"Clinical Ultrasound Physics: Compendium of Basic Concepts"

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Abstract

Ultrasound is a wave with a frequency exceeding the upper limit of human hearing. – greater than 20,000 Hz (hertz) .While the term ultrasound generally refers to sound waves with frequencies above 20,000 Hz (the frequency range of audible sound is 20 to 20,000 Hz), diagnostic ultrasound uses frequencies in the range of 1-10 million (mega) hertz.

An ultrasound wave is generated when an electric field is applied to an array of piezoelectric crystals located on the transducer surface. Electrical stimulation causes mechanical distortion of the crystals resulting in vibration and production of sound waves (i.e. mechanical energy). The conversion of electrical to mechanical (sound) energy is called the converse piezoelectric effect. Each piezoelectric crystal produces an ultrasound wave. The summation of all waves generated by the piezoelectric crystals forms the ultrasound beam.

In the case of echocardiography, the ultrasound probe emits a particular frequency, and the moving object is the heart, red blood cells and tissues. Reflected ultrasound waves from red blood cells return to the probe with a Doppler shift that is translated by a computer into a velocity.

Key words: Ultrasound, waves, physics, compendium

Introduction

It is very important to understand the basic physical principles of Ultrasound, its generation, transmission, reflection and the interpretation. The frequencies normally applied in clinical imaging lies between 1 MHz and 20 MHz. The sound is generated by a transducer that first acts as a loudspeaker sending out an acoustic pulse along a narrow beam in a given direction. The transducer subsequently acts as a microphone in order to record the acoustic echoes generated by the tissue along the path of the emitted pulse. These echoes thus carry information about the acoustic properties of the tissue along the path.

The emission of acoustic energy and the recording of the echoes normally take place at the same transducer, in contrast to CT imaging, where the emitter (the X-ray tube) and recorder (the detectors) are located on the opposite side of the patient. Ultrasound (as well as sound) needs a medium, in which it can propagate by means of local deformation of the medium. One can think of the medium as being made of small spheres (e.g. atoms or molecules), that are connected with springs. When mechanical energy is transmitted through such a medium, the spheres will oscillate around their resting position. Thus, the propagation of sound is due to a continuous interchange between kinetic energy and potential energy, related to the density and the elastic properties of the medium, respectively.

The two simplest waves that can exist in solids are longitudinal waves in which the particle movements occur in the same direction as the propagation (or energy flow), and transversal (or shearwaves) in which the movements occur in a plane perpendicular to the propagation direction. In water and soft tissue the waves are mainly longitudinal. The frequency, f, of the particle oscillation is related to the wavelength,λ, and the propagation velocity. The sound speed in soft tissue at 37°C is around 1540 m/s, thus at a frequency of 7.5 MHz, the wavelength is 0.2 mm. For the purposes of medical ultrasound, temporal resolution is synonymous with frame rate. Typical frame rates in echo imaging systems are 30-100 Hz. The temporal resolution or frame rate = 1/ (time to scan 1 frame). The time to scan one frame is equal to the pulse repetition period x number of scan lines per frame.

Discussion

Medical ultrasound machines generate and receive ultrasound waves. Brightness mode (B mode) is the basic mode that is usually used[1]. Ultrasound waves are emitted from piezoelectric crystals of the ultrasound transducer. Depending on the acoustic impedance of different materials, which depends on their density, different grades of white and black images are produced.

There are different methods that can control the quality of ultrasound waves including timing of ultrasound wave emission, frequency of waves, and size and curvature of the surface of the transducer. The received ultrasound signal can be amplified by increasing the gain. The operator should know sonographic artifacts which may distort the studied structures or even show unreal ones. The most common artifacts include shadow and enhancement artifacts, edge artifact, mirror artifact and reverberation artefact. Ultrasound is made up of mechanical waves that can transmit through different materials like fluids, soft tissues and solids. It has a frequency higher than the upper human auditory limit of 20 KHz[2]. Ultrasound frequency is defined as the number of ultrasound waves per second, and medical ultrasound machines use waves with a frequency ranging between 2 and 15 MHz[3]. The velocity of ultrasound in a specific medium equals the frequency of ultrasound multiplied by its wave length.

Medical ultrasound machines generate ultrasound waves and receive the reflected echoes. Brightness mode (B mode) is the basic mode that is usually used. The B mode gives a two dimensional (2D) black and white image that depends on the anatomical site of the slice. The body can be imaged in different planes depending on the position of the probe. These thin slices are of less than 1 mm each and can be sagittal, coronal, transverse, or oblique. Sound waves are emitted from piezoelectric crystals from the ultrasound transducer. Piezoelectric crystals are fabricated from material that changes electrical signals to mechanical vibrations and changes mechanical vibrations to electrical signals. As ultrasound waves pass through various body tissues, they are reflected back to the transducer creating an image on the ultrasound screen[4].

Acoustic impedance is defined as the resistance for propagation of ultrasound waves. This varies according to the density of the material ultrasound passes through. When the material is more solid, then the particles are denser and sonongraphic waves will reflect more[5]. Fluid transmits more sound waves than solid material. So less ultrasound waves will reflect back from fluids. This produces a "black" image. Stones and bones reflect more sound waves than fluid and produce "white" bright images. Since ultrasound waves cannot transmit through stones, a black acoustic shadow will be present behind them. Air is a strong ultrasound beam reflector making it difficult to visualize structures behind it.[6].The denser a material is, the more it reflects the sonographic waves. Fluid (like blood) transmits ultrasound waves and have minimum waves reflected back. This yields a black image. Stones yield white images with a shadow.

Changing the frequency of ultrasound waves will control the penetration and resolution of the images. The higher the frequency, the better is the resolution, however the depth of penetration decreases. The opposite will happen when using lower frequency transducers. Longer distances and higher frequencies result in greater attenuation. This implies that for obese patients and deep structures, probes of low frequencies should be used while probes of high frequency should be used for superficial structures. The received ultrasound signal can be amplified by increasing the gain. Decreased gain yields a black image and details are masked, while increased gain yields a whiter image[7]. Time gain compensation will change the gain factor so that equally reflective structures will be displayed with the same brightness regardless of their depth. Ultrasound waves are emitted perpendicular to the surface of the transducer. It is possible to widen the deep sonographic field by bending the surface of the transducer (convex array transducer). Waves will be parallel to each other when the probe surface is flat (linear array transducer).

Linear array transducers usually have high frequencies (10-12 MHz), less penetration, and excellent resolution. The ultrasound images obtained by a linear array transducer will be rectangular in shape while those obtained by a convex array transducer will be wider with increased depth. Reducing the surface of the transducer and using fan shaped sectors will enable the examiner to visualize thoracic structure between the ribs[8].

ARTIFACTS: Artifacts may distort the size, position and shape of the studied structures or even show structures that are not present. Some artifacts are very useful for diagnosing different conditions. Ultrasound is unable to transmit through solid structure like the stones or ribs. This causes a shadow artifact behind the solid structures[9]. Shadow artifact is very useful for diagnosing gall stones. Posterior enhancement artifact may occur when imaging fluid filled structures (like the gall bladder or urinary bladder). More ultrasound waves will penetrate the fluid filled structure, and a white enhancement area will appear behind it .The posterior enhancement will increase the gain behind the urinary bladder, and it is important to reduce the gain when looking for small amounts of pelvic fluid in Pouch of Douglas, otherwise it can be missed. The edge (refraction) artifact occurs when a beam of ultrasound refracts at the edge of a rounded structure like a kidney or urinary bladder. This artifact may disappear when changing the angle of the ultrasound beam clarifying the nature of the artifact.

The mirror artifact occurs when the sonographic waves are reflected by an angle by a high acoustic impedance tissue, for example like the diaphragm. The mirror artifact will mimic a virtual object similar to a true mirror on the opposite side of the structure [10]. The mirror image is more hypoechoic and somewhat more blurred and distorted than the image of the original structure as a result of absorption the of the ultrasound beam when passing through a long pathway.

Reverberation artifacts are a big hindrance in Ultrasound examination. They occur when ultrasound bounces between two interfaces especially with high acoustic impedance like the pleura. The waves will move forward and backward between these interfaces. The machine will recognize these waves as parallel lines with equal distances between them, and decreased density for the deeper lines, because the reflected waves become gradually lesser in number. This results in a stripped pattern having alternating dark and clear lines at regular intervals.

Conclusion

Continuous innovations in the field of technology has led to the manufacturing of very user friendly Ultrasound machines. These innovations are moving rapidly into widespread use, providing significant improvements in image quality and allowing broader application of the Ultrasound. Tissue Harmonic Imaging is one such innovation. 3-D/4D Ultrasound , Extended FOV Imaging modality and Spatial Compound Imaging are others.

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