Unit 4

Ultrasound Imaging Systems

Ultrasound Imaging Systems

- Diagnostic ultrasound
- Physics of ultrasonic waves
- Medical ultrasound
- Basic pulse echo apparatus
- Imaging modes
- Real time ultrasonic imaging systems
- Mechanical sector scanner
- Multi element linear array scanners
- Duplex scanners
- Modern ultrasound imaging systems
- Area array subsystem
- Portable ultrasound systems
- Biological effects of ultrasound

Introduction

- No harm
- Poses no known risk to the patient
- Least expensive tool
- Portable (necessary to move from bedside to operating room)

Basics of Ultrasound

- Process Overview
  - Transducer (electrical signal $\rightleftarrows$ acoustic signal) generates pulses of ultrasound and sends them into patient
  - Organ boundaries and complex tissues produces echoes (reflection or scattering) which are detected by the transducer
  - Echoes displayed on a grayscale anatomical image
    - Each point in the image corresponds to an anatomical location of an echo-generating structure
    - Brightness corresponds to echo strength

Ultrasound diagnostics

- Ultrasound diagnostics started to develop as a clinical method in early 50‘ of 20th century
- It allows to obtain cross-sectional images of the human body which can also include substantial information about its physiology and pathology.
- Ultrasound diagnostics is based mainly on reflection of ultrasound waves at acoustical interfaces
- We can distinguish:
  - Ultrasonography (A, B and M mode, 3D and 4D imaging)
  - Doppler flow measurement, including Duplex and Triplex methods (Duplex, Colour Doppler, Triplex, Power Doppler)
  - Tissue Doppler imaging
  - Ultrasound densitometry

1950s

1980s

1990s

Today

Physical properties of ultrasound

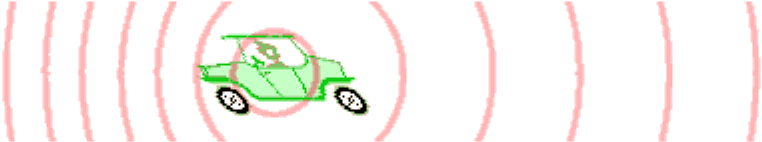
Ultrasound (US) is *mechanical oscillations* with frequency above 20 kHz which propagate through an elastic medium

In liquids and gases, US propagates as longitudinal waves

In solids, US propagates *also* as transversal waves

The Doppler Effect

- Change in frequency of the sound due to the relative motion of the source and/or receiver
  - Example: ambulance



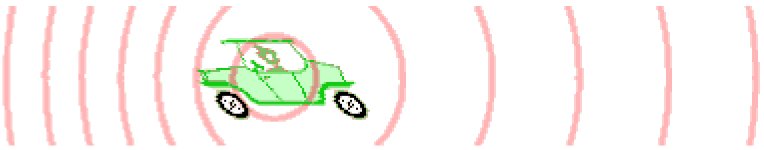
- The Doppler frequency in pulse echo mode will reduce to
  - $f_D = \left(\frac{2v\cos\theta}{c}\right) f_s$

Where, $f_D = f_T - f_O$

f_T is Frequency shift and f_O is fundamental frequency

The Doppler Effect

- Change in frequency of the sound due to the relative motion of the source and/or receiver
  - Example: ambulance



- $f_T = f_o \frac{c}{c+v}$, but the frequency shift is only dependent on the component of source velocity in the direction of the observer
- $f_T = f_o \frac{c}{c+v\cos\theta}$ where Ɵ is angle between the vector pointing from source to receiver and the vector pointing from source to direction of motion

The Doppler Effect

- The difference between observed and source frequencies is the Doppler frequency
  - $f_D = f_T - f_O$
  - Thus, $f_D = \left(\frac{v \cos\theta}{c - v\cos\theta}\right) f_O$, but because *c* >> *v*, $f_D = \left(\frac{v \cos\theta}{c}\right) f_O$
  - Sign of Doppler frequency indicates direction
    - + : Source moving towards observer
    - - : Source moving away from observer
  - Pulse echo mode: Transducer is both source of sound and receiver of the Doppler-shifted echo returning from the object.
    - Sound collected by transducer is received by moving object and retransmitted by moving object.

The Doppler Effect

- T is stationary source, O is moving receiver.
- Moving object observes a frequency, $f_O = \left(\frac{c + v\cos\theta}{c}\right) f_s$ [*]
- And the corresponding Doppler frequency, $f_D = f_O - f_S$
- Equivalent to $f_D = \left(\frac{v\cos\theta}{c}\right) f_s$

- In pulse echo mode, the echo received by T will be shifted by both the effects of a moving receiver and a moving source
  - Essentially 2x the Doppler Frequency than in either case alone

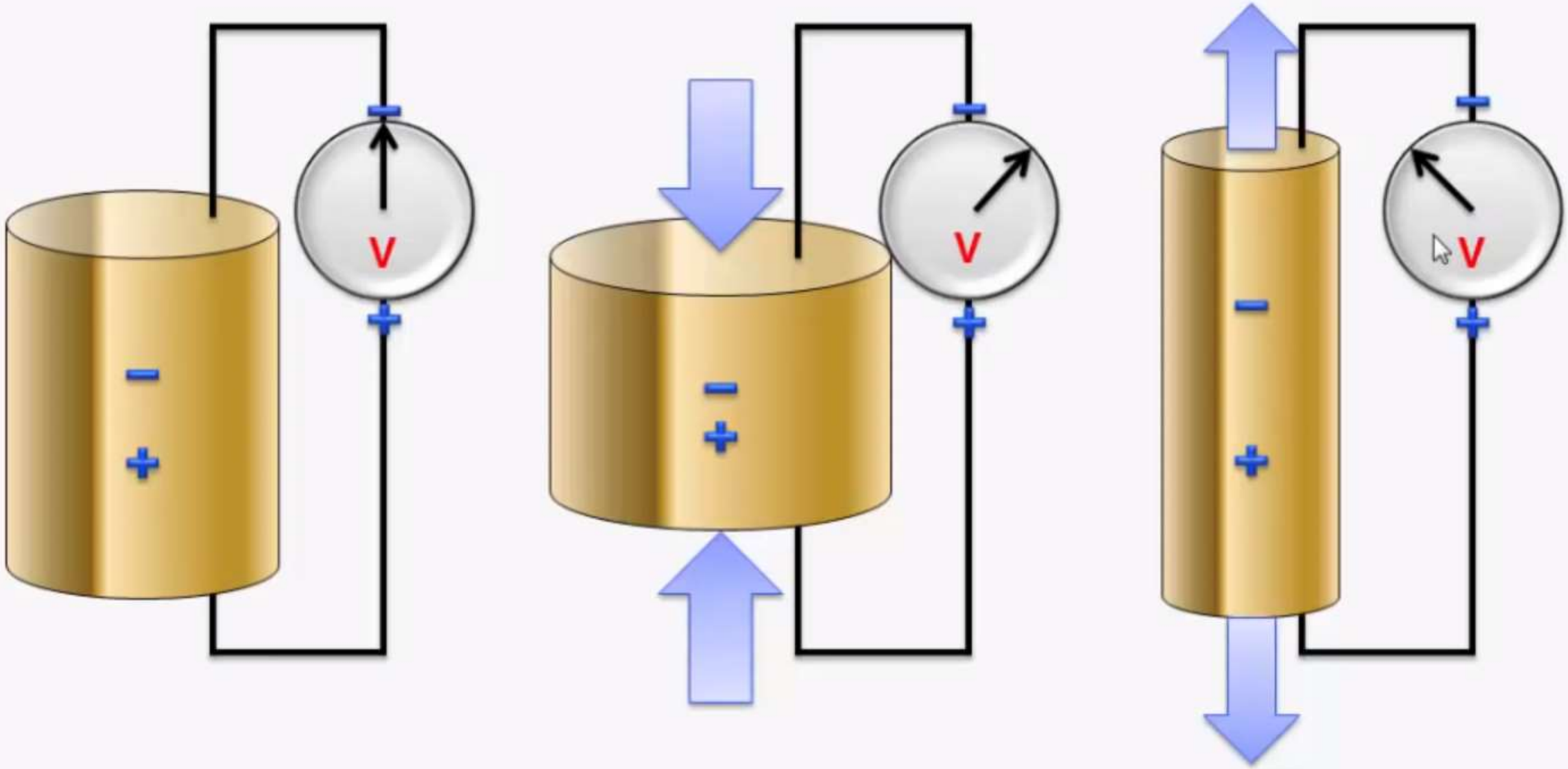
The Doppler Effect

- Transducer **T** generates wave with frequency f_S
- Object **O**, moving with velocity v at angle θ relative to u, receives a frequency f_O.
  - This frequency was shown before as [*]
- The object reflects or scatters the wave, so it is now a moving source with frequency f_O
- The stationary transducer now receives a frequency f_{T}
  - $f_T = \left(1 + \frac{2v\cos\theta}{c - v\cos\theta}\right) f_s$
- The Doppler frequency in pulse echo mode will reduce to
  - $f_D = \left(\frac{2v\cos\theta}{c}\right) f_s$

Generation and detection of Ultrasound

- The physical mechanism normally used to generate and detect ultrasonic waves is the piezo-electric effect exhibited by certain crystalline materials which have the property to develop electrical potentials on definite crystal surfaces when subjected to mechanical strain.
- The converse is also true, which means that mechanical displacement is produced when electrical charges are put on their surface. The effect is demonstrated by crystals of materials like quartz, tourmaline and Rochelle salt.
- This phenomenon offers an excellent method for converting electrical energy into mechanical energy and vice versa.

Piezoelectrics



Changing shape makes current

Adding current changes shape

Pizoelectric materials

- While working with natural crystals, it is difficult to establish the appropriate axis and cut the crystal in the required form. Therefore, quartz has generally been replaced by synthetic piezo- electric materials namely barium nitrate and lead zirconate titanate.
- They offer several advantages because they are far cheaper to produce and are much easier to construct transducers of complex shape and large areas.
- They can be moulded to any shape to obtain a better focusing action for producing high intensity ultrasonic waves.

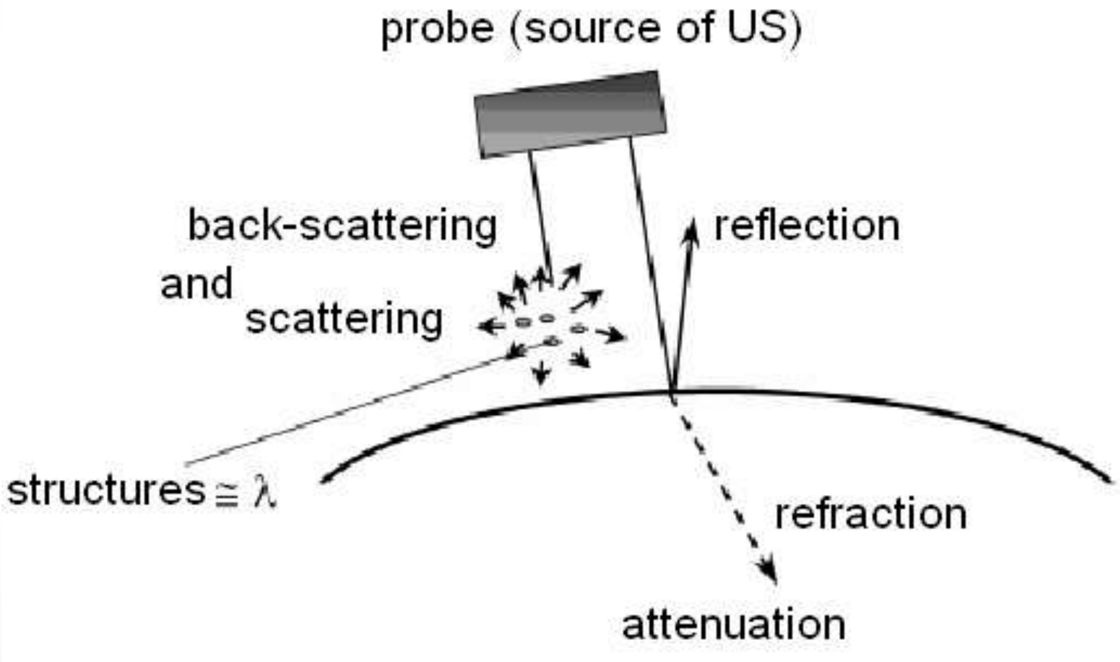
Pizoelectric materials

- The choice of piezo-electric material for a particular transducer depends upon its applications.
- Materials with high mechanical Q factor are suitable as transmitters whereas those with low mechanical Q and high sensitivity are preferred as receivers and in case of non-resonance applications.
- Lead zirconate Titanate (PZT) crystals are much better than quartz crystals upto a frequency of about 15 MHz, because of its high electro-mechanical conversion efficiency and low intrinsic losses.
- The properties of PZT can be adjusted by modifying the ratio of zirconium and titanium and introducing small amounts of other substances such as lanthanum.
- PZT can operate at temperatures up to 100°C or higher and it is stable over long periods of time.
- It is mechanically strong and can be machined to various shapes and sizes. At frequencies higher than this, quartz is normally used because of its better mechanical properties. Polyvinylidene difluoride (PVDF) is another ferro-electric polymer that has been used effectively in high frequency transducers.

Pizoelectric materials

- The surface of the synthetic crystals are normally silvered for making external electrical connections. Piezo-electric crystals are available in several shapes and the selection of a particular shape depends upon the application to which it is to be put.
- The application of a voltage to the transducer disc causes changes in its thickness, thereby giving rise to longitudinal waves propagated along the axis perpendicular to its face.
- The magnitude of the waves will be a maximum at the resonant frequency of the disc, which is determined by its thickness.
- Likewise, when the transducer is acting as a receiver, it will be most sensitive to ultrasonic vibrations at its own resonant frequency.
- Therefore, considerable attention is devoted to tailoring the dimensions of the transducer to the frequency at which it will be used.

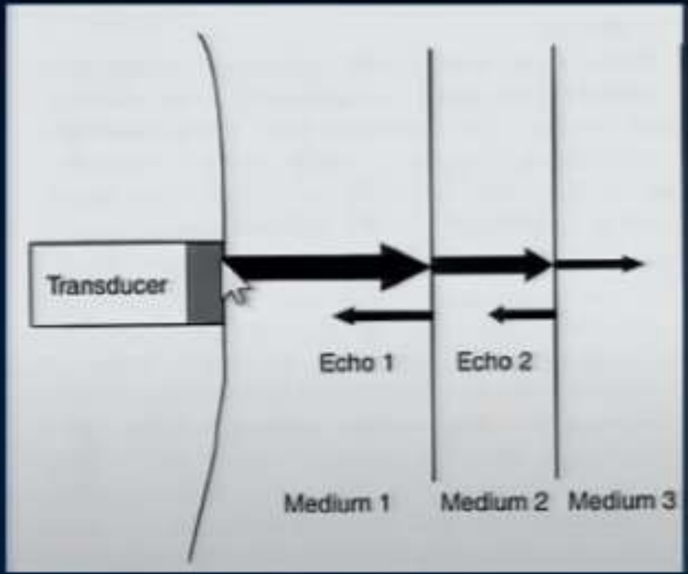
Acoustic parameters of medium:



Interaction of US with medium – reflection and back-scattering, refraction, attenuation (scattering and absorption)

Reflection and transmission

- A beam encounters multiple interfaces on its path through the body.
- At each one, a percentage of the incident beam intensity is reflected or transmitted.
- This includes the beam's return path.



Ultrasonography
Basic characteristics of US images

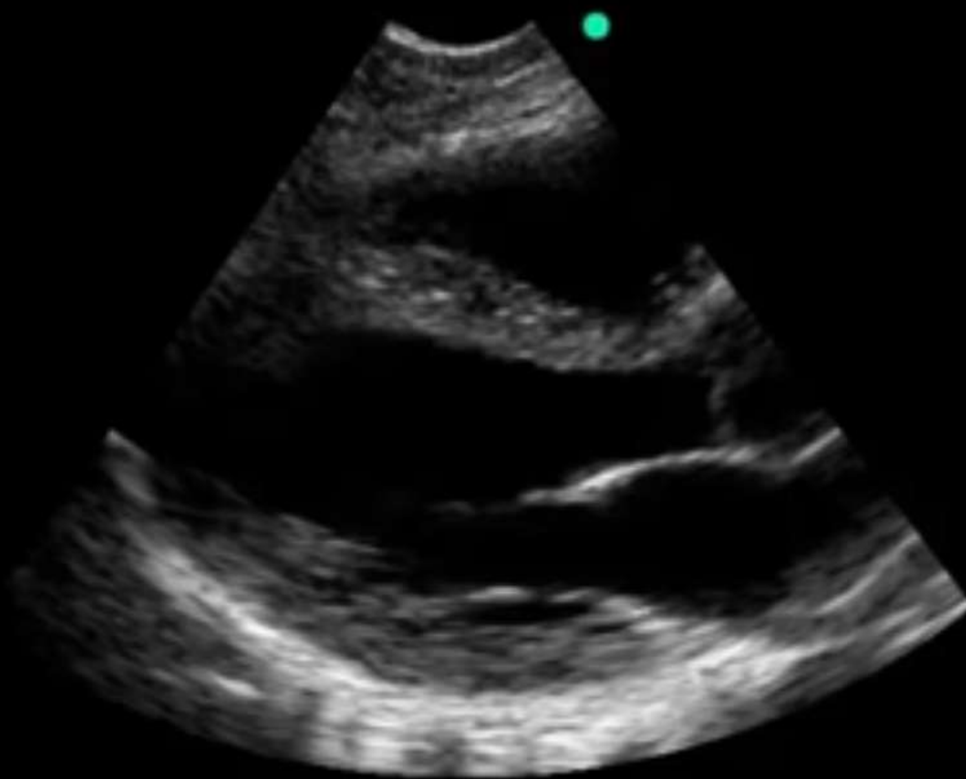
Degree of reflectivity – echogenity. The images of cystic (liquid-filled) and solid structures are different. According to the intensity of reflection *in the tissue bulk* we can distinguish structures:

hyperechogenic, izoechogenic, hypoechogenic, anechogenic.

- **Solid structures – acoustic shadow** (caused by absorption and reflection of US)

- **Air bubbles and other strongly reflecting interfaces cause repeating reflections** (reverberation, “comet tail“).

Echogenicity- relative brightness



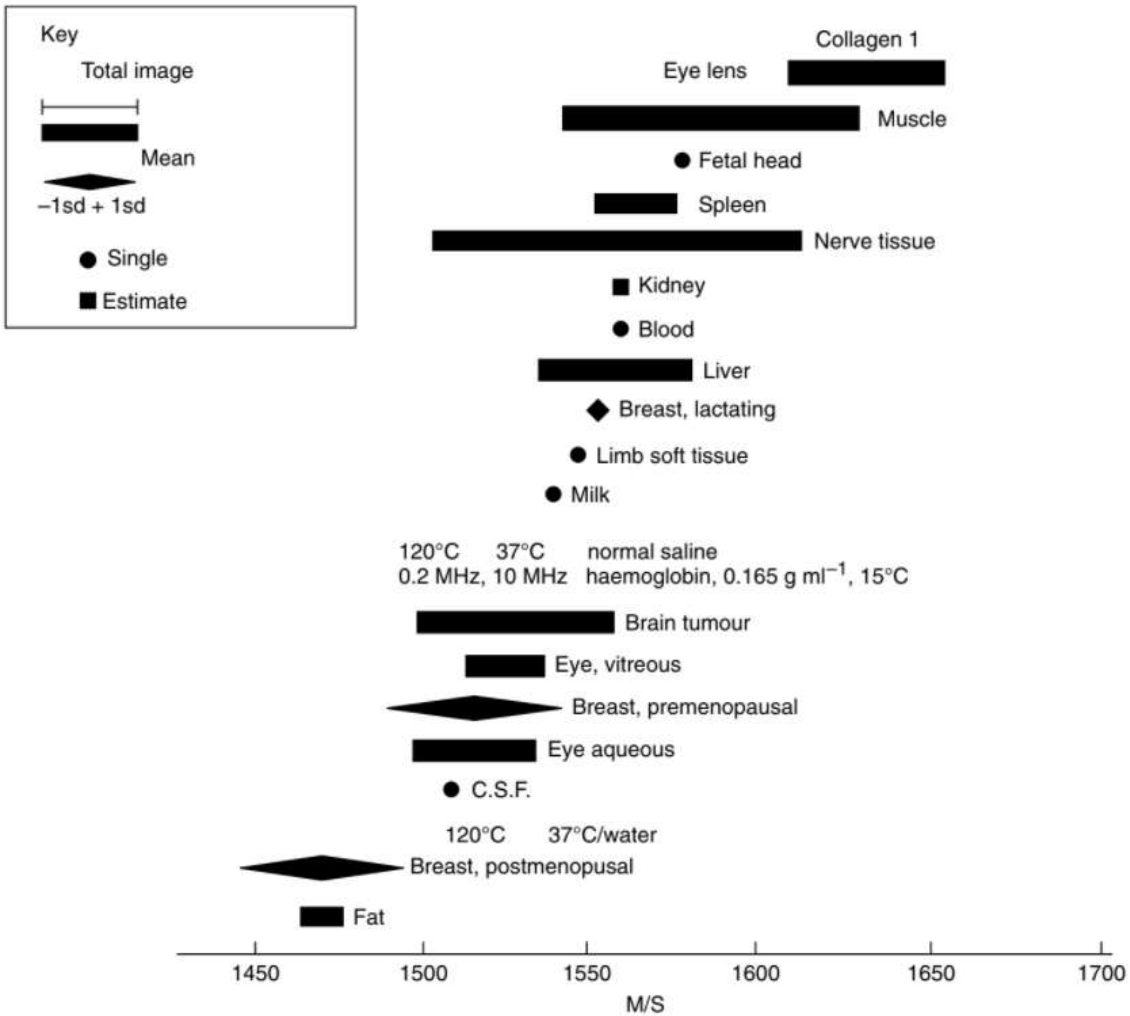
Hyperechoic- brighter (bone, air, capsules)
Isoechoic- same (muscle, fat)
Hypoechoic/anechoic- darker (fluid)

Acoustic parameters of medium

$$c = \sqrt{\frac{K}{\rho}} \quad \left[ms^{-1}\right]$$

Speed of US *c* depends on elasticity and density ρ of the medium: *K* - modulus of compression

Speed of ultrasound in various biological materials



(Redrawn after P.N.T. Wells, Biomedical Ultrasound, Academic Press, London)

Interactions of US with Tissue

- Reflection (smooth homogeneous interfaces of size greater than beam width or the US wavelength, e.g. organ outlines)

- Rayleigh Scatter (small reflector sizes, e.g. blood cells, dominates in non-homogeneous media)

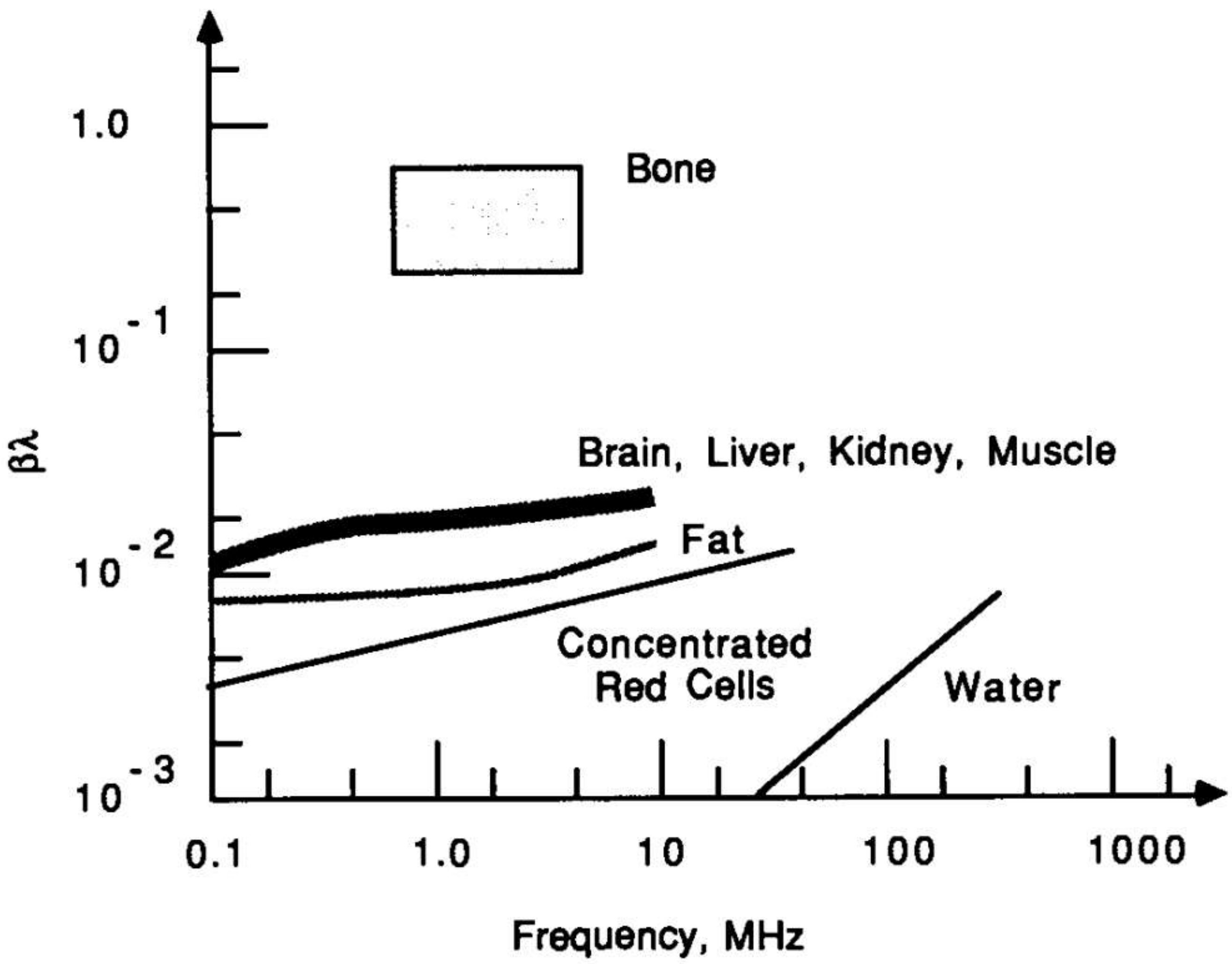
- Refraction (away from normal from less dense to denser medium, note opposite to light, sometimes produces distortion)

- Absorption (sound to heat)
  - absorption increases with f, note opposite to X-rays
  - absorption high in lungs, less in bone, least in soft tissue, again note opposite to x-rays

- Interference: ‘speckles’ in US image result of interference between Rayleigh scattered waves. It is an image artefact.

- Diffraction

Ultrasonic absorption and wavelength in several media



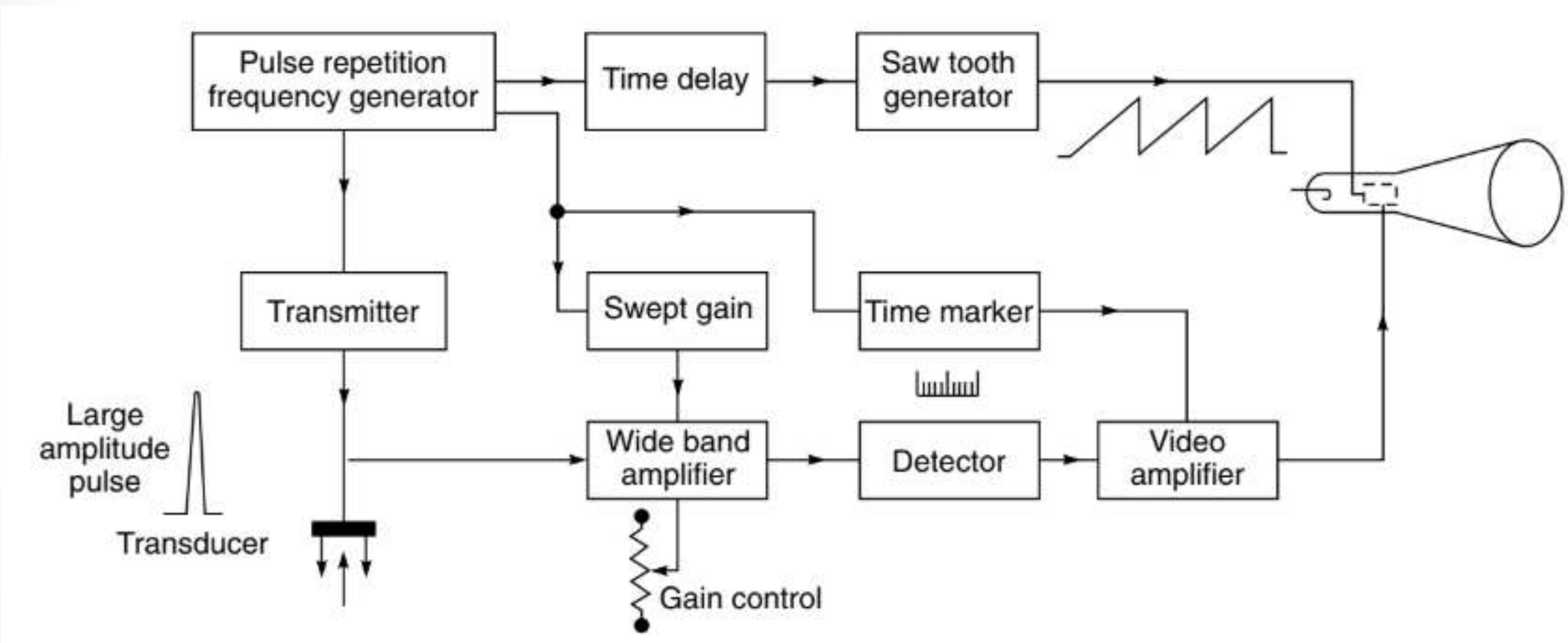
Pulse-Echo Imaging

- Two important augmentations to basic imaging
  - Phased arrays
  - Doppler imaging
- Ideal ultrasound imaging system would reconstruct and display the spatial distribution of reflectivity
- Users can manually adapt the system to more or less gain so that subtle features can be seen in images

Pulse Echo system

- The transmitter generates a train of short duration pulses at a repetition frequency determined by the PRF generator
- These are converted into corresponding pulses of ultrasonic waves by a piezo-electric crystal acting as the transmitting transducer
- The echoes from the target or discontinuity are picked up by the same transducer and amplified suitably for display on a cathode ray tube

Pulse Echo system



Ultrasound Transducers

- Transducer Materials
  - Piezoelectric Crystals – translates mechanical strain into electrical signal and vice versa
  - Most common material is Lead Zirconate Titanate (PZT)
  - Other materials include: Quartz, Polyvinylidene Fluoride (PVDF)

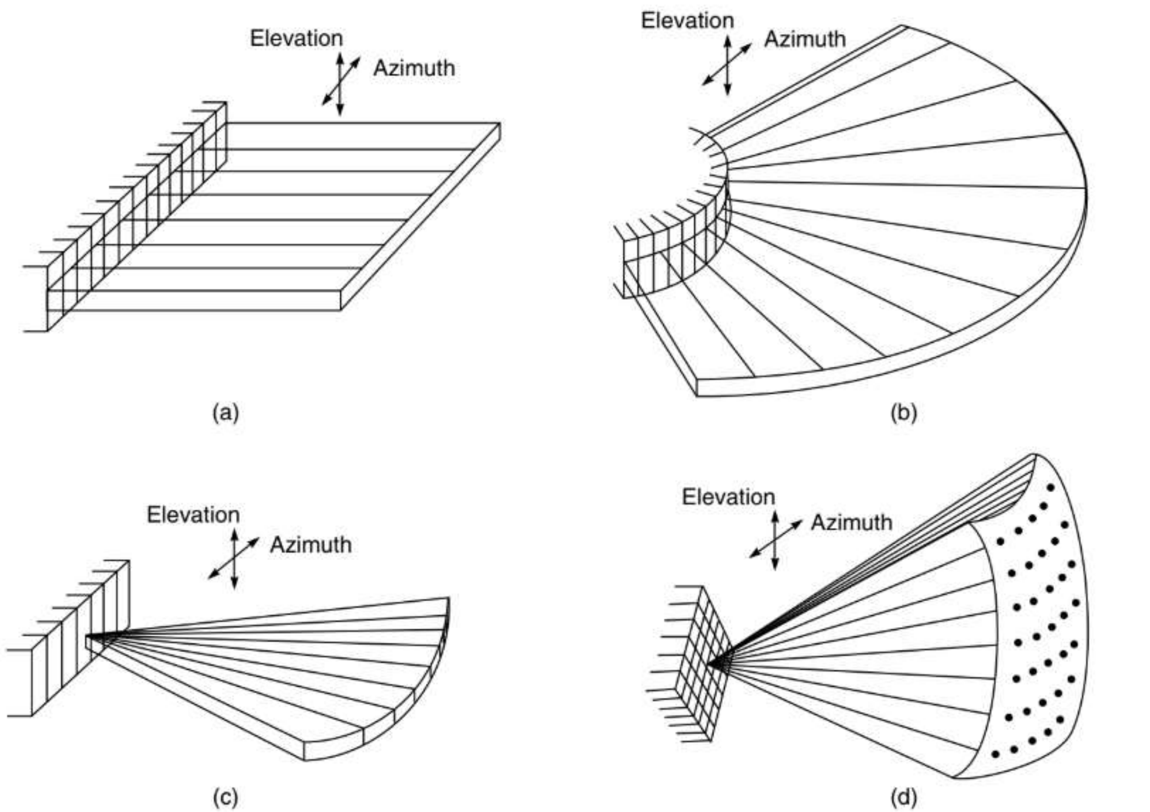
Ultrasound Probes

- Single Element Probes
  - Simplest assembly of transducer
  - Construction of a single element probe
  - Lens or curved crystal
  - Ultrasound beam requires steering
  - Modern systems of scanning allow for real-time imaging

Ultrasound Probes

- Electronic Scanners
  - Arrangement of elements in the assemblies is linear
  - Each element is rectangular
  - Focused using a lens
  - Linear array probe
    - Elements have widths on the order of a wavelength and are electronically grouped together making several elements appear as one.
  - Phased array probe
    - Elements have widths of a quarter wavelength and the timing of firing of the elements are electronically controlled in order to steer and focus the beam.

MULTI ELEMENT LINEAR ARRAY SCANNER



Different arrangements in multi-element array scanners

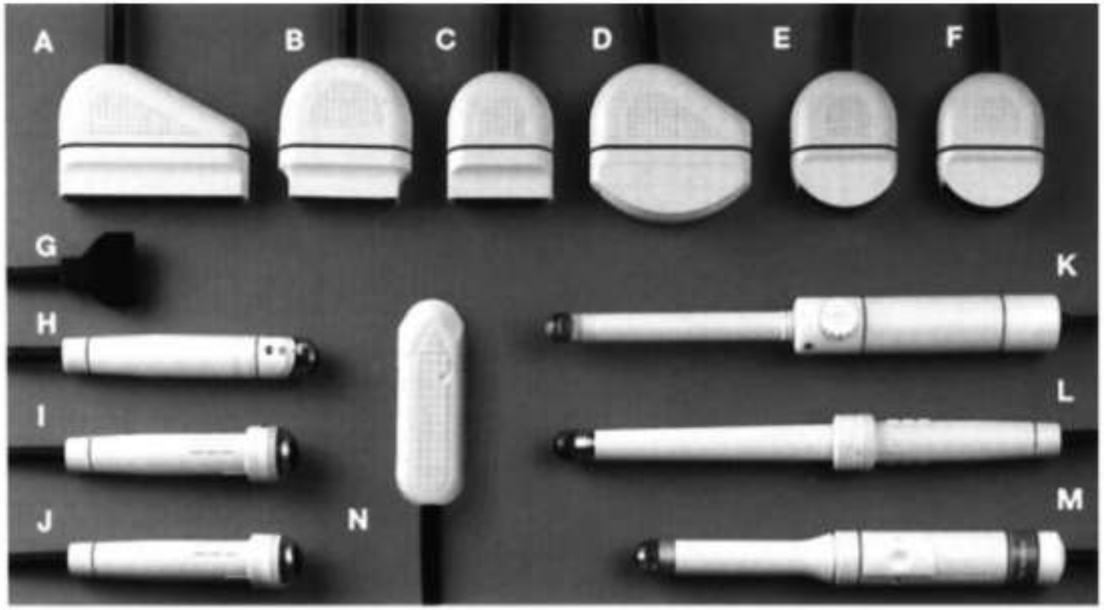
(a) linear sequential array (b) curvi-linear array

(c) linear phased array (d) phased array

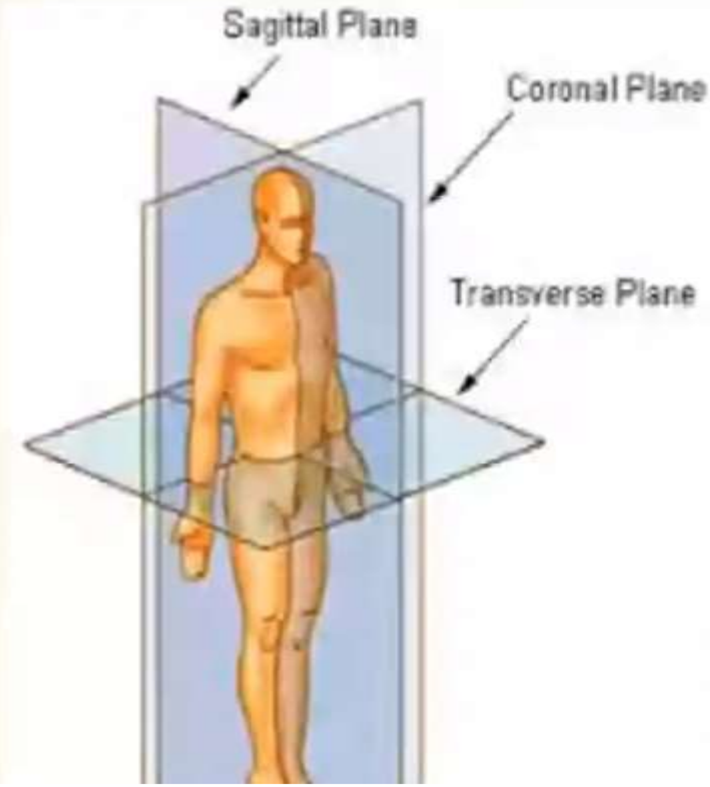
PROBES

Probes

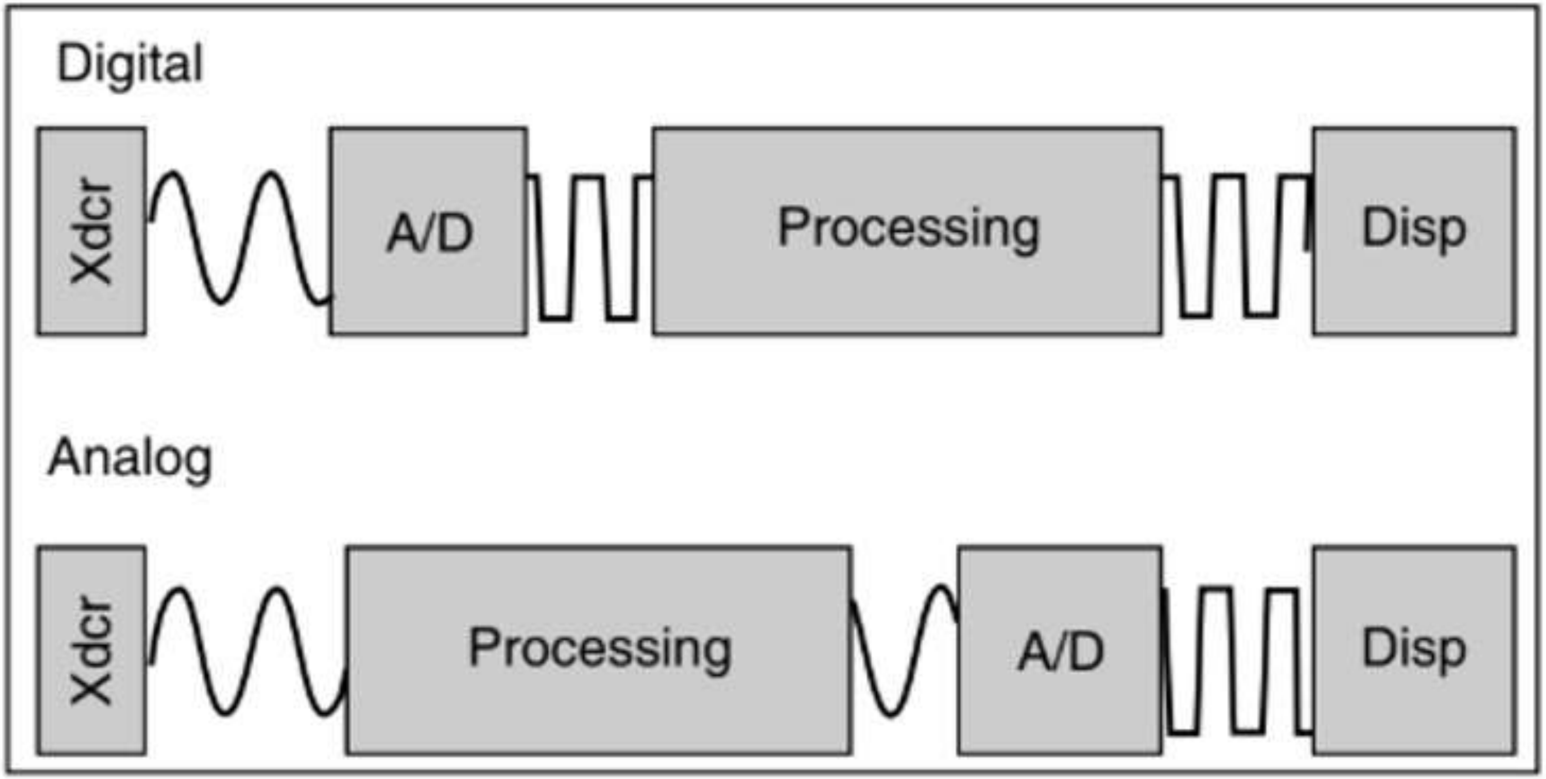
A Linear Array probe 3.5 and 3.5/5.0 MHz, 12 cm
B Linear Array probe 5.0/7.5 MHz, 7.4 cm
C Linear Array probe 7.5 MHZ, 6 cm
D Curved Array probe 3.5/5.0 MHz, R75
E Curved Array probe 3.5 and 3.5/5.0 MHz, R40
F Curved Array probe 5.0 MHz, R40
G Linear Array probe 7.5 MHz, 4 cm
H Multi-angle sector probe 5.0/7.5 MHz
I Annular Array sector probe 3.5 MHz
J Annular Array sector probe 5.0 MHz
K Multi-plane endorectal probe 5.0/7.5 MHz
L Endovaginal probe 5.0/7.5 MHz
M Multi-plane endovaginal probe 5.0/7.5 MHz
N Curved Array probe 5.0/7.5 MHz, R17



ANATOMICAL PLANES AND 3D PROBES

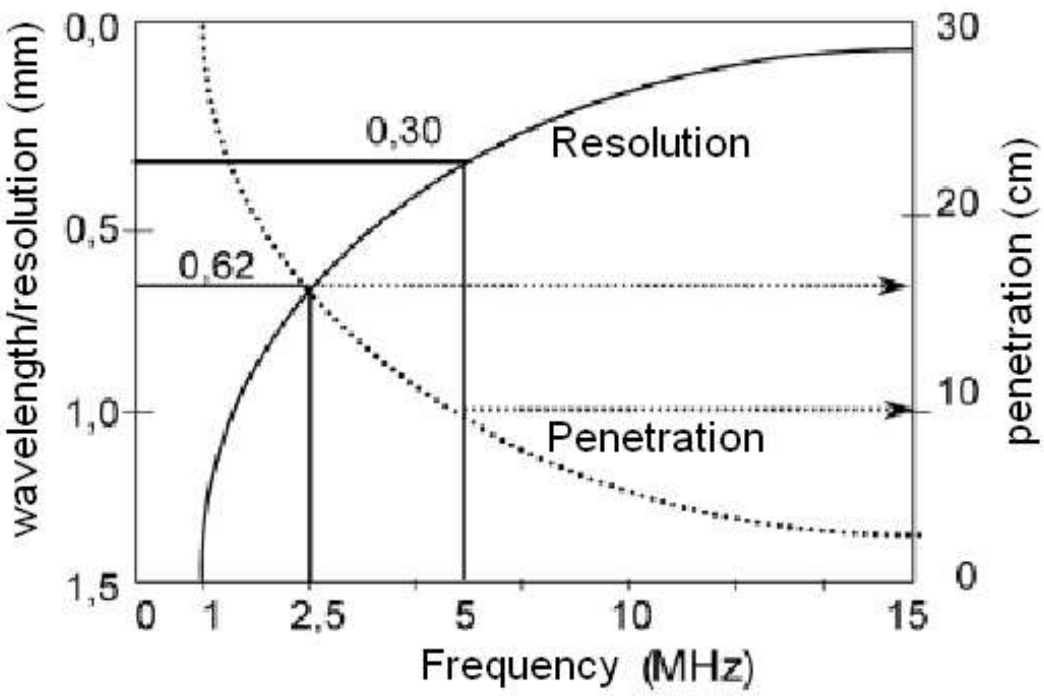


Ultrasound types



Ultrasonography

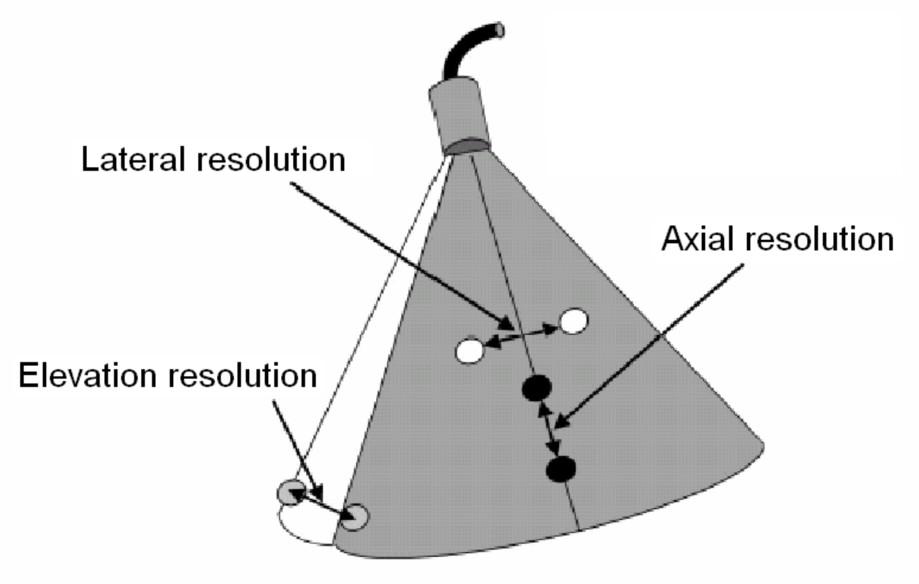
Spatial resolution of US imaging system is determined by the wavelength of the US. When the object dimension is smaller than this wavelength only scattering occurs. Hence higher spatial resolution requires higher frequencies



Limitation-
absorption of US increases with frequency of ultrasound = smaller penetration depth
Compromise frequency 3-5 MHz – penetration in depth of about 20 cm

Ultrasonography

Spatial Resolution



- **Axial spatial resolution** - it is given by the shortest distance of two distinguishable structures lying in the beam axis – it depends mainly on frequency (at 3.5 MHz about 0.5 mm)
- **Lateral spatial resolution** - it is given by the shortest distance of two distinguishable structures perpendicularly to the beam axis – depends on the beam width
- **Elevation** – ability to distinguish two planes (sections) lying behind or in front of the depicted tomographic plane – it depends on frequency and beam geometry

There are three parameters that are important in optimizing transducers for various types of applications (Hunt et al. 1983).

These are frequency, active element diameter and focusing.

Frequency: With increase in frequency, the sound beam becomes more directional and the axial resolution improves. However, due to attenuation of higher frequency ultrasound waves in the tissues, the penetration decreases.

For most abdominal ultrasound examinations, the frequencies used are in the range of 1-5 MHz, whereas the wavelength is in the range of 1 mm. Higher frequencies (10-15 MHz) are used for superficial organs, such as the eye, where deep penetration is not required and where advantage may be taken of the 0.1 mm wavelength to improve geometrical resolution.

↑Frequency ↑Axial Resolution ↑Lateral Resolution ↓Penetration

↓Frequency ↓Axial Resolution ↓Lateral Resolution ↑Penetration

Frequency also influences lateral resolution by affecting beam divergence. The following rule applies, assuming all other factors remain constant.

↑Frequency ↓Beam divergence ↑Lateral Resolution

Active Element Diameter (AED): As the transducer face diameter increases, the beam width decreases and therefore, lateral resolution improves

↑A.E.D. ↓Rate of Divergence ↑Lateral Resolution

Spatial Resolution

The best resolving power can be found in the narrowest part of the US beam profile.

Focusing – US beam is converged at the examined structure by means of acoustic lenses (shapes of the layer covering the transducer) or electronically.

- The probes can be universal or specially designed for different purposes with different focuses.
- The position of focus can be changed in most sector probes.

Ultrasonography

A-mode – one-dimensional

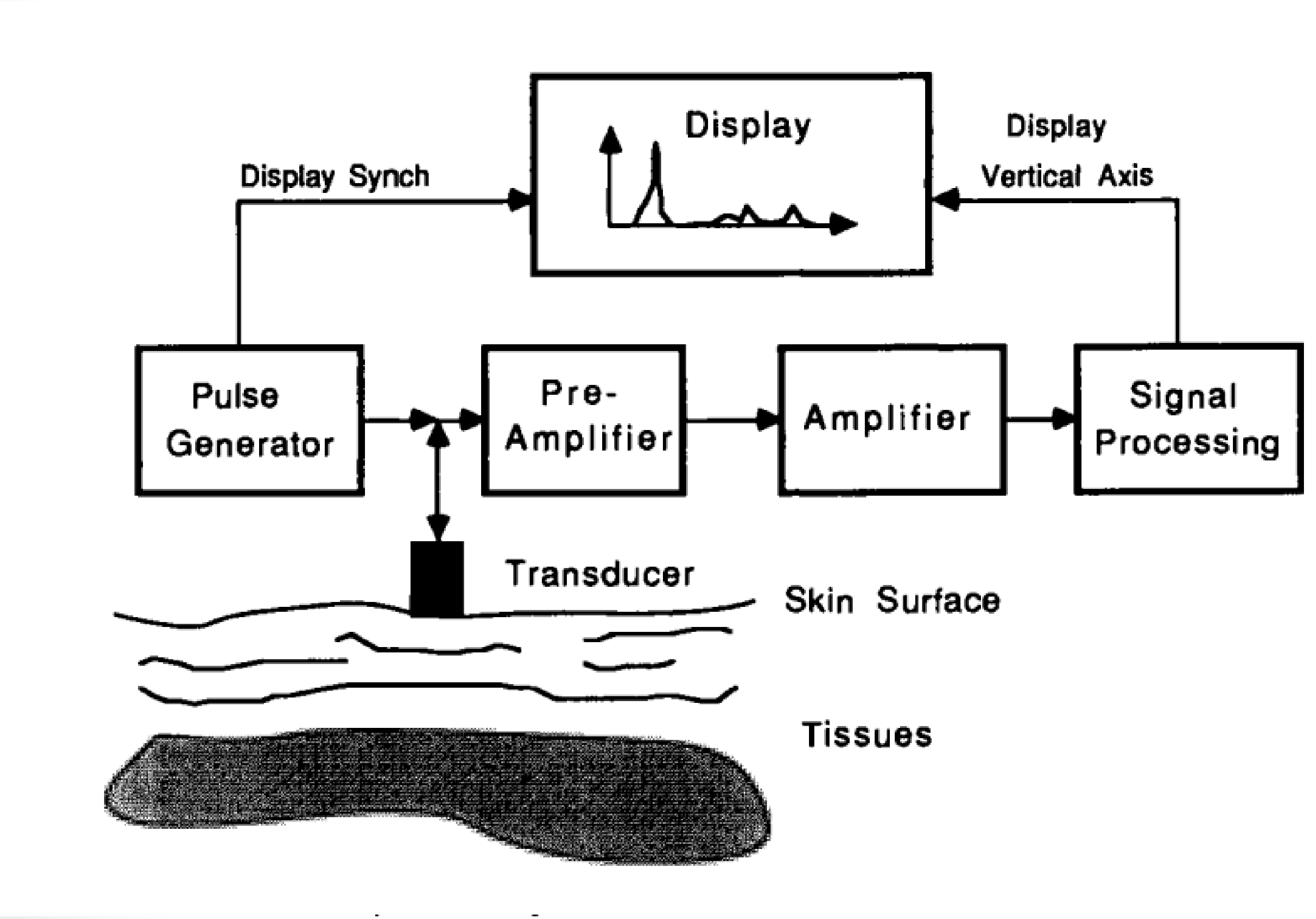
- Distances between reflecting interfaces and the probe are shown.
- Reflections from individual interfaces (boundaries of media with different acoustic impedances) are represented by *vertical deflections* of base line, i.e. the echoes.

Echo amplitude is proportional to the *intensity of reflected waves* (Amplitude modulation)

Distance between echoes shown on the screen is approx. proportional to real distance between tissue interfaces.

Today used mainly in ophthalmology.

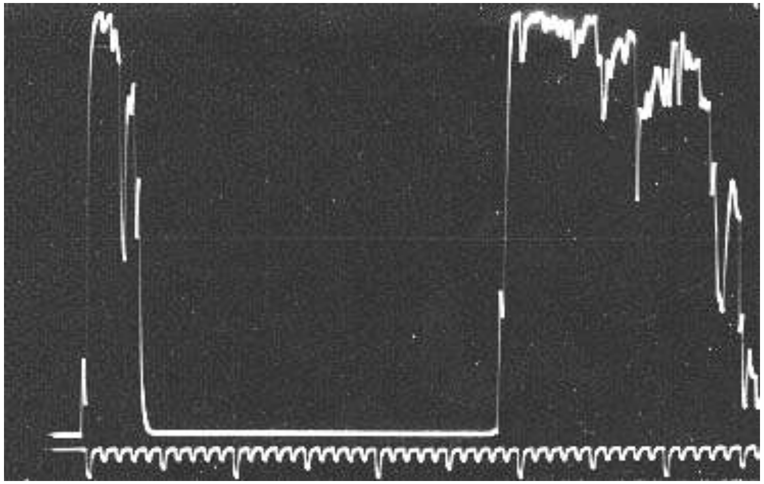
BD- A scan

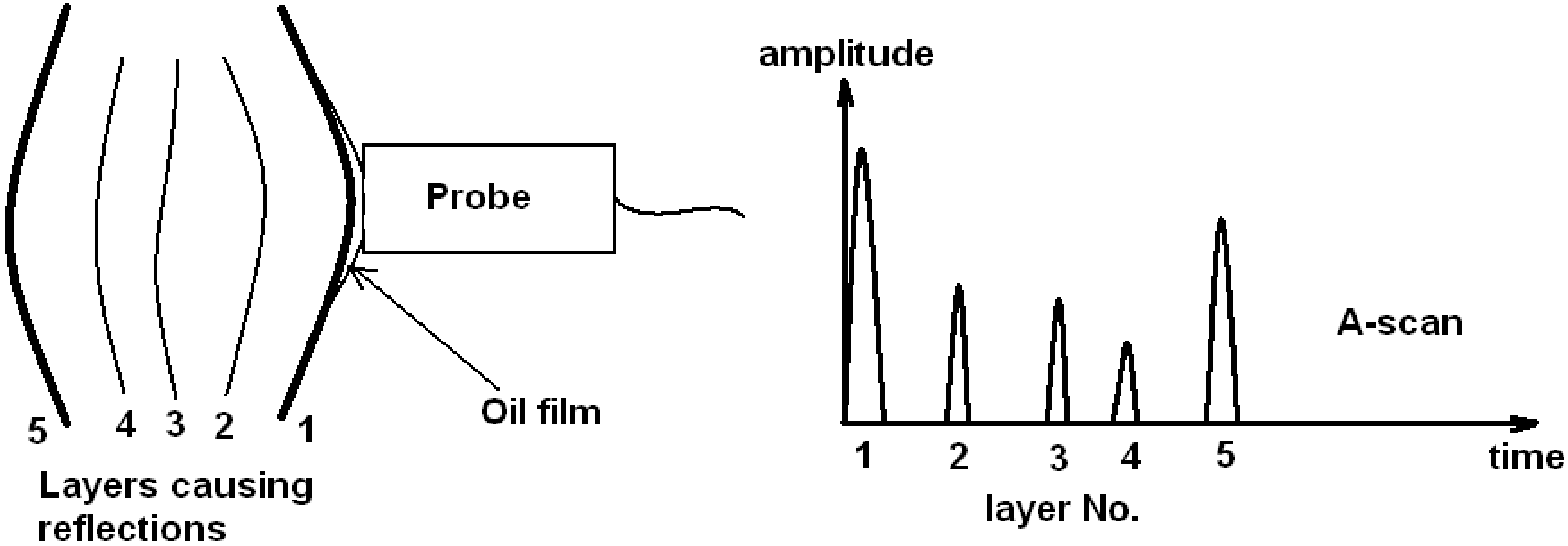


Display
Display Synch
Display
Vertical Axis
Pulse
Generator
Pre-
Amplifier
Amplifier
Signal
Processing
Transducer
Skin Surface
Tissues

Ultrasonography

A-mode – one-dimensional





PRINCIPLE OF A-MODE SCAN

Ultrasound Imaging Modes

- A-Mode Scan
  - Amplitude-mode signal
  - Transducer is fired rapidly and a succession of signals can be displayed on an oscilloscope
  - The time between successive firings is called repetition time
    - Interval should be long enough so that returning echoes have died out, but fast enough to capture motion
  - Useful when looking at heart valve motion

Ultrasonography

B-mode – two-dimensional

A tomogram is depicted.

Brightness of points on the screen represents intensity of reflected US waves (Brightness modulation).

Static B-scan: a cross-section image of examined area in the plane given by the beam axis and direction of *manual* movement of the probe on body surface. The method was used in 50‘ and 60‘ of 20th century

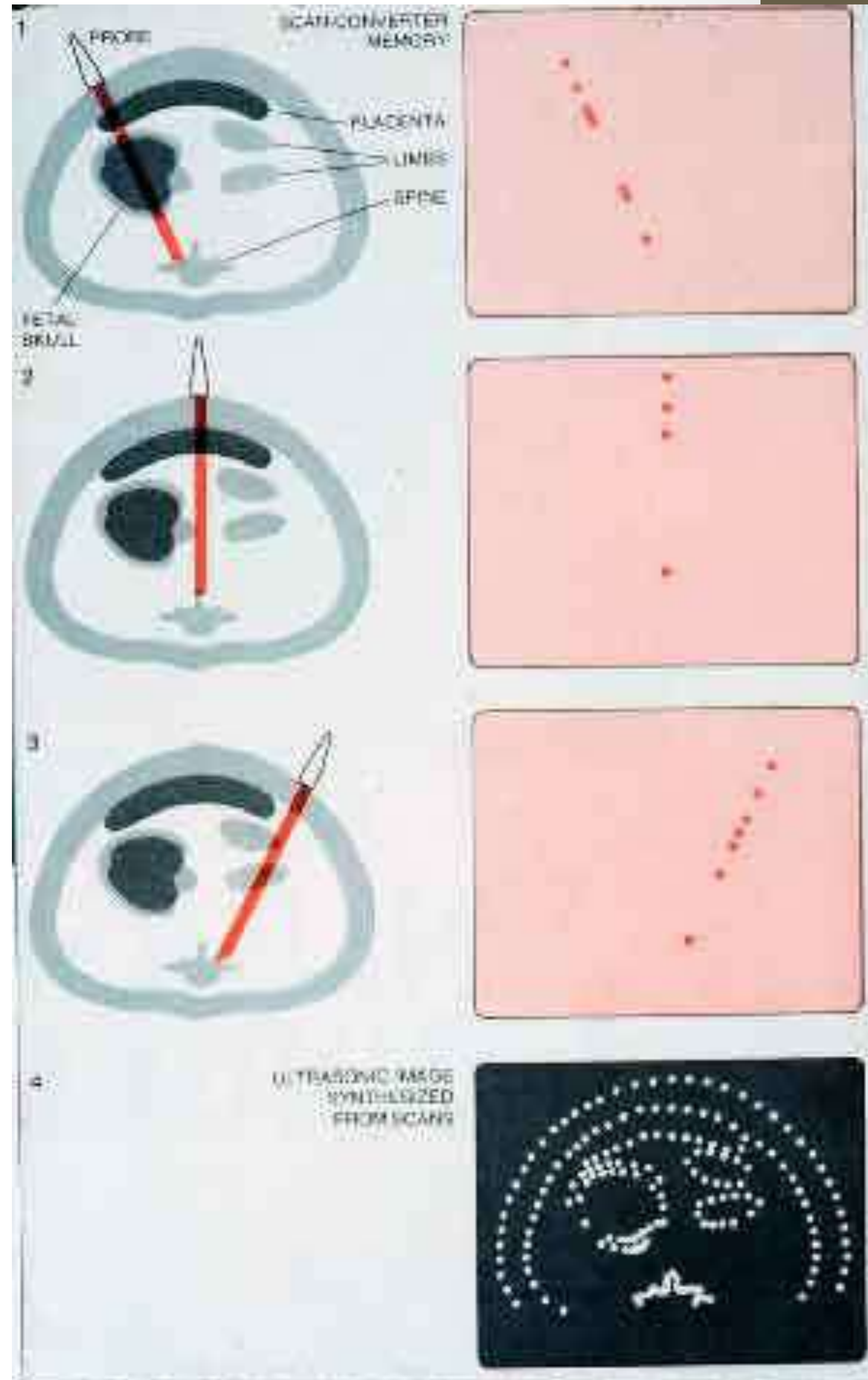
Ultrasound Imaging Modes

- B-mode scanners
  - Linear scanner – collection of transducers arranged in a line, does not require motion. Requires large flat area with which to maintain contact with the body.
    - Abdominal imaging
    - Obstetrics
  - Mechanical sector scanner – pivots a transducer about an axis orthogonal to the transducer's axis.
  - Phased array sector-scanner – collection of very small transducer elements arranged in a line. Smaller than linear scanner. Advantage is that focus can be varied over time providing a dynamic focus. Disadvantage is that sidelobes of acoustic energy are generated and can lead to artifacts.

Ultrasonography

B-mode – two-dimensional - static

Foetus in abdomen of pregnant woman



Ultrasonography

B-mode - dynamic

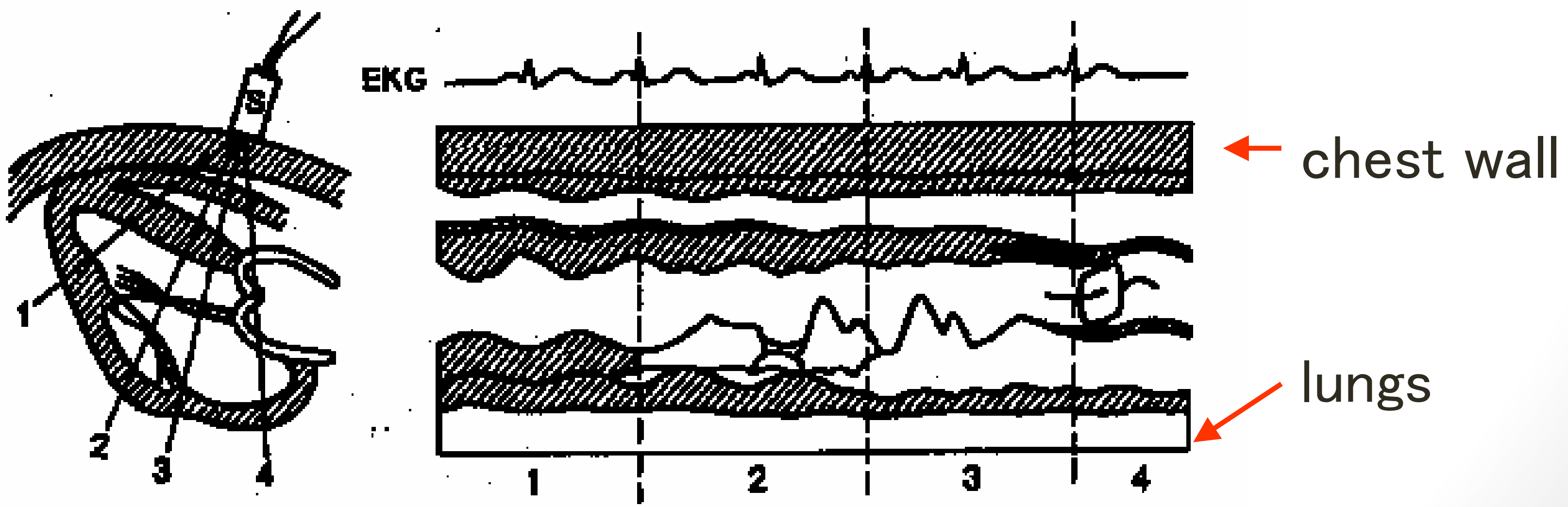
Repetitive formation of B-mode images of examined area by fast deflection of US beam mechanically (in the past) or electronically “in real time“ today.
Electronic probes consist of many piezoelectric transducers which are gradually activated.

Ultrasonography # M-mode

One-dimensional static B-scan shows movement of reflecting tissues. The second dimension is time in this method.

Static probe detects *reflections* from moving structures. The bright *points* move *vertically* on the screen, *horizontal shifting* of the record is given by slow time-base.

Displayed curves represent *movement* of tissue structures



Ultrasound Imaging Modes

- M-Mode Scan
  - Using each A-mode signal as a column in an image
  - Value of A-mode signal becomes the brightness of the M-mode image
  - Motion is revealed by bright traces moving up and down across the image
  - Most often used to image motion of heart valves and is therefore shown along with ECG.

Ultrasound Imaging Modes

- Depth of penetration
  - Limited by attenuation
  - $z = \frac{-L}{af}$ is total range wave can travel before attenuated below system threshold
  - $d_p = \frac{L}{2af}$, depth of penetration can only be half of the above equation (round trip)
- Pulse Repetition Rate
  - New pulse generated only after echoes from previous pulse are gone
  - $T_R \geq \frac{2d_p}{c}$, pulse repetition interval – round trip time to max depth of penetration
  - $f_R = \frac{1}{T_R}$, pulse repetition rate

Ultrasound Imaging Modes

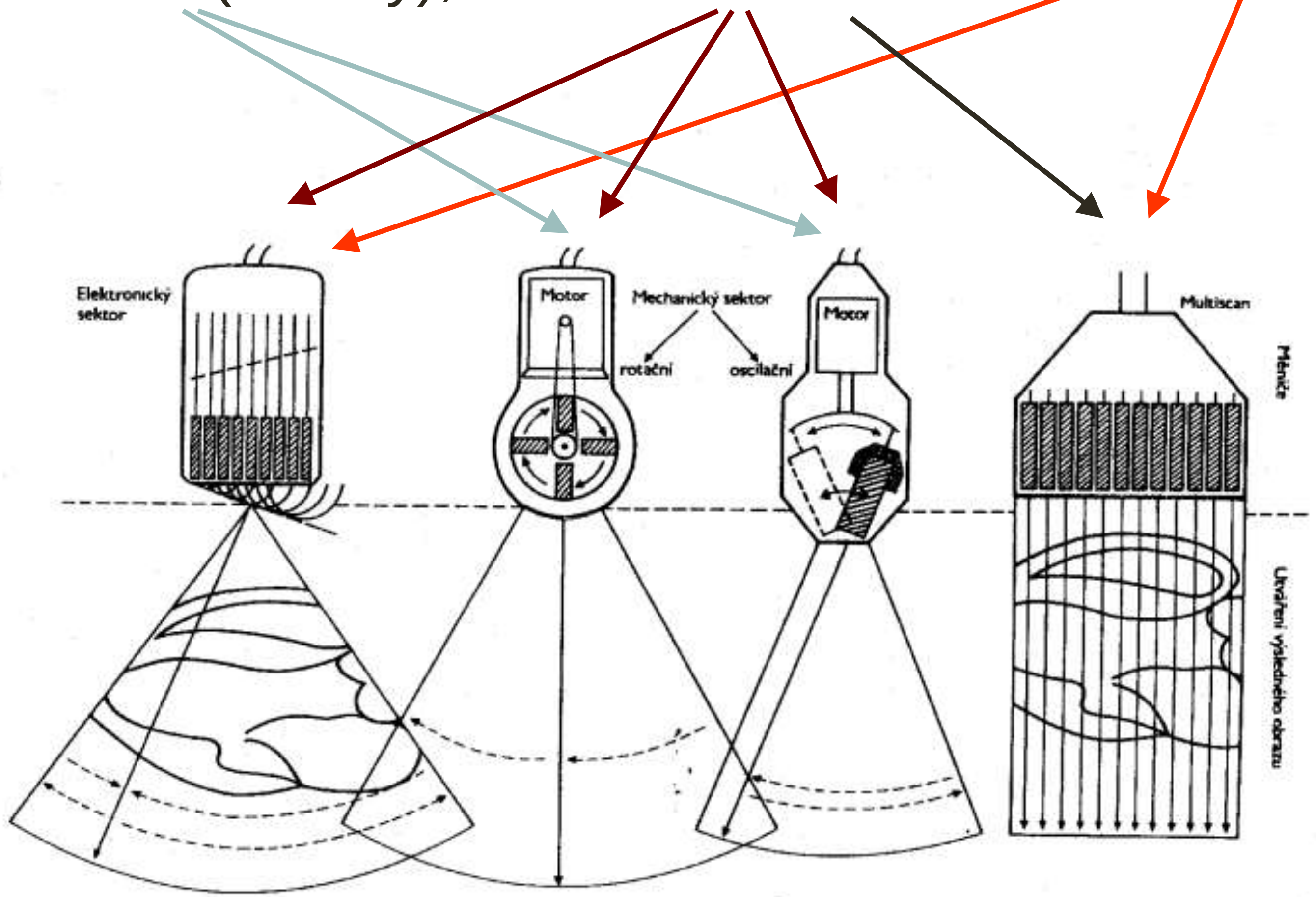
- B-Mode Image Frame Rate
  - If N pulses are required to generate an image → Frame rate

    $F = \frac{1}{T_R N}$
  - Typical frame rates in commercial ultrasound systems around 10-100 frames/sec
  - Low end values create a great deal of flicker, unacceptable
  - Scan conversion solves this (converts polar to rectangular) by reading out data at higher rate.
  - Can also reduce field of view to enable increased frame rate (reduce N)

Ultrasonography

B-mode - dynamic

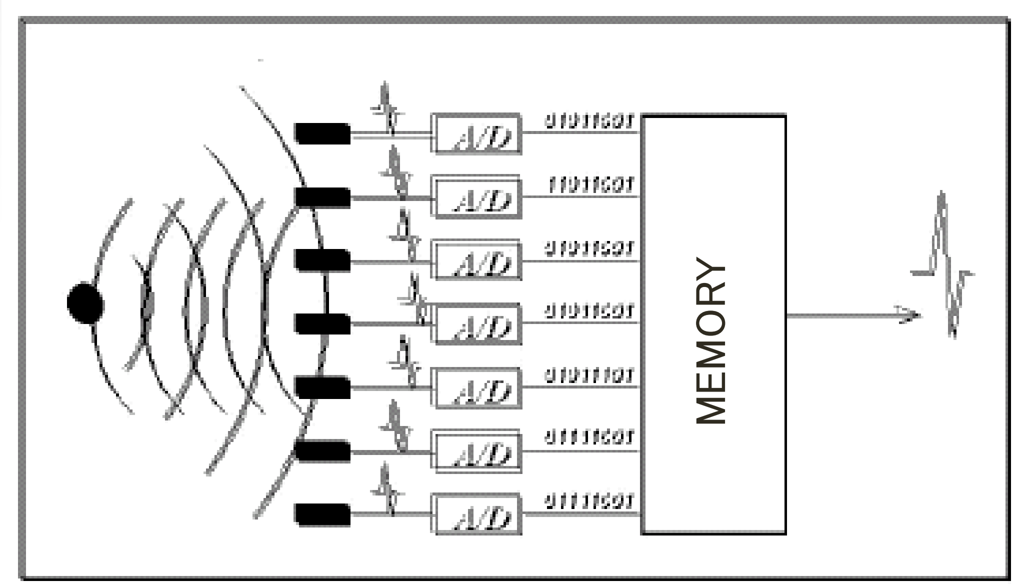
Ultrasound probes for dynamic B-mode: electronic and mechanical (history), sector and linear.

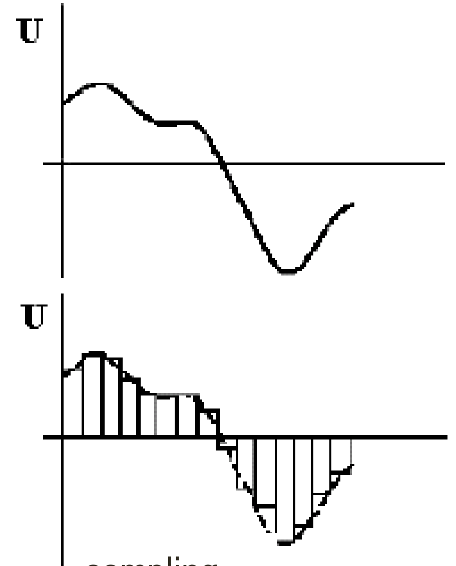


Abdominal cavity is often examined by convex probe – a combination of a sector and linear probe.

Ultrasonography

B-mode - dynamic

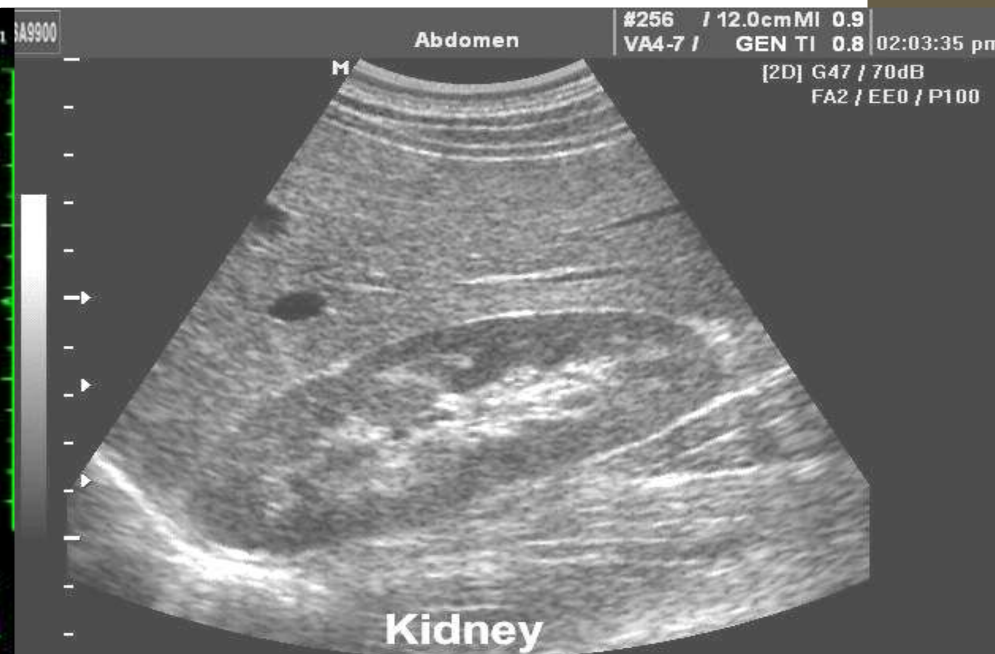




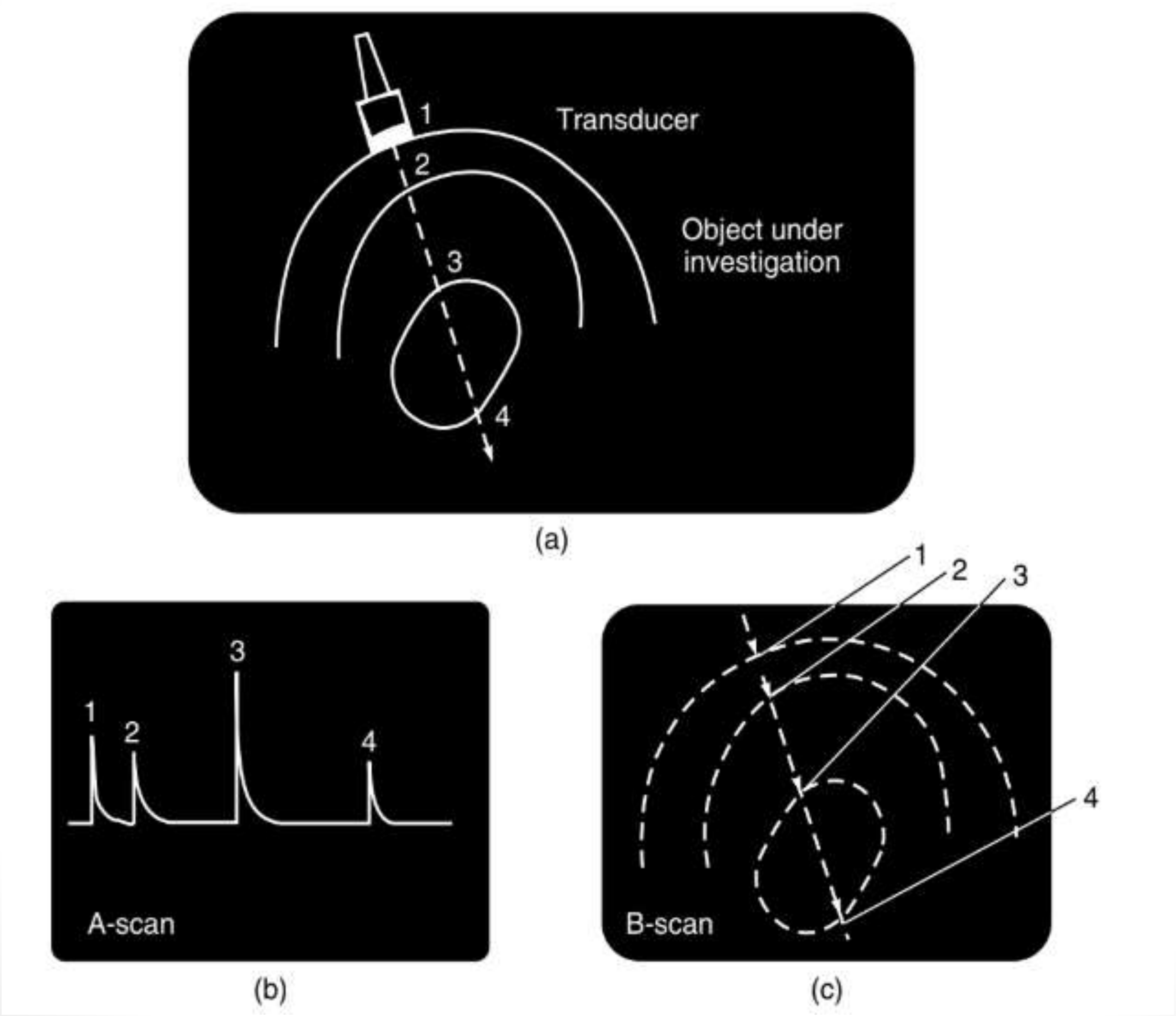
Modern ultrasonography - digital processing of image

- Analogue part – detection system
- Analogue-digital converters (ADC)
- Digital processing of signal – possibility of programming (preprocessing, postprocesssing), image storage (floppy discs, CD, flash cards etc.)

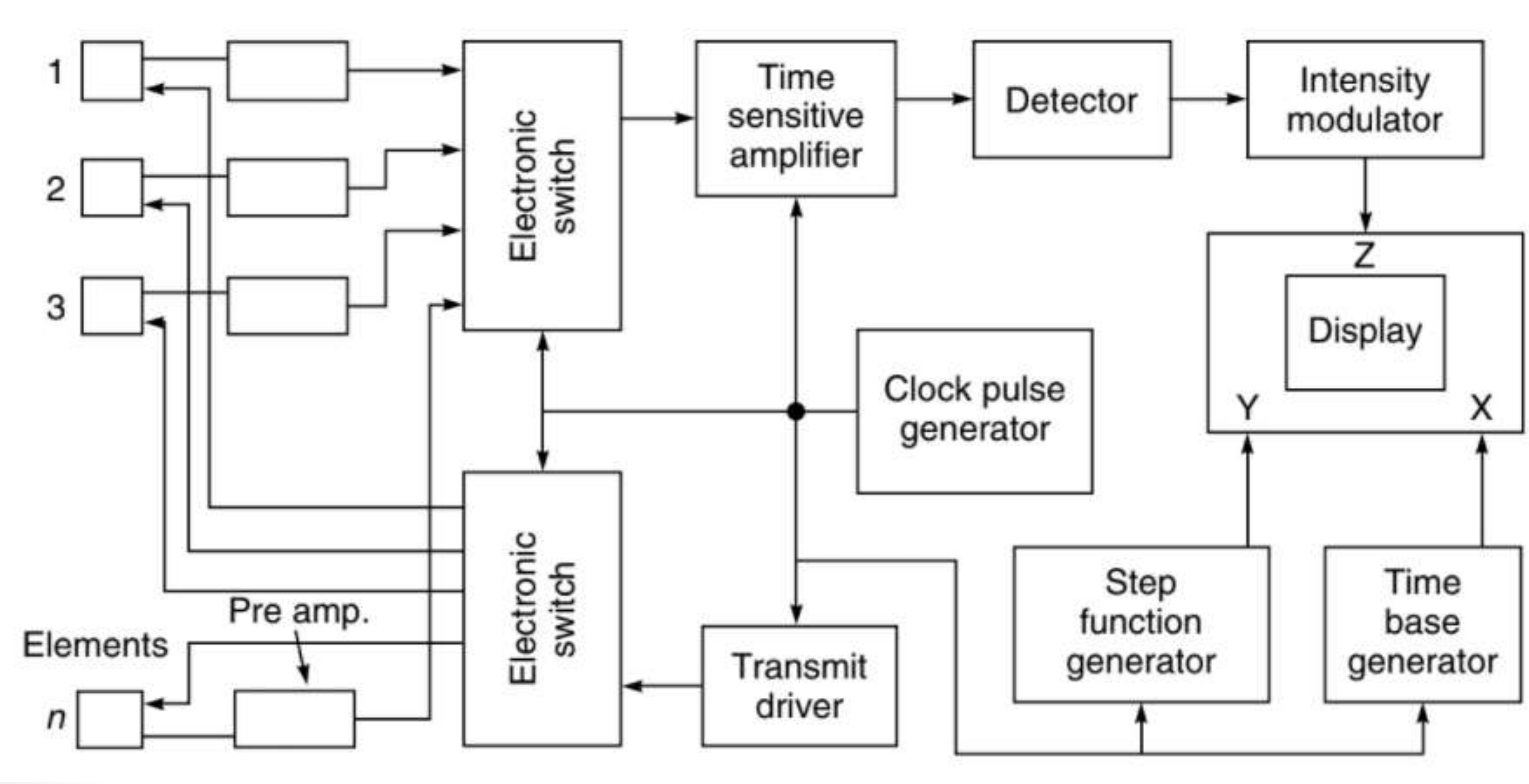
Ultrasonography B-mode - dynamic



Difference between A mode and B mode



Linear array scanner



Linear array scanner

- The principle of linear array scanners is described by Bom et al. (1973) and can be summarized as the use in rapid succession of a number of parallel single elements with the display of each element in the brightness mode (B-mode) at almost the same instant.
- The transducer used comprises 20 elements placed on a line array of 8 cm. Each element measures 4 by 10 mm and the active area of the transducer is 80 ¥ 10 mm.
- The depth penetration is designed for 16 cm, and therefore, the cross-section covered measures about 8 x16 cm.

Medical Ultrasound

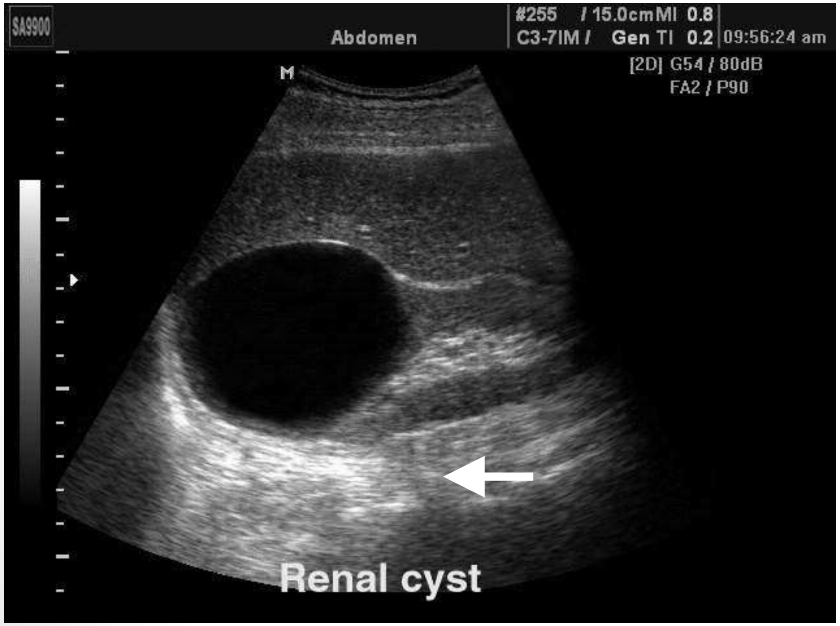
The use of ultrasound in the medical field can be divided into two major areas: the therapeutic and the diagnostic

The major difference between the two applications is the ultrasonic power level at which the equipment operates

- In therapeutic applications, the systems operate at ultrasonic power levels of upto several watts per square centimetre while the diagnostic equipment operates at power levels of well below 100 mW/cm2

Ultrasonography

Acoustic shadow caused by absorption and reflection of US by a kidney stone (arrow)



Hyperechogenic area below a cyst (low attenuation of US during passage through the cyst compared with the surrounding tissues – arrow)

Portable ultrasound

The smallest ultrasound system on the market, the GE Vscan, is designed to be easy to use

Portable ultrasound

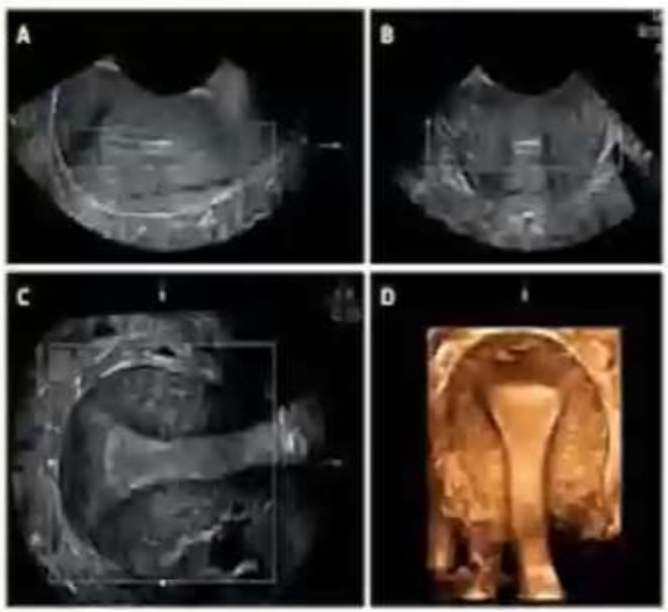
Recent advances

- Recent advances in ultrasound transducer and electronics have enabled an extension of the ultrasound frequency for imaging beyond the conventional 5–10 MHz range
- A high speed 40 MHz A/D converter has raised the Nyquist frequency, making 20 MHz imaging a possibility, to achieve a spatial resolution as fine as 70 micron
- GE Medical offers a linear transducer which provides 12 MHz imaging frequency. With this system, objects smaller than 200 microns have been seen, opening an era of micron imaging
- These systems have demonstrated axial, lateral and contrast resolution similar to that of Magnetic Resonance Imaging (MRI)

Recent advances

3D/ 4D Ultrasound

- Surface rendering and gives information about the coronal plane
- Provides more clinical values to assess the abnormalities



Biological effects

- The experiments conducted include studies on whole animals, individual organs, isolated cultured cells and biochemical studies.
- Surveys of human populations which have been exposed to ultrasound, though on a limited scale, have also been taken
- The zone of safety was valid for 0.5 to 15 MHz and for all anatomic sites except the eyes. Re-exposures were limited to l0% and 30% per year.
- Zone of safety for continuous wave ultrasound lay below a log/log line connecting 1 ms of 1 kW/cm^2ultrasound, with 200 s of 100 mW/cm^2ultrasound
- A pulse-echo system operating with pulses of 1 ms duration and 10 W/cm^2on intensity, at a pulse repetition frequency of 100/ s should not be used to examine any individual patient for a total time exceeding 2.75 hours

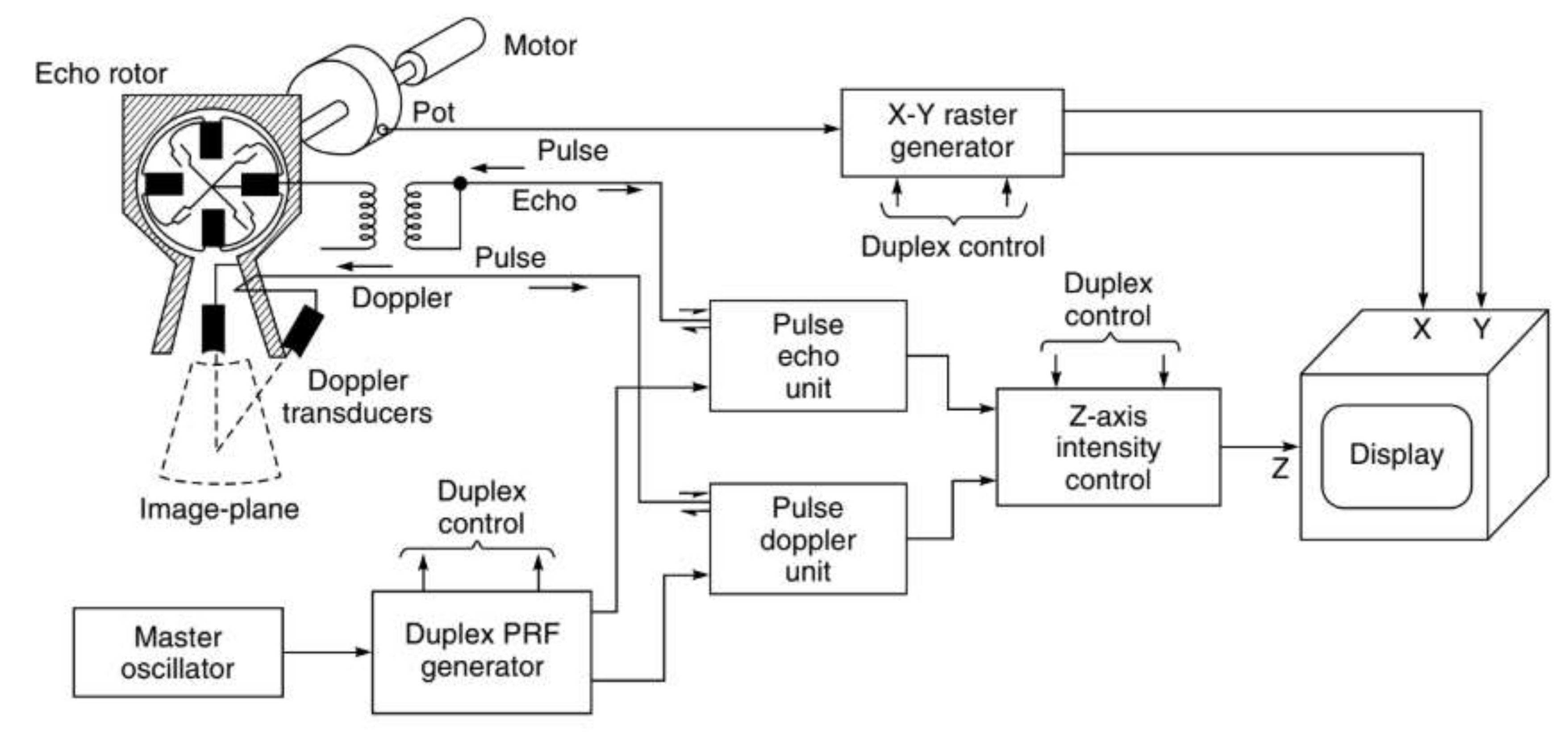
More on Imaging Modes

- **A-mode**: A-mode (amplitude mode) is the simplest type of ultrasound. A single transducer scans a line through the body with the echoes plotted on screen as a function of depth. Therapeutic ultrasound aimed at a specific tumor or calculus is also A-mode, to allow for pinpoint accurate focus of the destructive wave energy.
- **B-mode or 2D mode**: In B-mode (brightness mode) ultrasound, a linear array of transducers simultaneously scans a plane through the body that can be viewed as a two-dimensional image on screen. More commonly known as 2D mode now.
- **M-mode**: In M-mode (motion mode) ultrasound, pulses are emitted in quick succession – each time, either an A-mode or B-mode image is taken. Over time, this is analogous to recording a video in ultrasound. As the organ boundaries that produce reflections move relative to the probe, this can be used to determine the velocity of specific organ structures.

More on Imaging Modes

- **Doppler mode**: This mode makes use of the Doppler effect in measuring and visualizing blood flow
    - **Color Doppler**: Velocity information is presented as a color coded overlay on top of a B-mode image
    - **Continuous Doppler**: Doppler information is sampled along a line through the body, and all velocities detected at each time point is presented (on a time line)
    - **Pulsed wave (PW) Doppler**: Doppler information is sampled from only a small sample volume (defined in 2D image), and presented on a timeline
    - **Duplex**: a common name for the simultaneous presentation of 2D and (usually) PW Doppler information. (Using modern ultrasound machines color Doppler is almost always used, hence the alternative name **Triplex**.)

DUPLEX SCANNER



Links

- How ultrasound works
- https://www.youtube.com/watch?v=I1Bdp2tMFsY
- Basic Ulrasound physics
- https://www.youtube.com/watch?v=s23_d-qeEn4