IV. Sound

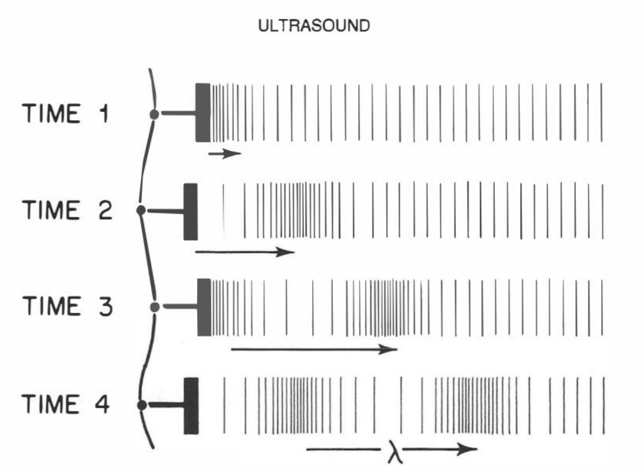
Production and propagation – velocity wave length frequency- ultrasound- properties & problems and application in clinical field.

Sound is a form of energy. It is the perception of pressure fluctuations travelling through a medium; its waves are transmitted as a series of compressions and rarefactions. There are a number of ways in which this pressure fluctuation can be transmitted which give rise to three classes of wave which are outlined below.

Ultrasound is defined as sound above the range of hearing of the human ear. This is usually taken to be 20 **kHz** although the appreciation of sound above 16 **kHz** is exceptional. The following table gives an indication of the classification of sound and some natural and manmade phenomena and uses.

Frequency Range	Type
Up to 20 Hz	Infra sound
117.1 Hz	Middle C
500 Hz	Underwater navigation
1.77 kHz	Upper soprano
16 kHz	Upper limit of normal hearing
20 kHz	Ultrasound
30 kHz	Early submarine detection
70 kHz	Upper limits of bats
≥70 kHz	Sonar
500 kHz	Lower limit of NDT
500 kHz – 12 MHz	Medical imaging up to 12 MHz
	Doppler 2,4,6,8 MHz
12 MHz – 100 MHz	Scanning Acoustic Microscope (SAM)

Longitudinal waves



It is the motion of the particles in which the medium is parallel to the direction of wave propagation. The length of the wave is the distance between two bands of compression or rarefaction which is represented by λ. Ultrasound, by definition, has a frequency of greater than

20,000 cycles per second. Audible sound has a frequency between 15 and 20,000 cycles per second (the frequency of the average man's voice is about 100 cycles per second, and that of the average woman is about 200). The sonic beams used in diagnostic imaging have frequencies from 1,000,000 to 20,000,000 cydes per second. One cycle per second is called a Hertz; a million cycles per second is a megahertz (abbreviated MHz). The term "Hertz" honors the famous German physicist Heinrich R. Hertz, who died in 1894.

Velocity of Sound

For body tissues in the medical ultrasound range, the velocity of transmission of sound is independent of frequency, and depends primarily on the physical makeup of the material through which the sound is being transmitted. The important characteristics of the transmitting medium are (1) its compressibility and (2) density.

Compressibility. The velocity of sound is inversely related to the compressibility of the conducting material; that is, the less compressible a material, the more rapidly it transmits sound. Sound waves move slowly in gases because the molecules are far apart and are easily compressed. They behave as though they are held together by loose springs. A particle must move a relatively long distance before it can affect a neighbour. Liquids and solids are less compressible because their molecules are closer together. They only need to move a short distance to affect a neighbour, so liquids and solids propagate sound more rapidly than gases.

Density. Dense materials tend to be composed of massive molecules, and the molecules have a great deal of inertia. They are difficult to move or to stop once they are moving. Because the propagation of sound involves the rhythmic starting and stopping of particulate motion, we would not expect a material made up of large molecules (i.e., large in mass) such as mercury to transmit sound at as great a velocity as a material composed of smaller molecules, such as water. Mercury is 13.9 times denser than water, so we would expect water to conduct sound much more rapidly.

The relationship between wavelength and wave velocity is as follows:

$v = \acute{\upsilon} \lambda$.

v = Velocity of sound in conducting media (m/sec)

$\acute{\upsilon}$= Frequency (Hz)

λ. = Wavelength (m)

In the ultrasonic frequency range, the velocity of sound is constant in any particular medium. When the frequency is increased, the wavelength must decrease.

Properties of Ultrasonics

(i) They are highly energetic

(ii) They travel through long distance

(iii) They are reflected, refracted and absorbed similar to ordinary sound waves

(iv) When ultrasonic waves are passed through the liquid, it produces a stationary wave pattern and makes the liquid to behave as acoustical grating element.

(v) When an object is exposed to ultrasonics for a longer time, it produces heating effect.

Production of Ultrasonics

The earliest instrument for producing ultrasonic wave in air was the Galton whistle. This device produces sound waves by blowing a jet of high pressure air from a narrow slit against a sharp metal edge at one end of an organ pipe. With the help of this whistle frequencies of the order of 30 kHz can be produced.
Ultrasonic waves cannot be produced using an electronic oscillator connected to a loud speaker. At such high frequencies, the inductive effect of the loudspeaker coil is so large that practically no current passes through it. Also the diaphragm of a loudspeaker cannot vibrate at such high frequencies. Hence two other methods namely magnetostriction and piezoelectric are most widely used now a days.

PROPAGATION OF SOUND

Ultrasound (US) is produced by a transducer by piezoelectric effect and US pulse is passed in straight line. Sound is a mechanical energy that propagates through an elastic medium in the form of waves with compression and rarefaction. It is a longitudinal wave (sinusoidal) and wavelength (λ) is the distance between successive wave crests. Frequency (f) is the number of cycle per second (hertz) and one hertz (Hz) = 1 cycle/second. Period (T) is the time taken for one complete cycle and it is equal to 1/f. The velocity of sound (C), wavelength and frequency are related as follows: $C = \lambda f$, m/second The velocity, $C = \sqrt{B/\rho}$, where B is the bulk modulus (measure of stiffness of the medium), and ρ is the density. Velocity is inversely $\propto$ to compressibility and it depends on temperature of the medium. Intensity of ultrasound is measured in watts per mm^2 which is proportional to the square of the amplitude. Relative sound intensity is measured in a logarithmic scale, and the unit is decibel (dB).

INTERACTION OF ULTRASOUND WITH MATTER

Ultrasound undergoes reflection, refraction, scattering and absorption in matter, depends upon the acoustic properties of matter. Reflection occurs at tissue boundary, where there is a difference in acoustic impedance. Reflection may be a boundary reflection or tissue reflection and tissue reflection mostly gives scattering. Refraction refers the change in direction of the transmitted ultrasound energy. Scattering occurs by both reflection and refraction (small particles). Absorption refers the conversion of acoustic energy into thermal energy in the medium. The acoustic impedance (Z) is the product of density (ρ) and speed (c) of sound, i.e.
$Z = \rho \times c$, kg/sq m/s (Rayl)
It depends on density and elasticity of the interface and independent of frequency. The acoustic impedance can also be related to modulus of elasticity (E) as follows:
$Z = \sqrt{E \times \rho}$, Ray
The acoustic impedance of various body tissues

Material	Velocity (msec^{-1})	Acoustic impedance, Rayl
Air	330	0.0004 × 10^6
Fat	1450	1.34 "
Blood	1560	1.65 "
Muscle	1600	1.71 "
Bone	3300	7.8 "
Metals	> 4000	> 30.0 "

CLINICAL APPLICATIONS

(1) PULSE ECHO OPERATION

US is intermittently transmitted and major time is spent for listening the echoes. The pulse is created with short voltage waveform, with 2–3 cycles long. The time delay between the transmission pulse and echo is related to depth of the interface.

Time (μs) = 2D/c

= 2D(cm)/0.154 (cm/μs)

= 13 μs × D

Distance (cm) = (c × Time)/2

= (0.154 cm/μs × Time)/2

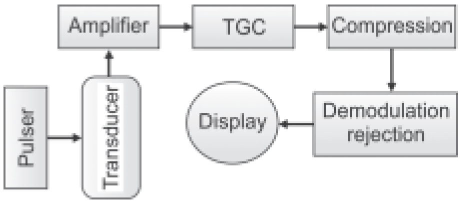
= 0.077 × Time (μs)

The pulse repetition, period (PRP) is the inverse of the pulse repetition frequency (PRF) and the common PRF used is 2 or 4 kHz. An increase in PRF results in a decrease in echo listening time. Maximum PRF is determined by the time required for echoes from the most distant objects to reach the transducer. High PRF limits the penetration and low PRF limits line density and frame rate (ability to follow motion). The duty cycle is the fraction of ON time = pulse duration/PRP. In real-time imaging, it is 0.2–0.4%, hence > 99.5% of the scan time is spent in listening the echoes. The PRF, PRP and duty cycle of various US modes are given in Table

Mode	PRF (kHz)	PRP (μs)	Duty cycle (%)
M-Mode	0.5	2000	0.05
Real-time	2–4	500–250	0.2–0.4
Pulsed Doppler	4–12	250–83	0.4–1.2

ULTRASOUND EQUIPMENT

The ultrasound hardware components include; (i) pulser, (ii) amplifier (iii) TGC, (iv) compression (v) demodulation and rejection, and (vii) display

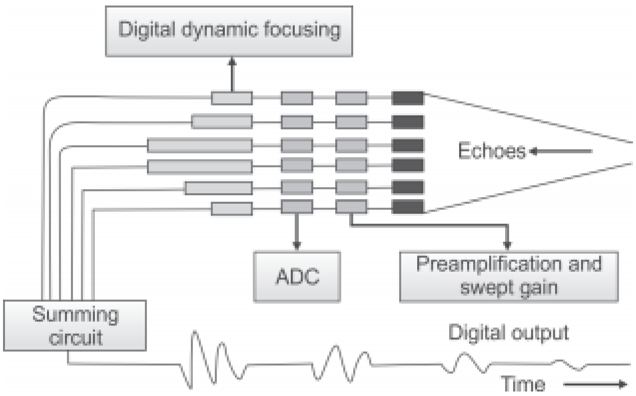


Pulser

The pulser controls the output transmit power by adjustment of the applied voltage. It provides electrical voltage for exciting the transducer elements. An increase in transmit amplitude creates higher intensity, improves echo detection from weaker reflectors. It provides higher signal to noise ratio, but the power deposition to the patient is higher. Pulser also has user control labels such as; output, power, dB, and transmit. It helps low power setting for obstetric imaging and also has power indicators; thermal index (TI) and mechanical index (MI).

Amplifier

Each PZT has its own preamplifier and analog to digital converter (ADC). Each element produces a small voltage of the echoes, and has a preamplifier, combined with swept gain. Initial pre-amplification increases the detected voltages to useful signal levels (100 dB) and swept gain compensate for the exponential attenuation of signal. The ADC has larger bit depth, to digitize the signals directly from the preamplification stage.



TGC

The time gain compensation (TGC) amplify the signal proportional to the time delay between transmission and detection of US pulses. The amplification may be linear or nonlinear and bring the signal in the range of 40–50 dB. This process compensates for tissue attenuation and makes all equally reflective boundaries equal in signal amplitude, irrespective of depth.

Compression

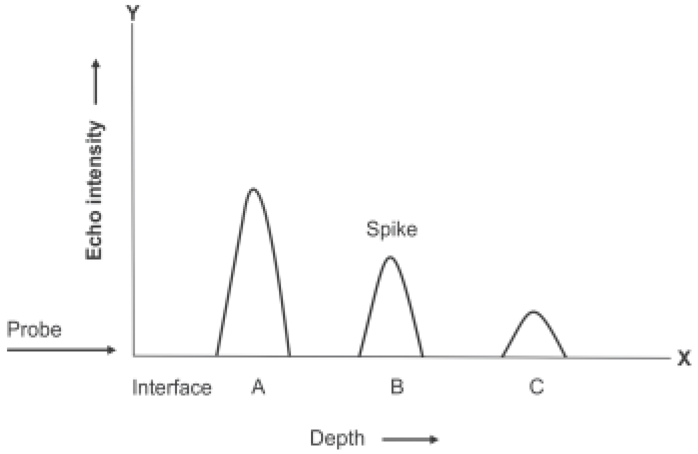
The logarithmic compression increases the smallest echo amplitudes and decreases the largest amplitudes. It reduces signal range, to fit the dynamic range of video monitor and film (20–30 dB). The output signal is proportional to the logarithm of the input signal. Rectification inverts the negative amplitude echoes to positive.

ULTRASOUND IMAGE DISPLAY

The US image is an electronic representation of data generated from returning echoes and displayed on a TV monitor. The image is assembled, one bit at a time, like television image. Echo generates one bit of data, and many bits together forms the electronic image. This image may be displayed as (i) Amplitude (A)-Mode, (ii) Motion (M or TM)- Mode, and (iii) Brightness (B)-Mode.

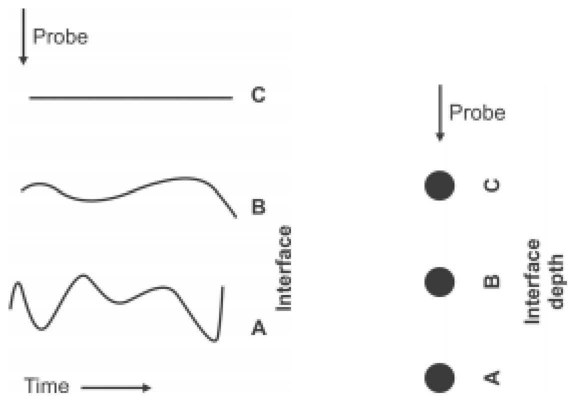
AMPLITUDE (A)-MODE

The probe is held stationary, and pulses of nanosecond duration is sent into the patient, and echo is generated. Each interface gives one echo pulse. Echoes are displayed as spikes projecting from baseline, which identifies the central axis of the beam. It displays the depth on X-axis and echo intensity on the Y-axis. It is a simple US technique, shows only the position of interfaces. The application of A-mode includes ophthalmology-distance measurements, echoencephalography, echocardiography, examinations of the eye, detecting a cysts in the breast, studying midline displacement in the brain, etc.



MOTION (M OR TM)-MODE

The A-mode spikes are converted into dots and brightness represents amplitude. When the interface moves, the dots also move back and forth. Sequential US pulses are displayed adjacent to each other, allowing the change in position of interfaces. It is recorded over a period of time. It provides excellent temporal resolution of motion patterns and displays the time on the X-axis and depth on the Y-axis. Its application includes evaluation of cardiac value motion and other cardiac anatomy. Real-time 2D echocardiography, Doppler and color flow imaging reduces the importance of M-mode today.



BRIGHTNESS (B)-MODE

In B-mode, a slice of an anatomy of the patient is imaged. The transducer is moved back and forth, so that beam scans a 2D section of the patient. It may be a linear or sector scanning. Echoes are displayed as dots, and brightness is proportional to echo intensity (Fig. 14.17). Thus, thousands of echo signal strengths of varying brightness of points gives grey scale image. The image displays a section of an anatomy. The image depth depends on transducer frequency, focus, etc. The B-mode scanning is usually done with electronic scanning either with linear array or phased array.

Doppler effect

The Doppler effect is used in practice to visualize directional blood flow on ultrasound, to estimate cardiac output and in some types of flow meter.

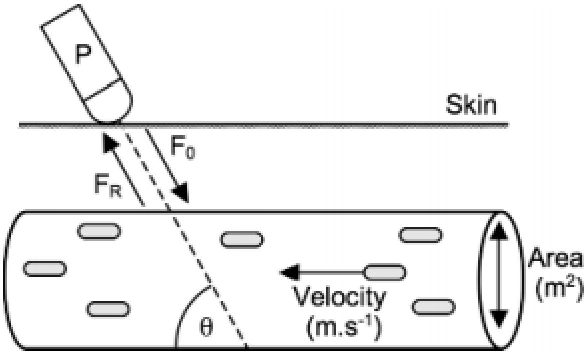
The phenomenon by which the frequency of transmitted sound is altered as it is reflected from a moving object. It is represented by the following equation:

$$V = \frac{\Delta F . c}{2F_0 \cos\theta}$$

where V is velocity of object, ΔF is frequency shift, c is speed of sound in blood, F_0 is frequency of emitted sound and θ is the angle between sound and object.

Principle

Sound waves are emitted from the probe (P) at a frequency F_0. They are reflected off moving red blood cells and back towards the probe at a new frequency, F_R. The phase shift can now be determined by $F_R - F_0$. The angle of incidence (θ) is shown on the diagram. If a measurement or estimate of the cross-sectional area of the blood vessel is known, flow can be derived as area multiplied by velocity ($m^2.m.s^{-1} = m^3.s^{-1}$). This is the principle behind oesophageal Doppler cardiac output monitoring.



It is also possible to calculate the pressure gradients across heart valves using the Doppler principle to measure the blood velocity and entering the result into the Bernoulli equation.

Bernoulli equation

$\Delta P = 4v^2$

where ΔP is the pressure gradient and v is the velocity of blood.