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2.1 Frequency and wavelength

Ultrasound refers to any sound that is above the audible range. The human ear is capable of hearing sounds in a frequency range between 20 and 20,000 hertz, so 20 to 20,000 cycles per second (1000 cycles per second = 1 kilohertz = 1 KHz). Only young children hear the high range while, with aging, the upper limit drops to about 12,000 cycles per second. Some animals are able to hear frequencies as high as 100,000 cycles per second. Thus, the ultrasonic range of frequencies runs from 20 kilohertz to 1 gigahertz. Medically applied ultrasound frequencies range from 2,000,000 hertz (2 MHz) to 50,000,000 hertz (50 MHz). These sound waves travel through the human body at a velocity of 1540 meters per second, so after 0.0000649 seconds, a distance of 10 cm has been traveled. Within the timeframe of one second, about 1000 ultrasound waves can be emitted and received from an object at a distance of 10 cm. Most structures relevant to rheumatology are much closer, often situated in the skin no deeper than 5 cm from the surface. Frequency (f) and wavelength (λ) are inversely proportional, i.e. \( f = \frac{1}{\lambda} \). There is also a relationship between frequency, beam penetration and resolution. Sound wave beams with a higher frequency penetrate less than lower frequency waves, but a sharper ultrasound image is outlined. Conversely, a transducer producing a lower frequency (longer wavelengths) will produce greater depth of penetration but less well-defined images. As already mentioned, in rheumatology diagnostics, most structures are located relatively superficially, so high-frequency ultrasound can be used. To be able to distinguish between two interfaces lying closely together, a distance of at least half a wavelength is needed between the two interfaces.

2.2 Generating ultrasound waves

Ultrasound waves are generated by a transducer consisting of a disc with crystals of lead zirconate titanate. These crystals are piezoelectric, in other words they transform electrical potentials into mechanical vibrations and vice versa. Every time an electrical current is passed through the crystals, the disc generates an ultrasound pulse; conversely, when the disc receives a wave of ultrasound, it will deform and a voltage is generated on the transducer surface. To produce a well-directed beam, the transducer disc is mounted at the end of a cylindrical tube, often called a probe. At the other end of the tube, damping material is mounted to damp down the ultrasonic waves generated at the back of the disc.

2.3 Reflection and transmission

The emitted waves are reflected when an ultrasound pulse bounces off a structure, and are transmitted when a pulse passes through one tissue into another. The greater the difference in tissue density, the more reflective the boundary will be, while with similar densities waves pass easily through the tissues. The mathematical equation determining the
amount of reflection and transmission is given by the speed of sound \( c \) and the specific acoustic impedance \( Z \) of the tissue. The impedance of sound in air is low; in muscle it is 10,000 times higher than in air and in bone the impedance is so high – about 50,000 times higher than in air – that the sound beam does not penetrate bone at all.

The boundary between two different tissues is called the acoustic interface. As there is an interface between air and skin, we have to apply a coupling medium on the transducer, such as a gel with an impedance similar to human tissue, otherwise only 0.1% of the ultrasound pulse would be transmitted into the skin tissue and 99.9% would be reflected off the skin surface. Similarly, almost 99% of the sound beam is reflected at the interface of air and muscle, while liquids – such as blood or synovial fluid – do not reflect sound waves.

When the surface of an object is flat and no air is present between the source and the object, almost all the ultrasound waves will be reflected from the object at right angles; the returning echoes are then detected by the transducer. The crystal reconverts the returning ultrasound wave, which has the same wavelength as the emitted wave, into an electronic potential. Subsequently, the electronic potential is converted by a computer into an ultrasound image. The transducer acts as the receiver of ultrasound echoes for about 99.9% of the time, and it only emits sound waves in the very small amount of time remaining.

### 2.4 Attenuation

Ultrasound loses its energy as it propagates through a tissue. This loss of energy is called attenuation. There are three causes of attenuation: diffraction, scattering, and absorption. Attenuation results in echoes from deep body tissues being displayed less intensely than those returning from superficial structures. A function of the ultrasound system, called time-gain control (or swept-gain), will correct the attenuation, and intensifies the echoes returning from deeper structures.

### 2.5 A glossary of ultrasound

It is handy to be familiar with a number of ultrasound concepts or nomenclatures.

- **B-mode or grayscale ultrasonography.** B (=brightness)-mode is the precursor of grayscale ultrasound and is limited to defining boundaries of structures and differentiating fluid from solid. Grayscale ultrasound includes the whole range of possible intensities of the gray, black and white dynamic images. However, it cannot differentiate between fibrous tissue and active synovitis.

- **Doppler ultrasonography.** Doppler ultrasound relies on the Doppler principle, which states that sound waves increase in frequency when they reflect from objects (e.g., red blood cells) moving towards the transducer and decrease when they reflect from objects moving away. This information is transferred into sound. Furthermore, it is possible to delineate flow curves and to determinate the direction of blood flow.

- **Color Doppler ultrasonography.** In color Doppler ultrasound, the Doppler effect is combined with real-time imaging. The real-time image is created by rapid movement of the ultrasound beam. The information from Doppler ultrasound is integrated in the grayscale image as a color signal. This signal indicates the direction of blood flow. Red signals indicate flow that is directed towards the ultrasound probe, while blue signals indicate flow directed away from the probe.

- **Duplex ultrasonography.** Duplex
ultrasound combines the color Doppler image with Doppler ultrasound. It depicts the anatomical image with color signals and Doppler curves and makes it possible to estimate the velocity of flow in combination with correction of the beam angle.

- **Power Doppler ultrasonography.** Positive Doppler ultrasound displays the total integrated Doppler power in color. It increases the sensitivity of the machine, particularly for small vessels and for slow blood flow. Some ultrasound equipment provides unidirectional images with only one color, independent of the direction of blood flow. Other equipment provides bidirectional information as described for color Doppler ultrasound. Positive Doppler shows hyperemia in inflamed tissues. It also differentiates between cysts and blood vessels, and in this way can help in ultrasound-guided aspirations, by avoiding blood vessels and correctly picking the site of biopsy.

- **Transducer or probe.** The transducer is the heart of the ultrasound machine. It generates the sound waves in terms of millions per second and receives the echoes. The frequency of the sound wave determines how deeply it will penetrate the tissue. The frequency also determines the resolution, so the higher the frequency, the greater the resolution, and the lesser the penetration.

- **Anisotropy.** Anisotropy is a typical ultrasound artifact, usually occurring in sonograms of tendons. The tendon may appear hyporeflexive, thus simulating disease. However, this is not due to pathology but to scattering of a beam which is not perpendicular to the surface. Scattered sound waves are not captured by the probe and so the tendon appears dark.

- **Resolution.** Resolution is the optical ability to distinguish detail, such as the separation of closely adjacent objects. Axial resolution distinguishes two objects lying in the same line of the beam at different depths. It is determined by the frequency of the ultrasound signal. Lateral or horizontal resolution refers to the ability to distinguish two objects when they lie side by side. The modern transducers used for musculoskeletal ultrasound reach an axial resolution of 0.1 mm and a horizontal resolution of 0.2 mm. 20 MHz transducers reach an axial resolution power of 0.04 mm.

- **Time or B-mode gain.** Time or B-mode gain corrects the attenuation of the ultrasound beam due to scattering and tissue absorption. Time gain compensation amplifies the echoes returning to the transducer using an exponential function based on the time of flight. The examiner can modify the time gain from his control panel.

- **Refraction.** Refraction is an artifact depicting real structures in the wrong position, caused by the bending of an ultrasound wave at the interface of two materials; we can minimize this phenomenon by keeping the incident beam as close to 90° as possible.

- **Reverberation.** Reverberation is the phenomenon of the beam bouncing back and forth between the transducer and the object, giving rise to multiple echoes. It causes repetition echoes below a structure, e.g. below a metal object, such as a prosthesis or needle. This can be seen for example when a needle is introduced in the tissue.

- **Edge shadows.** In ultrasound, edge shadow refers to the shadows behind the edge of spherical, fluid-filled structures.

- **Comet tail.** A comet tail is an artifact caused by reverberation. It creates characteristic bands of increased echogenicity distal to the object.

- **Acoustic shadowing.** Acoustic shado-
wing means that almost all of the beam is reflected when it hits a highly reflective surface, such as bone, air, calcifications and calculi. It produces a dark shadow below the highly reflective surface.

- Echogenicity (echotexture). A structure may appear anechoic (black), hypoecholic (dark-gray), midecholic (gray, akin to soft tissue), a mixture of hyperechoic and hypoechoic, and hyperechoic (white). Bone sharply reflects ultrasound waves and the bony edge appears white. Cartilage appears as a hypoechoic band overlying the bone. Fluid collections are hypoechoic or anechoic structures that may exhibit acoustic enhancement, demonstrated by brighter echoes behind the structure.

- Aliasing. Aliasing is a Doppler artifact occurring when velocities of red blood cells are higher than the pulse repetition frequency (PRF). This occurs for example in areas of stenosis, where the reduced lumen of the vessel is seen with a red to blue shift. Red represents flow towards the transducer, within the range of the PRF, and blue velocities beyond the range of the PRF, not reversed flow.

- Harmonic imaging. Harmonic imaging transmits signals at a low frequency and uses the second harmonic signal at a higher frequency, by filtering out the first returning echoes from the received signal to produce an image. Three-dimensional (3D) ultrasound has several advantages over conventional 2D ultrasound, because it is composed of multiple 2D images and unlike 2D ultrasound, it is not dependent on the angle of scanning to the body. Microbubble contrast agents remain in the circulation for a few minutes and result in a marked increase of the ultrasound image.