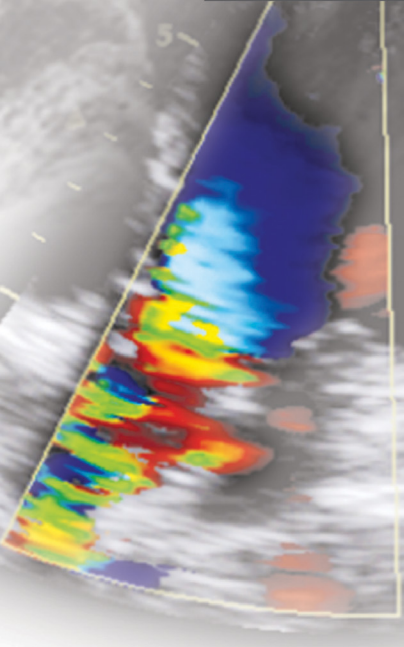
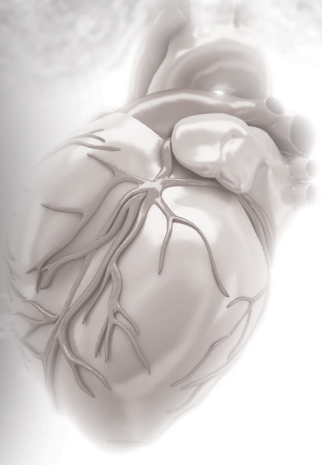
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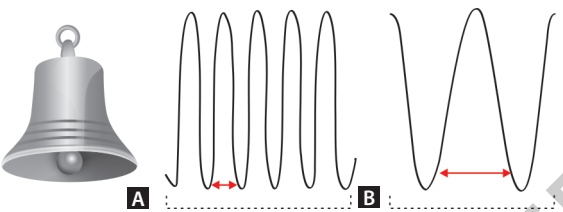
1 CHAPTER

What is an Echo?

PRINCIPLES OF ULTRASOUND

- Sound is a mechanical disturbance produced by passage of energy through a medium which may be gas, liquid or solid. Every sound has a particular frequency, a wavelength, its own velocity and an intensity.
- Sound energy is transmitted through a medium in the form of cycles or waves. Each wave consists of a peak and a trough. The peak coincides with an adjacent group of molecules moving towards each other (compression phase). The trough coincides with adjacent group of molecules moving away from each other (rarefaction phase).
- Frequency of sound is the number of times per second, sound undergoes a cycle of rise and fall. It is expressed in cycles per second, or hertz (Hz) and multiples thereof.
  1 hertz (Hz) = 1 cycle per second
  1 kilohertz (KHz) = 10^3 Hz = 1000 Hz
  1 megahertz (MHz) = 10^6 Hz = 1000000 Hz
- Frequency is appreciated by the listener as pitch of sound.
- Wavelength is the distance travelled by sound in one cycle of rise and fall. The length of the wave is the distance between two consecutive peaks.
- Frequency and wavelength are inter-related. Since, sound travels a fixed distance in one second, more the cycles in a second (greater the frequency), shorter is the wavelength **(Figs. 1.1A and B)**.
- Therefore, Velocity = Frequency × Wavelength.
- Velocity of sound is expressed in meters per second (m/sec) and is determined by the nature of the medium through

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Figs. 1.1A and B: Relationship between frequency and wavelength: (A) High frequency, short wavelength; (B) Low frequency, long wavelength.

which sound propagates. In soft tissue, the velocity is 1540 m/sec.

- Intensity of sound is nothing but its loudness or amplitude expressed in decibels. Higher the intensity of sound, greater is the distance up to which it is audible.
- The normal audible range of sound frequency is 20 Hz to 20 kHz. Sound whose frequency is above what is audible to the human ear (more than 20 kHz) is known as ultrasound.
- The technique of using ultrasound to examine the heart is known as echocardiography or simply echo.
- Electricity and ultrasound are two different forms of energy that can be transformed from one to the other by special crystals made of ceramic such as barium titanate.
- Ultrasound relies on the property of such crystals to transform electrical current of changing voltage into mechanical vibrations or ultrasound waves. This is known as the piezoelectric (pressure-electric) effect **(Fig. 1.2)**.
- When electrical current is passed through a piezoelectric crystal, the crystal vibrates. This generates ultrasound waves, which are transmitted through the body by the transducer, which houses several such crystals.
- Most of these ultrasound waves are scattered or absorbed by the tissues, without any obvious effect. Only a few waves are reflected back to the transducer and echoed.
- Reflected ultrasound waves again distort the piezoelectric crystals and produce an electrical current. These reflected

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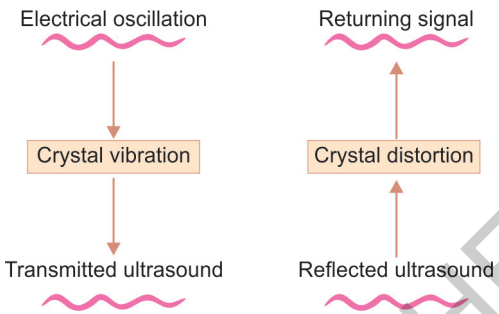


Fig. 1.2: The piezoelectric effect in ultrasound.

echoes are processed by filtration and amplification, to be eventually displayed on the cathode-ray tube.

- The reflected signal gives information about the depth and nature of the tissue studied. Most of the reflection occurs at interfaces between tissues of different densities and hence a different echo-reflectivity.
- The magnitude of electrical current produced by the reflected ultrasound determines the intensity and brightness on the display screen.
- On the grayscale, high reflectivity (from bone) is white, low reflectivity (from muscle) is gray, and no reflection (from air) is black **(Table 1.1)**.
- The location of the image produced by the reflected ultrasound depends upon the time lag between transmission and reflection of ultrasound.
- Deeper structures are shown on the lower portion of the display screen while superficial structures are shown on the

Table 1.1: Echo-reflectivity of various tissues on the grayscale.

Tissue	*Reflectivity*	*Shade*
Bone	High	White
Muscle	Low	Gray
Air	Nil	Black

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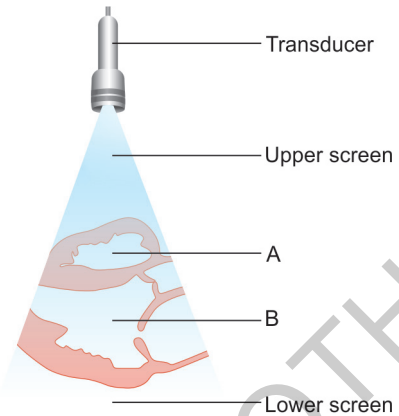


Fig. 1.3: Transducer is at the apex of visual display: (A) Right ventricle in the upper screen; (B) Left ventricle in the lower screen.

upper portion. This is because the transducer is at the apex of the triangular image on the screen **(Fig. 1.3)**.

- When ultrasound is transmitted through a uniform medium, it maintains its original direction but gets progressively scattered and absorbed.
- When ultrasound waves generated by the transducer encounter an interface between tissues of different density and thus different echo-reflectivity, some of the ultrasound waves are reflected back.
- It is these reflected ultrasound waves that are detected by the transducer and analyzed by the echo-machine.
- The wavelength of sound is the ratio between velocity and frequency (Wavelength = Velocity/Frequency).
- Since wavelength and frequency are inversely related, higher the frequency of ultrasound, shorter is the wavelength. Shorter the wavelength, higher is the image resolution and lesser is the penetration.
- Therefore, high-frequency probes (5.0–7.5 MHz) provide better resolution when applied to superficial structures and in children **(Table 1.2)**.

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Table 1.2: Features and applications of probes having different frequency.

Frequency (MHz)	*Penetration in tissue*	*Resolution of image*	*Study depth*	*Age group*
2.5–3.5	Good	Less	Deep	Adults
5.0–7.5	Less	Good	Superficial	Children

- Conversely, lower the frequency of ultrasound, longer is the wavelength. Longer the wavelength, lower is the image resolution and greater is the tissue penetration.
- Therefore, low-frequency probes (2.5–3.5 MHz) provide better penetration when applied to deeper structures and in adults **(Table 1.2)**.

PRINCIPLES OF DOPPLER

- The Doppler acoustic effect is present and used by us in everyday life, although we do not realize it. Imagine an automobile sounding the horn and moving towards you, going past you and then away from you.
- The pitch of the horn sound is higher when it approaches you (higher frequency) then when it goes away from you (lower frequency).
- This means that the nature of sound depends upon the relative motion of the listener and the source of sound.
- The change of frequency (Doppler shift) depends upon the speed of the automobile and the original frequency of the horn sound.
- Ultrasound reflected back from a tissue interface gives information about the depth and echo-reflectivity of the tissue. On the other hand, Doppler utilizes ultrasound reflected back from moving red blood cells (RBCs).
- The Doppler principle is used to derive the velocity of blood flow. Flow velocity is derived from the change of frequency that occurs between transmitted (original) and reflected (observed) ultrasound signal.

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- The shift of frequency (Doppler shift) is proportional to ratio of velocity of blood to speed of sound and to the original frequency.
- It is calculated from the following formula:

$$F_D \frac{V}{C} F_O$$

F_D: Doppler shift V: Velocity of blood
F_o: Original frequency C: Speed of sound

Therefore, velocity of blood flow is:

$$V \frac{F_D C}{F_O}$$

Further refinement of this formula is:

$$V = \frac{F_D \times C}{2F_o \times \text{Cos } \theta}$$

- The original frequency (F_o) is multiplied by 2 since Doppler shift occurs twice, during forward transmission as well as during backward reflection.
- Cosine theta (Cos θ) is applied as a correction for the angle between the ultrasound beam and blood flow. The angle between the beam and flow should be less than 20° to ensure accurate measurement.
- Cos θ is 1 if the beam is parallel to blood flow and maximum velocity is observed. Cos θ is 0 if the beam is perpendicular to blood flow and no velocity is detected.
- It is noteworthy that for Doppler echo, maximum velocity information is obtained with the ultrasound beam aligned parallel to the direction of blood flow being studied.
- This is in sharp contrast to conventional echo, where best image quality is obtained with the ultrasound beam aligned perpendicular to the structure being studied.
- Since, the original frequency value ($2 \times F_o$) is in the denominator of the velocity equation, it is important to remember that

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maximum velocity information is obtained using a low frequency (2.5 MHz) transducer.

- There is a direct relationship between the peak velocity of blood flow through a stenotic valve and the pressure gradient across the valve.
- Understandably, when the valve orifice is small, blood flow has to accelerate in order to eject the same stroke volume. This increase in velocity is measured by Doppler.
- The pressure gradient across the valve can be calculated using the simplified Bernoulli equation:

$$\Delta P = 4 V^2$$

P: Pressure gradient (in mm Hg)
V: Peak flow velocity (in m/sec)

- This equation is frequently used during Doppler evaluation of stenotic valves, regurgitant lesions and assessment of intracardiac shunts.
- The velocity information provided by Doppler complements the anatomical information provided by standard M-mode and 2D Echo.
- Analysis of the returning Doppler signal not only provides information about flow velocity, but also flow direction.
- By convention, velocities towards the transducer are displayed above the baseline (positive deflection) and velocities away from the transducer are displayed below the baseline (negative deflection) **(Fig. 1.4)**.
- The returning Doppler signal is a spectral trace of velocity display on a time axis. The area under curve (AUC) of the spectral trace is known as the flow velocity integral (FVI) of that velocity display.
- The value of FVI is determined by peak flow velocity and ejection time. It can be calculated by the software of most echo machines.
- Careful analysis of the spectral trace of velocity also gives densitometric information. Density relates to the number of RBCs moving at a given velocity.

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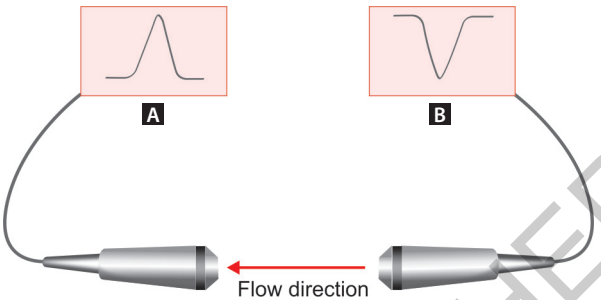


Fig. 1.4: Direction of blood flow and the polarity of deflection: (A) Towards the transducer, positive deflection; (B) Away from transducer, negative deflection.

- When blood flow is smooth or laminar, most RBCs travel at the same velocity, since they accelerate and decelerate simultaneously.
- The spectral trace then has a thin outline with very few RBCs travelling at other velocities **(Figs. 1.5A and C)**. This is known as low variance of velocities.
- When blood flow is turbulent as across stenotic valves, there is a wide distribution of RBCs velocities and the Doppler signal appears "filled in" **(Fig. 1.5B)**. This is known as high variance of velocities, "spectral broadening" or "increased bandwidth".
- It is to be borne in mind that turbulence and spectral broadening are often associated but not synonymous with high flow velocity.



Figs. 1.5A to C: Various patterns of blood flow seen on Doppler: (A) Laminar flow across a normal aortic valve; (B) Turbulent flow across astenotic aortic valve; (C) Normal flow pattern across the mitral valve.

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- The intensity of the Doppler signal is represented on the gray-scale as darker shades of gray **(Fig. 1.6)**.
- Maximum number of RBCs travelling at a particular velocity cast a dark shade on the spectral trace. Few RBCs travelling at a higher velocity cast a light shade.
- This is best seen on the Doppler signal from a stenotic valve. The spectral display is most dense near the baseline, reflecting most RBCs moving at a low velocity close to the valve **(Fig. 1.6A)**.
- Few RBCs accelerating through the stenotic valve are at a high velocity **(Fig. 1.6B)**.
- The Doppler echo modes used clinically are continuous wave (CW) Doppler and pulsed wave (PW) Doppler.
- In CW Doppler, two piezoelectric crystals are used, one to transmit continuously and the other to receive continuously, without any time gap.
- It can measure high velocities but does not discriminate between several adjacent velocity components. Therefore, CW Doppler cannot precisely locate the signal which may originate from anywhere along the length or breadth of the ultrasound beam.
- In PW Doppler, a single piezoelectric crystal to first emits a burst of ultrasound and then receives it after a preset time gap.

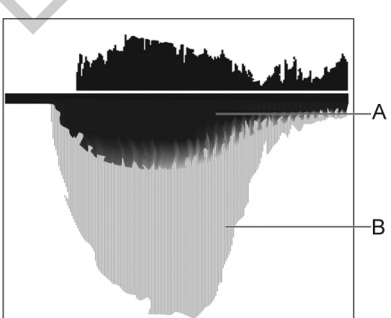


Fig. 1.6: Doppler signal across a stenotic aortic valve: (A) Most RBCs moving at low velocity; (B) Few RBCs moving at high velocity.

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This time is required in order to switch-over into the receiver mode.

- To locate the velocity, a "sample volume" indicated by a small box or circle, is placed over the 2D image at the region of interest. The "sample volume" can be moved in depth along the path of PW beam indicated as a broken line, until a maximum velocity signal is obtained **(Fig. 1.7)**.
- PW Doppler can precisely localize the site of origin of a velocity signal, unlike CW Doppler.
- Because of the time delay in receiving the reflected ultrasound signal, PW Doppler cannot accurately detect high velocities exceeding 2 m/sec.
- However, PW Doppler provides a spectral tracing of better quality than does CW Doppler **(Fig. 1.8)**.
- The single crystal of PW Doppler can emit a fresh pulse only after the previous pulse has returned. The time interval between pulse repetition is therefore the sum of the time taken by the transmitted signal to reach the target and the time taken by the returning signal to reach the transducer.
- The rate at which pulses are emitted is known as the pulse repetition frequency (PRF). Obviously, greater the depth of interrogation, more is the time interval between pulse repetition and lower is the PRF.

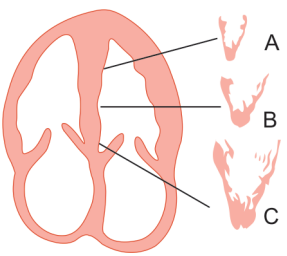


Fig. 1.7: Doppler signal from various levels of LV: (A) LV apex; (B) Mid LV; (C) Sub-aortic.

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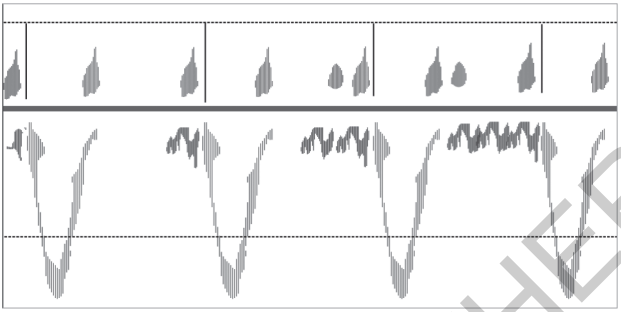


Fig. 1.8: Doppler signal from a regurgitant aortic valve showing laminar flow.

- Pulse repetition frequency (PRF) should be greater than twice the velocity being measured. The PRF decreases as the depth of interrogation increases.
- The maximum value of Doppler frequency shift that can be accurately measured with a given pulse repetition frequency (PRF) is called the Nyquist limit.
- The inability of PW Doppler to detect high-frequency Doppler shifts is known as aliasing. Aliasing occurs when the Nyquist limited is exceeded.
- Aliasing are an artificial reversal of velocity and distortion of the reflected signal. The phenomenon of aliasing is also called "wrap around."
- Aliasing can be tackled by one of these modifications:
  - High pulse repetition frequency
  - Multigate acquisition technique
  - Reduced depth of interrogation
  - Shifting of display baseline.

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- Newer topics such as 3D-ECHO, strain imaging and TAPSE has been included for the better understanding. It is my privilege to present this edition, wherein several striking real-time images, illustrative diagrams and explanatory tables have been incorporated.
- The book should serve as an ideal ready-reckoner for students, resident-doctors, nurses and technicians working in cardiology units as well as for general physicians interested in echocardiography.

Rohit Goel MBBS MD DM is an Interventional Cardiologist from the prestigious Postgraduate Institute of Medical Education and Research (PGIMER), Chandigarh, India. He has received several gold medals in his MBBS and recipient of most outstanding student in his postgraduate degree. After completion of his superspeciality in cardiology he worked at several reputed institutions such as Fortis Hospital, Vasant Kunj, New Delhi; Medanta-The Medicity and Fortis Memorial Research Institute, Gurugram, Haryana. Being from an academic background he has a keen interest in research and teaching his colleagues and juniors. He is an active participant in several national and international conferences and involved with various clinical trials and editorial board meetings.

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