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Ultrasound in Medical Applications

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Abstract: Ultrasound technology has revolutionized medical diagnosis and treatment in various medical disciplines. This paper provides an overview of ultrasound principles, technological advances, and its wide-ranging applications in medicine. Ultrasound, based on sound waves with frequencies above the human audible range, provides non-invasive imaging capabilities with real-time visualization of internal body structures. The development of high-resolution imaging technologies has enhanced diagnostic accuracy and enabled accurate anatomical assessments. Furthermore, ultrasound, such as Doppler, facilitates the assessment of blood flow dynamics, which aids in the diagnosis of cardiovascular diseases and vascular malformations. Beyond diagnosis, ultrasound-guided interventions have become common in minimally invasive procedures, including biopsies, injections, and surgeries, with positive impact on public health. In addition, therapeutic ultrasound techniques, such as high-intensity focused ultrasound (HIFU) and ultrasound-mediated drug delivery, have emerged as promising modalities for targeted tissue ablation and topical drug administration, respectively. In conclusion, ultrasound technology continues to evolve, offering versatile solutions for medical imaging, diagnosis, interventions, and treatments, with significant implications for improving patient care and advancing medical research.

Introduction:

Sound waves are a type of longitudinal waves that move through physical media such as air or liquids [1,2,3]. These waves are characterized by propagation through pressure and rarefaction in the molecules of the medium through which they pass, as the molecules in the medium through which the wave passes are moved back and forth in the direction of propagation of the wave.[4]

Sound waves propagate at a certain speed in the medium, and this speed changes depending on the type of medium through which the wave passes. For example, sound waves propagate faster in liquids than in gases, and travel faster in solids than in liquids.[5]

Sound waves are characterized by specific frequencies, as the frequency of the sound wave is known as the number of times the wave is stretched and compressed in a unit of time, and is measured in Hertz (Hz). Sound waves can be represented by different frequencies according to their frequency range:

Infrasonic waves: They are a type of sound waves that are characterized by frequencies lower than the sound that can be heard by humans, which falls within the frequency range of 20 Hz or less. The frequency of infrasonic waves ranges between 0.001 and 20 Hz. Although humans cannot hear these waves, they are used in a variety of industrial and scientific applications.

Sound waves (audible sounds):

Audible sound waves range in frequencies from 20 Hz to about 20 kHz.

Humans can hear these waves and use them to communicate and interact with the surrounding environment. They are used in voice communication and entertainment technologies such as telephone communication and voice recording.[6]

Ultrasound:

Ultrasound waves range in frequencies above the 20 kHz barrier and cannot be heard by humans. Ultrasound can be used in medical imaging, where three-dimensional images of internal tissues and organs can be generated without exposing the body to radiation.

These technologies allow for a clear view of internal tissues and organs, and facilitate non-invasive diagnostic and surgical procedures[7].

Aim of the study

This research aims to explore the applications of sound waves and ultrasound in the medical field, focusing on their mechanisms of action and recent developments in this field. Modern techniques of medical acoustics and diagnostic and therapeutic medical ultrasound will be reviewed, including three- and four-dimensional ultrasound imaging, Doppler examination techniques to assess blood flow, the use of ultrasound to destroy tumors without surgery, and treatment guidance and imaging to improve the accuracy of drug and surgical treatments.

In addition, the benefits and challenges facing the applications of sound waves and ultrasound in the medical field will be discussed, and recent research will be reviewed that highlights their potential benefits in improving patient care and developing new and effective treatments for a variety of medical conditions.

What is an ultrasound device?

An ultrasound device (in English: Sonogram) is a device that images internal organs such as fetuses in cases of pregnancy, the thyroid gland in case of enlargement, and some arteries such as the carotid artery in cases of heart disease.[8] It is also called (Sonogram). The use of this device in the medical field is one of the most important achievements of the century, due to its accuracy, ease of use, and speed of examination, in addition to its relatively low cost compared to other imaging methods such as magnetic resonance imaging or computed tomography**.**

Working principle: The ultrasound device sends a set of high-frequency ultrasonic waves (higher than the frequency of human hearing), meaning that its frequency is higher than twenty thousand hertz, to the organ to be diagnosed, and then the device reflects it and sends it to a computer that converts it into an image that can be seen and examined easily**[8].**

Properties of Ultrasound:

An ultrasound wave is a mechanical disturbance in a gas, liquid, or solid that travels outward from the source at a specific speed. We can use a loudspeaker that vibrates back and forth in the air at a frequency f to demonstrate the behavior of sound. The vibrations cause local increases and decreases in pressure relative to atmospheric pressure (Figure 1). These increases in pressure, called compression and decreases, called rarefaction, propagate outward as a longitudinal wave, that is, a wave in which the pressure changes occur in the same direction as the wave travels. Compression and rarefaction can also be described by density changes and displacements of atoms and molecules from their equilibrium positions. [9] The relationship between the frequency of vibration (f) of a sound wave, the wavelength (A), and the speed (v) of a sound wave is v=f

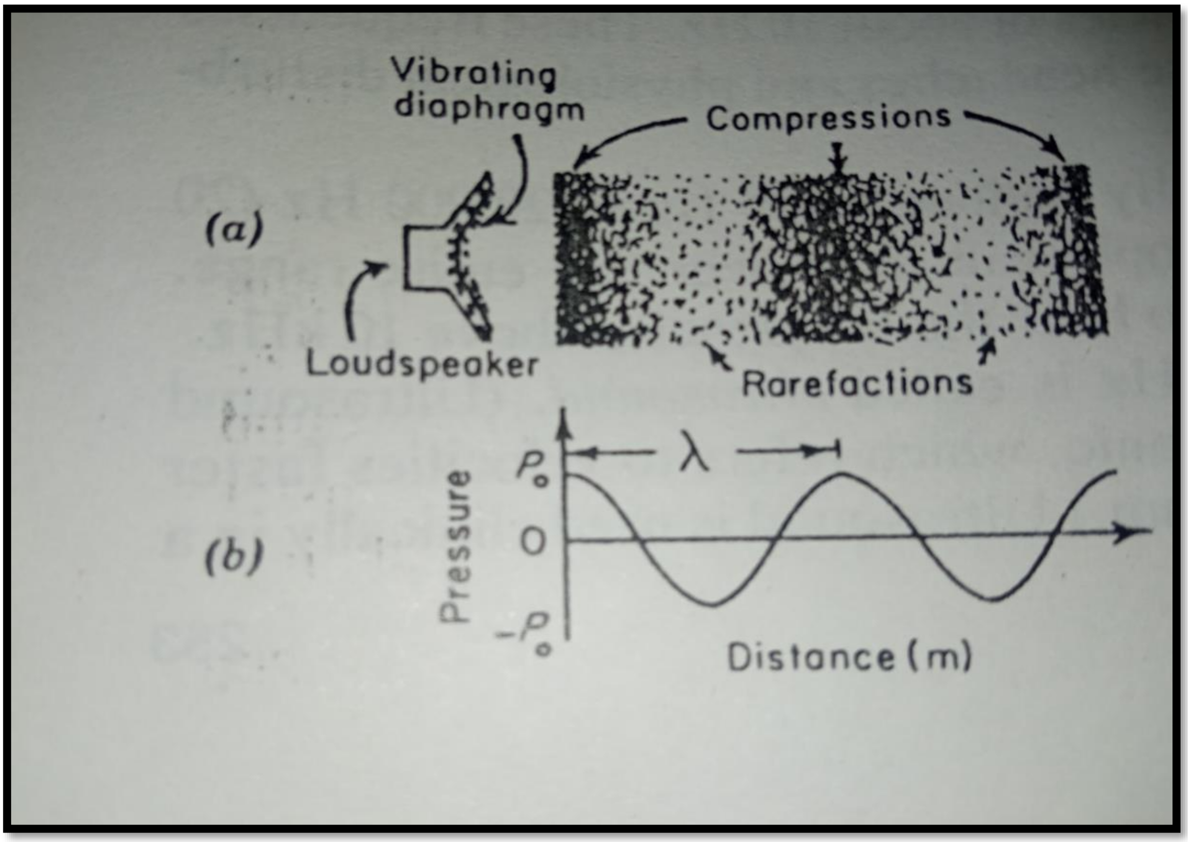


Figure 1// Schematic representation of a sound wave from a loudspeaker. (a) The diaphragm vibrates at frequency f and produces compressions (pressure increases) and rarefactions (pressure decreases) in the air. (b) Pressure relative to atmospheric pressure versus distance. P^{o} is the maximum pressure difference from the atmosphere, and a is the wavelength[9]

Mechanism of transmission from one medium to another

The acoustic impedance of a material is the ratio of the sound pressure to the velocity of the particles associated with it. It can be shown that for plane waves this is equal to the product of the sound density and its velocity in the medium. The acoustic impedance at 20 °C for air, distilled water and bone is 415, 1.48 × 106 and 5.3 × 106 Pa m-1 respectively. Since the bulk of soft tissue consists of water, it is logical that the acoustic impedance of soft tissue in the body does not differ significantly from that of water. Fatty tissue has a slightly lower acoustic impedance due to its lower density and the speed of sound. The main exceptions are the lungs, which have much lower acoustic impedance due to the large number of air spaces (0.1 × 106 Pa s m−1 inflated, 1.4 × 106 Pa s m−1 deflated), and bones, which have a higher density and sound velocity and therefore higher resistance (4–8 × 106 Pa m−1). For an ultrasound wave incident normal to an interface between materials with acoustic impedance z1 and z2, it can be shown that the reflection intensity and transmission coefficients, R and T, are

$$R = \frac{z_2 - z_1}{z_2 + z_1}^{2} \quad (1)$$

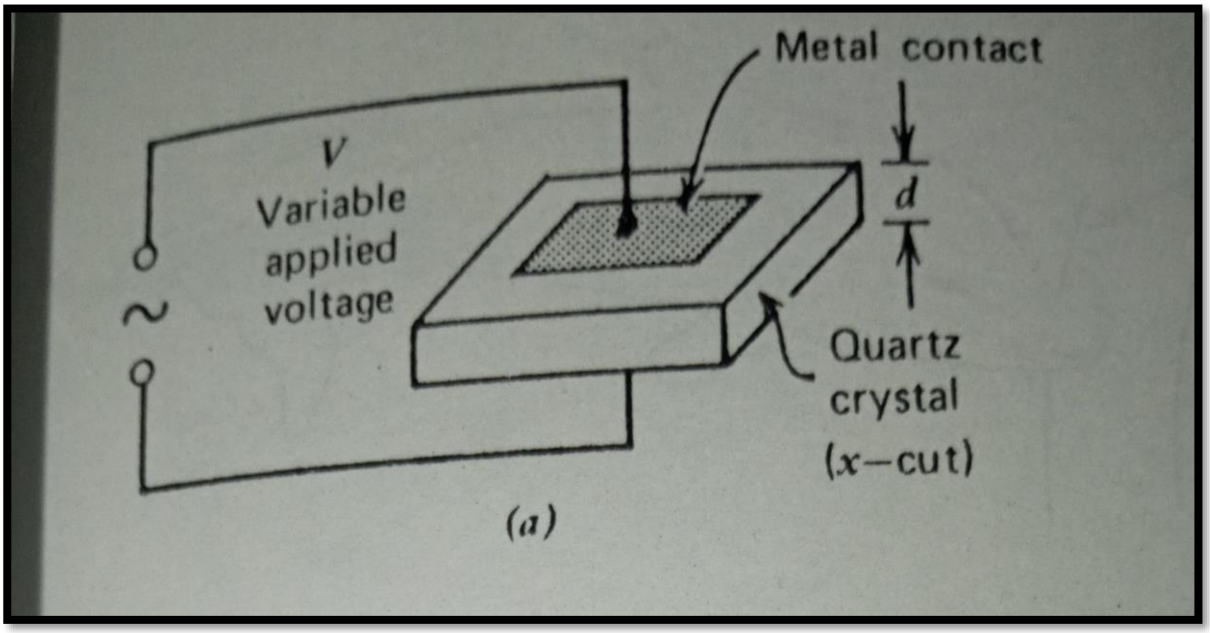
$$T = \frac{4z_2 z_1}{z_2 + z_1^{\,2}} \quad (2)$$

It can then be seen that if R = 0 where 2z = 1z , all the wave energy is transmitted; this is essentially the case in soft tissue, where the acoustic impedance is similar and the losses due to reflections are small. However, at the tissue-air interface, almost the entire incident wave is reflected back into the tissue. At the soft tissue-bone interface, about 60-70% of the incident wave is typically transmitted. For obliquely incident waves at the soft tissue-bone interface, the transmitted wave is reduced to a critical angle of 25-30 degrees, at which point the entire wave is reflected. The above is true for longitudinal waves beyond the critical Snell's angle, but in fact at the tissue-bone interface, there is a mode of conversion of the incident longitudinal wave into a shear wave. The velocity of the longitudinal wave in the tissue is similar to the velocity of the shear wave in the bone, and as a result there is a better matching of the acoustic impedance between these modes. This is of practical importance primarily for transcranial imaging; although distortion tends to be less as the shear wave propagates through the skull, there is more attenuation and heating in the skull, which can lead to complications in high-energy therapeutic applications[10].

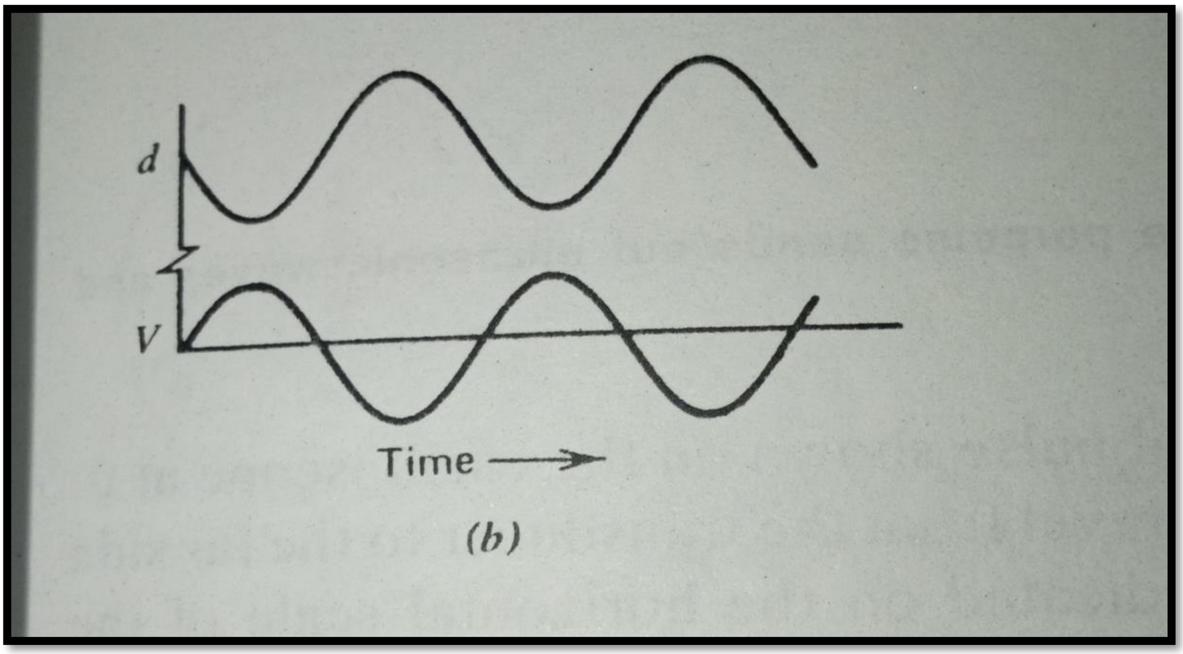
Ultrasound generation mechanism:

Ultrasound is used to produce images for medical diagnosis. Basically, an ultrasound source sends a beam of sound pulses of 1 to 5 MHz into the body. The time required for the sound pulses to reflect provides information about the distances to various structures or organs in the path of the ultrasound beam.[9] While there are several methods for generating ultrasound, the most important for medical applications involves the piezoelectric effect.

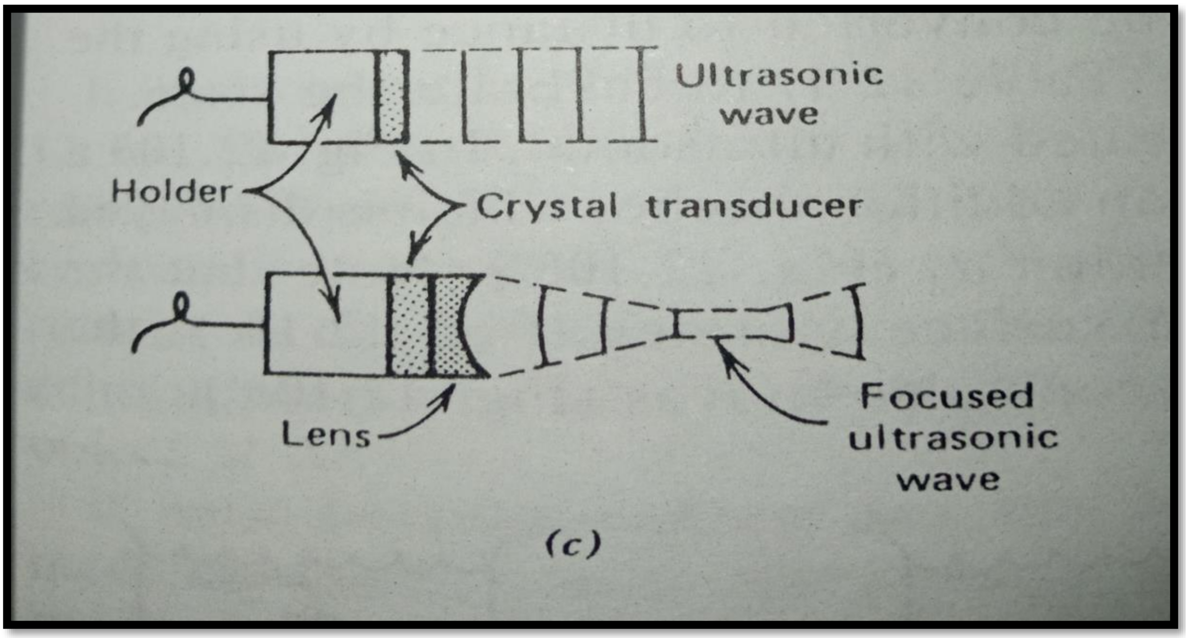
This effect was discovered by Jacques and Pierre Curie around 1880. Many crystals can be cut so that the oscillating voltage across the crystal produces a vibration similar to the crystal, thus generating a sound wave. (Figure-2)



(a.2)



(b.2)



(c.2)

Figure 2. Behavior of a quartz crystal used in the production of ultrasound. (a) Attachment of electrodes; (b) Change in crystal thickness d (greatly exaggerated) due to the applied alternating voltage V; (c) Crystal mounted in a holder for the production of an ultrasound beam. A focused beam is produced when an acoustic lens is attached to the crystal[9].

Transducer:

A device that converts electrical energy into mechanical energy or vice versa is called a transducer. Ultrasound generators are often referred to as transducers.

Each transducer has a natural resonant frequency of vibration. The thinner the crystal, the higher the frequency at which it will oscillate. For a quartz crystal cut along a given axis (x-cut), a thickness of 2.85 mm gives a resonant frequency of about 1 MHz. Typical frequencies for medical work range from 1 to 5 MHz. The average power level for diagnostic applications is a few milliwatts per square centimeter.

Ultrasound pulses are transmitted to the body by placing the vibrating crystal in close contact with the skin, using water or a gel paste to remove air. This provides good coupling with the skin and greatly increases the transmission of ultrasound waves into the body and the return of the echo to the detector.

The same transducer that produced the pulse acts as a detector. The vibrations of the crystal resulting from the echoes generate an electrical voltage across it, which is the opposite of what happens when ultrasound is produced. The weak signals are then amplified and displayed on an oscilloscope[9].

Previous works:

The first written document dealing with the use of waves in spatial orientation dates back to 1794 by the Italian physicist Lazaro Spallanzani, who studied how bats were able to fly in complete darkness and hypothesized that nocturnal creatures relied on the use of sound to navigate rather than light to orient themselves[11,12] It was not until 1880, nearly ninety years after the publication of Spallanzani's theory, that Galton invented and produced a device that was able to produce sound waves at a frequency of 40 Hz.

In the same year, the brothers Jacques and Pierre Curie observed that electricity could be generated in a quartz crystal. By applying electrical currents to quartz crystals, they produce sound, more specifically, ultrasonic waves. This phenomenon was called the piezoelectric effect[12,13] . The Curie brothers also discovered the reverse piezoelectric effect, which is the ability of a liquid crystal to produce electricity under the vibrations produced by ultrasound waves[14].

The Russian physicist Sy Sokolov was the first to envision the use of ultrasound for imaging techniques in 1928. However, he was more interested in using this method to find defects in metal structures than in saving lives through diagnosis. However, the device he invented created silhouette images that could be interpreted.

The scientist George Ludwig was one of the first to use ultrasound imaging techniques. In his research on gallstones, he turned to ultrasound to detect masses when they were embedded in soft tissue. His analysis of the use of these sound waves on animal tissues helped the next scientist in the future.

Ian Donald was the first to integrate ultrasound with diagnostic medicine in 1956. Naturally, his first use of the device was to determine the diameter of the fetal head. In just two years, technology has helped create a way to visualize ultrasound findings, increasing the potential for life-saving diagnostics[12].

Medical applications of ultrasound:

1 -Scan-A

The A scan procedure, echocardiography, has been used to detect brain tumors. Pulses of ultrasound waves are sent to a thin area of the skull just above the ear and echoes from various structures inside the head are displayed on an oscilloscope (Figure 3).

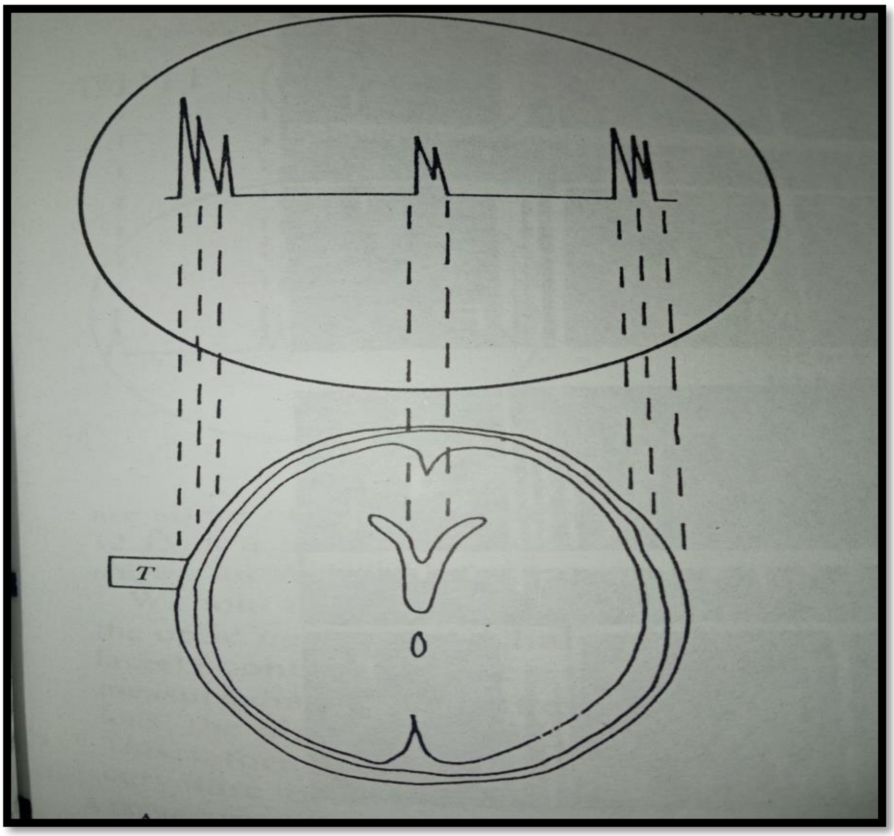
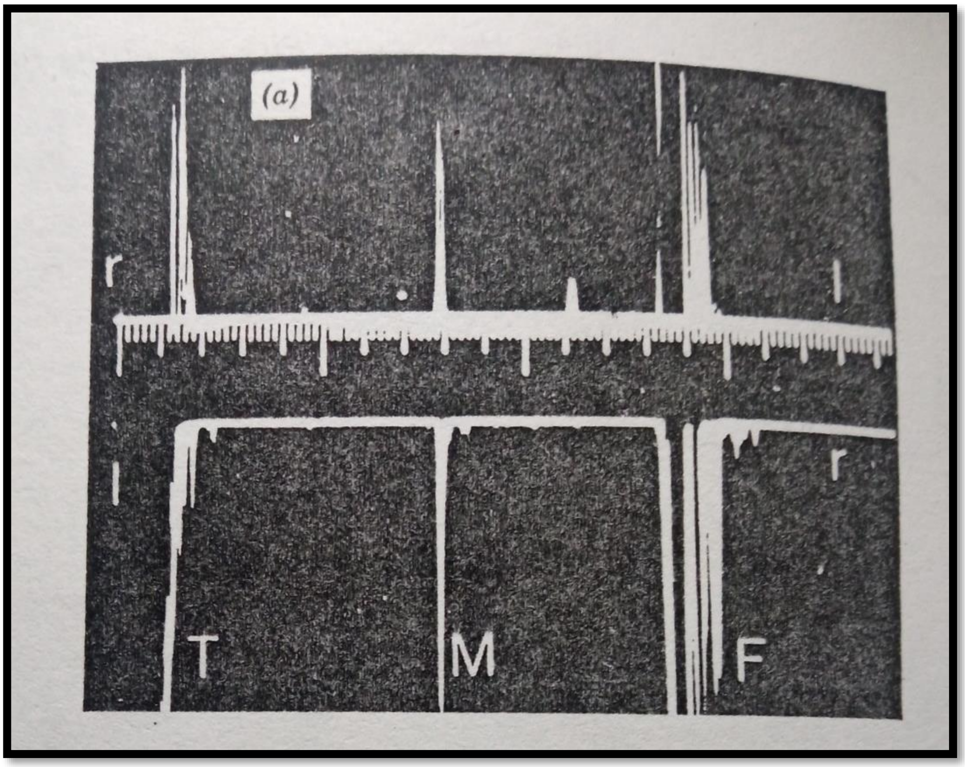
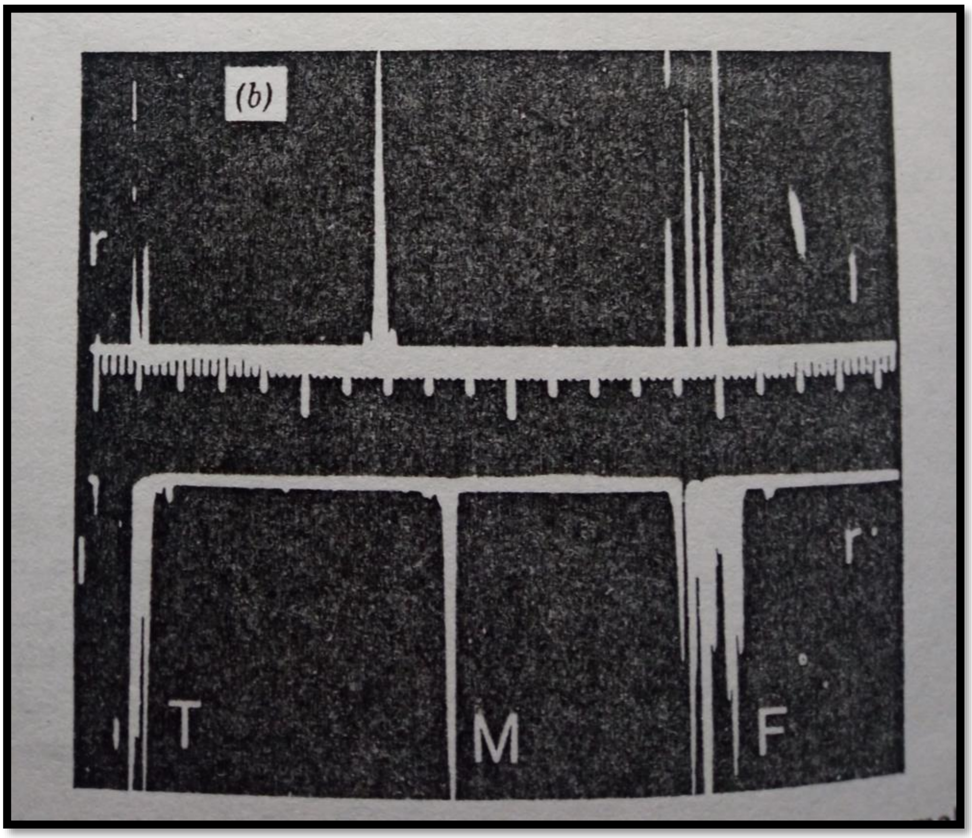


Figure 3. Scanning method to determine the midline of the brain. (Echoencephalography). Ultrasound pulses are sent to the brain by a T-transducer, and the echoes are displayed on an oscilloscope. The usual procedure is to compare the echoes from the left side of the head with those from the right side and look for a shift in the midline structure. A tumor on one side of the brain tends to shift the midline toward the other side (Figure 4).

(a.4)





(b.4)

Figure 4. Echocardiogram of normal and abnormal brain. (a) Pair of scans of normal brain. The T transducer is on the right side of the head in the upper scan and on the left side in the lower scan. F indicates echoes from the distal side of the skull. There is no shift in the midline M echo. (b)

Pair of scans of an abnormal brain showing a 7 mm shift to the right side that could be caused by a tumor on the left side of the brain[15].

Generally a shift of more than 3 mm in an adult or 2 mm in a child is considered abnormal.During echocardiography, care must be taken to ensure that the device can detect the echo immediately after the initial pulse from the proximal side of the skull. This information is essential for comparing right-to-left and left-to-right scans. It is also necessary to be careful in interpreting echo patterns when the skull is asymmetrical to avoid making a misdiagnosis.

Applications of A-scans in ophthalmology can be divided into two areas:

- One is concerned with obtaining information for use in the diagnosis of eye diseases;
- The second involves biometric measurements, or measurements of distances in the eye. At the low energy levels used, there is no risk to the patient's eye. Ultrasound frequencies up to 20 MHz are used. These higher frequencies can be used in the eye to produce better resolution because there is no bone to absorb most of the energy and absorption is not important because the eye is small.

Diagnostic ultrasound techniques are complementary to the ophthalmic examinations that are generally performed. They can provide information about deep areas of the eye and are particularly useful when the cornea or lens is opaque. The use of A-scan information in addition to visual information and even X-rays may be necessary for a complete diagnosis. Tumors, foreign bodies, and retinal detachment (the light-sensitive part of the eye).

(Figure 5) is a schematic representation of a normal eye scan.

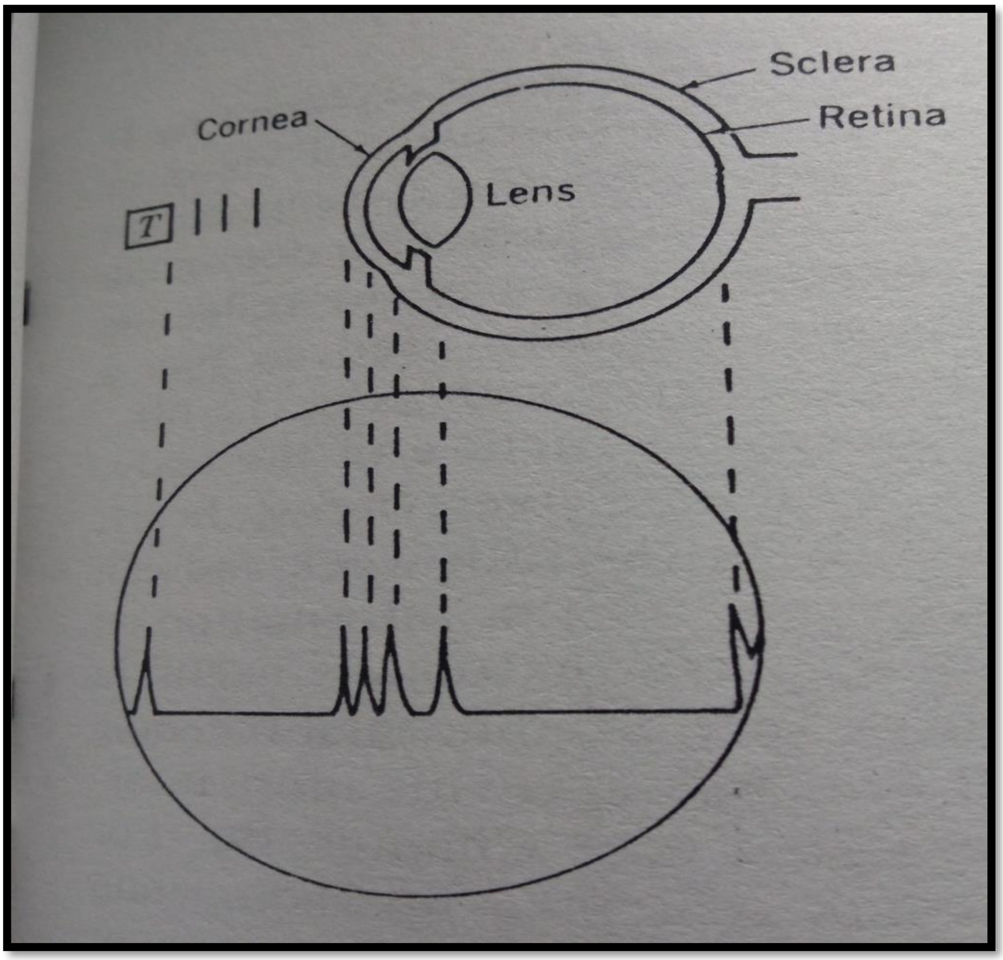


Figure 5. The ultrasonic transducer T transmits sound through the water to the eye, and the reflected sound is displayed on an oscilloscope.

Figure 6 shows an examination of severe retinal detachment.

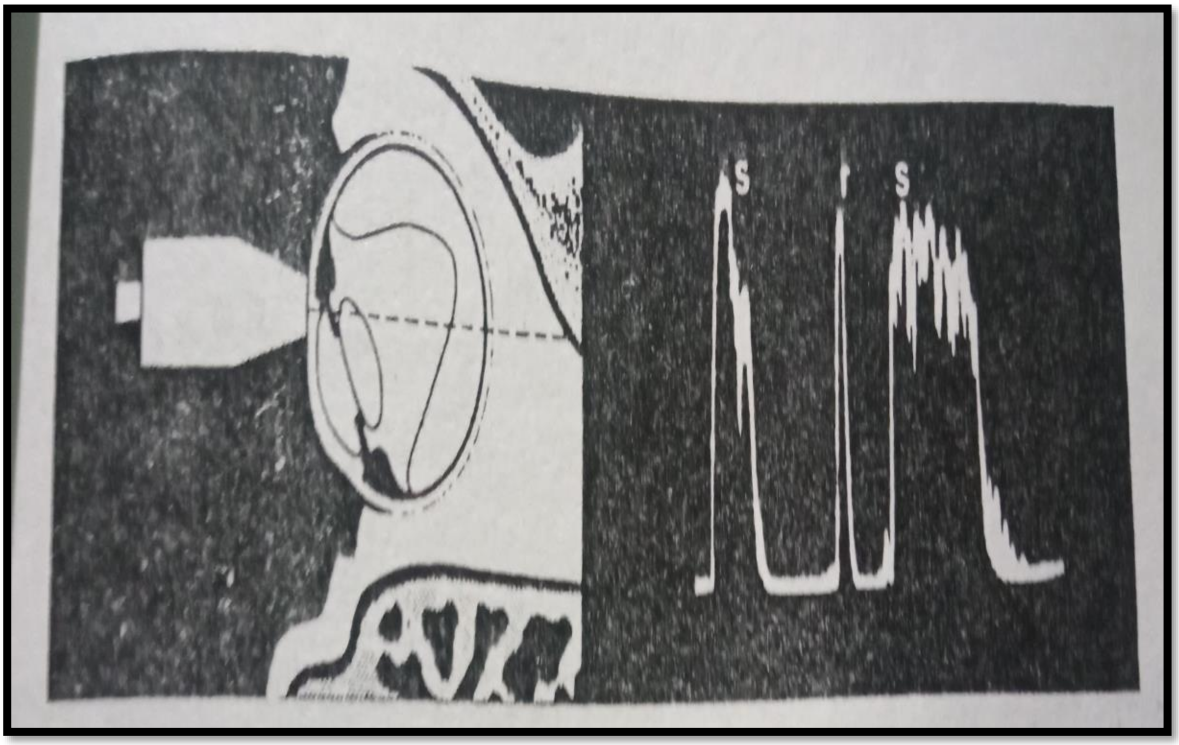


Figure 6. Ultrasound studies of a detached retina. CRT shows echoes from the anterior sclera, echoes from the retina, and echoes from the sclera at the back of the eye. In a normal eye, the echoes from the retina blend with the echoes from the back of the sclera.[16]

Without ultrasound, ophthalmologists can look into a living eye as far as the optic nerve, but measurements of the eye are largely limited to the outer segment. With ultrasound, it is possible to measure distances in the eye such as lens thickness, depth from the cornea to the lens, distance to the retina, and thickness of the vitreous humor. This information can be combined with other quantities such as corneal curvature and prescription of corrective eyeglasses to determine refractive indices of the eye components.[9] For many clinical purposes, the A-scan procedure has largely been replaced by the B-scan procedure

Scan-B

The B-scan method is used to obtain two-dimensional views of body parts. The principles are the same as in the A-scan except that the transducer is moved. As a result, each echo produces a point on the oscilloscope at a position corresponding to the location of the reflective surface (Figure 7).

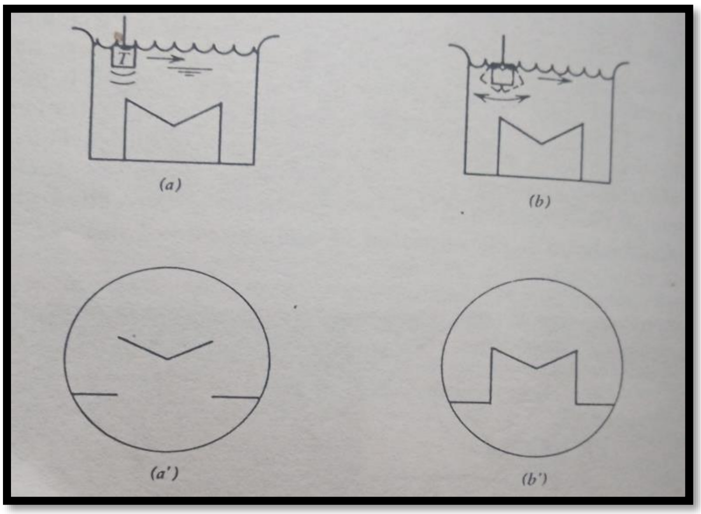


Figure - 7. Schematic diagram of scanning method B. (a) As the transducer T is moved to the right it produces echoes from the immersed object.)'a) The storage oscilloscope shows a point corresponding to the location of each echo received. The points mark the top surface of the object. (b) As the transducer is vibrated while being moved to the right it produces echoes from other surfaces. ('b) The resulting scan shows the sides of the object.

A storage oscilloscope is typically used to form a permanent image and take a photograph (Figure 8).

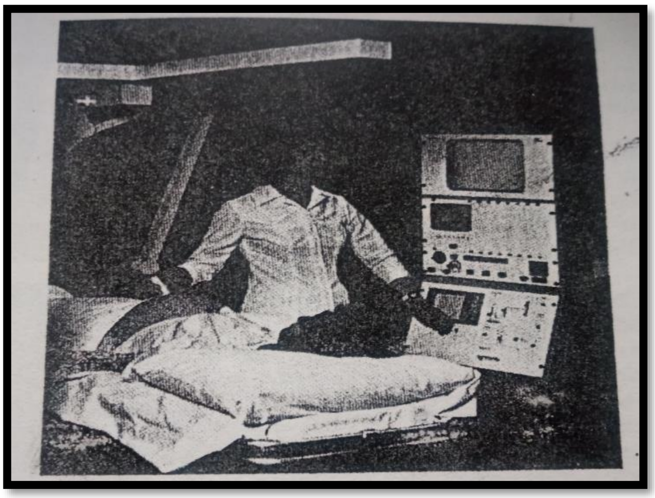


Figure 8. An ultrasound technician moves the B-scan transducer over the bare abdomen of a pregnant patient while adjusting the brightness of the image on the screen[17].

B-scans provide information about the internal structure of the body. They have been used in diagnostic studies of the eye, liver, breast, heart, and fetus. They can detect pregnancy as early as the fifth week and can provide information about uterine abnormalities (Figure 9).

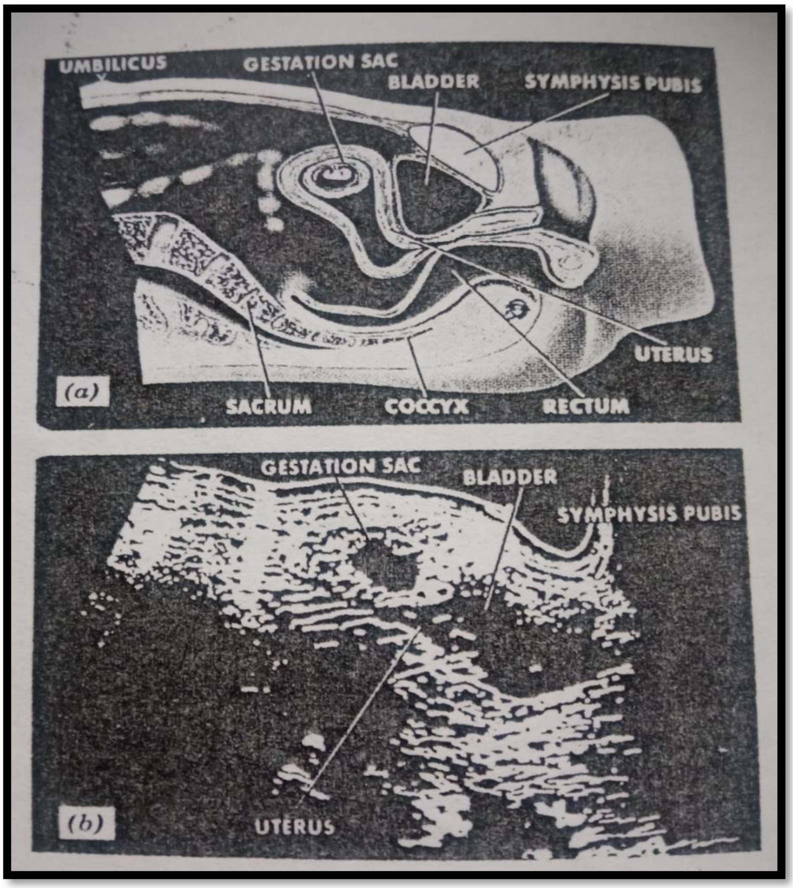


Figure 9. B-scans have important uses in obstetrics. (a) Schematic cross-section of a woman showing a small fetus in the gestational sac. (b) B-scan of a patient showing the gestational sac, uterus, and bladder[18].

Information about the size, position, and change of the fetus over time is very useful in both vaginal deliveries (Figure 10)

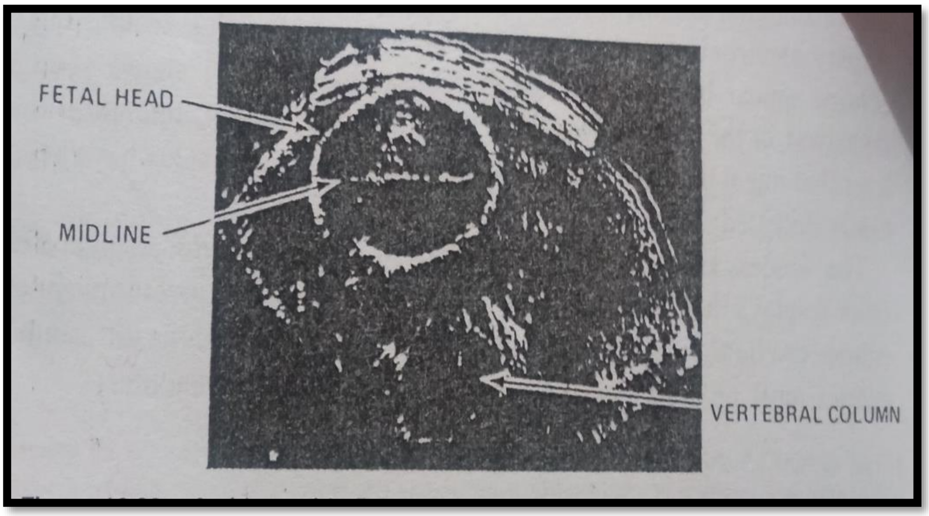
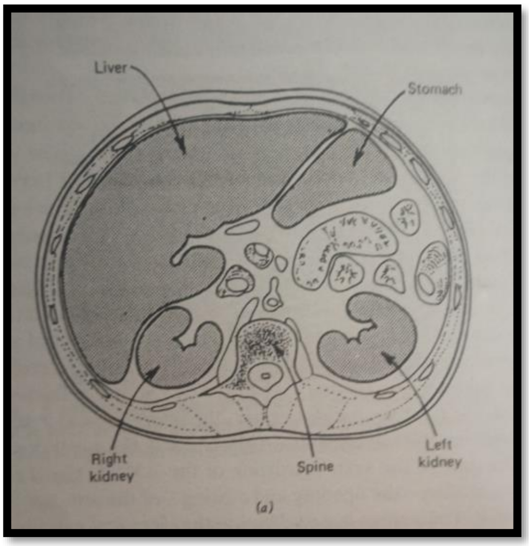


Figure 10. Side-by-side B-scan of a more developed fetus than that shown in Figure 9. The fetal head and midline of the brain are clearly visible[19].

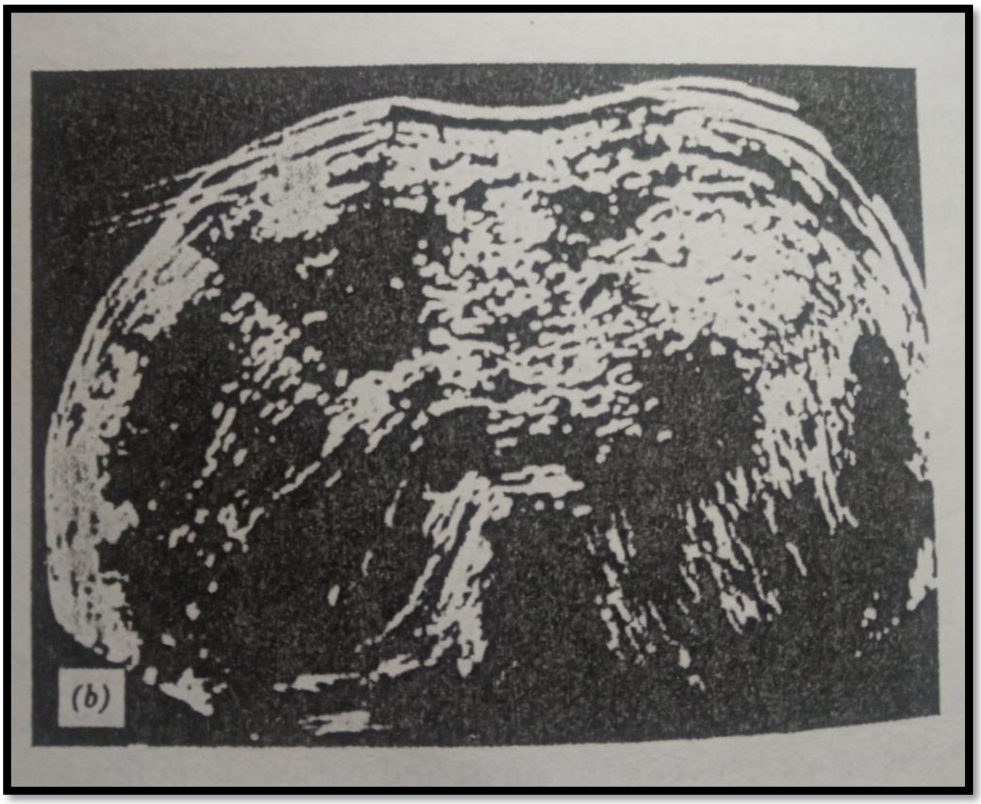
Conditions such as abnormal bleeding and threatened miscarriage. In many cases, B-scans can provide more information than X-rays, and they also pose less risk. For example, X-ray studies can detect cysts that only consume radiopaque solutions, whereas ultrasound can be used to quantitatively image many types of cysts.

In early B-scan work, all echoes displayed on the CRT were the same brightness. The operator could exclude low-magnitude echoes by adjusting the electronic control to a chosen threshold value. While this mode, called leading-edge display, is very useful for many purposes, it gives no information about the sizes of the echoes.

The enhanced grayscale display electronically changes the brightness on the CRT so that large echoes appear brighter than weak echoes. .Figure 11 shows the scan displayed in both modes



(a.11)



(b.11)

(c.11)

Figure 11. Transverse B-scan of the upper abdomen. (a) Schematic diagram identifying the different structures on the scans. (b) Advanced B-scan in which all the selections are equally bright. (c) Gray-scale B-scan of the same patient in which large echoes are brighter than small echoes . [20]

Using the gray-scale display, liver tumors that might not have been detected using the front-facing display were easily detected.

The success of the gray-scale display led to the development of color displays that display a wider range of echoes. A wider range of echoes can be displayed using a digital display. In this case, the ultrasound echoes must be processed electronically and fed into a computer.

Two methods are used to obtain information about body movement using ultrasound; the M (motion) scan, which is used to study such movement as the heart's flow valves and probe, and the Doppler technique, which is used to measure blood. The M-scan combines certain features of the A-scan and the B-scan. The transducer is positioned as in the A-scan and the echoes appear as dots as in the B-scan.

Figure (12.A) shows a transducer mounted in one position emitting an ultrasound pulse into a beaker of water containing a vibrating interface. Figure (12.B) is a standard B-scan showing the motion of the interface on the oscilloscope screen. When the oscilloscope trace is made to move vertically as a function of time, the motion of the interface is displayed as an M-scan as shown in Figure (12.C).

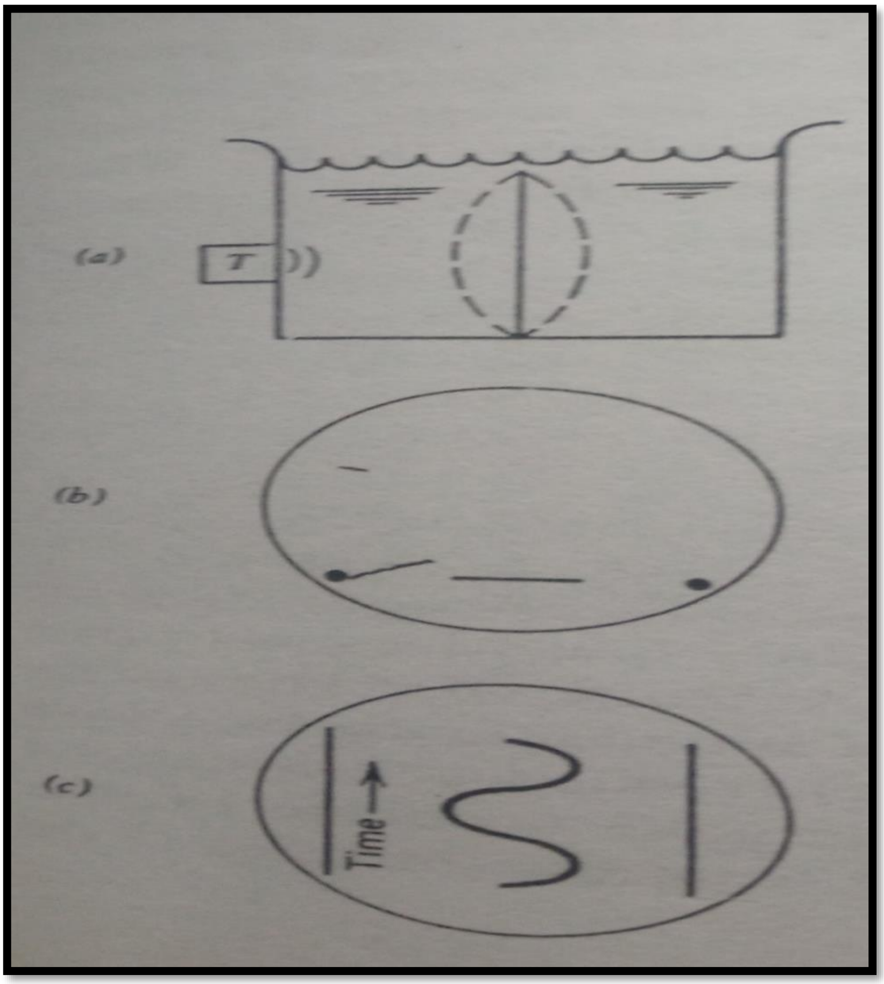


Figure 12. Schematic diagram of the M-scan method. (a) A vibrating interface in a cup of water reflects sound pulses from the T-transducer. (b) In a static B-scan, the vibrating membrane appears as a line in the middle of the scan. (c) When the CRT's electron beam is moved vertically, the movement of the vibrating interface is displayed as an M-scan[9].

Motion Scan:

M-scans are used to obtain diagnostic information about the heart. The locations where the heart can be scanned are very limited because of the poor transmission of ultrasound waves through lung and bone tissue. The usual approach is to place the transducer on the patient's left side, point it between the ribs over the heart, and tilt it at different angles to explore different areas of the heart (Figure 13).

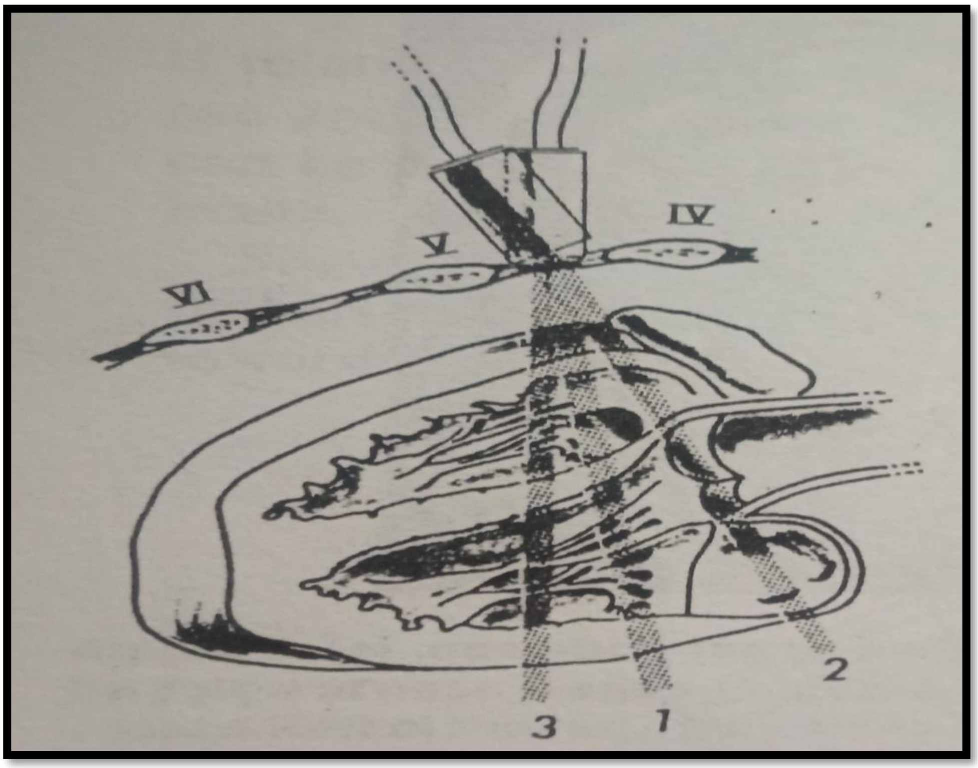
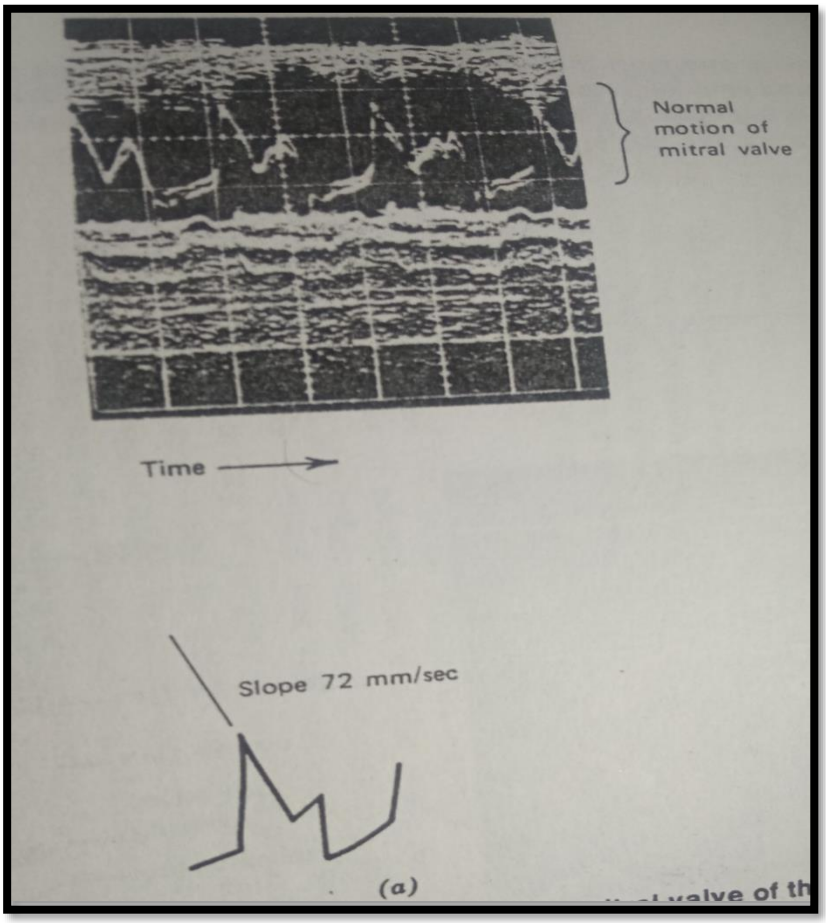


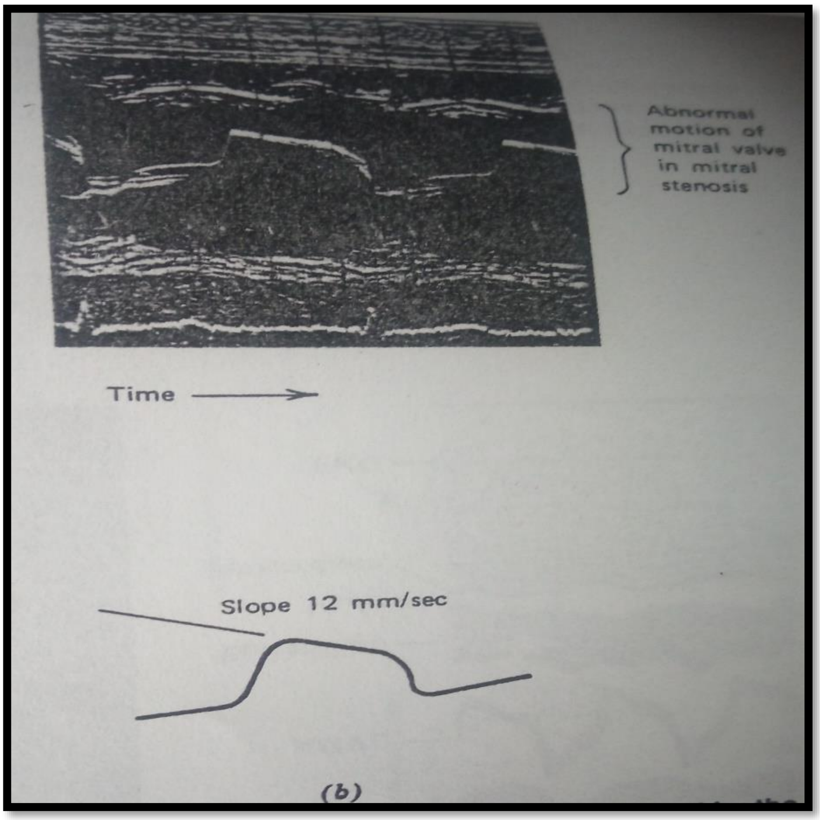
Figure 13. Schematic view of the heart being examined by ultrasound. The ribs are indicated by Roman numerals[21].

By moving the probe, information can be obtained about the behavior of a particular valve or section of the heart. The examiner must be familiar with the specific echo patterns of the heart to interpret the information. Many heart diseases can be diagnosed by M scans; we consider here M scans of the mitral valves and M scans showing fluid accumulation in the heart sac (pericardial effusion).

The I-position scan in Figure 13 shows reflections from the chest wall, the right ventricular cavity, the interventricular septum (IVS), the anterior mitral valve leaflet (AMVL), and the posterior wall of the heart. The part of the scan consisting of the AMVL signal (Figure 14, a) shows the opening and closing motion of the anterior mitral valve leaflet. The motion is related to the electrical activity of the heart (ECG), which is recorded simultaneously. The information of interest is the rate of mitral valve closure. The normal valve closing rate is indicated by the slope in (Figure 14A); in this case the closing rate is 72 mm/s. (Figure 14B) is an M scan showing a defect called mitral stenosis (narrowing of the valve opening). The low slope of mitral stenosis is quite different from the normal slope; the slower the closing rate, the greater the amount of stenosis. Other heart valves can be examined in a similar way.



(a.14)



(b.14)

Figure 14. M-scan showing the movement of the mitral valve of the heart; the rate of valve closure

is indicated by the slope, which is plotted below each scan. (a) A slope of 72 mm/s is normal. (b) A slope of less than 35 mm/s indicates a defect called mitral stenosis (narrowing of the opening).[22]

Pericardial effusion can be easily detected on an M-scan. The pericardial sac surrounding the heart is usually in direct contact with it. Thus, an M-scan of a normal heart taken from position I in Figure 13 will show the anterior right ventricular wall in direct contact with the anterior pericardium, a fixed chest wall, and a posterior left ventricular wall in direct contact with the posterior pericardium. When pericardial effusion occurs, the space between the heart and pericardium is filled with fluid from the sac and the heart from anterior to posterior (Figure 15).

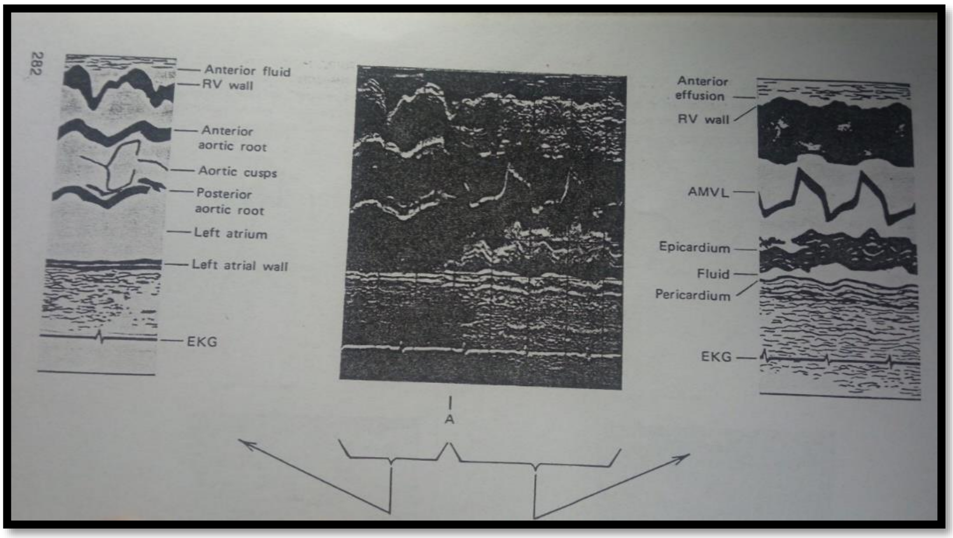


Figure 15. M scan shows fluid accumulation in the sac surrounding the heart (pericardial effusion). The probe is moved at point A. The drawing on the left identifies the structures on the left side of the M scan, up to point A. The drawing on the right, corresponding to the right side of the M scan, shows fluid between the heart and pericardium.[23] This examination may be repeated during treatment to determine if progress is being made[9].

Doppler effect

Since the early studies of sound in the nineteenth century, physicists have realized that a sound source with frequency °f has a higher pitch when it moves toward the listener (Figure 16.a), and a lower pitch when it moves away from him (Figure 16.b).

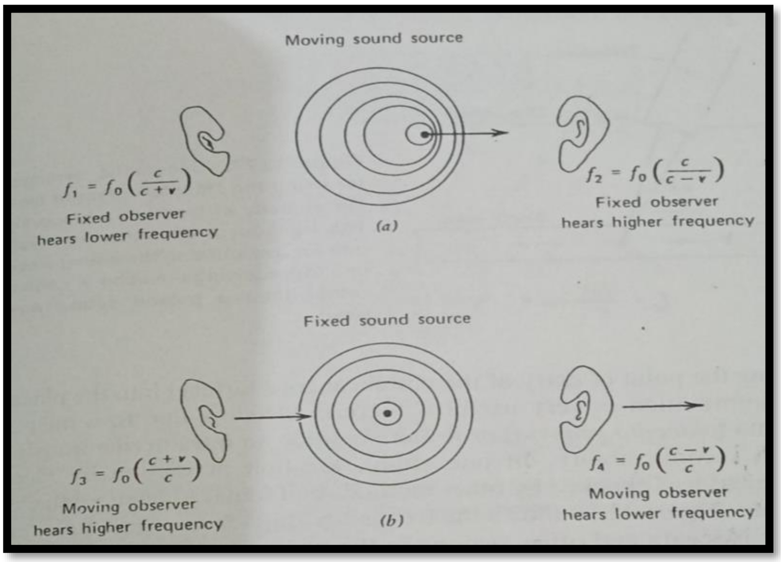


Figure 16. Doppler effect. (a) A listener hears a higher frequency from a sound source moving toward him and a lower frequency when he is moving away from it. (b) A listener hears a higher frequency when moving toward a sound source than when moving away from it. Here c is the speed of sound in air, v is the speed of the source at a and the listener at b, and f is the frequency in the absence of motion.

The change in frequency is called the Doppler shift. When a sound source moves toward the listener or when he moves toward the source, the sound waves rush together and he hears a higher frequency of sound. When the source moves away from the listener or when he moves away from the source, he hears a lower frequency f^o. If we know the frequency of the source, f, and can measure the frequency that the listener receives, we can determine how fast the sound source or listener is moving. This technique has been used to measure the speed of missiles: the missile receives a radio frequency signal and then rebroadcasts it to the transmitter, which compares the received signal to the original signal to determine the relative speed of the missile.

The Doppler effect can be used to measure the speed of moving objects or fluids within the body, such as blood. When some red blood cells receive a continuous beam of ultrasound in an artery moving away from the source, the blood "hears" a frequency slightly lower than the original frequency. The blood sends out scattered echoes of the sound it makes. "hears," but since it is now a source of sound moving away from the detector, there is another shift to a lower frequency. The detector receives a back-scattered signal that has undergone a double Doppler shift. When the blood is moving at an angle of 0 to the direction of the sound waves, the frequency change is

fd=2f°v/v.cos0

where f is the frequency of the initial ultrasound wave, V is the velocity of the blood, v is the velocity of sound, and v is the angle between V and v (Figure 17).

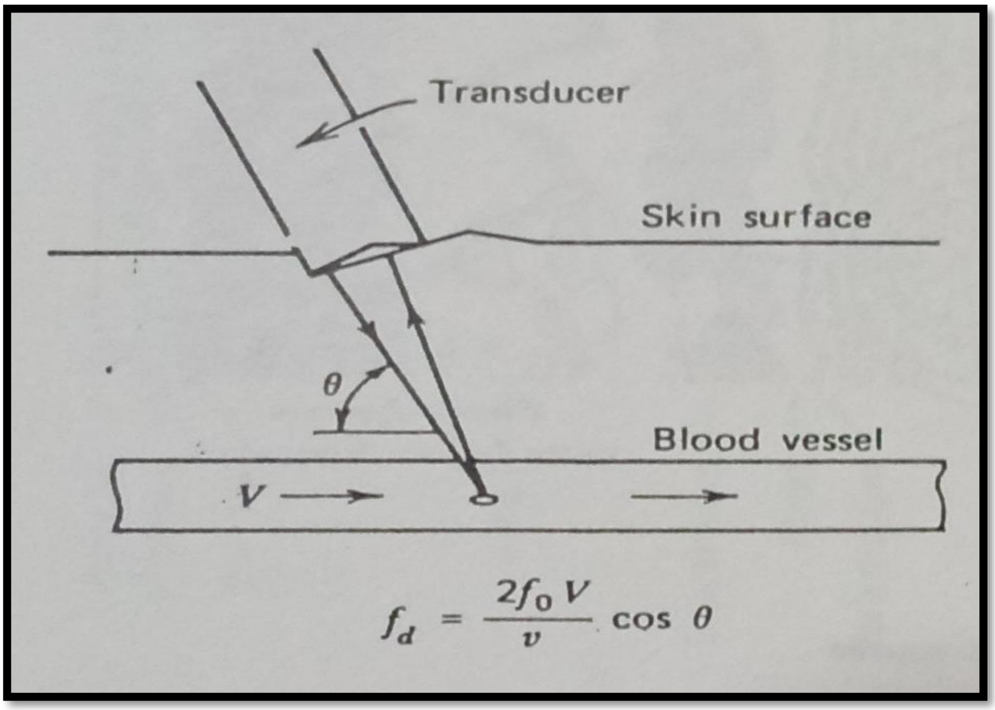


Figure 17. Schematic arrangement of using the Doppler effect to measure the velocity of blood in the blood vessels. The transducer has two crystals - one for transmitting the sound wave and the other for receiving the echo. A continuous sound wave is used instead of a pulsed one.

This method has the definite advantage of not requiring catheterization in the artery or surgical implantation of measuring devices.

The Doppler effect is also used to detect the movement of the fetal heart, umbilical cord and placenta in order to determine the life of the fetus during the gestation period of 12 to 20 weeks when radiological and clinical signs are irresponsible. When a continuous sound wave with a frequency of f^0 falls on the fetal heart, the reflected sound is transformed into frequencies slightly higher than the frequencies of f^0 when the fetal heart moves towards the sound source and slightly lower than the frequencies of f^0 when the fetal heart moves away from it. The differences in frequency give the fetal heart rate. Figure 18 shows the arrangement of the instrument for monitoring the fetal heart.[9]

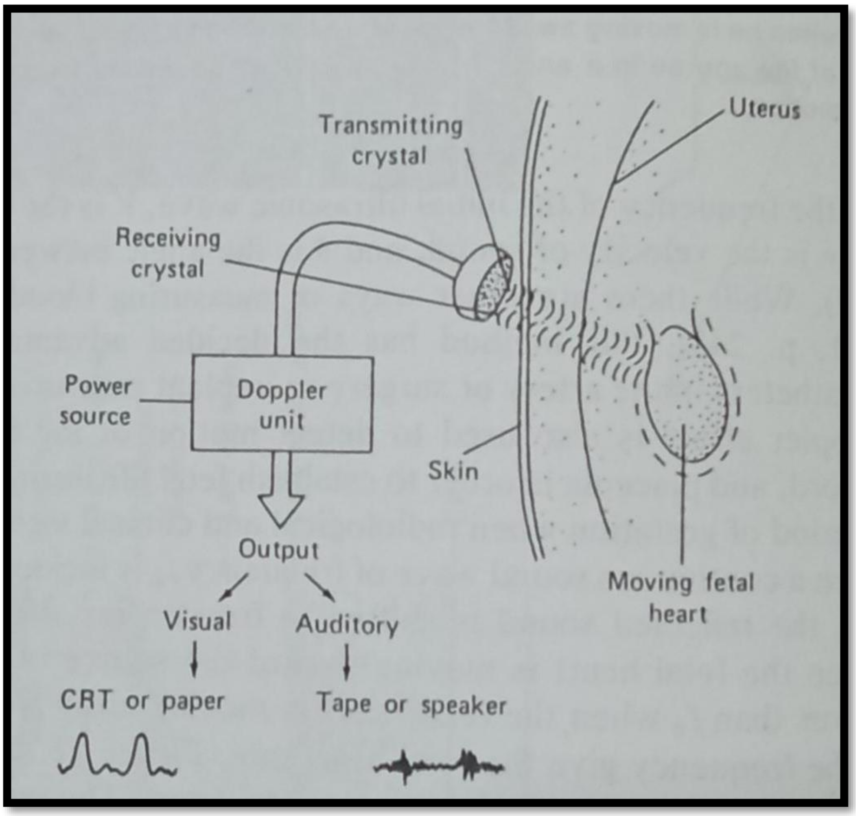


Figure 18. Schematic diagram of the ultrasound motion sensor for fetal heart monitoring[24] .

The output can be audible or displayed on an oscilloscope. Perhaps the most common use of the Doppler effect in obstetrics is to determine the location of the umbilical cord (artery) entry point into the placenta. This information is very useful if there is bleeding due to misplaced placenta (placenta previa) or if an intrauterine blood transfusion is scheduled due to Rh incompatibility. In one study, prediction of location by Doppler ultrasound was verified by other methods and found to be more than 90% accurate. Figure 19 shows frequency shifts from the Doppler effect for the placenta and other areas of the pregnant uterus. Care should be taken to avoid observing maternal arteries and veins, which have a much lower rate [9]

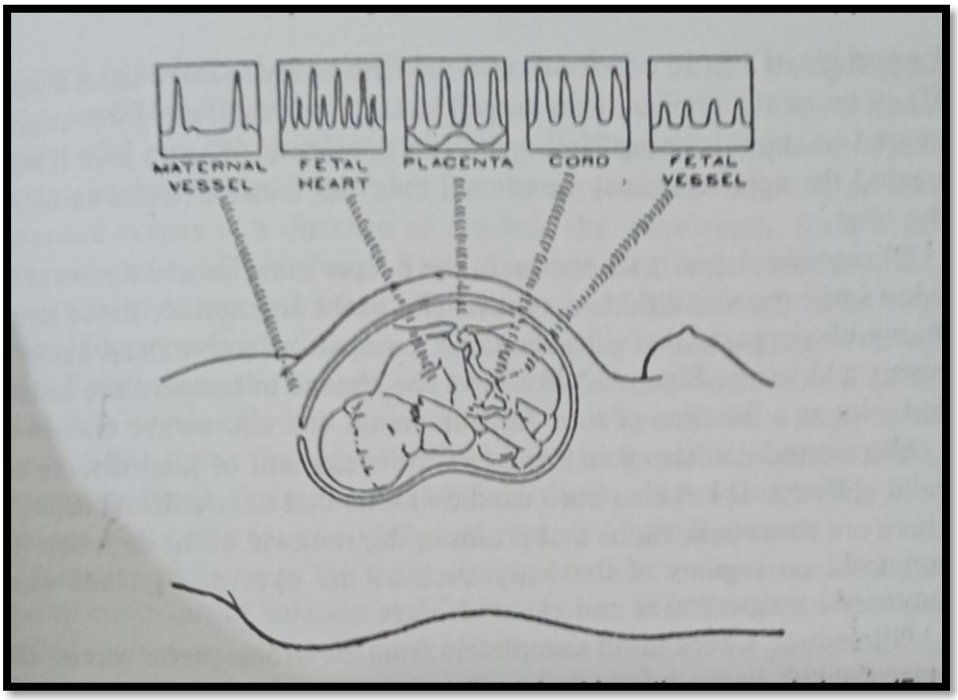


Figure 19. Different types of “sounds” elicited from the pregnant uterus[25].

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