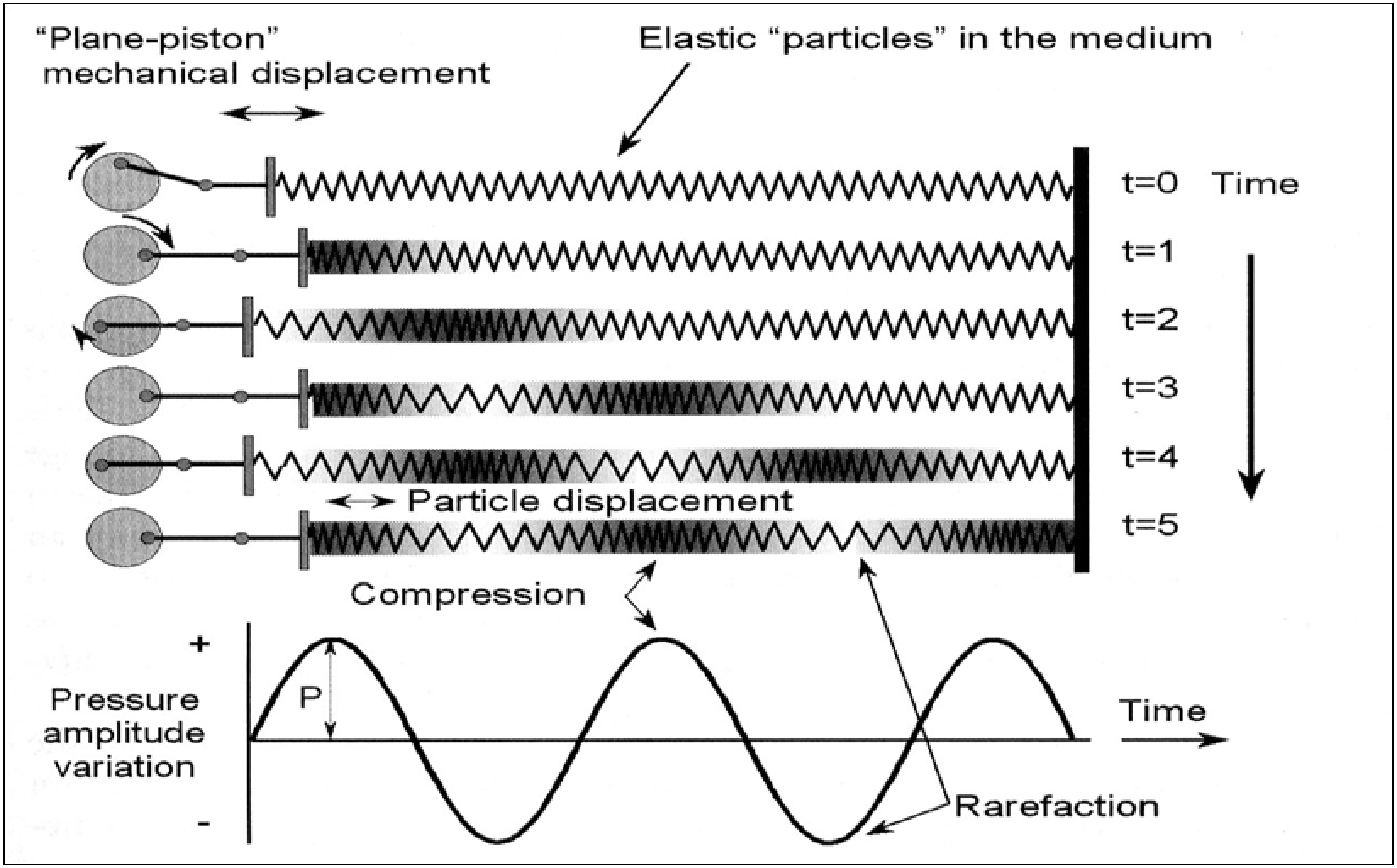
- 一般聲頻：15 Hz ~ 20 kHz
- 超音波：＞20 kHz
- 醫用超音波：2 ~ 10 MHz

聲波/超音波特性

- 機械波 (Mechanical wave)
  - 透過介質的局部振動傳遞波動：介質波

- 依介質振動和波傳遞方向的關係可分
  - 縱波：介質為氣體、液體
  - 橫波：固體、黏滯性強的液體

聲波的傳遞


"Plane-piston"
mechanical displacement
Elastic "particles" in the medium
t=0
Time
t=1
t=2
t=3
t=4
t=5
Particle displacement
Compression
+
P
Pressure
amplitude
variation
-
Time
Rarefaction

波速

- Sound velocity

$$C = \lambda f$$

  - C: 聲波波速
  - λ: 波長
  - f: 頻率

- 空氣中聲波的速度？

傳遞介質的影響

- 波速會受到介質所影響

$$C = \sqrt{\frac{B}{\rho}}$$

  - B: bulk modulus, kg/m-sec^2, 描述物質彈性
  - ρ: density, kg/m^3, 介質密度

人體各組織的波速

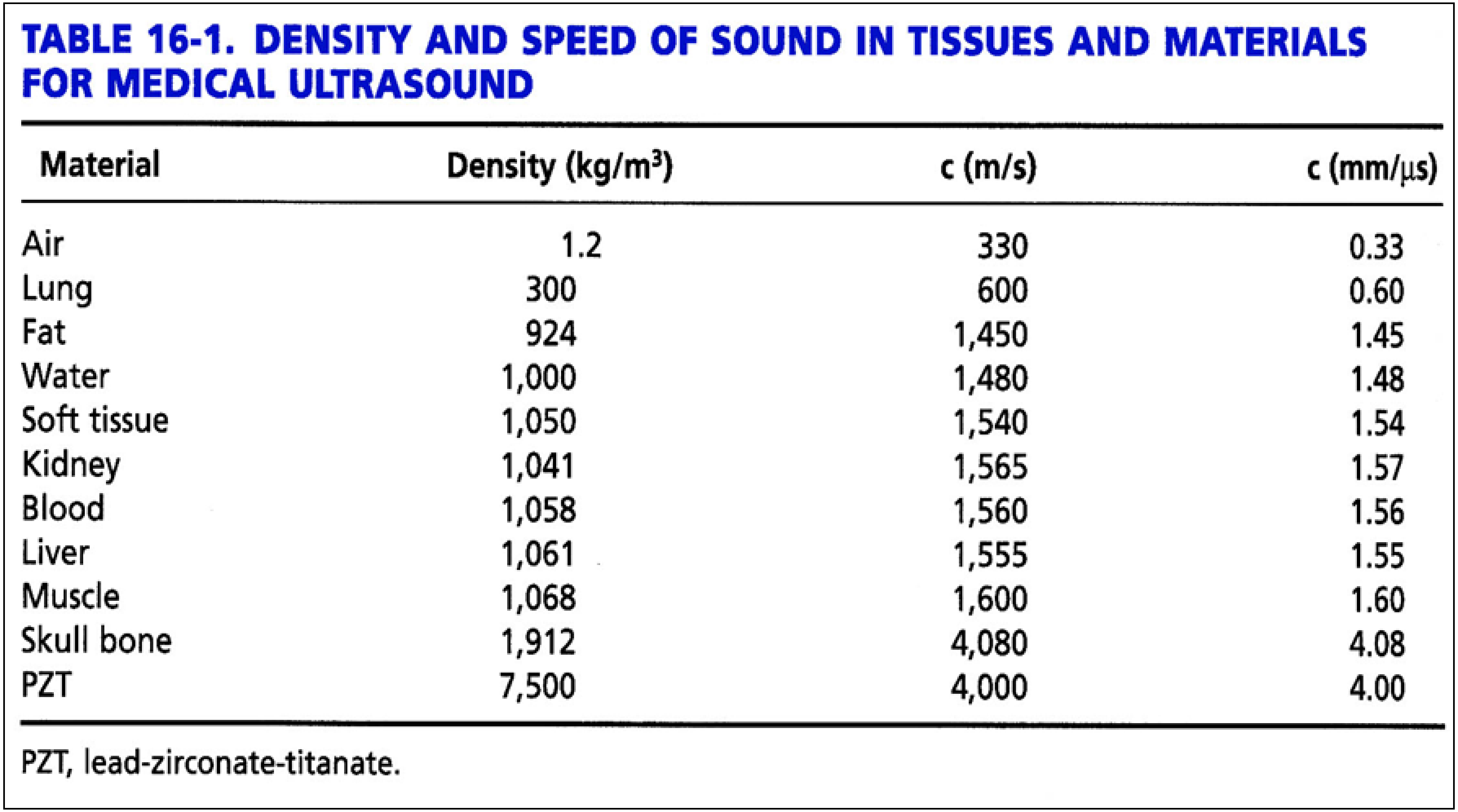


TABLE 16-1. DENSITY AND SPEED OF SOUND IN TISSUES AND MATERIALS FOR MEDICAL ULTRASOUND

Material	Density (kg/m³)	c (m/s)	c (mm/μs)
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

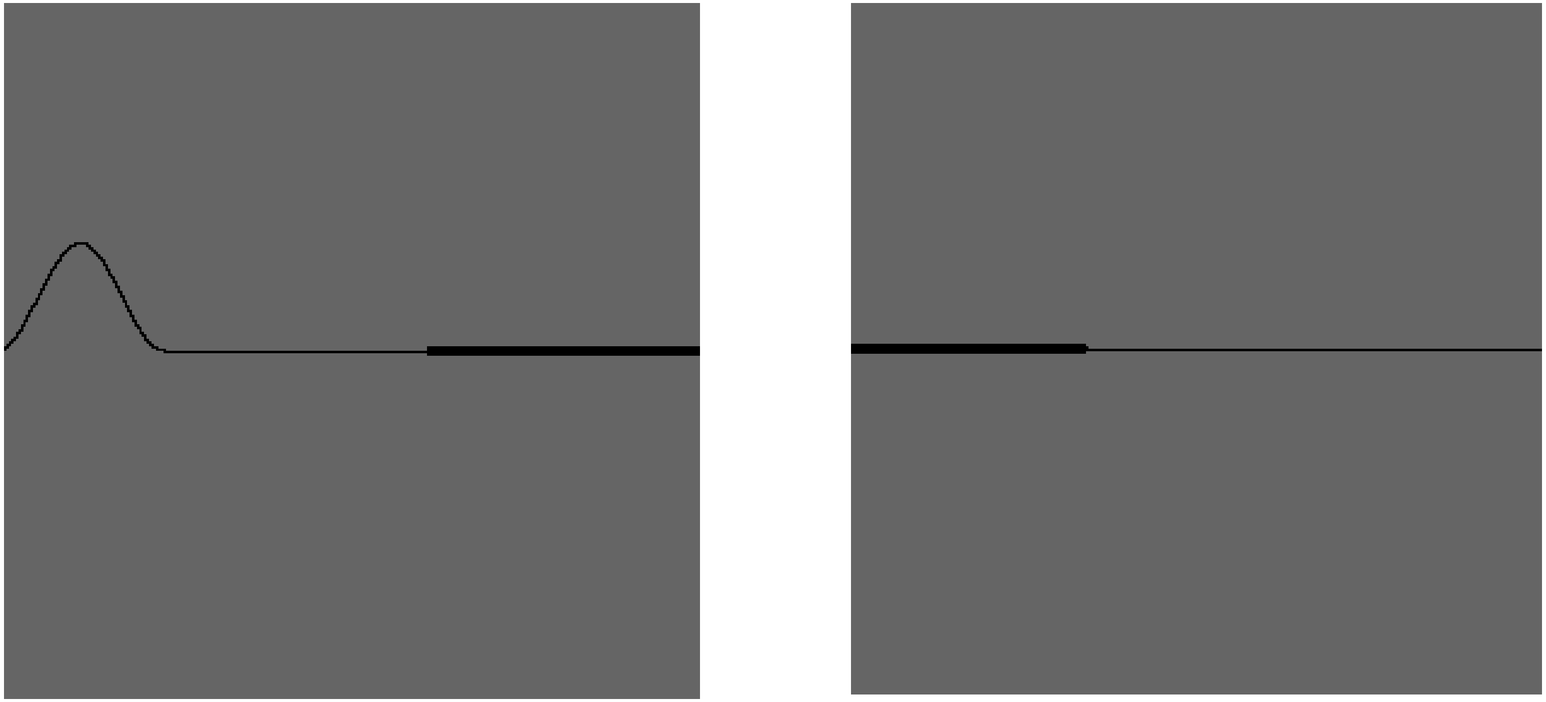
PZT, lead-zirconate-titanate.

超音波在介質傳遞的特性

- 在不同介質中傳遞
  - 頻率不變，聲速與波長改變

- 反射 (Reflection)
- 折射 (Refraction)
- 散射 (Scattering)
- 衰減 (Attenuation)

簡單波反射示意圖

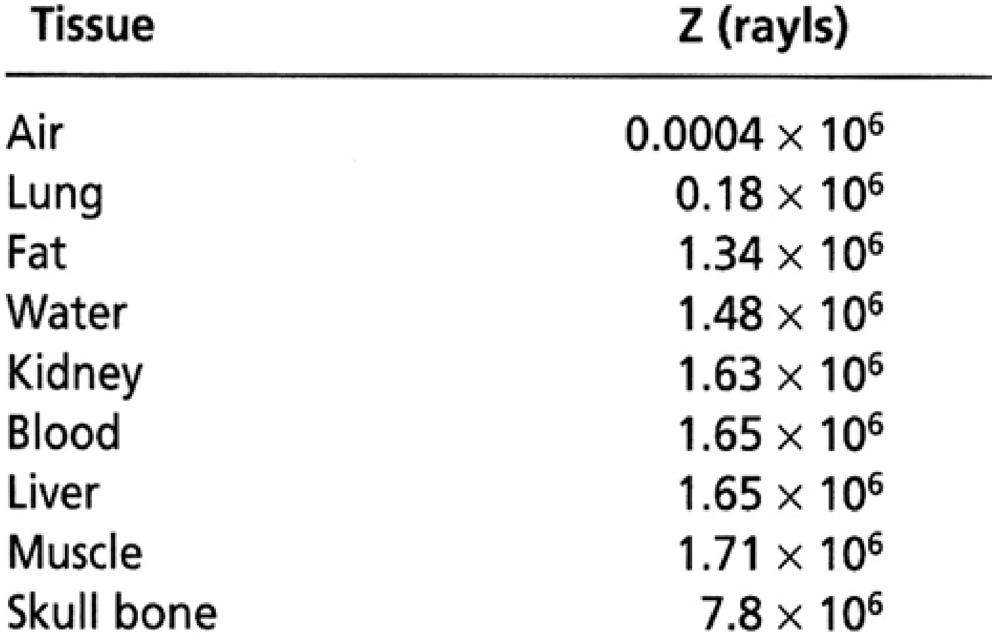


普物應該提過吧...

Reflection

- 波進入不同的物質會產生反射
- Acoustic impedance

$$Z = \rho \cdot C = \sqrt{B\rho}$$

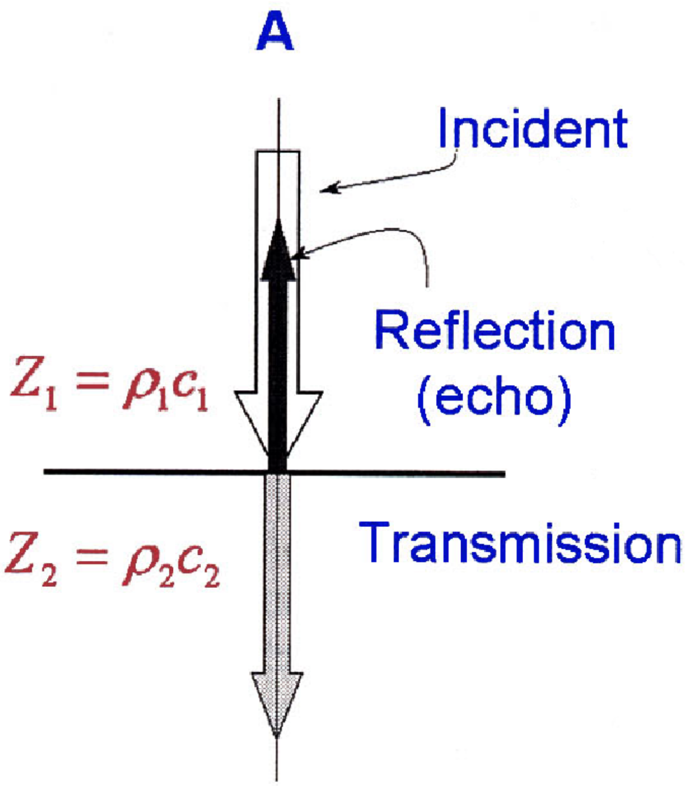


Tissue	Z (rayls)
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

其實跟電路震盪系統類似

Electrical circuit	Pressure wave
Charge (q) 電荷	Displacement (d) 位移
Voltage (V) 電壓	Pressure (p) 壓力
Current (I) 電流	Particle velocity (v) 介質粒子速度
Resistance (R) 電阻	Impedance (Z) 阻抗
Power ($P = VI$) 功率	Intensity ($I = p^2/Z$) 能量

Reflection/transmission coefs.



- Conservations at interface

Particle velocity

$$\frac{p_i}{Z_1} = \frac{p_t}{Z_2} + \frac{p_r}{Z_1}$$

Intensity

$$\frac{p_i^{\,2}}{Z_1} = \frac{p_t^{\,2}}{Z_2} + \frac{p_r^{\,2}}{Z_1}$$

- Reflection coefficient

$$R_c = \frac{p_r}{p_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

- Transmission coefficient

$$T_c = \frac{p_t}{p_i} = \frac{2Z_2}{Z_2 + Z_1}$$

如果超音波直接由空氣進入人體

$$\because \frac{Z_{air}}{Z_{tissue}} \approx \frac{0.0004}{1.6} = 2.5\times10^{-4}$$

and $$R_c = \frac{Z_{tissue} - Z_{air}}{Z_{tissue} + Z_{air}}$$

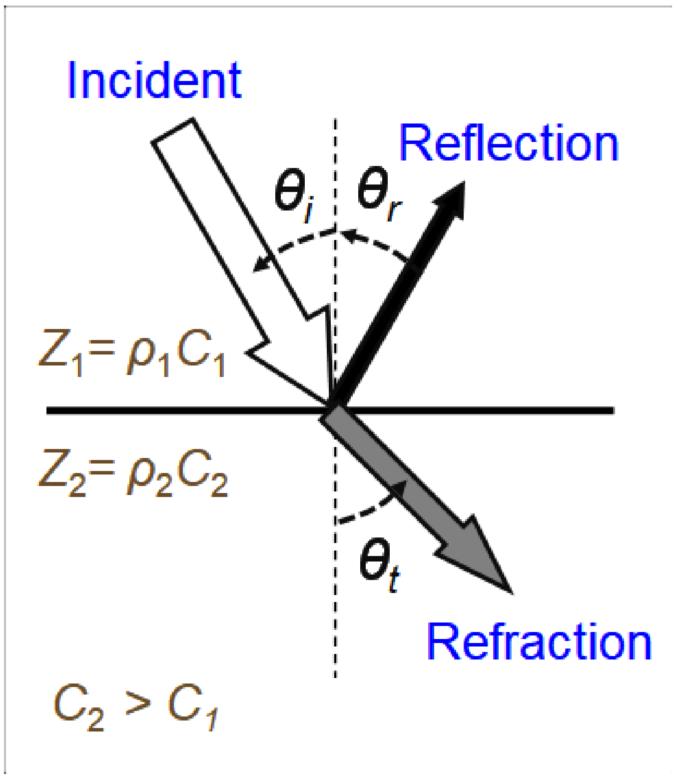
$$\therefore \frac{I_{reflection}}{I_{incident}} = \left(\frac{Z_{tissue} - Z_{air}}{Z_{tissue} + Z_{air}}\right)^2 \sim 99.9\%$$

只有30 dB 的訊號進入人體，有打跟沒打一樣！
再加上探頭 (PZT材質，阻抗超大)…

做超音波檢查都需要傳導膠

避免探頭與人體間的空氣造成過大反射

Refraction



Snell's Law

$$\frac{C_1}{C_2} = \frac{\sin\theta_i}{\sin\theta_t}$$

- Conservations at interface

$$\frac{p_i \cos\theta_i}{Z_1} = \frac{p_t \cos\theta_t}{Z_2} + \frac{p_r \cos\theta_i}{Z_1}$$

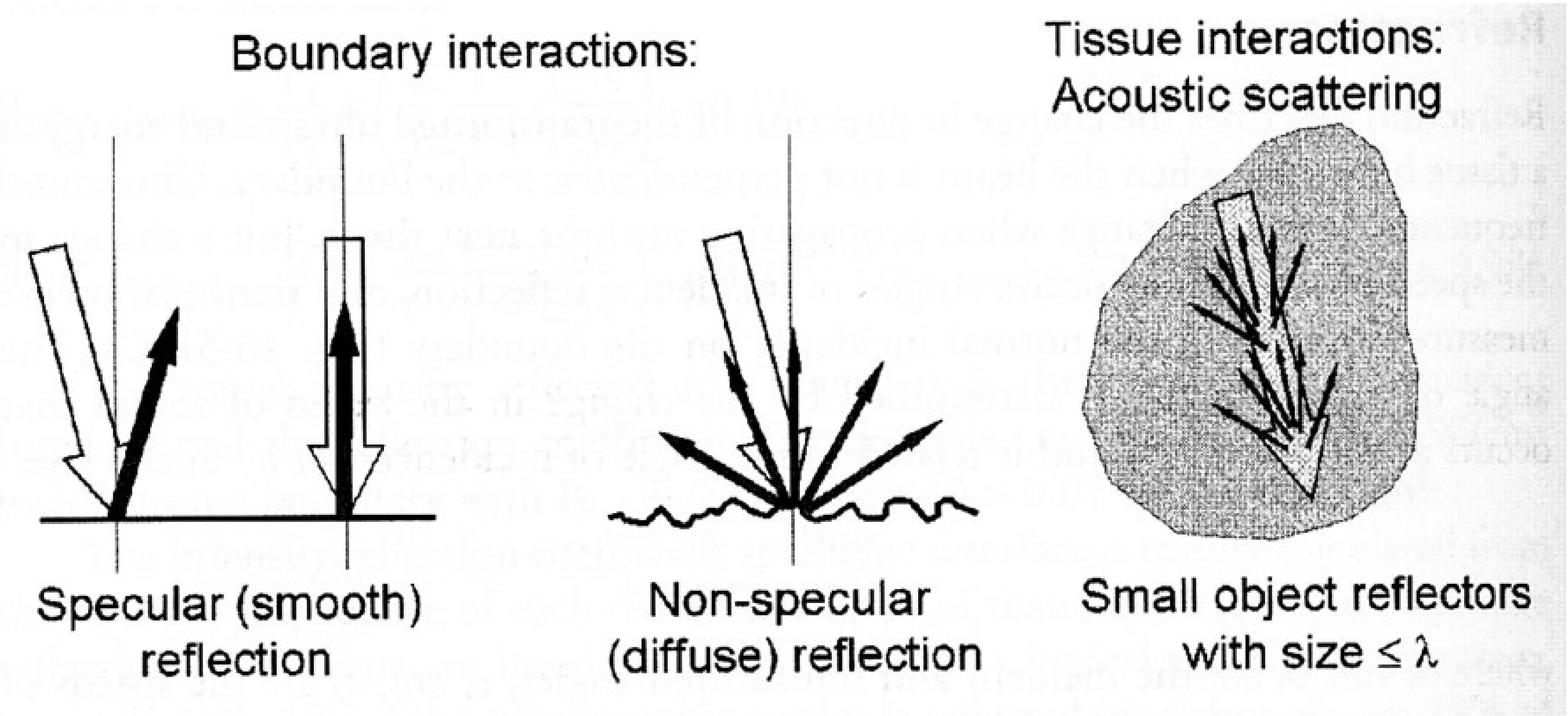
- Reflection coefficient

$$R_c = \frac{p_r}{p_i} = \frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}$$

- Transmission coefficient

$$T_c = \frac{p_t}{p_i} = \frac{2 Z_2 \cos\theta_i}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}$$

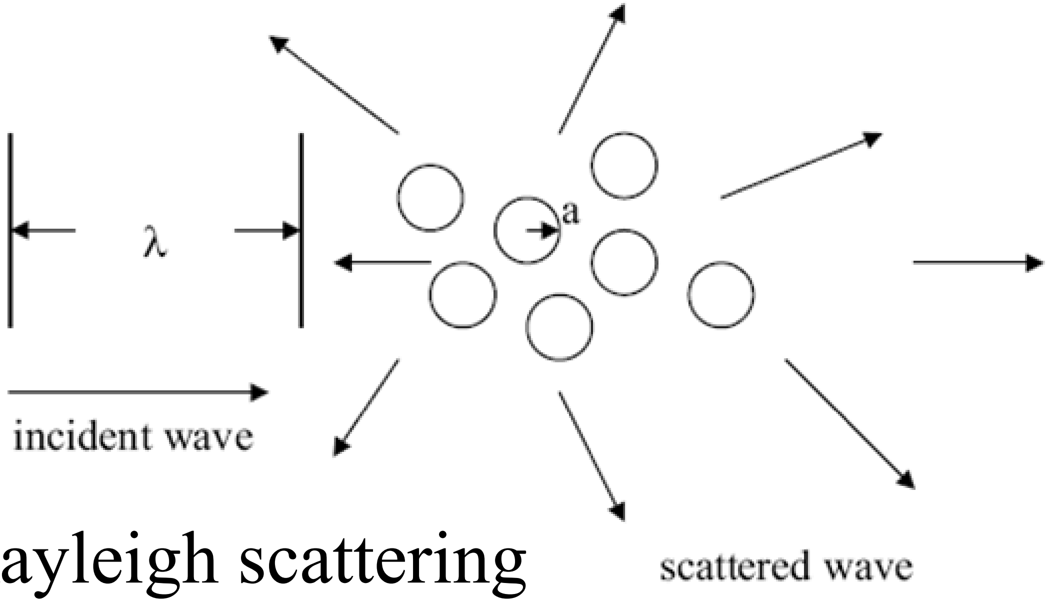
Scattering



臨床超音波的波長？

Ultrasonic scattering in bio-tissues

- 發生於波長大於散射源 (scatterers)時
  - 人體軟組織的散射源約小於100 μm

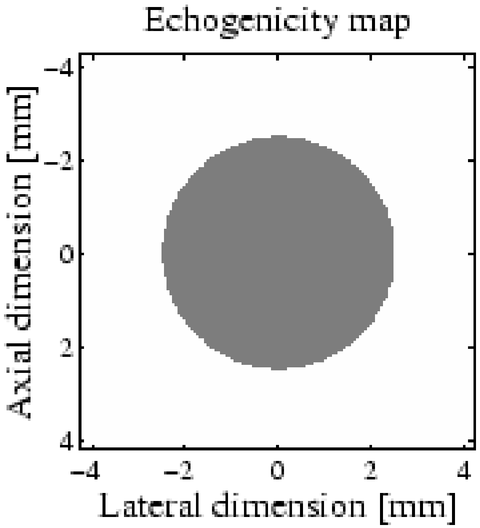


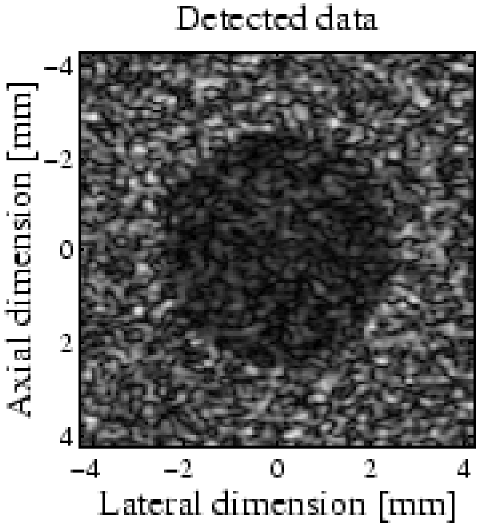
Rayleigh scattering

Ultrasonic scattering in bio-tissues

- 超音波在隨機散佈的散射源中產生許多散射
  - Backscattering
  - Coherent interference of scatterers
  - Linear summation of all scattering
- 散射的程度和散射源的大小與組織特性有關

Speckle


Echogenicity map


Detected data

為什麼超音波影像總是有點模糊？

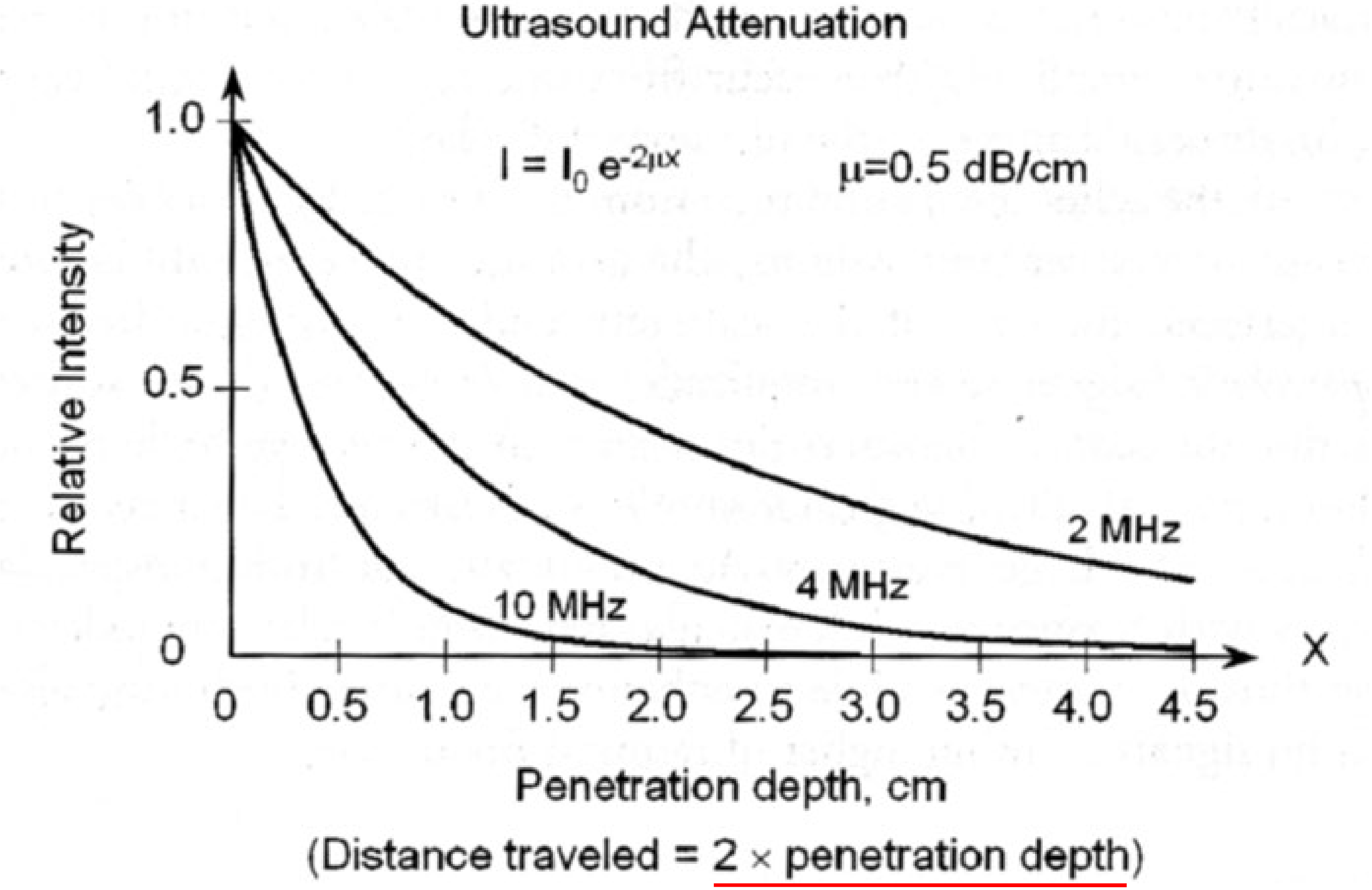
Speckle noise

- 超音波散射會產生班點狀雜訊(speckle)
  - 影響低對比影像的判讀
- 與組織特性有關，但與散射源的幾何分佈無關
- Multiplicative noise
  - 一般超音波影像大約為 4.34 dB

Attenuation

- 由組織吸收(mainly)和散射所造成！
- 介質粒子受壓力波作用過程將部分能量吸收，轉換成熱能
- Attenuation coefficient (*μ*)
  - Attenuation (of intensity) in soft tissue：0.5~1 dB/cm-MHz
  - 頻率越高，衰減速度越快

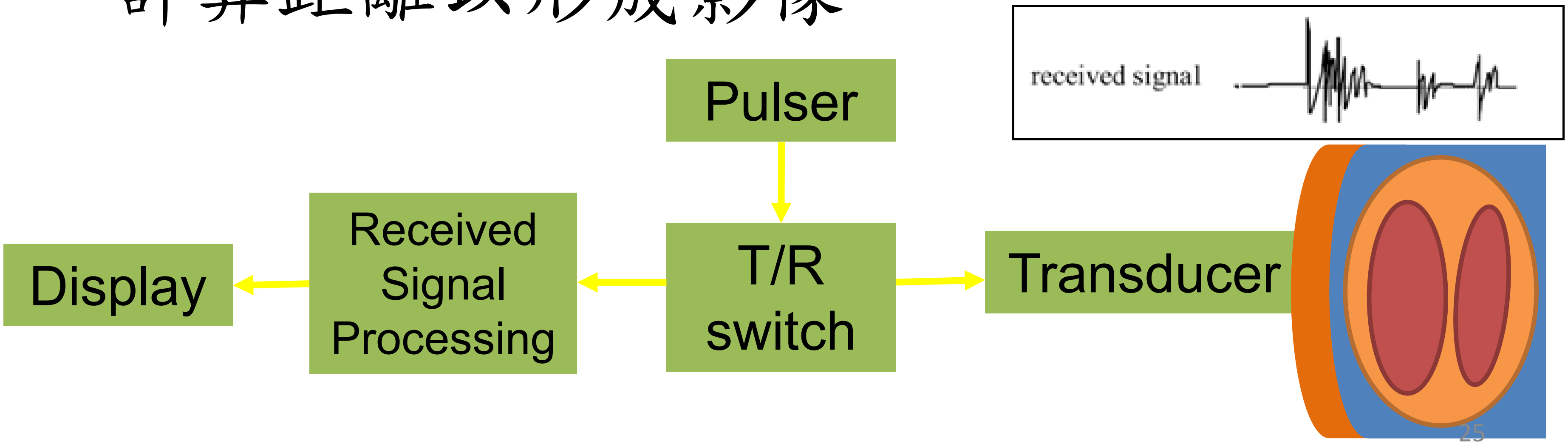
Attenuation



超音波影像原理

超音波影像原理

- 超音波發射源
- 組織介面形成反射
- 接收器接收反射波
- 計算距離以形成影像



received signal

Pulser

T/R switch

Transducer

Received Signal Processing

Display

超音波影像原理

- **超音波發射源**
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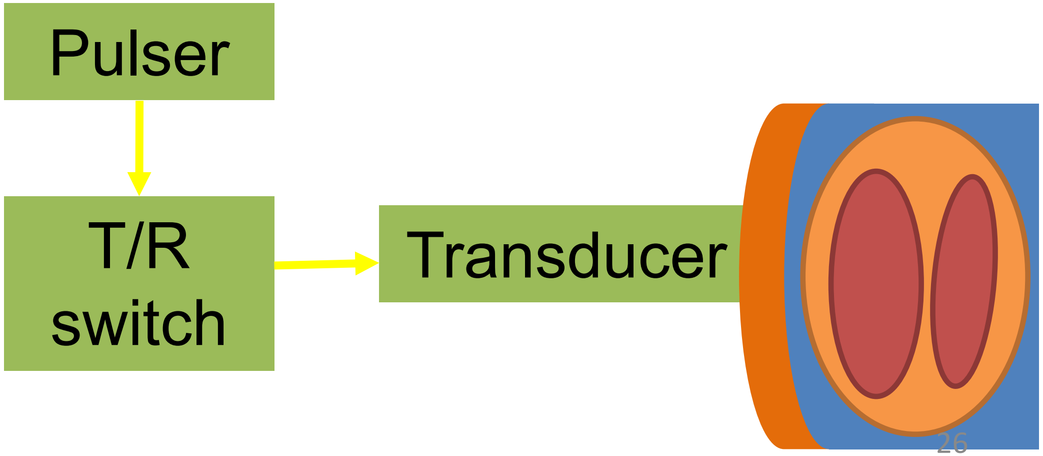
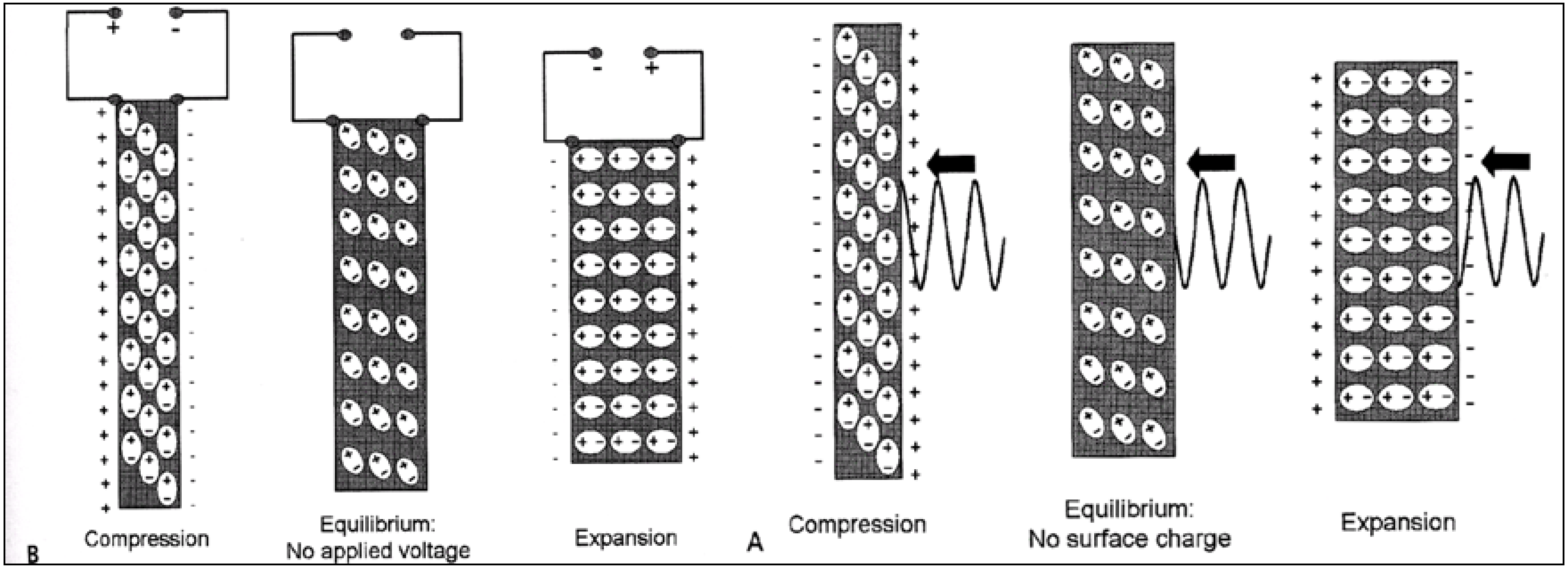


超音波發射源與接收器

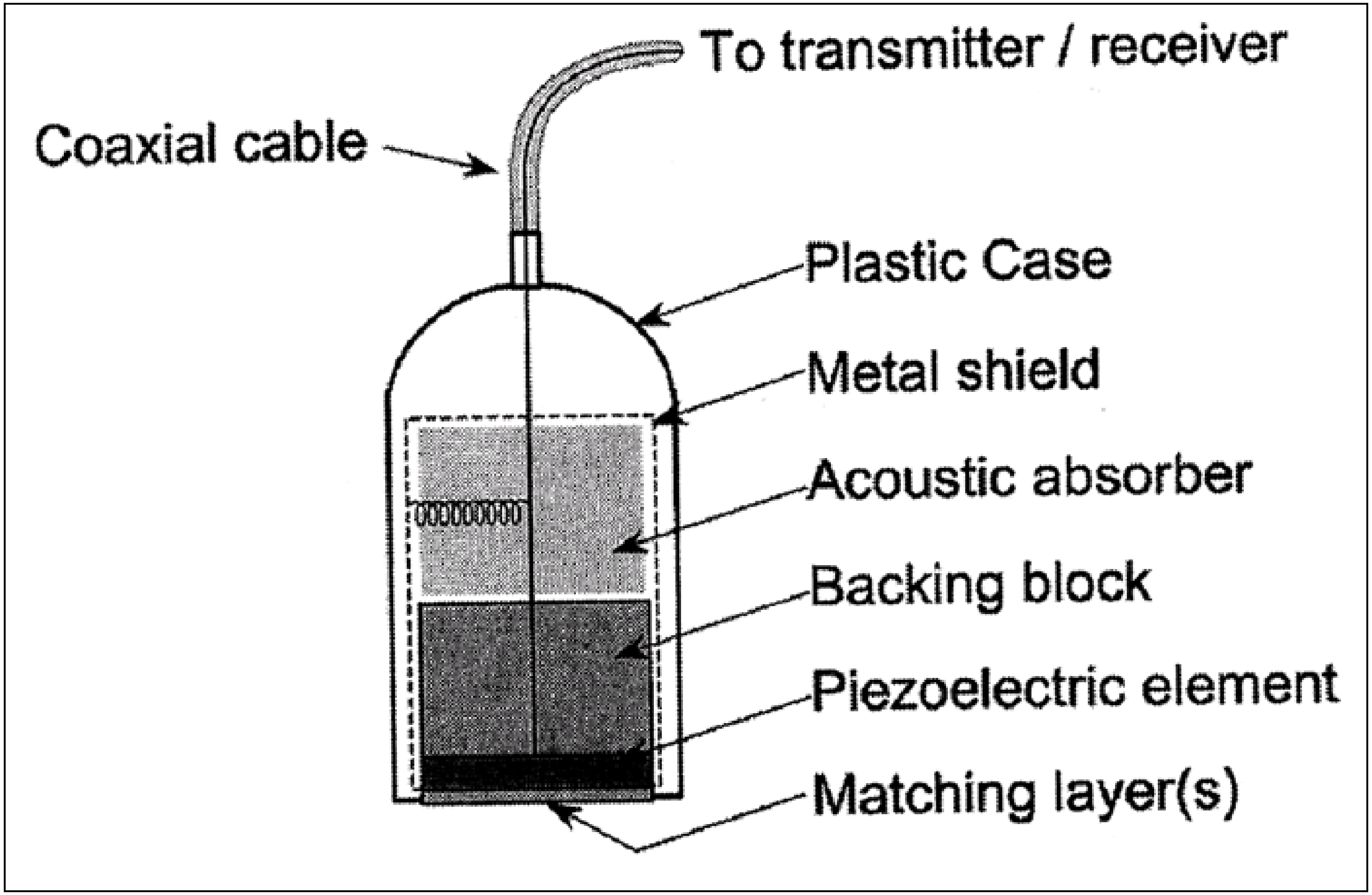
- 探頭 (probe, transducer)
  - 壓電 (piezoelectric) 效應
  - 電壓 ←→ 機械波
  - Lead zirconate-titanates (鋯鈦酸鉛, PZT)
- 發射訊號：電訊號→超音波
- 接收訊號：超音波→電訊號

壓電效應材料示意圖



「形變」造成「電壓」，反之亦然

超音波探頭原理

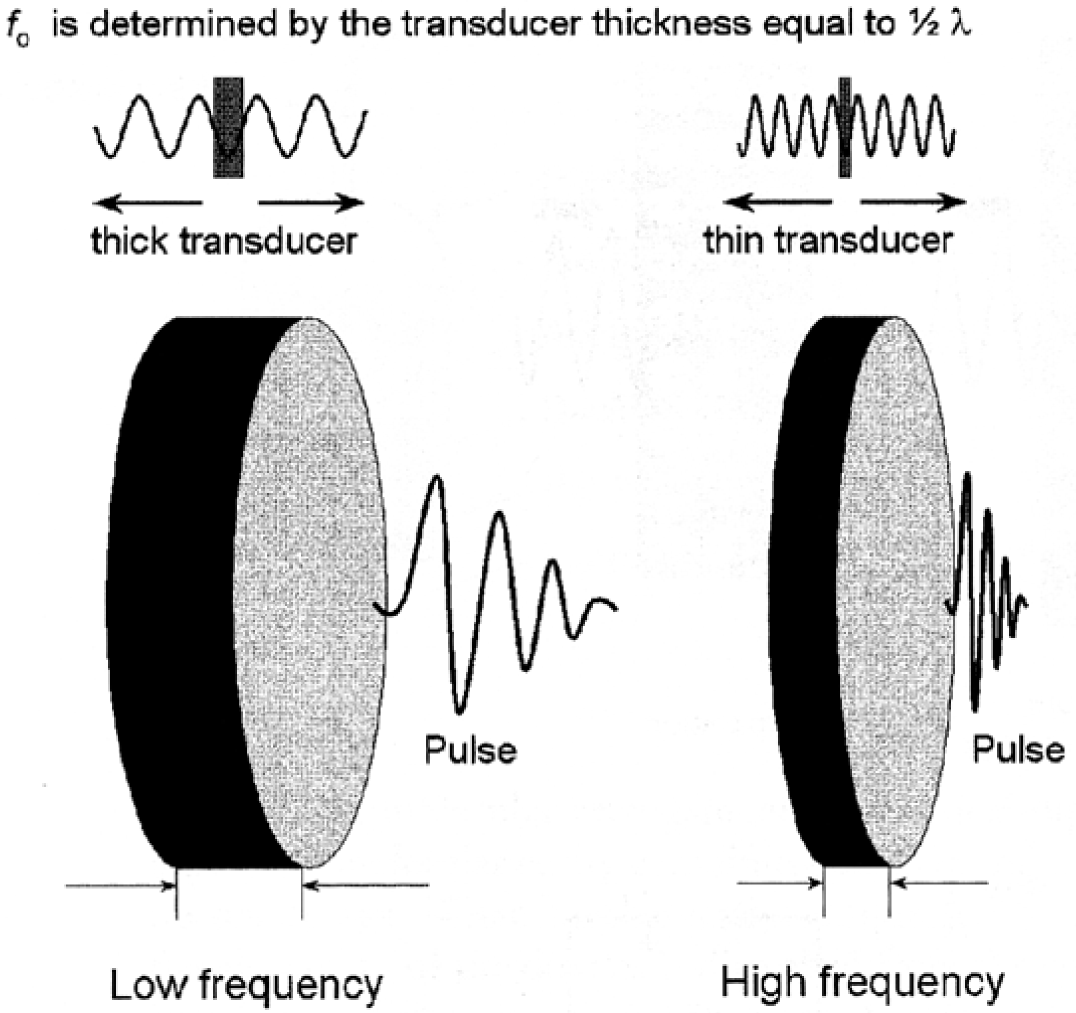


雙向轉換：發射器與接收器相同！

Resonance in Piezoelectric materials

- 壓電材料產生的弦波訊號在自體產生共振
  - Fundamental resonance frequency (f_0)
- 共振頻率與材料厚度有關
  - $\lambda_0 = C/f_0 = 2d_T$
- 每個探頭都有自己的共振頻率

Resonance frequency of transducer



Question.

What is the thickness of the PZT layer in a 10-MHz ultrasound transducer? (sound speed in PZT = 4000 m/sec)

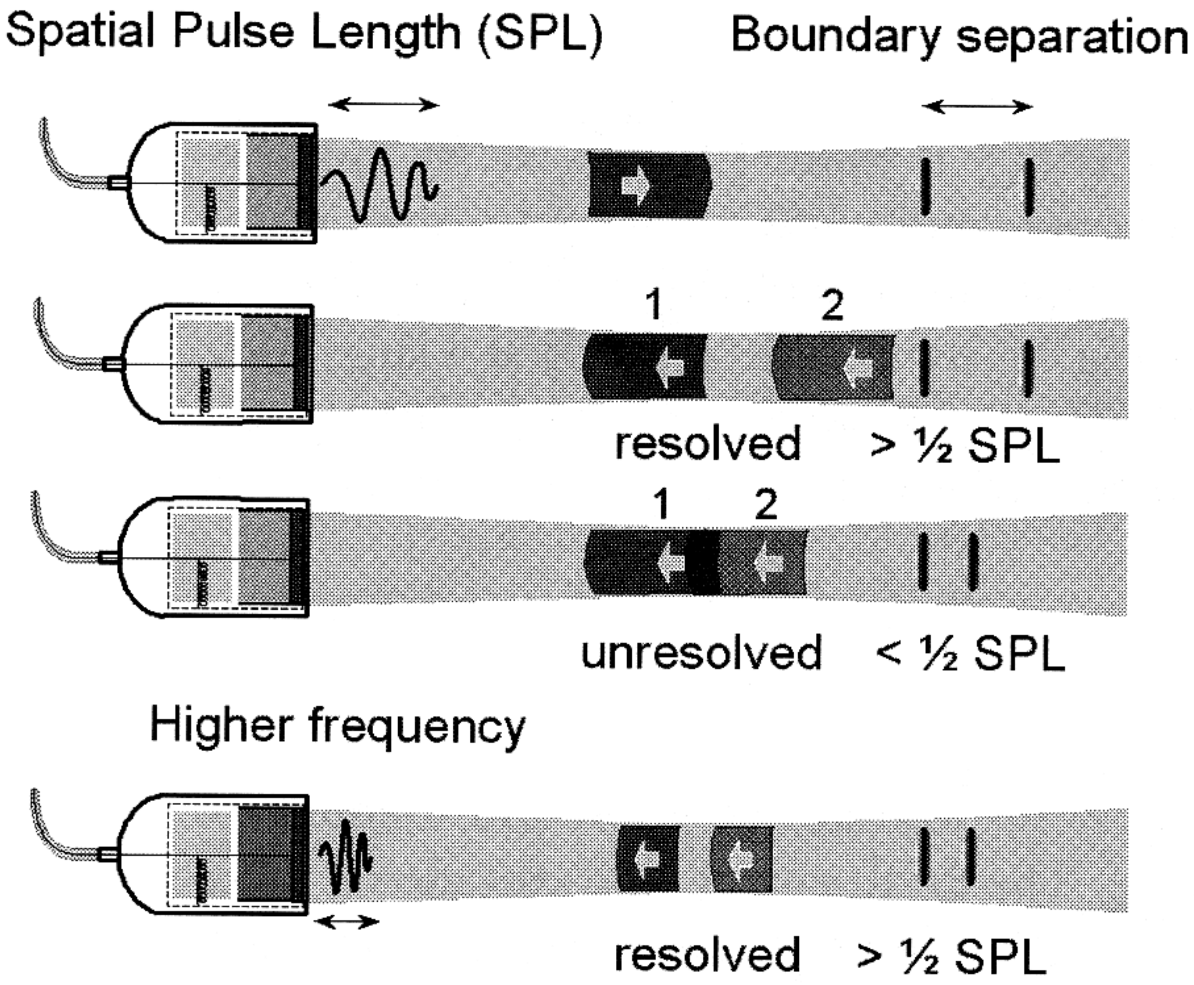
Matching layer

- 壓電材料與人體的阻抗相差數十倍
- 直接接觸 → 超音波無法有效送入人體
- Matching layer 增加入射效率
  - 單層或多層結構
  - 根據中心頻率決定厚度

總算可以把超音波送入人體了...

- 送入脈衝(pulse)，等待回波(echo)
- 根據回波的時間與強度成像
  - Pulse Echo Imaging
- 脈衝時間越短，軸向解析度(Axial resolution) 越好
  - Wide band signal

Axial resolution



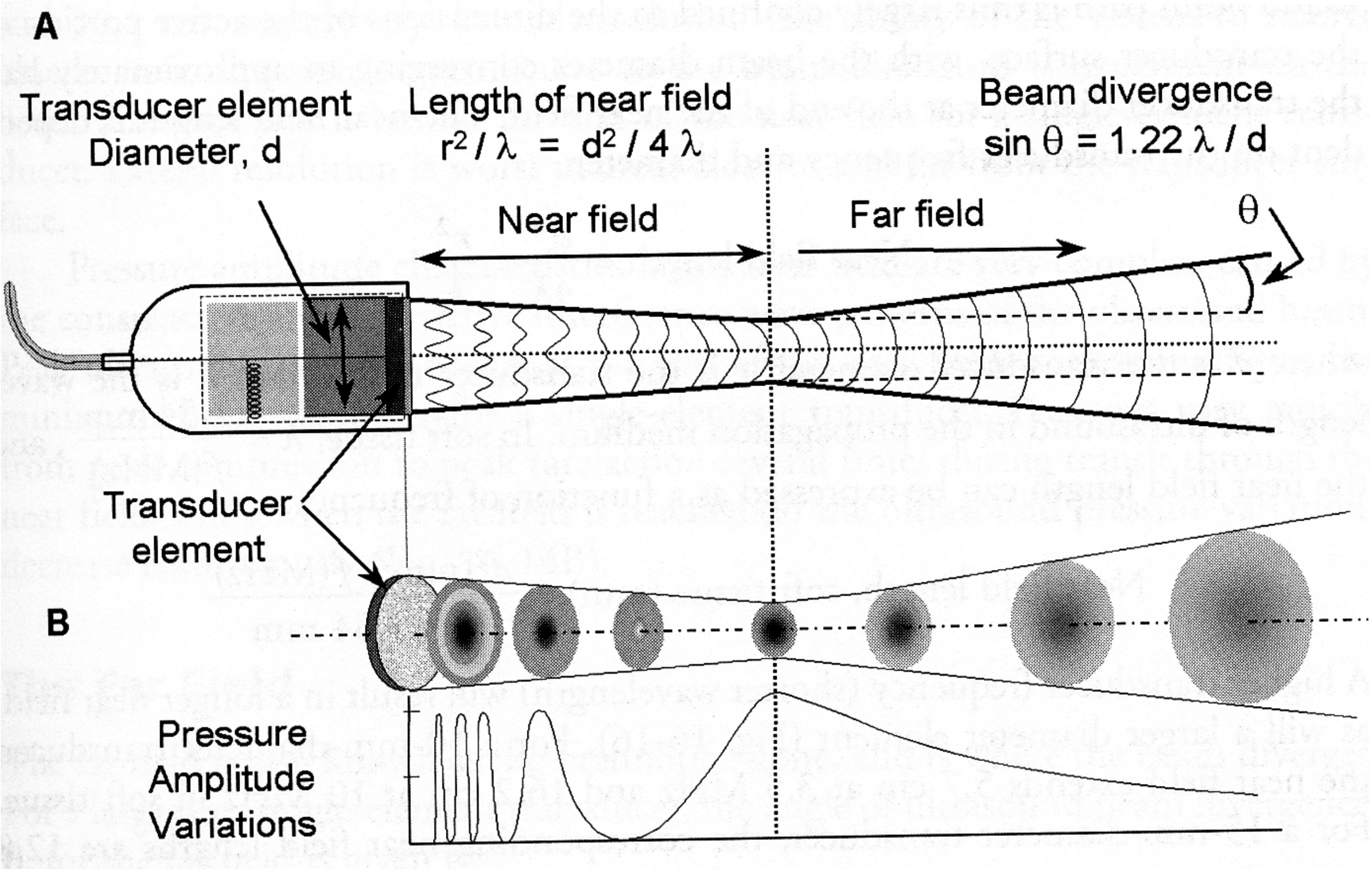
超音波脈衝

- 為了有良好的軸向解析度，每個脈衝多半由2-3個週期所組成
- 探頭需要有良好的減振(high damping)，才能有效控制脈衝長度

超音波波束成型(beam formation)

- 單一平板(single-element)探頭寬度有限
- 近場(near field, or Fresnel field)
  - 振幅與相位隨位置變化快速
  - 不適合成像
- 遠場(far field, or Fraunhofer field)
  - 振幅與相位變化小
  - Lateral beam width 隨深度增加

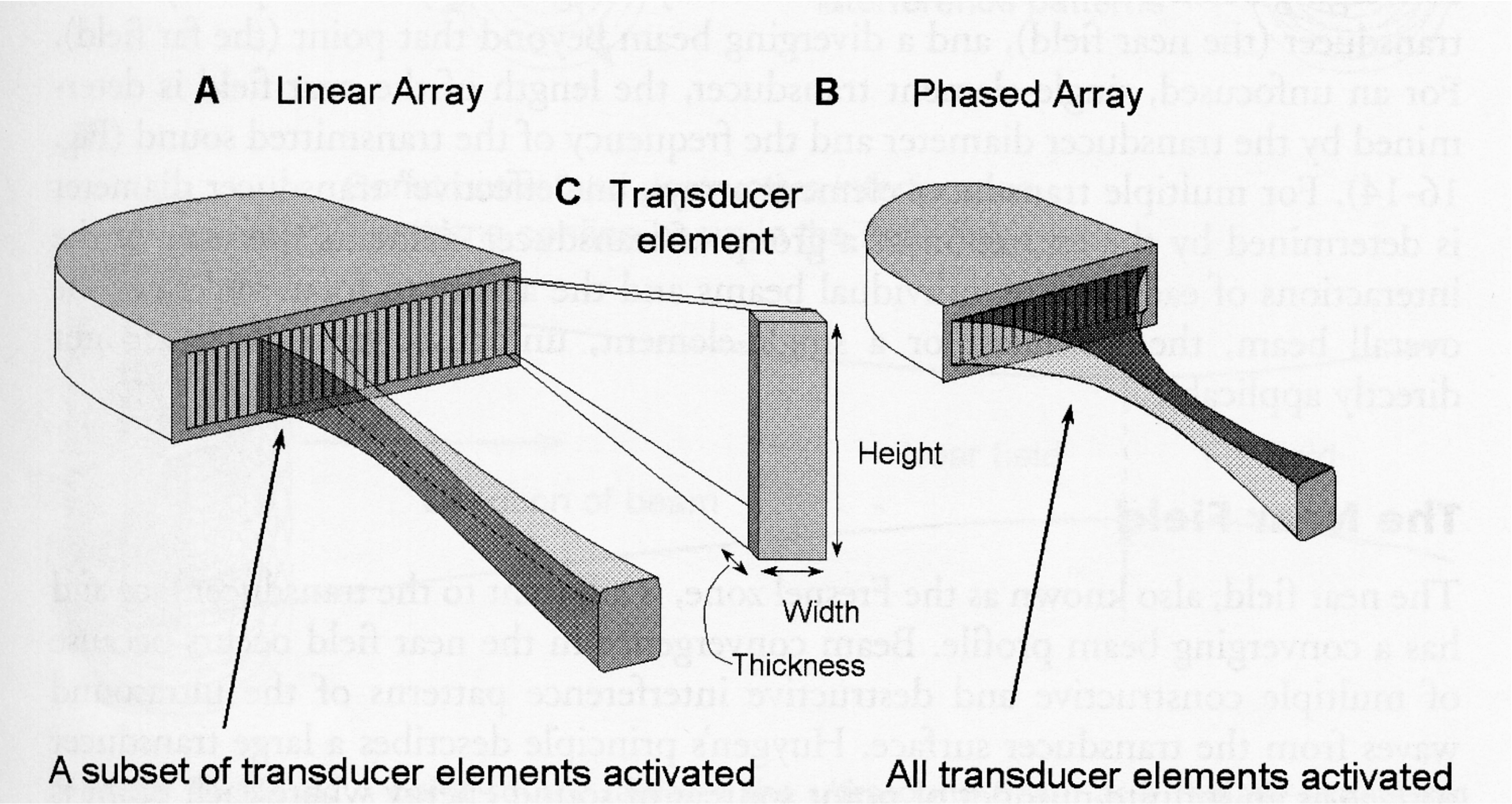
Beam pattern formation



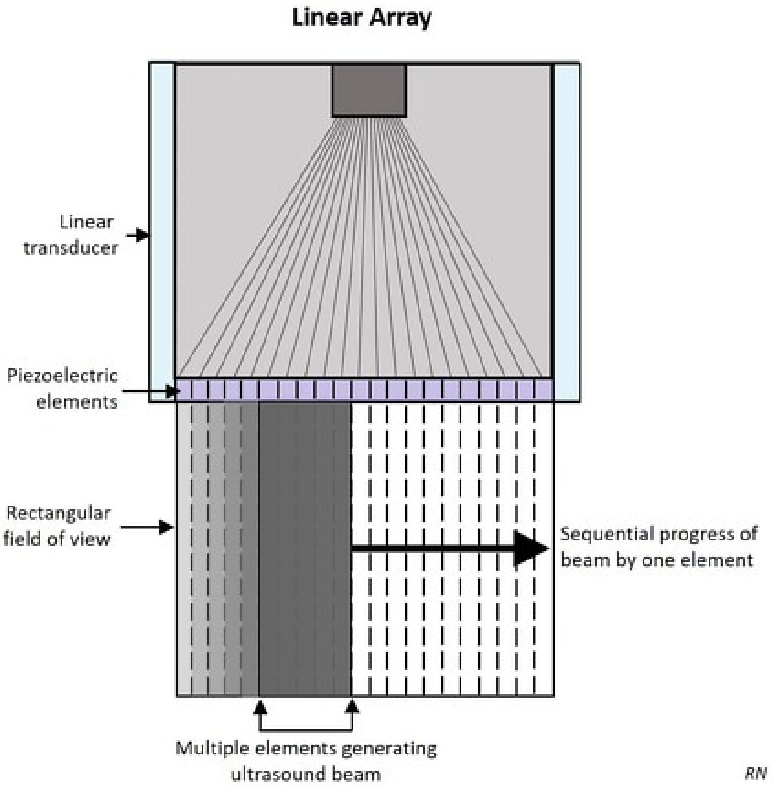
超音波陣列探頭

- 現今超音波探頭多採用一維陣列(array)，由許多大小相同的單元(element)整齊排列而成
- Linear array: ～10-15 cm in length
- Phased array: ～1-3 cm in length

Transducer arrays



Linear array



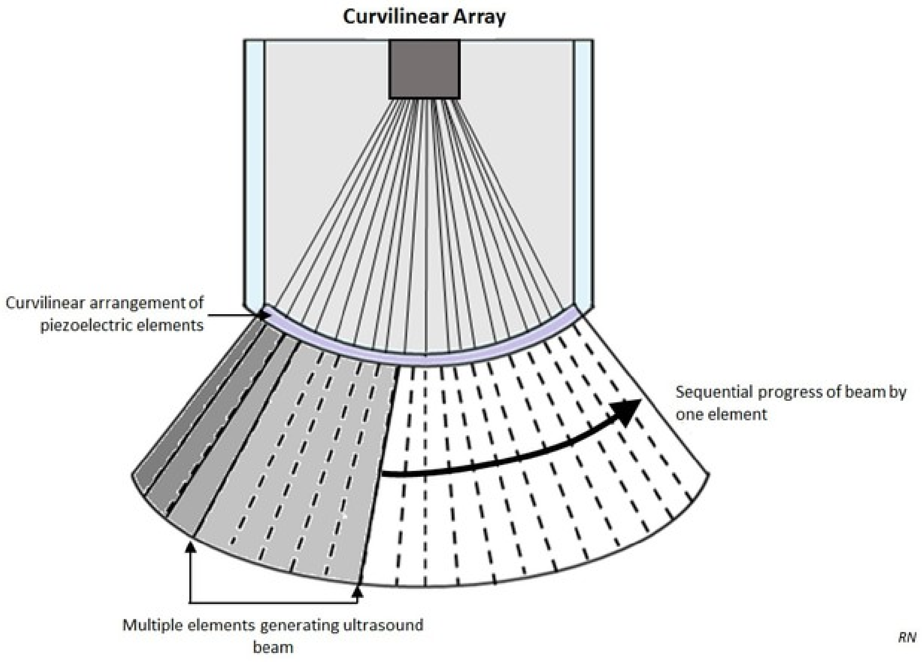
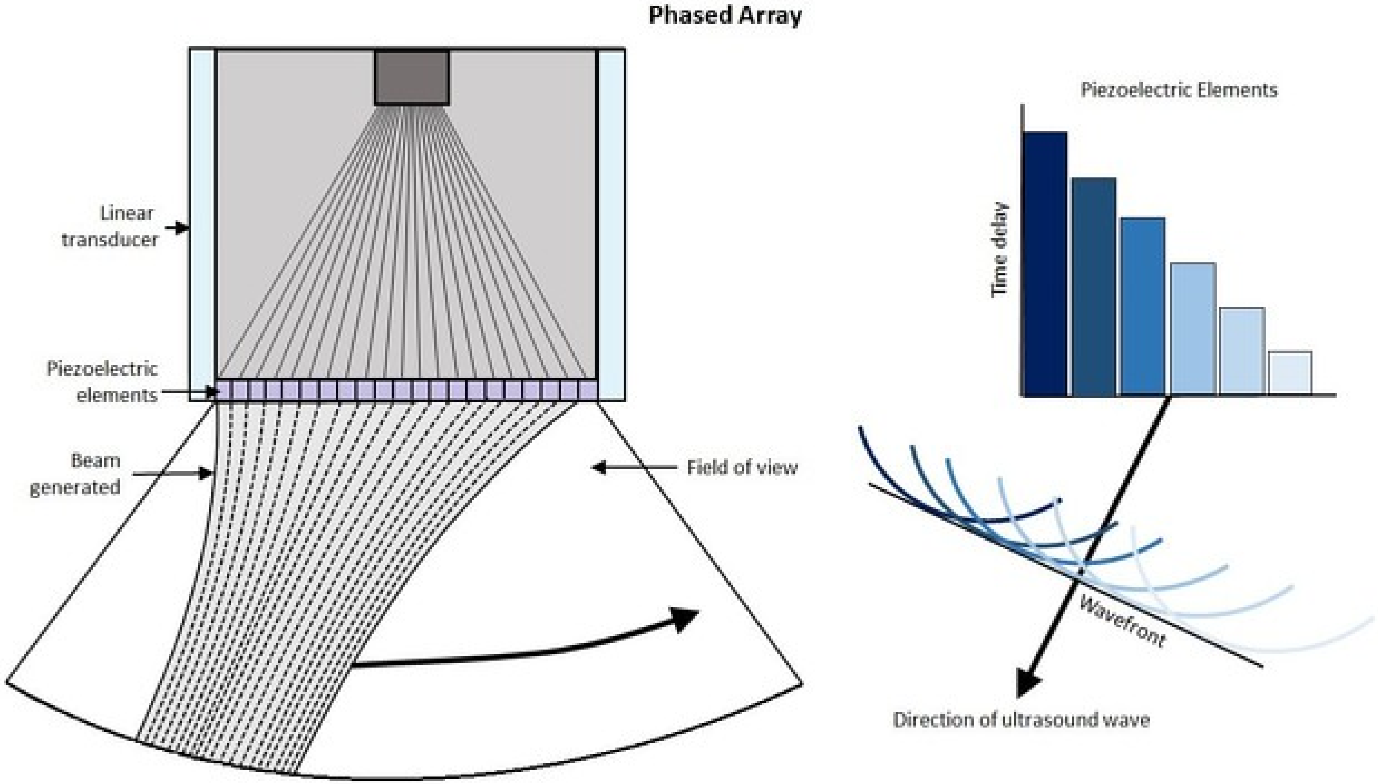


Photo credit: Radiopaedia.org

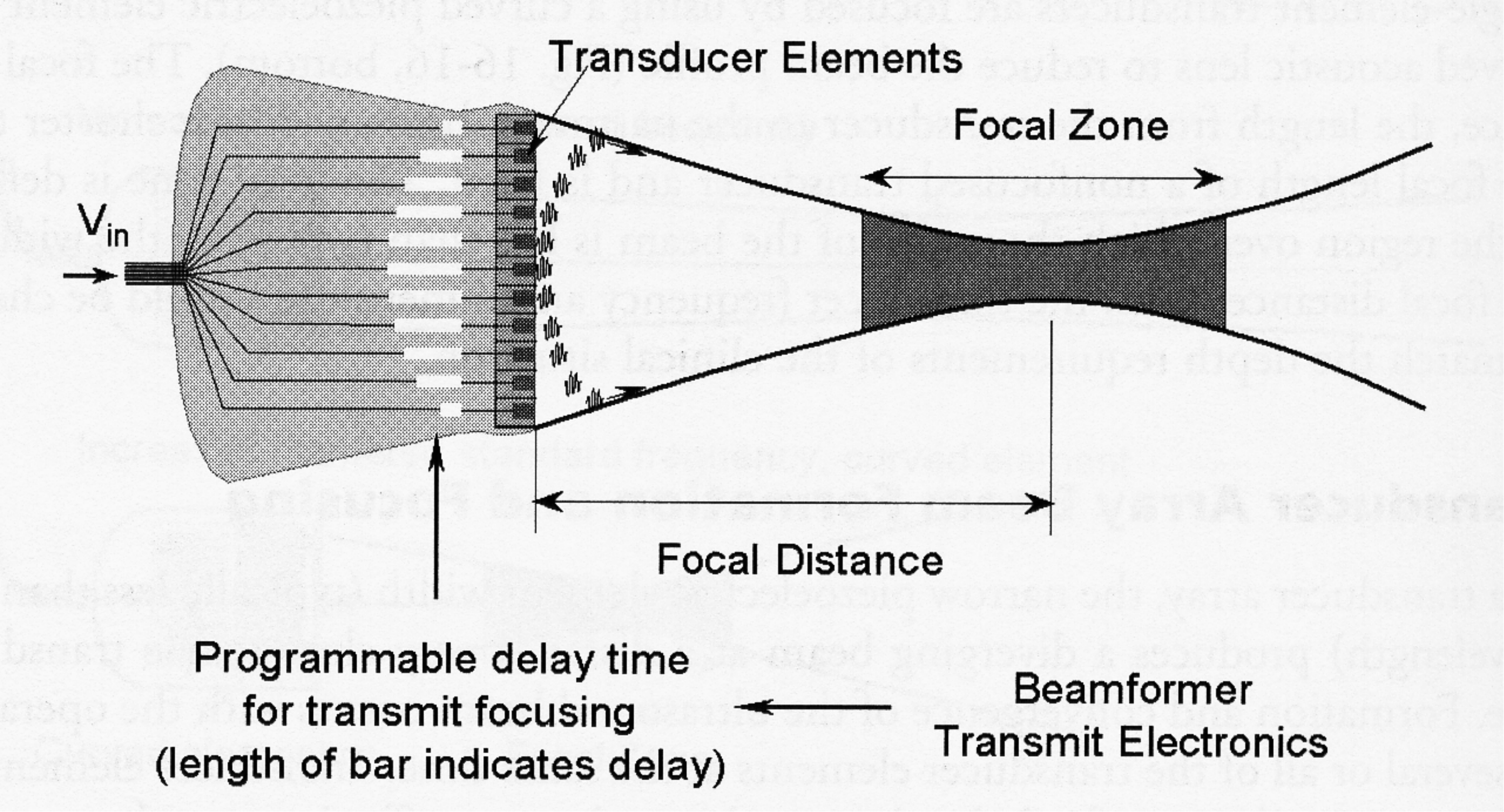
每次使用數個單元依序產生脈衝

Phased array

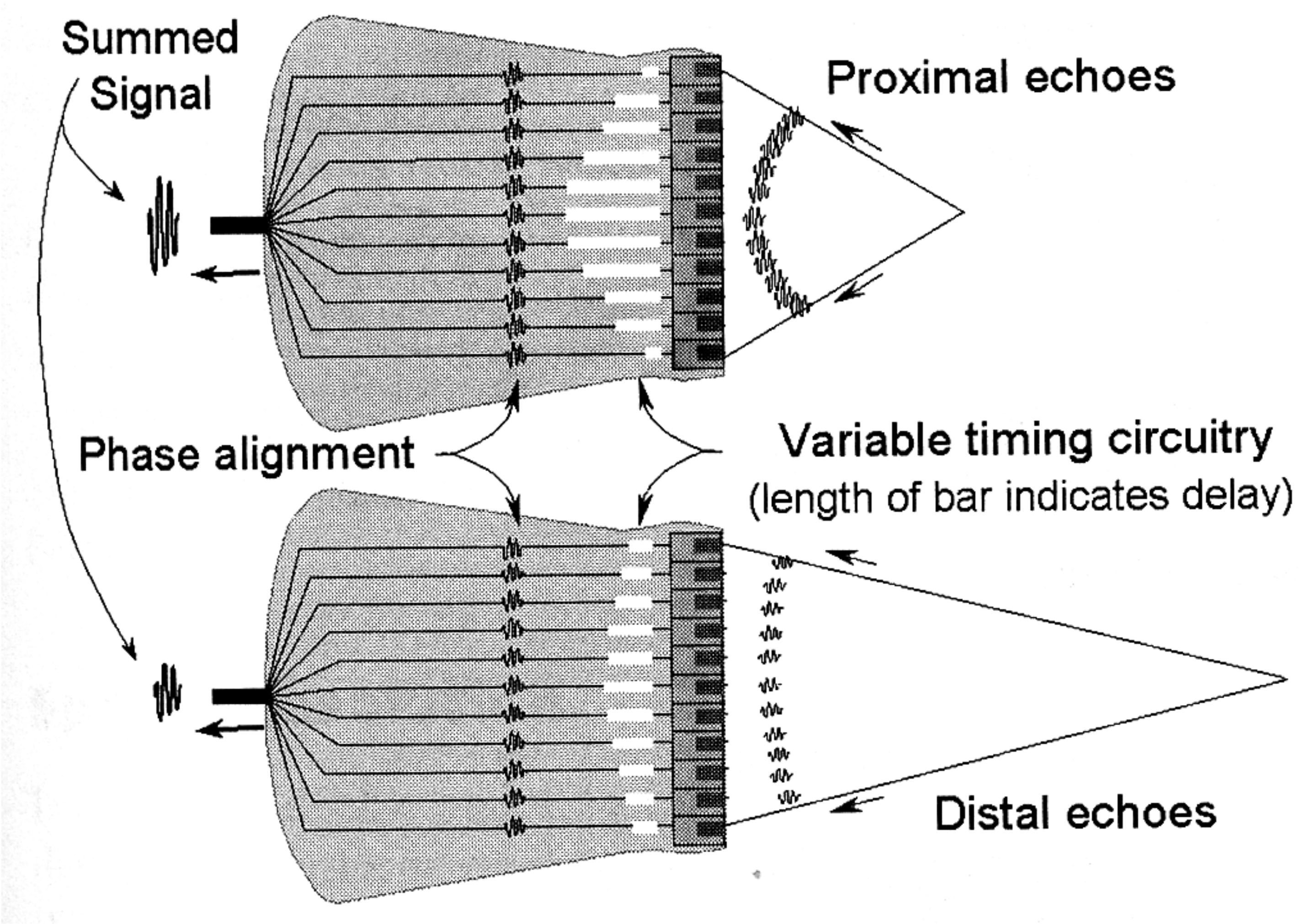


每次使用全部單元產生脈衝

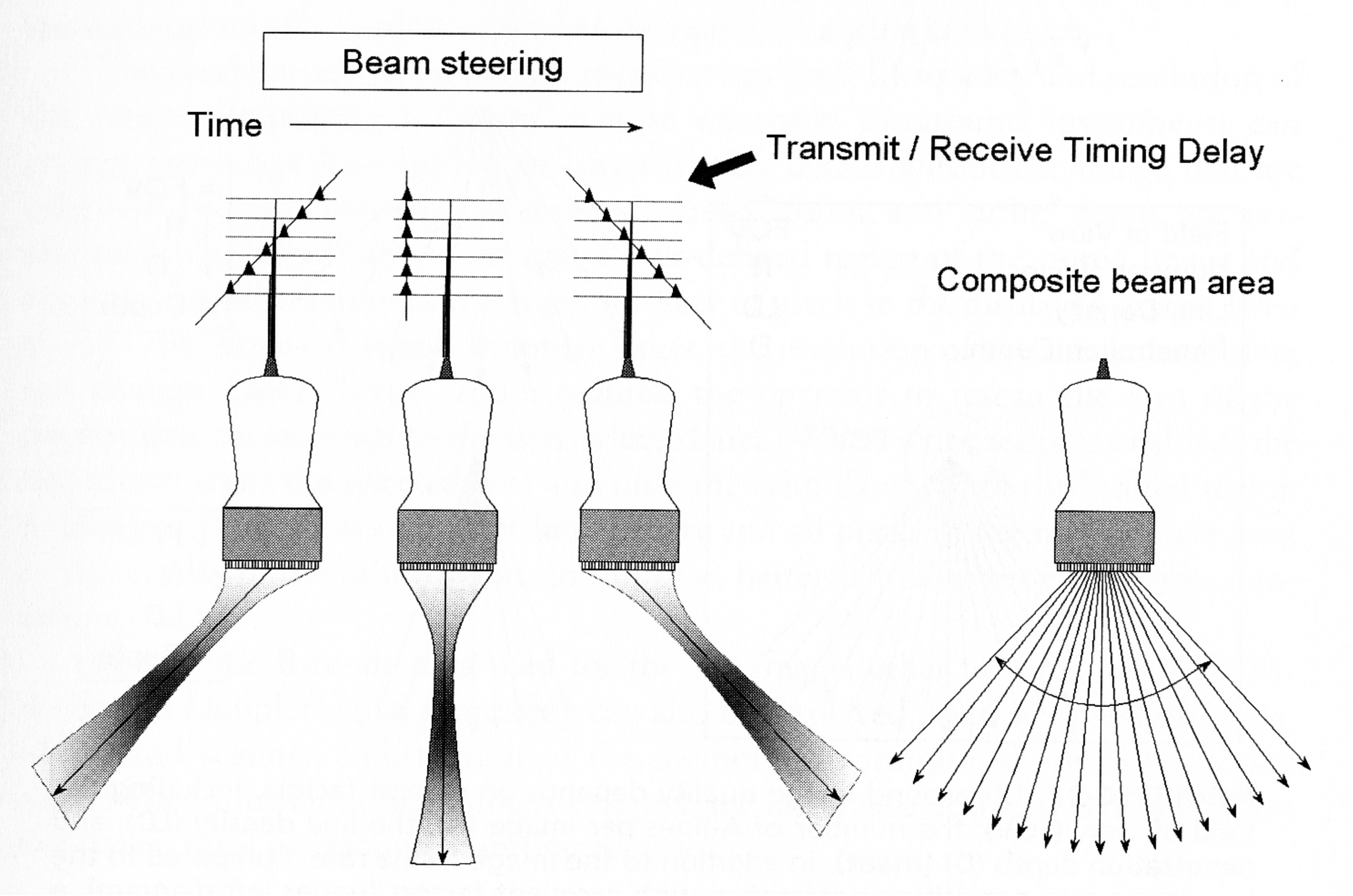
發射聚焦


Transducer Elements
Focal Zone
V_{in}
Focal Distance
Programmable delay time for transmit focusing (length of bar indicates delay)
Beamformer Transmit Electronics

接收聚焦


Summed Signal
Proximal echoes
Phase alignment
Variable timing circuitry
(length of bar indicates delay)
Distal echoes

Beam Steering



超音波探頭

超音波影像原理

- 超音波發射源
- 組織介面形成反射
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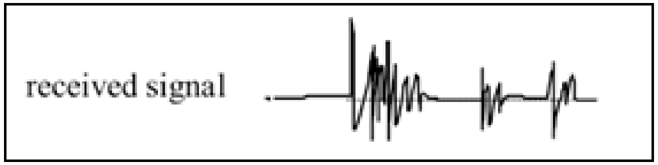

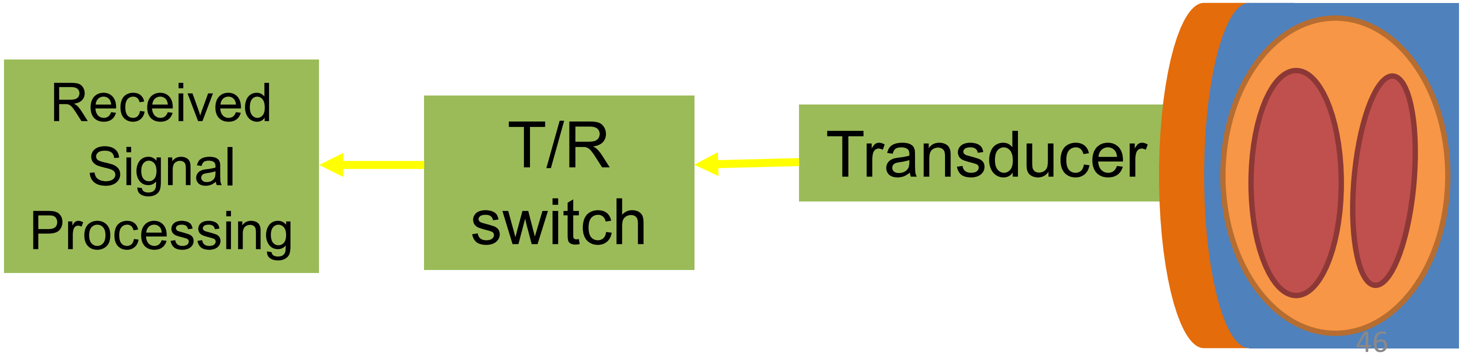

Received Signal Processing

T/R switch

Transducer

Acoustic Impedance (相對值) 與波速

水	1.48	1484 (m/sec)
血液	1.65	1550
心肌	1.62	1550
脂肪	1.34	1450
肝臟	1.65	1570
腎臟	1.63	1560
骨骼	6.0	3360
鋁	17.0	6420
空氣	0.0004	343

超音波影像對比的來源！

超音波影像原理

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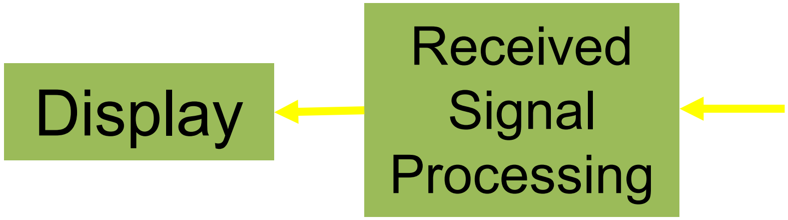


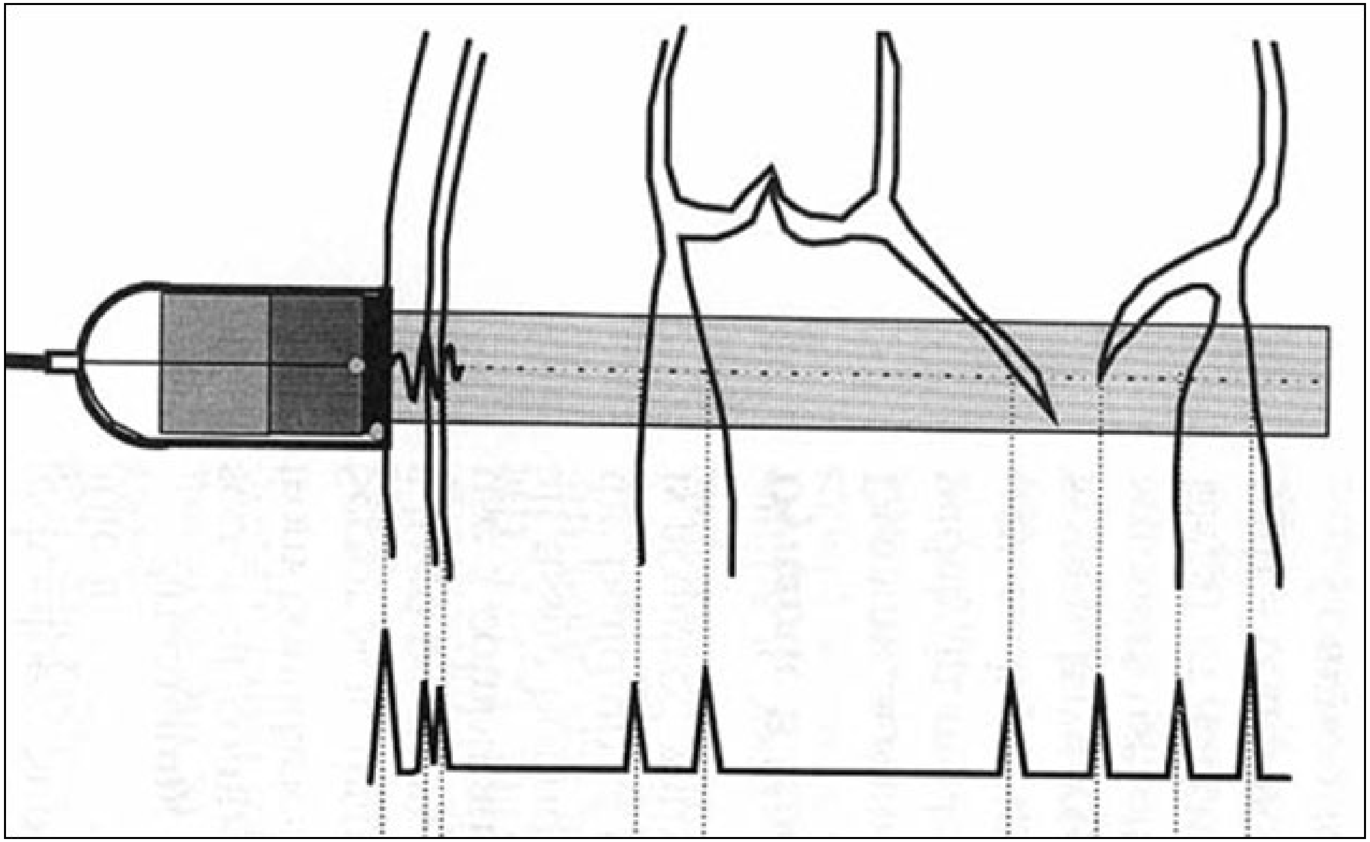
超音波影像形成與應用

- Amplitude (A) mode
- Brightness (B) mode
- Motion (M) mode
- Color Doppler 血流測定 …

A Mode 超音波影像

- 單方向發射超音波
- 接收反射波的時間換算成距離
- 反射波強度以振幅顯示
- 二維圖形 ＝ 一維影像

A mode ultrasound

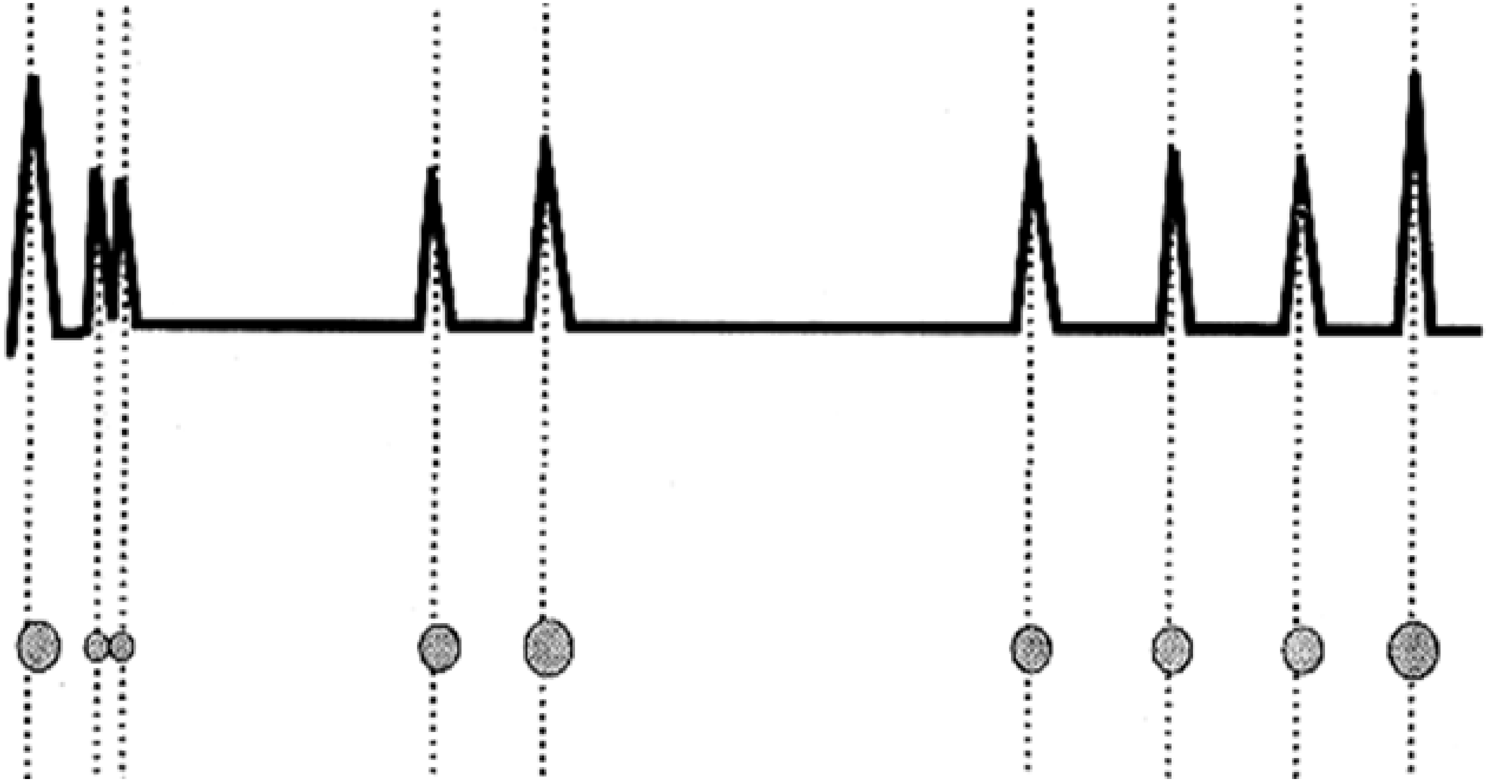


已經滿少見到了

B Mode 超音波影像

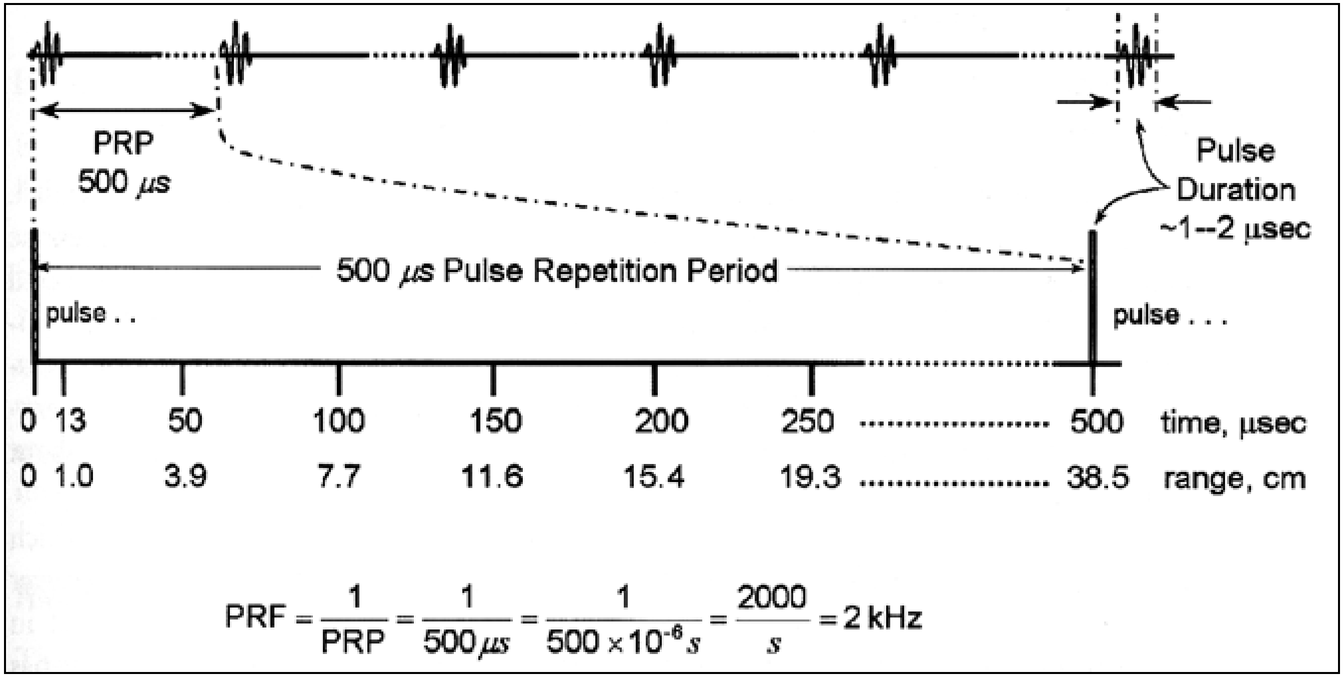
- 只是把振幅改用 亮度顯示
  - 從一個圖改為一條線
- 多條線掃瞄 → 二維影像
- 最常見到的臨床使用方式

B mode ultrasound 原理

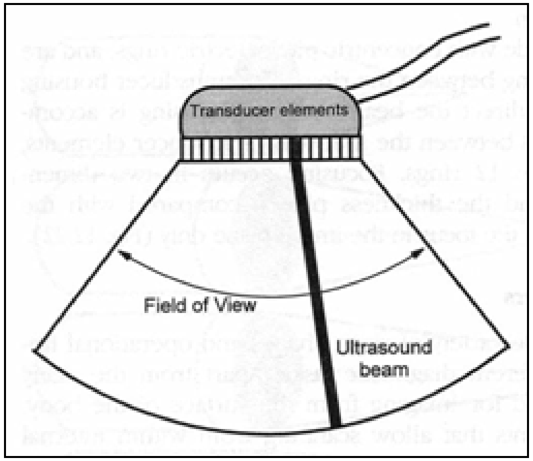


A-mode 振幅轉換為影像亮度

B mode ultrasound 原理



$$\mathrm{PRF} = \frac{1}{\mathrm{PRP}} = \frac{1}{500\,\mu s} = \frac{1}{500 \times 10^{-6}\,s} = \frac{2000}{s} = 2\,\mathrm{kHz}$$



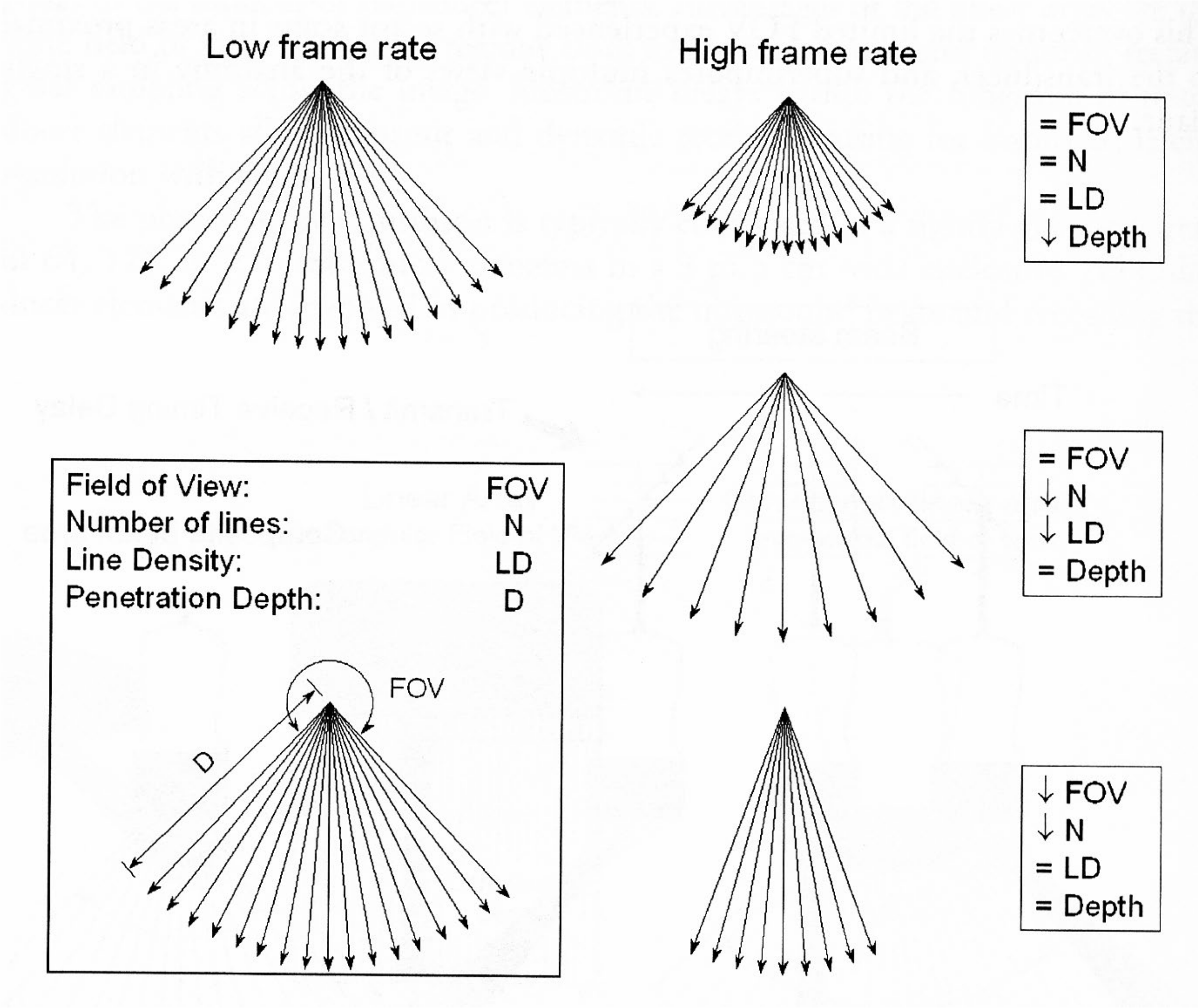
Pulse repetition period (PRP): 大部分時間在收訊

B mode成像時間

- 成像深度決定每條線所需時間(PRP)
  - 根據待測物的條件決定PRP
- 成像範圍(field of view)與橫向解析度(lateral resolution)決定線數(N)

- 單張影像成像時間 = PRP x N
  - 倒數為單位時間成像張數(frame rate)

Frame rate and spatial sampling

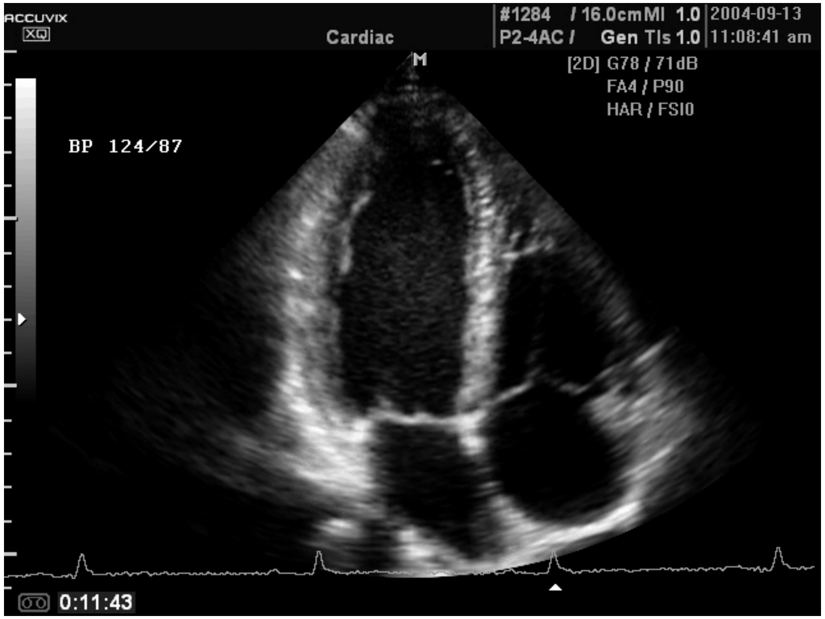


B Mode 掃瞄時間

- 每條掃瞄線 = 2 x 距離 / 波速
  - 40 cm ~ 0.5 msec
  - 視覺暫留 ~ 1/16 sec
- 基本上是 real time imaging

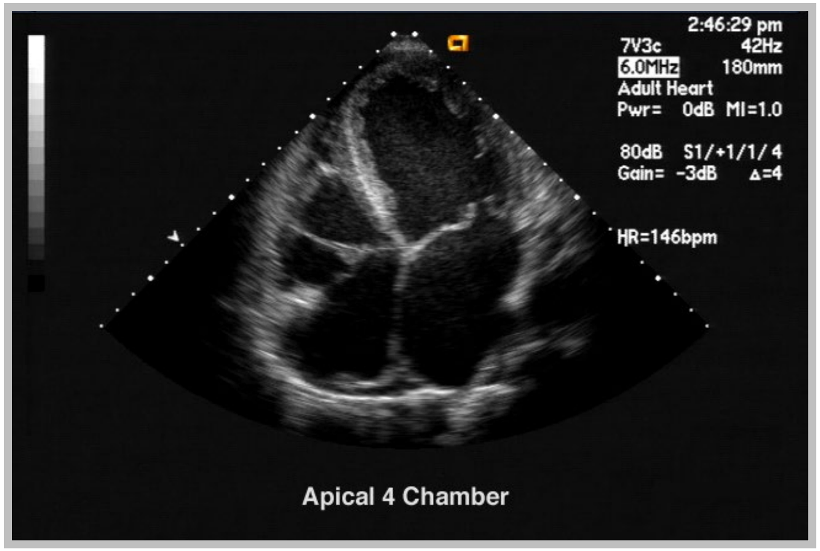
Real Time Imaging 重要性

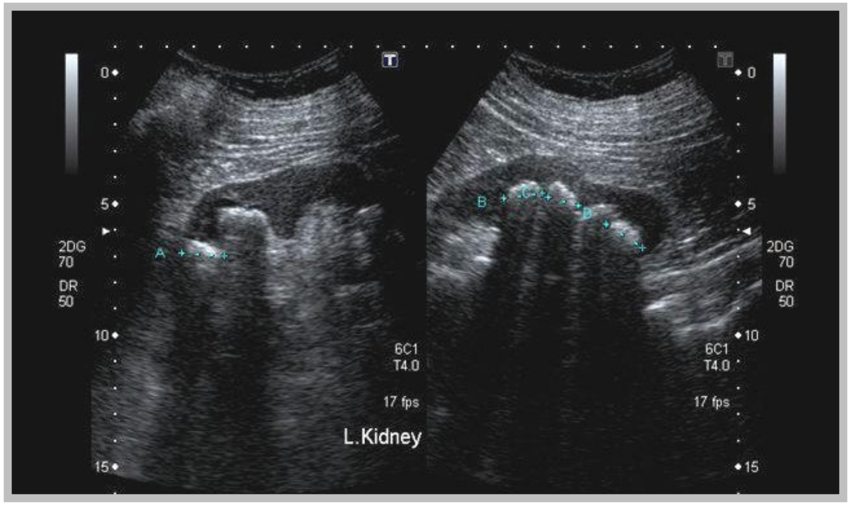
- Interactive (一邊看一邊移動)
- 目視判斷彌補影像品質的不足
- 不受器官運動的影響
  - 心跳、胎兒 …

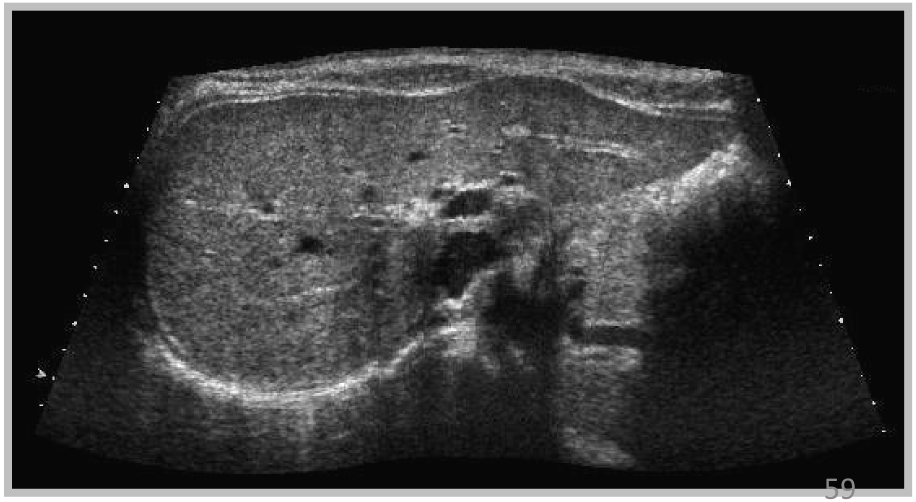


Apical four-chamber view

B mode ultrasound



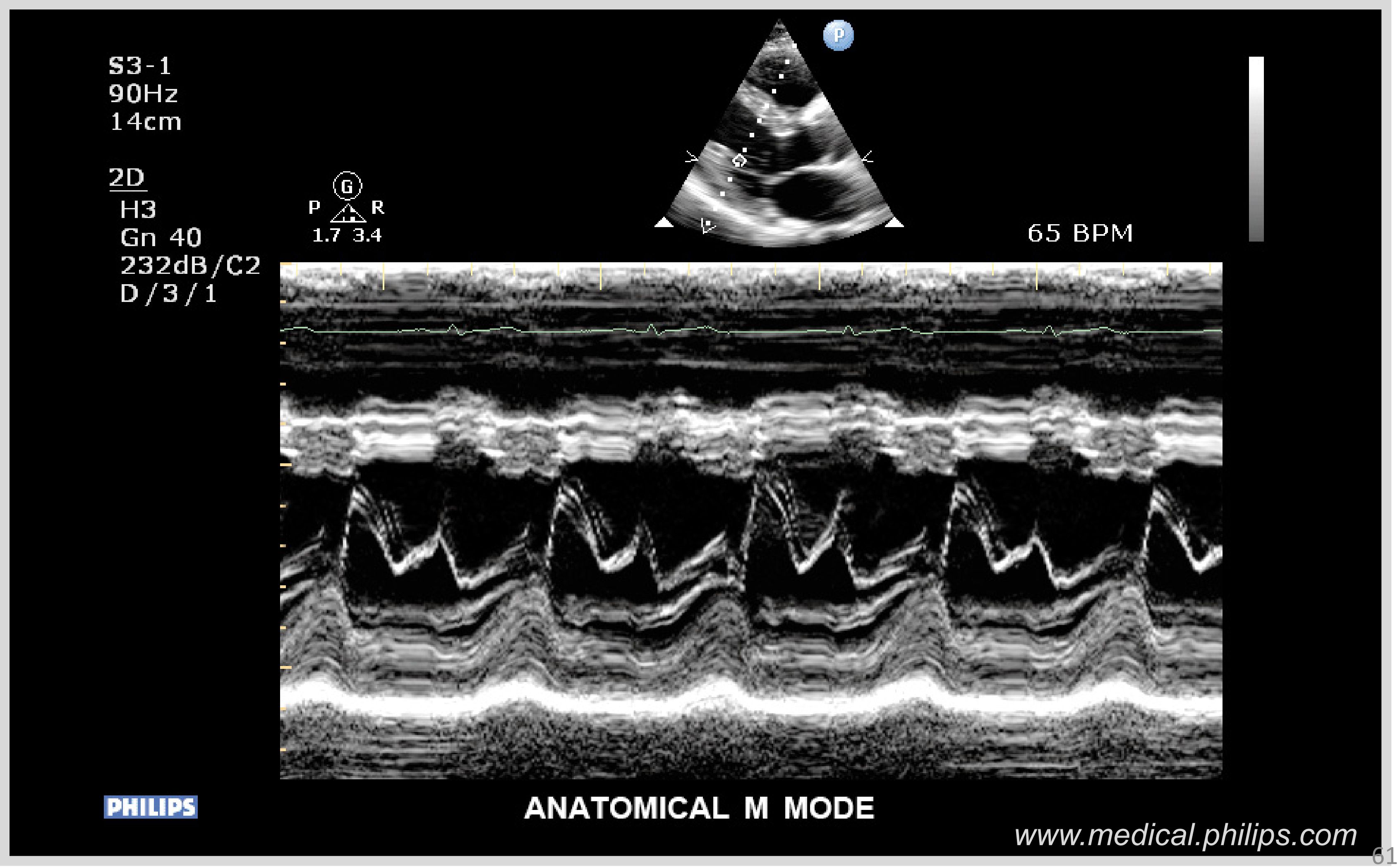




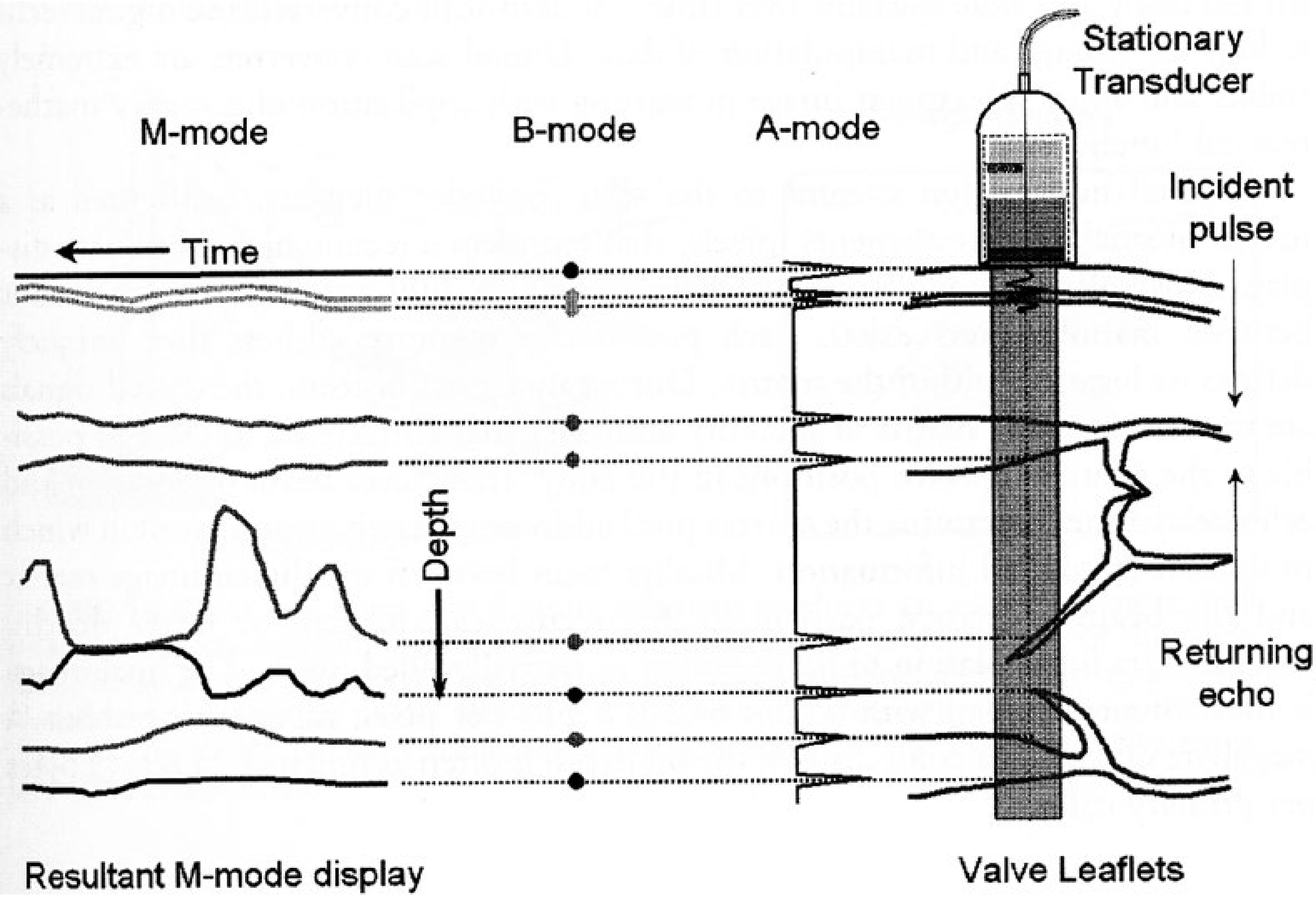
M Mode 超音波影像

- 單方向發射超音波＋亮度顯示
  - 一維影像
- 隨時間做追蹤以檢視器官運動
  - 二維＝空間軸 vs. 時間軸

M mode ultrasound



Echo display mode



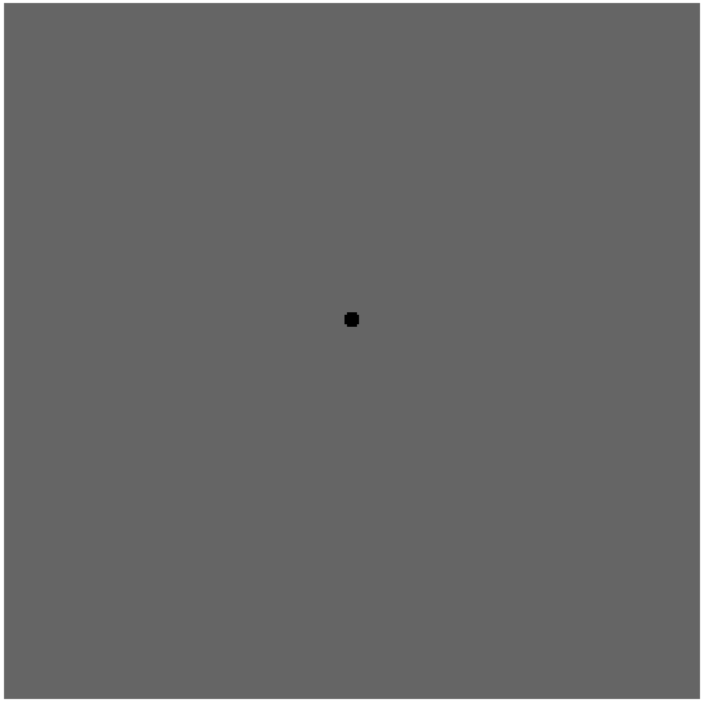
Color Doppler Ultrasound

- 都卜勒效應 (Doppler effect)

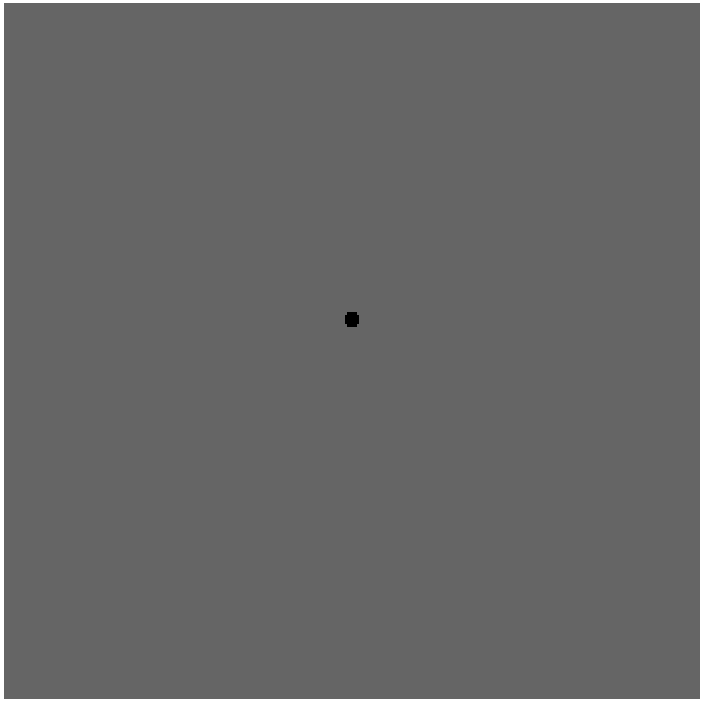
$$f = \frac{C + V_R}{C - V_S} f_S$$

  - f : the observed frequency
  - V_R : the velocity of the receiver toward source
  - V_S : the velocity of the source toward receiver

Doppler Effect



靜止不動



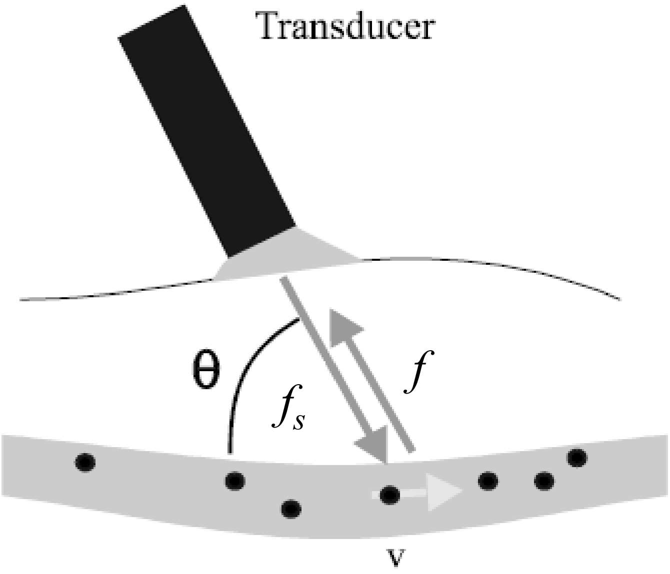
移動物體

Color Doppler Ultrasound

- 假設物體（如：血液）運動速度與波動方向有一夾角θ，超音波探頭所接收到的回波頻率應為

$$f = \frac{C - v \cdot \cos\theta}{C + v \cdot \cos\theta} f_S$$

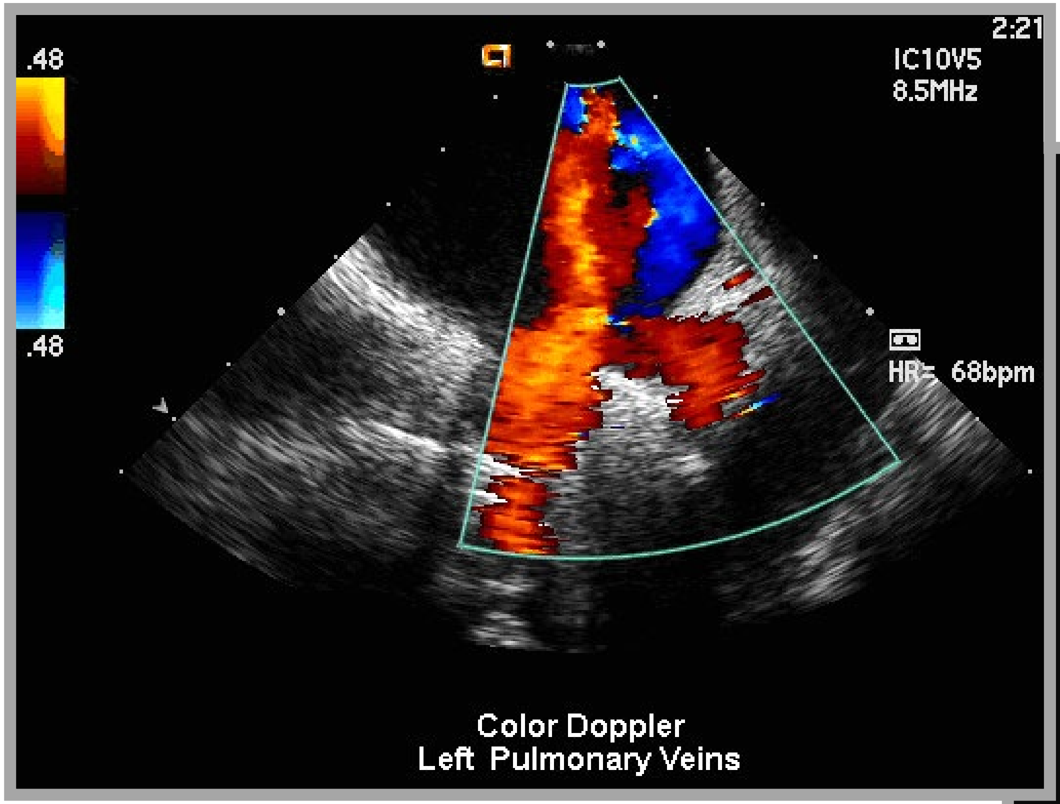
$$\therefore f_D \sim \frac{2v \cdot \cos\theta}{C} f_S$$

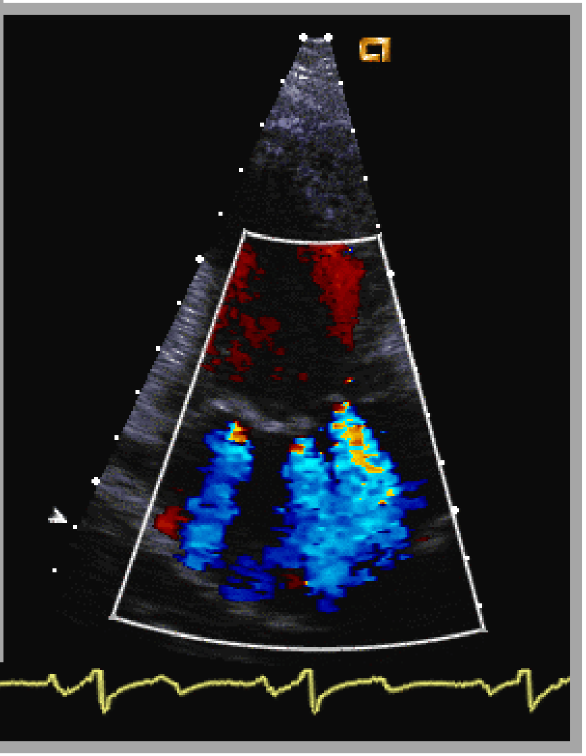


Color Doppler Ultrasound

- 利用都卜勒效應檢視流速
  - 介質速度改變超音波頻率(波長)
  - 假設角度已知
- 以聲音或色彩顯示頻率所換算的流速

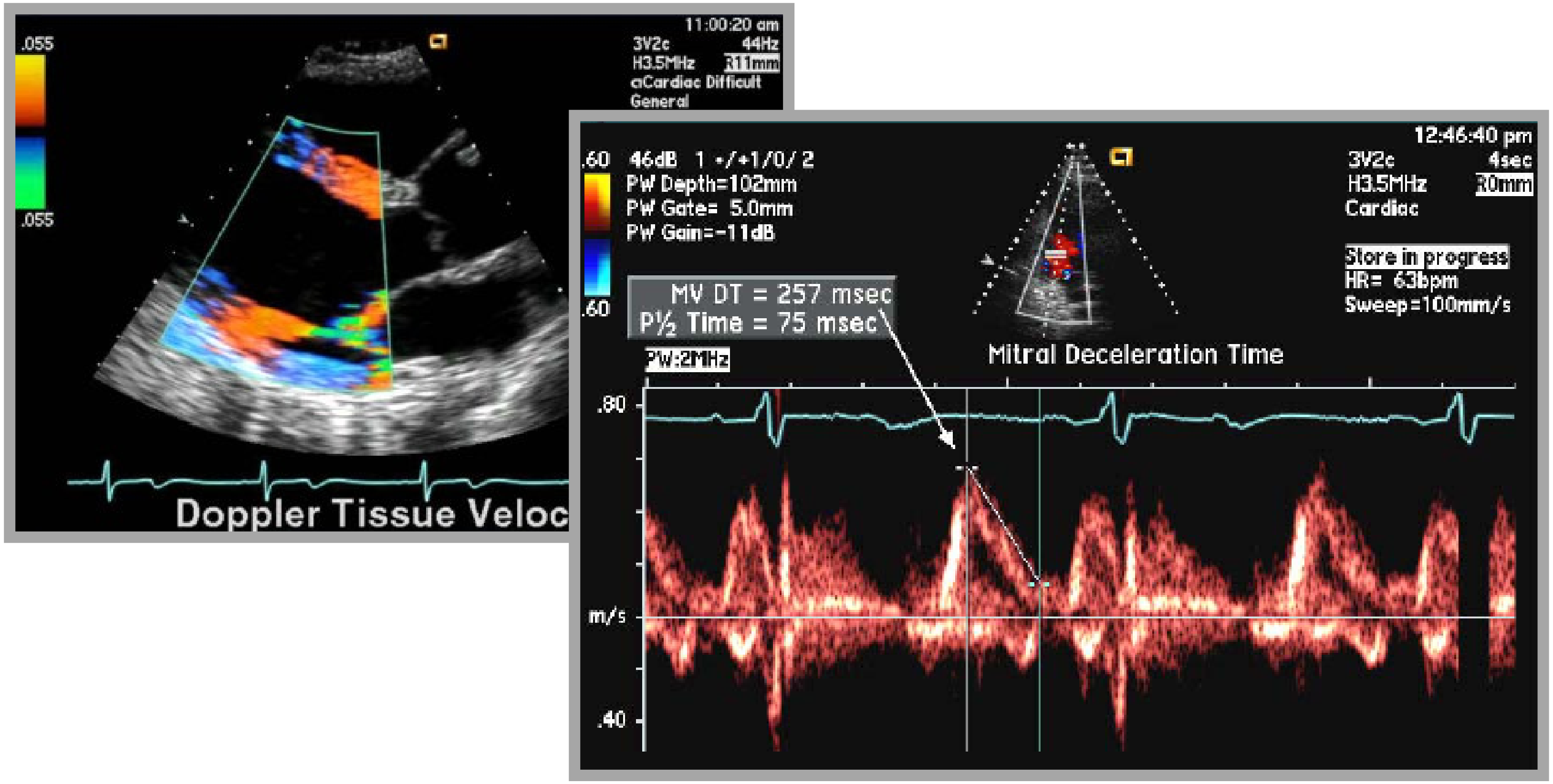
Doppler Ultrasound





量測血液流速

Doppler Ultrasound



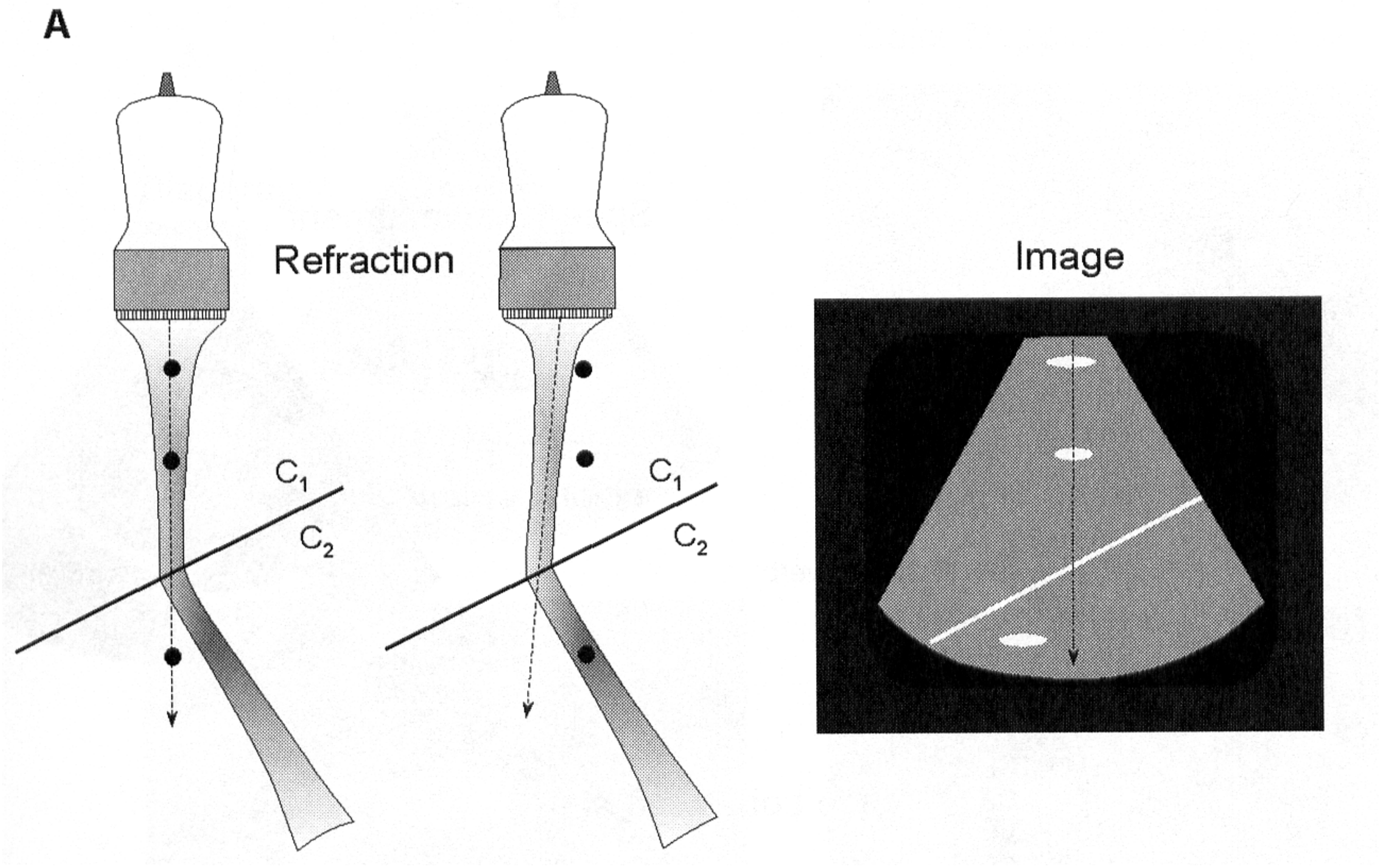
速度 與 速度隨時間的變化

Artifact

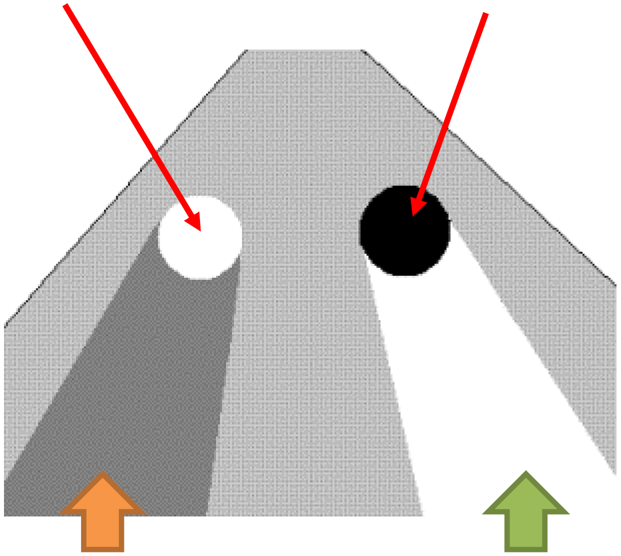
- 何謂假影(Artifact)？
  - 不應該有，卻出現了。
  - 應該有，卻沒有或出現在不對的位置。

- 可能造成錯誤的診斷！

Refraction



Shadowing and enhancement

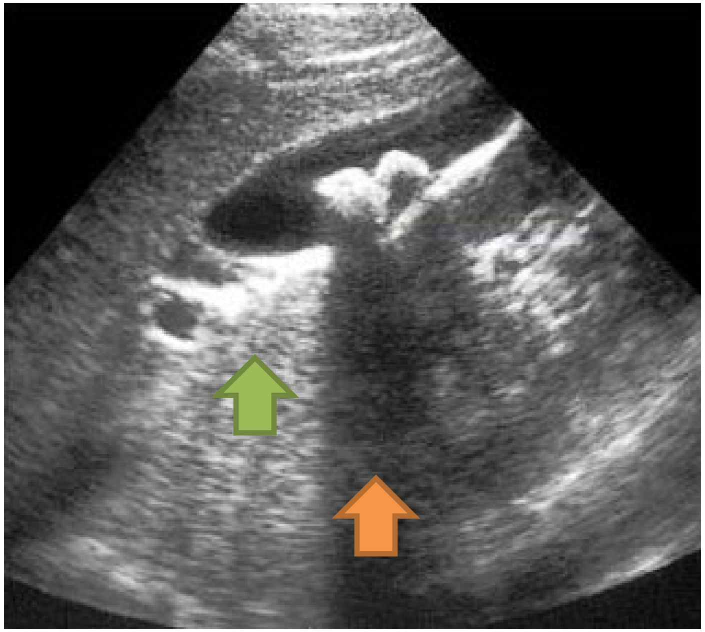


High attenuation

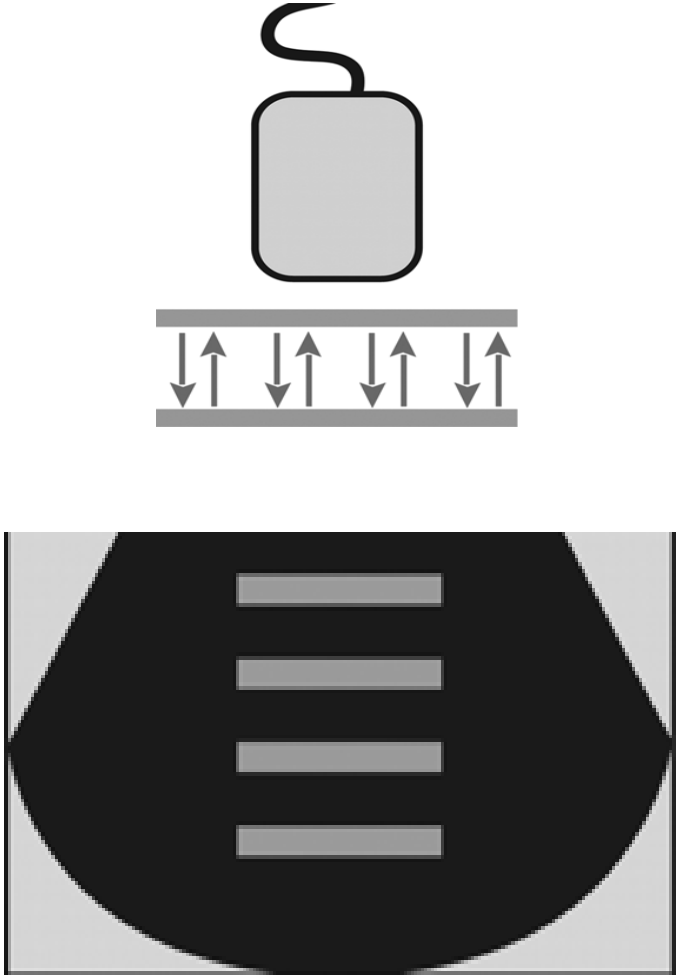
Low attenuation

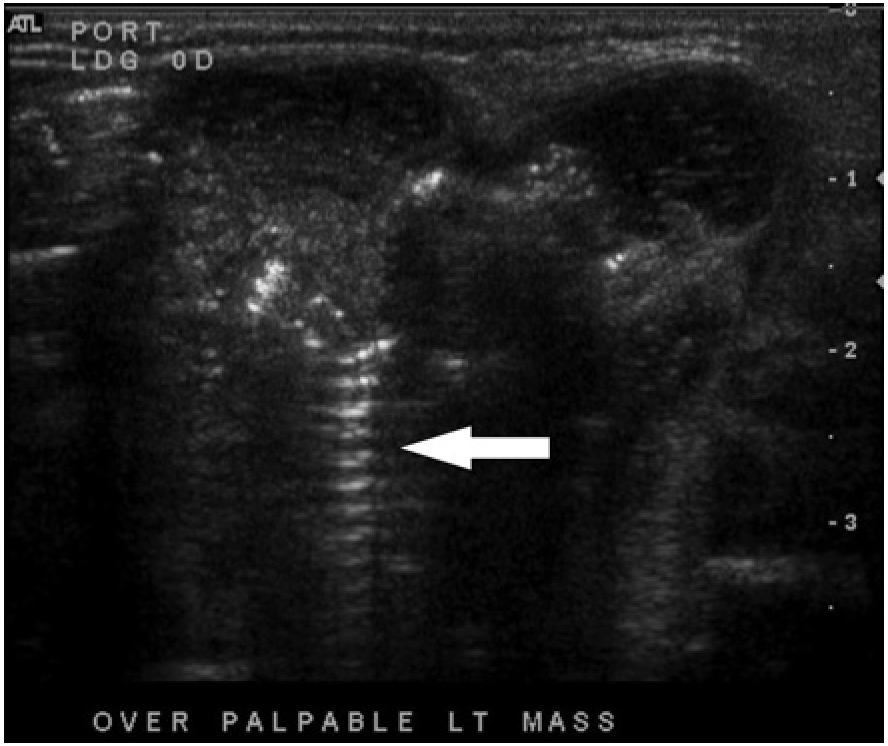
Shadowing

Enhancement

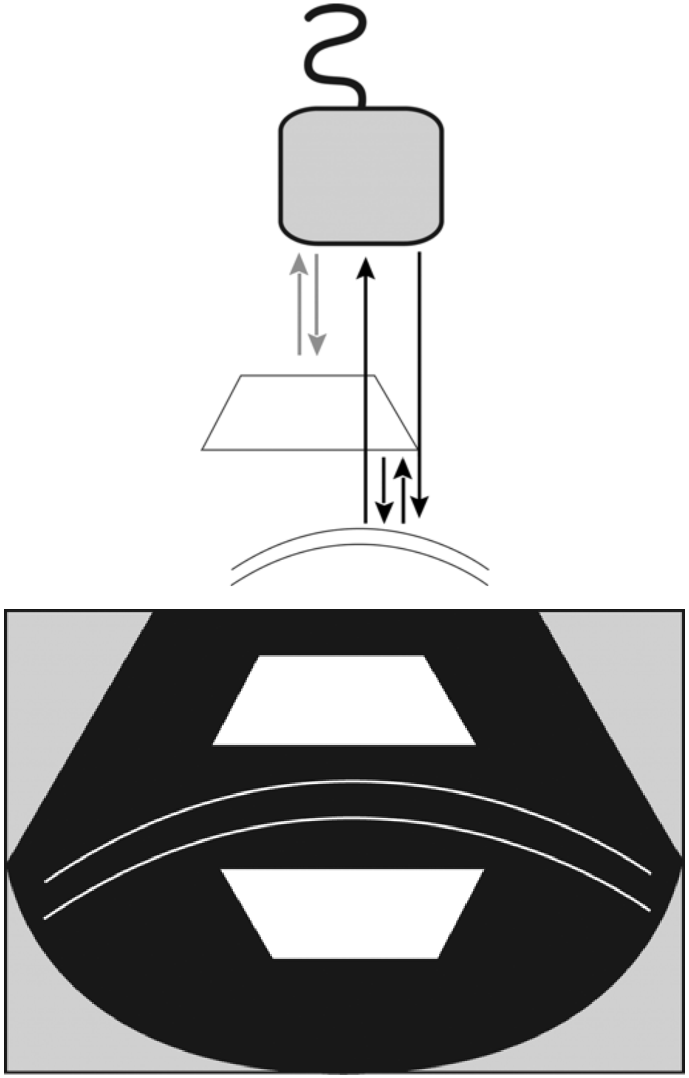


Reverberation

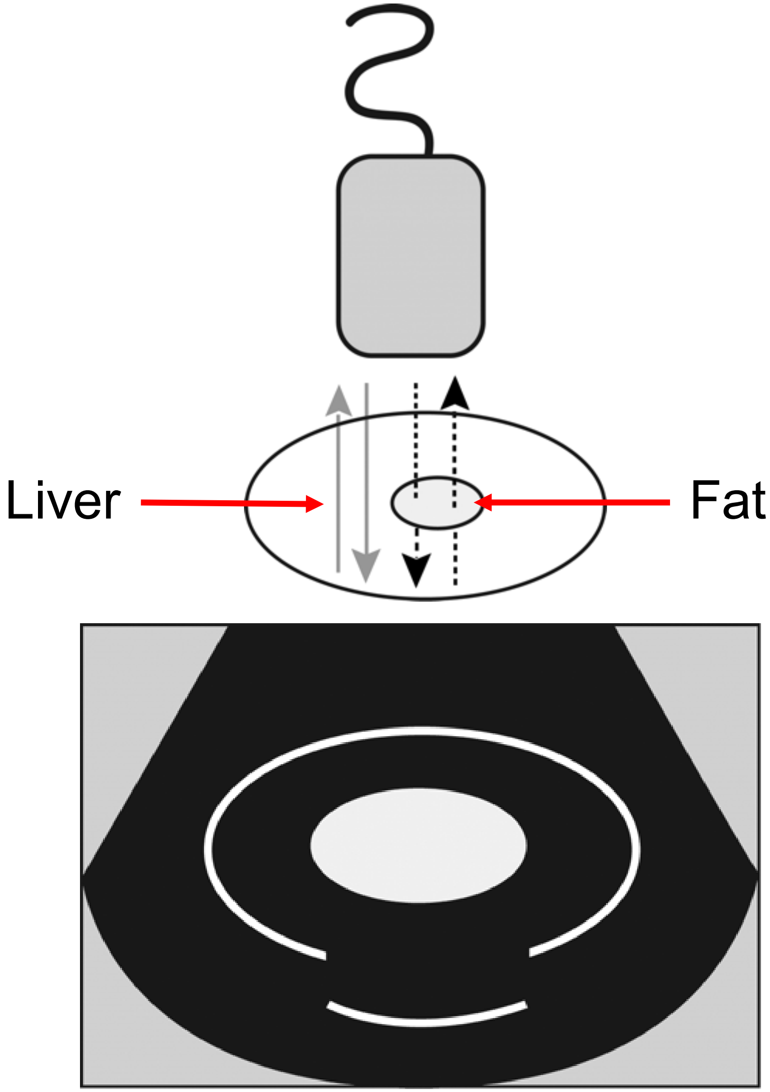


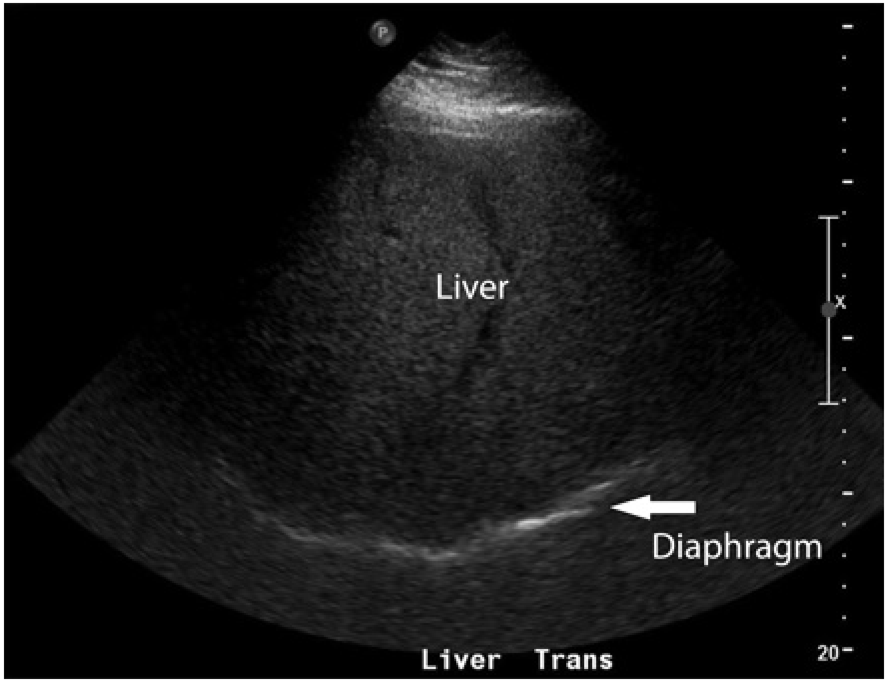


Mirror image

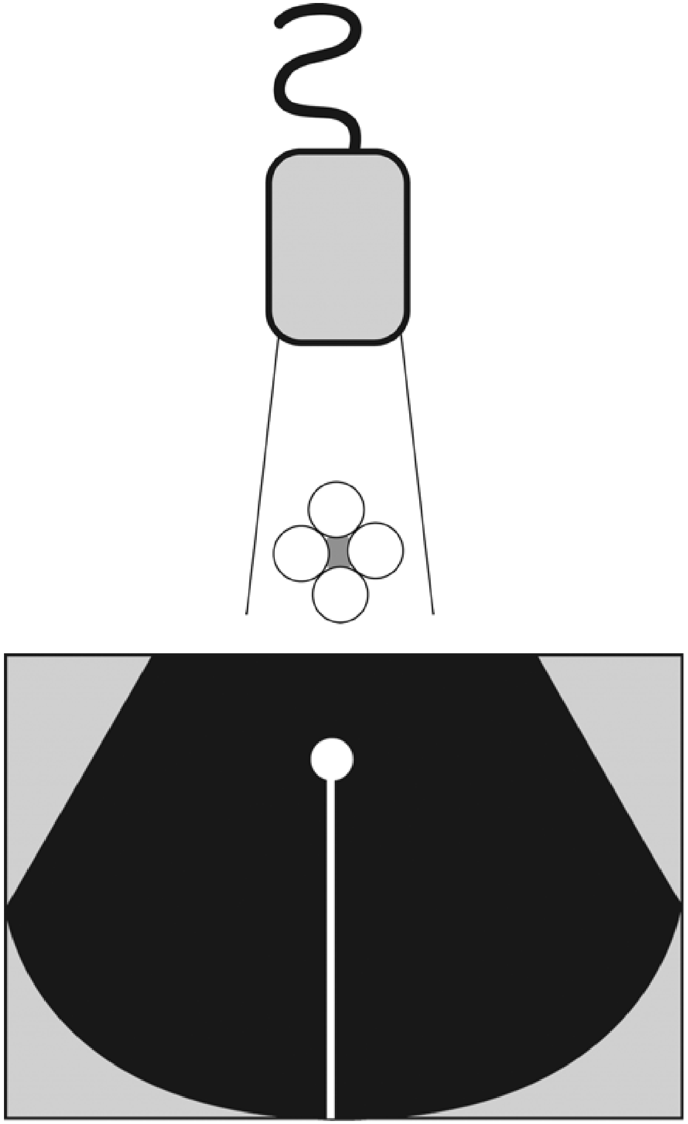


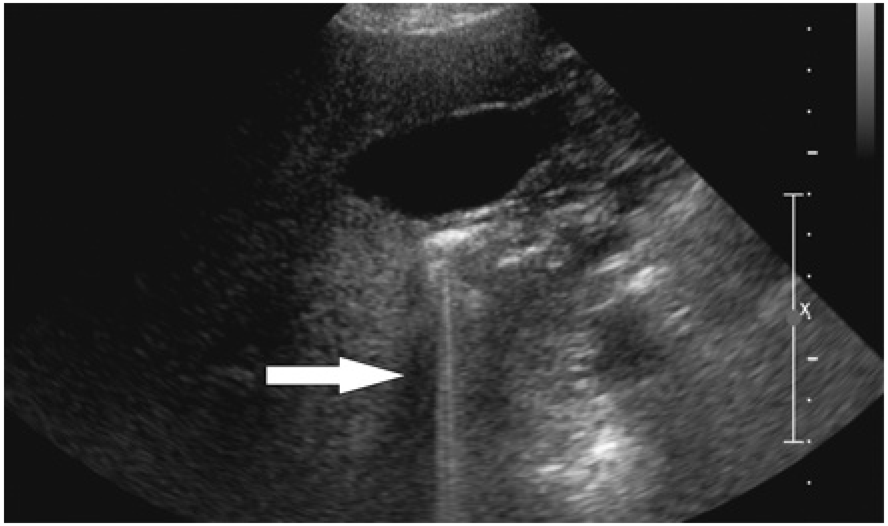
Speed displacement





Ring-down artifact





超音波的優劣勢

- 價廉、便利性、即時顯像、無放射性、合併治療潛力(HIFU)
- 缺點：CNR較低、穿透深度受限、組織不均勻度導致 body-type dependent image quality

超音波的發展

- 3D ultrasound imaging
- Harmonic imaging
- Contrast enhanced ultrasound
- Therapy (High Intensity Focused Ultrasound)
- Drug delivery …

醫學影像系統：超音波影像