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Basics of Ultrasound and Its Use in Medicine: A Review Article

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ABSTRACT

This paper aims to present the basics of ultrasound and its application in medicine. It introduces parts of an ultrasound machine and gives information about the transducer, which is the main component of an ultrasound machine. The- image producing process and ultrasound wave characteristics are explained. Different methods for two- and three-dimensional imaging of the human anatomy are demonstrated. Ultrasound wave penetration, attenuation, acoustic impedance, and resolution are stated. Different types of diseases and different types of ultrasounds for their diagnosis are presented.

Keywords- basics, ultrasound, image, transducers.

I. INTRODUCTION

The audio spectrum frequencies range from 20 Hz to 20,000 Hz, which shows that the "Audible Band" is a tiny slice of the total available bandwidth. Ultrasonic devices operate with frequencies above 20 kHz. Frequencies above 20 kHz are referred to as ultrasonic frequencies or supersonic frequencies.

Ultrasonic waves have the following properties:

1. They travel slowly. Ultrasonic waves travel approximately 10^5 times slower than electromagnetic waves.
2. They can easily pass through opaque materials.(Cheeke, 2010)

Understanding the basics of ultrasound is needed for doctors who use ultrasound and make decisions after its use. Ultrasound is made up of mechanical waves that can be transmitted through fluids, soft tissues, and solids. Its frequency is higher than the upper human auditory limit, which is approximately 20 kHz.(McGahan & Goldberg, 1997)

Sound waves and ultrasound waves propagate in solids and fluids, namely liquids and gases(Laugier & Haïat, 2011).

Frequencies f_0 from 2 MHz to 15 MHz are used in medical ultrasound. The speed of sound c at these frequencies is approximately 1540 m/s in the human body, and the wavelength is $\lambda = \frac{c}{f_0}$, which takes values from 0.77 mm to 0.10 mm(Carson & Fenster, 2009; Jensen, 2007).

Ultrasound is a manual, high-powered, and practical examination(Khoury et al., 2007).

Ultrasound's first practical application was recorded during the First World War in the detection of submarines. In medicine, its application began in the 1950s. It was first introduced in obstetrics, and after that in all other fields of medicine such as abdominal diagnostics, the diagnostics in the field of the pelvis, cardiology, ophthalmology, orthopedics, and so on(Bijelic & Cocic, 1985).

The ultrasound machine, which basically contains a transducer, transmitter pulse generator, compensating amplifiers, the control unit for focusing,

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digital processors, and systems for display, is used in the cases of: breast examination, abdominal, maternity, cardiac, gynecological, cerebrovascular, and urological examination, and small pieces of tissue, as well as in pediatric and operational review(Carovac et al., 2011).

For the imaging of nearly all soft tissue structures in the body, modern medical ultrasound transducers are used, and the anatomy of the body parts can be studied from gray-scale B-mode images(Jensen, 2007).

Many specific types of interactions happen between the incident ultrasound pulse and the structures in the tissue medium, whose result is echo generation. A tissue property that is significant to all of them is called the acoustic impedance, and it is usually called the specific acoustic impedance of the medium. The result of the interactions is a partially reflected echo, which goes back toward the transducer, and a partially transmitted pulse, which goes deeper into the patient (Zagzebski, 1996).

The intensity of the ultrasound pulses and echoes that travel through tissue is reduced or attenuated. This loss results from the induced oscillatory tissue motion that is generated by the pulse, the result of which is the change of energy from the original mechanical form into heat. This loss of energy to localized heating is called absorption, and it is the most significant component of ultrasound attenuation(Carson & ARBOR, 2000).

Tissue harmonic imaging is an essential, commonly used US mode. The term harmonic refers to the integral multiples of the frequency of the first harmonic (i.e., transmitted pulse). The frequency of the second harmonic is twice that of the first harmonic(Fowlkes & Averkiou, 2000).

II. ULTRASOUND MACHINE

A basic ultrasound machine has the following parts:

- Transducer: A transducer is a probe that sends and receives sound waves.
- Central Processing Unit (CPU): It is a computer that performs all the calculations and has the electrical power supplies for itself and the transducer.
- Transducer pulse controls: It changes the amplitude, frequency, and duration of the pulses emitted from the transducer.
- Display: It shows the image from the ultrasound data, which is processed by the CPU.
- Keyboard/Cursor: It inputs data and gets measurements from the display.
- Disk storage device (hard, floppy, CD): It stores the acquired images.
- Printer: It prints the image from the shown data(Arellano Jr, 2015).

The transducer is the main component in an ultrasound machine, which is responsible for the production of ultrasound beams and the detection of returning echoes(Tomà & Rossi, 2001). Its frequency can vary from 2.0 MHz to 16.0 MHz, and its choice is basically based upon the patient’s body habits and the area to be scanned. A transducer with a frequency range of 7.0 MHz to 14.0 MHz is called a high-frequency transducer. Its two types, namely linear and sector, are more suitable for children. It provides increased resolution for images, though their penetration is reduced. Linear transducers are best for the assessment of outward or superficial structures like the thyroid, scrotum, etc. A transducer with frequency range of 3.0 MHz to 5.0 MHz is called a medium-frequency transducer. Its curvilinear or sector transducers are commonly used for adult abdominal imaging. A transducer with frequency of 2.0 MHz is called a low-frequency transducer. Its sector type provides increased depth of penetration but also results in a loss of resolution. It is more suitable for the ultrasound studies of obese patients(Abraham et al., 2010).

III. IMAGE PROPERTIES AND ITS GAINING PROCESS

An ultrasound machine has a transducer, sometimes called a probe, which is attached to the machine via a cord. The transducer has a linear array of very thin crystals, each of which is linked to the machine’s electrical system (Kremkau, 1998).

To produce an ultrasound wave, the machine applies alternating electrical current to the transducer crystals, which vibrate because of it. The vibrating crystals produce a sinusoidal sound wave, which is mechanical energy. This transformation of electrical to mechanical energy is known as piezoelectricity (Kremkau, 1998) and piezoelectric materials are those materials that have the capability of changing mechanical pressure and vibration energy into electrical energy(Sekhar et al., 2021). The produced sound wave can be described by its frequency, wavelength, speed, and amplitude. The range of frequencies that the transducer can produce is determined by the material characteristics of the piezoelectric crystals and their thickness. The frequency and amplitude of the electrical current used to motivate the crystals determine the frequency and amplitude of the produced sound waves. Sound waves require a medium to travel in; they pass through ultra-sonographic coupling gel into the body (Kremkau, 1998). In order to exclude air, applying suitable gel or oil between the transducer surface and the patient's skin is needed (Tole, 2005).The sound waves travel deep into the body until they face an acoustic interface. Acoustic interfaces happen at the point where there is a change in the density or stiffness of adjacent tissues. The acoustic interface reflects a portion of the sound wave’s energy, while giving permission to some

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of it to pass and penetrate deeper into the body. Acoustic interfaces that reflect a great deal of sound energy appear brighter on the screen, while interfaces with less reflection appear darker. The acoustic interface reflectivity depends on the differences in material properties of the constituent tissues. More sound energy is reflected at interfaces composed of very different tissues. For instance, a great amount of sound energy is reflected at the interface between bone and muscle, which results in bone appearing very bright on the display screen (Kremkau, 1998).

Transducer detects reflected sound wave and functions as a receiver. The received mechanical sound energy is transformed into an electrical signal for processing and it is called the inverse piezoelectric effect (Rosas, 2022). The received ultrasound wave might be amplified by increasing the gain to produce a whiter image (Lichtenstein, 2010). Decreased gain produces a black image. The gain factor is changed by time gain compensation, so equally reflective structures are displayed with the same brightness without consideration for their depth (Guachi-Guachi et al., 2023).

The amplitude of the returning beam and the depth of the reflecting structure are recorded by the ultrasound machines. To produce a 2-dimensional black-and-white image of the body, complex computer software is used by ultrasound machine. Ultrasound software was developed by VuSystem, which is a UNIX-based programming environment. The above stated process is also referred to as pulsed ultrasound, which is used to produce a B-mode image. To record and display the gained information, different modes are used. These display modes are differently stated as A-mode, B-mode, M-mode, etc. Some of them give information in a single dimension, some in two dimensions, and some are particularly designed to show moving structures (Tole, 2005).

Resolution can be lateral; lateral resolution is the ability to resolve targets lying close together, side by side at the same range; or it can be axial; axial resolution is the ability to resolve targets close together, one behind the other on the beam axis (Thadani, 1997).

Static B-mode transducers were more useful because of their large imaging field of view, though they were lost with the introduction of mechanical and electronic automatic scanning (Weng et al., 1997).

Images gained by a linear array transducer are rectangular, and those gained by a convex array transducer are wider, having increased depth (Whittingham, 2007).

To produce images in real time, modern transducers are used that are composed of piezoelectric linear or multi-element phased arrays, which have the capability of producing images in real time. Most arrays with 128 or more elements are one-dimensional. One-dimensional arrays have fixed focusing in the direction perpendicular to the array. Other systems have additional transducer elements that produce 1.5D arrays, that allow for more flexibility in focusing in the elevation direction. Nowadays, two-dimensional arrays are available in high-end systems that allow for both focusing in the elevation direction and real-time 3D and 4D imaging(Von Ramm et al., 1991).

IV. ATTENUATION, ACOUSTIC IMPEDANCE AND RESOLUTION

The progressive loss of sonic energy or acoustic energy as a wave passes through tissue is called attenuation. Attenuation through tissue is usually explained as the loss of intensity in $dB/cm/MHz$. Ultrasound attenuation through tissue is nearly proportional to the total path length and the ultrasound frequency. Attenuation varies between particular types of soft tissue but for the most part occurs in the range of about 0.3– 0.8 $dB/cm/MHz$(St John Sutton et al., 1996).

The resistance for propagation of ultrasound waves is called acoustic impedance. Acoustic impedance varies according to the density of the material through which the ultrasound waves pass. Ultrasound waves reflect more when the material is more solid (Guachi-Guachi et al., 2023).

The penetration and resolution of the images will be controlled by changing the frequency of the waves. If the frequency of the wave is higher, the resolution of the image is better, and the depth of penetration decreases. While using lower frequency transducers, the opposite occurs (Cosby & Kendall, 2006).

Less ultrasound waves reflect back from fluids as fluids transmit more sound waves than solid material. Stones and bones reflect more sound waves than fluid and produce bright images. A black acoustic shadow is present behind stones, as ultrasound waves cannot transmit through them. A strong ultrasound beam reflector is air, and it makes it difficult to visualize the structures behind it (Abu-Zidan et al., 2011).

The ability of an ultrasound machine to distinguish one object from another is called resolution (Picard et al., 2008).

Resolution can be spatial; spatial resolution is the ability to distinguish between objects in space; or it can be contrast; contrast resolution is the ability to distinguish between waves of different sizes; or it can be temporal; temporal resolution is the ability to separate between events in time. A good-quality image contains information that is associated with high spatial resolution, high contrast resolution, and high temporal resolution (Tole, 2005)

Resolution can be lateral; lateral resolution is the ability to resolve targets lying close together, side by side at the same range; or it can be axial; axial resolution is the ability to resolve targets close together, one behind the other on the beam axis (Whittingham, 2007).

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V. ULTRASOUND WAVE CHARACTERISTICS

Ultrasound waves are commonly emitted perpendicular to the surface of the transducer. In the case of a convex array transducer, it is possible to widen the deep sonographic field by bending the surface of the transducer. In the case of a linear array transducer, waves are parallel to each other as the transducer surface is flat, usually having higher frequencies in the range of 10 MHz to 12 MHz, excellent resolution, and less penetration (Whittingham, 2007).

To control the way ultrasound waves are emitted from the ultrasound transducers, different methods exist. Ultrasound waves can be emitted either intermittently or continuously. Interrupted emission of ultrasound waves produces brightness (B) mode images, while continuous emission produces Doppler mode, which shows blood flow. Imaging one line over time is the moving mode (M Mode) (Cosby & Kendall, 2006).

VI. ULTRASOUND IN MEDICINE

Ultrasound is used broadly. It is especially expanding in the food industry for food analysis and process supervision (McClements, 1995). Ultrasound is usually used in medical imaging and diagnostics (Hill et al., 2004). The first endeavor to use ultrasound for diagnosis was based on a transmission technique in 1937 (Hill, 1973).

In 1951, the emerging clinical importance of ultrasound technology was recognized by a group of 24 physiatrists and the American Institute for Ultrasound in Medicine was founded by them. Real-time ultrasound imaging became common and widely available. It was facilitating a more effective, interactive, and clinically significant examination by the 1980s. In the late 1980s, high-frequency transducers were introduced, providing the detailed anatomic imaging needed to evaluate the musculoskeletal system (Valente & Wagner, 2005).

The pulses of ultrasound travel through biological tissues with an average velocity of approximately 1,540 m/sec. The real value of velocity varies in specific tissues. For instance, the sound speeds of fat, amniotic fluid, kidney, muscle, and skull bone are approximately 1,450, 1,540, 1,565, 1,600, and 4,080 m/sec, respectively (Zagzebski, 1996). The propagation of ultrasound waves through tissue is done in a nonlinear fashion. The wave velocity is slightly lower for lower-pressure wave phases than for higher-pressure phases (Fowlkes & Averkiou, 2000).

Different ultrasound systems use different ultrasound transducers that are typically designed for use at different frequencies and for particular applications like endo-cavity, vascular, abdominal, small parts, and so on. Imaging (Von Ramm et al., 1991).

Approximately 3 MHz is typical of abdominal applications in adults; about 5 MHz in children; in superficial regions such as the breast or neck, increasing to about 10 MHz; for the anterior chamber of the eye or intra-vascular scanning, about 30 MHz; or in very superficial applications such as imaging the cornea, it increases to even about 100 MHz (Whittingham, 2007).

Two methods of application, namely continuous wave (CW) ultrasound and pulsed wave (PW) ultrasound, can be used during diagnostic applications. Most diagnostic ultrasounds employ the pulse-echo principle (Tole, 2005).

For the identification of vessels during interventional procedures, all machines offer high-sensitivity Doppler imaging, giving permission for the detection of abnormal blood flow in diseased tendons (Teh, 2006).

For the purposes of diagnosing pathology or guiding real-time interventional procedures, a great number of doctors have merged musculoskeletal ultrasound into their practices to image soft tissues and bony structures in the body (Smith & Finnoff, 2009).

An infectious disease called periodontitis, which is caused by intraoral biofilm, has aerobic and anaerobic bacteria (Van Dyke, 2008). For the removal of supra- and sub- gingival bacterial biofilms and dental calculus from tooth surfaces, ultrasonic mechanical instrumentation is used as an effective method (Ioannou et al., 2009).

Real-time cross-sectional images of the arterial wall in vivo at high resolution are produced by intravascular ultrasound (IVUS), which is the only medical imaging modality (Doyley et al., 2001).

Chronic liver disease, which is a significant cause of morbidity and mortality in developed countries, is generally caused by viral hepatitis and alcohol abuse (Schuppan & Afdhal, 2008). The typical method for its determination, staging, and grading is liver biopsy (Brunt, 2000). Computed tomography, magnetic resonance imaging and ultrasound are among the less invasive methods for its determination, staging, and grading (Manning & Afdhal, 2008).

Using simple ultrasound-based rules, we can correctly classify most adnexal tumors as benign or malignant (Timmerman et al., 2008).

For the detection of proximal deep-vein thrombosis of the lower extremities in patients with clinical indications of the first episode of deep-vein thrombosis, real-time B-mode ultrasound is a highly accurate, objective, and reproducible method (Lensing et al., 1989). After an acute episode of deep-vein

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thrombosis, the serial ultrasound measurement of thrombus mass may allow the correct identification of patients who develop a recurrent proximal-vein thrombosis (Prandoni et al., 1993).

Approximately one in 800 live-born babies is affected by Down's syndrome (Cuckle et al., 1987). Down's syndrome in the antenatal period can be detected by the first trimester ultrasound (Alldred et al., 1996).

The doctor can visualize the thoracic structure between the ribs by reducing the surface of the transducer and using fan- shaped sectors (Whittingham, 2007).

VII. CONCLUSION

The paper has detailed basics of ultrasound, whose learning is essential for physicians who have merged musculoskeletal ultrasound into their practices to image soft tissues and bony structures in the body. Since the beginning of its application in medicine, its use has been expanding. It has shifted from simple 2D displays of anatomy to real-time 3D imaging. Due to its rapid advancement, it is expected that its diagnostic capability will be further expanded.

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