Annex 12.1. Ultrasonography: Physical principles

12.1.1. Characteristics of the ultrasound beam

Sound waves are characterized by wavelenght (λ), frequency (f) and amplitude (A). The frequency refers to the number of cycles that occur in one second, and is usually described in Hertz (Hz) (Aldrich, 2007). One cycle per second is 1 Hertz; 1000 cycles are 1 kilohertz (kHz) and 1 million cycles 1 megahertz (MHz) (Nyland, Mattoon, Herrgessel & Wisner, 2002). Ultrasound waves range from 18 Khz to 150 Mhz, but in veterinary medicine the ultrasound units usually use ultrasounds between 3.5 Mhz to 10 Mhz (Martinat-Botté, Renaud, Madec, Costiou & Terqui, 1998).

The wave length is the distance between corresponding points of two consecutive waves and can be calculated basesd on equation 1, where λ corresponds to the wavelength, c to velocity and f for frequency (Kossoff, 2000).

Equation 1: Relation between wavelength, velocity and frequency.

$$\lambda = c/f$$

Frequency and wavelength are, thus, inversely related if the velocity within the medium remains constant. The sound velocity is independent of frequency and, although it varies according to the medium (table 2), it is assumed as nearly constant in the body’s soft tissues, around 1540 m/s (Merritt, 2011). Selecting a higher frequency transducer will result in decreased wavelength and, therefore, an increase in the image resolution but a decrease in the penetration capacity of the soundwaves (Nyland et al., 2002).

Table 1: Sound wave propagation speed and density of different media (adapted from Gorgas, 2011).

Media	Speed (meters/second)	Density (g/cm^3)
Air	331	0.0013
Water	1492	0.998
Fat	1470	0.97
Kidneys	1560	1.03
Spleen	1565	1.06
Muscle	1568	1.04
Liver	1570	1.05
Compact Bone	3600	1.7

12.1.2. Production and detection of ultrasounds

The use of ultrasounds is based on the capacity of a crystal to convert pressure – a mechanical energy – into an electric energy, which is called piezoelectric effect. To produce an ultrasound wave, an electric voltage is applied to a crystal (piezoelements in the transducer), which is converted into mechanical energy, causing oscillation of the crystal. This oscillation is transmitted, then, as an ultrasound wave into the body. These piezoelements act not only as transmitters, but also as receivers. The reflected echoes transmit their energy back to the transducer, causing a mechanical compression of the piezoelectric crystal. The compression forces the dipoles within the crystal to change their orientation, resulting in an electric voltage at the surface of the crystal that will be amplified and processed for display (Gorgas, 2011).

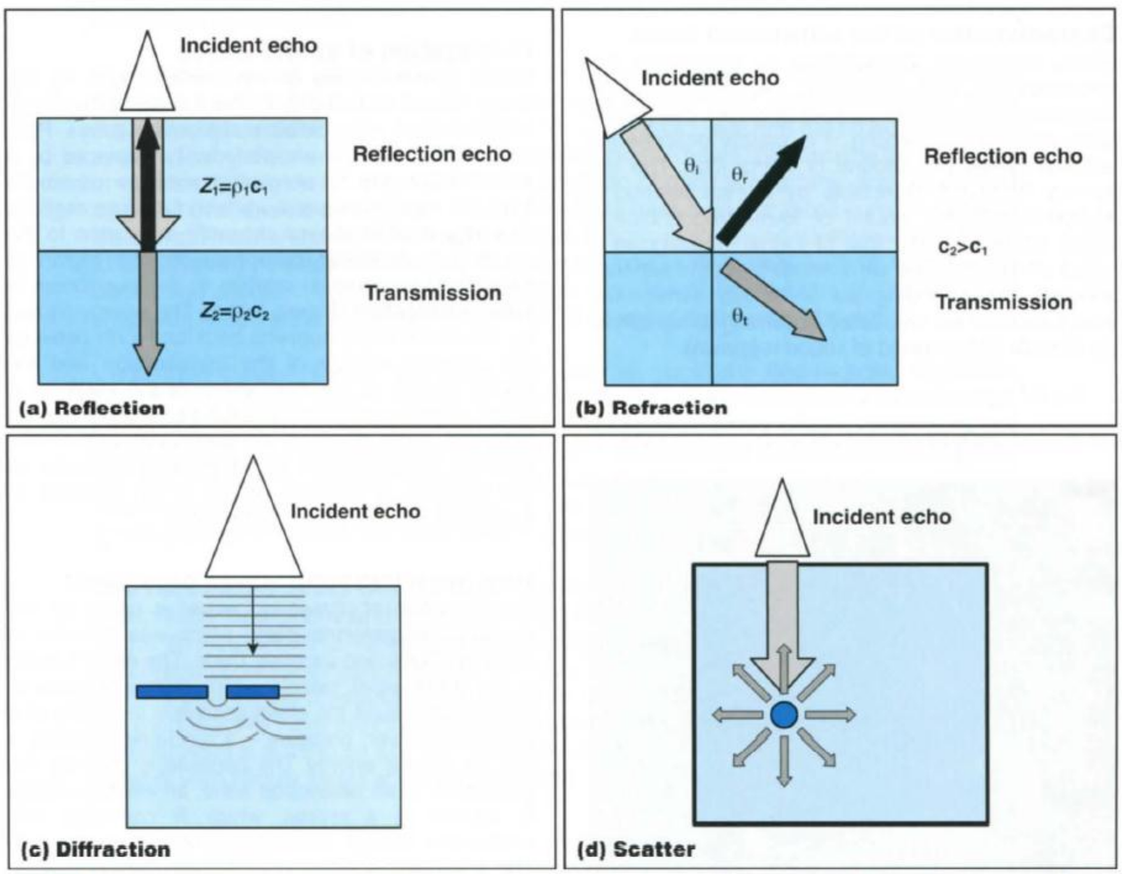
As the pulse crosses different tissues, sound waves are reflected back to the transducer at different times. Measuring the time gap between the transmission of an ultrasound pulse and its return to the transducer, it is simple to calculate the depth of the interface that generated the echo, providing the propagation of sound in soft tissues is fairly constant, around 1540 m/s (Merritt, 2011).

Although the piezoelements work as transmitter and receiver, these two actions are done alternately. First, the transducer sends the echoes which takes about 1% of the total time, and then receives them, which takes about 99% of the time. The echoes are sent as pulses and each pulse contains, usually, two or three waves. The length of the pulse is, thus, defined by the number of waves and their wavelength (spacial pulse length). The pulse rate or pulse repetition frequency refers to the numbers of separate little packets of sound waves that are sent each second (Gorgas, 2011).

12.1.3. Interactions between sound waves and tissue

As sound waves pass through the tissues, four types of interactions can occur: reflection, refraction, diffraction or attenuation (figure 8).

Figure 1: Interactions between sound waves and media. **(a)** An echo hits a reflecting surface at a 90 degree angle, is reflected and goes back to the transducer. **(b)** In refraction, an echo hits a reflecting surface at an angle other than 90 degrees and is reflected with the same angle of incidence. **(c)** Difraction consists in a change of direction of the echoes caused by an obstacle or a hole. **(d)** Scatter causes a wide diffusion of the beam in many directions, with a minor part of them returning to the transducer. Adapted from Gorgas, 2011.



The reflection of ultrasound pulses by structures within the body is the interaction that creates the ultrasound image (Sprawls, 1995). This effect is produced by sound waves that are reflected and then return to the probe called echoes. It occurs mainly when the sound waves cross tissues that differ in terms of a physical characteristic known as acoustic impedance (Z), causing a change in their speed. The acoustic impedance is an indicator of the resistance of each tissue to the sound waves, and is the product of the density (ρ) and the speed of sound (c) within the medium (Gorgas, 2011; Boon, 2011).

The proportion of sound waves that are transmitted or reflected at an interface depends of the difference in impedance of both media. If a sound waves crosses two soft tissues with nearly the same acoustic impedance that will result in little reflection; on the other hand, an interface between tissues and either gas or bone involves a considerable change in acoustic impedance and will create a strong echo (Rizk, 2010). Transducers, therefore, must be directly coupled to the patient's skin without an air gap, which is accomplished by use of gel between the transducer and the skin (Aldrich, 2007).

Even if there's a strong reflecting surface, the returning echoes might miss the transducer and not be displayed if the angle of incidence isn't perpendicular to the interface between the two media (Rizk, 2010). Since the angle of reflection is equal to the angle of incidence, a 90^o incidence will produce echoes that return to the transducer, while in a 45^o incidence the echoes will be reflected away from it (Merritt, 2011).

However, not all sound waves are reflected and some continue through the tissues. As they pass from one tissue to another with different acoustic impedance, their frequency remains the same but the wavelength changes, causing a change in its direction. This phenomenon is called refraction and can lead to the development of artifacts in the image like edge shadowing, which will be discussed later (Gorgas, 2011). The greater the mismatch in acoustical impedance between the two tissues the greater the degree of refraction (Boon, 2011).

Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. This effect is directly related to wavelength: increasing the wavelength increases diffraction and vice-versa. In fact, when the wavelength of the wave is smaller than the obstacle or opening, no noticeable diffraction occurs (Henderson, 2011).

As the ultrasound pulse moves through matter, it continuously loses energy. This is generally referred to as attenuation (Sprawls, 1995) and is traduced by a decrease in the wave's intensity. It is due to two phenomenons: absorption and scatter (Kossoff, 2000). Absorption is the direct conversion of the sound energy into heat and is directly proportional to the frequency of the beam; higher frequencies are attenuated much more than lower frequencies in a given medium (Aldrich, 2007), which explains the use of high frequency sound waves to visualize superficial tissues and low frequencies for deeper examinations. Scatter occurs when ultrasound waves encounter a medium with a nonhomogeneous surface. A small portion of the sound wave is scattered in random directions while most of the original wave continues to travel in its original direction (Hoffmann, Rumsey, & Nixon, 2008). Each organ, with its unique internal structure, causes different and characteristic patterns of scatter. These patterns are responsible for their echotexture, with a speckling of echoes which range from fine to coarse (Gorgas, 2011).

12.1.4. Modes of ultrasonography

12.1.4.1. A-mode

A-mode (amplitude mode) is the most simple and least frequently used, although it has still some applications, namely as a therapeutic method on oncology. It's a one-dimensional view, wherein a single-element transducer scans a line through the body (Nyland et al., 2002; Rizk, 2010). The echo's origin and amplitude are displayed as spikes originating from a vertical baseline. The transducer is located at the top of the baseline and each spike represents a returning echo; the position of the spikes along the baseline represents the depth at they were originated and the height represents their amplitude (Nyland et al., 2002).

12.1.4.2. B-mode

B-mode (brightness mode) displays the returning echoes as dots whose brightness is proportional to their amplitude (Nyland et al., 2002). This two-dimensional (2D), gray-scale image is possible by using a probe that contains a row (array) of many transducers (typically 100–200). The vertical position of each bright dot is determined by the time delay from pulse transmission to return of the echo and the horizontal position by the location of the receiving transducer element (Rizk, 2010).

12.1.4.3. M-mode

In M-mode or TM-mode (motion or time-motion mode) a fast sequence of B-mode images follow each other in sequence on the screen, with the depth of the tissue on the vertical axis and time on the horizontal axis (Nyland et al., 2002). The echo tracings produced by this mode are useful for precise cardiac chamber and wall measurements and quantitative evaluation of valve or wall motion over time (Mannion, 2006).

12.1.4.4. Real-Time B-Mode

B mode, real-time ultrasound, is currently the most commonly used mode in diagnostic imaging. (Mannion, 2006). This mode provides a moving gray-scale image of cross-sectional anatomy, which is accomplished by sweeping repeatedly a thin ultrasound beam across a triangular, linear, or curvilinear field of view in the patient, around 20 to 30 times per second. The image is composed by many single B-mode lines, each one constantly renewed by a subsequente sweep of the beam (Ginther, 2007; Nyland et al., 2002).

12.1.4.5. Doppler ultrasonography

Doppler ultrasonography allows determination of the direction and velocity of blood flow by using information from the Doppler shift effect (Burk & Feeney, 2002). In ultrasound scanners, echoes from stationary tissue are the same from pulse to pulse. However, echoes from moving objects (for example red-blood cells) exhibit slight differences in the time for the signal to be returned to the receiver – the Doppler effect (Rizk, 2010). If motion is toward the transducer, the frequency of the returning echoes is higher than that of the transmitted sound. If the motion is away from the transducer, the echoes have a lower frequency than the transmitted sound (Nyland et al., 2002).

The magnitude of the shift is related to 3 variables: blood velocity, angle between the ultrasound beam and the moving reflectors and frequency of the transmitted ultrasound beam. (Rizk, 2010). As it increases the blood velocity, so it does the Doppler shift (Burk & Feeney, 2002; Nyland et al., 2002). Concerning the angle between the beam transmitted and the moving red blood cells, the shift is maximum when the beam is parallel to the blood flow (angle of 0^{o}), and null when the beam is perpendicular (90^{o}) (Rizk, 2010). For greatest accuracy the angle of interrogation should be less than

60° (Mannion, 2006; Nyland et al., 2002). Finally, an increase in the frequency of the transmitted ultrasound beam leads equally to the increase in the Doppler shift (Gorgas, 2011).

12.1.5. Artifacts

The International Dictionary of Medicine and Biology defines an artifact as "any record or image obtained in the course of applying a medical diagnostic technique which is not representative of the structures under study but is adventitious" (Kirberger, 1995). Although affecting the quality of the images and therefore their interpretation, some of them are actually useful and helpful in the final diagnosis (Mannion, 2006). Artefacts may be produced by technical errors (such as improper machine settings or improper scanning procedures) or by physical interaction between the ultrasound beam and matter (Nyland et al., 2002). Only the latter and most common will be discussed here, regarding the B-mode ultrasonography used in this study.

12.1.5.1. Acoustic shadowing

Acoustic shadowing results from nearly complete reflection or absorption of the sound (Nyland et al., 2002; Martinat-Botté et al., 1998) and is produced by structures such as gas or bone (Ziegler, 2007). As a result, almost no echoes pass beyond the surface into the deeper tissues and the image displays a bright, echogenic line at the surface and an echoic or black area in the deeper tissues (Mannion, 2006).

This shadow might be either "clean" or "dirty". The first one occurs, for instance, in a soft tissue–bone interface, where a significant portion of sound waves are absorbed, leading to an almost complete absence of reverberations and thus a ''clean'' (uniformly black) shadow. In the case of a soft tissue–gas interface, most of sound waves are reflected and the shadow appears ''dirty'' (inhomogeneous) as a result of the multiple reflections and reverberations (Nyland et al., 2002; Laing, 1983, cited by Kamonrat, 2010)

A special type of acoustic shadowing, called edge shadowing, is produced at the lateral margins of rounded structures containing material of lower acoustic velocity such as gallbladder and urinary bladder (Mannion, 2006; Nyland et al., 2002). This is due to the slight refraction that the sound waves suffer as they penetrate the edge of these structures (Gorgas, 2011).

12.1.5.2. Acoustic enhancement

Acoustic enhancement (also known as through-transmission) represents a localized increase of echo amplitude occurring distal to a structure of low attenuation (Moïse & Fox, 1999). While travelling through a structure with low attenuation, such as the gallbladder, the sound beam loses less energy than in the surrounding tissues. As a result, the returning echoes from distant to this structure have more amplitude producing, thus, a bright or echogenic area that can be seen immediately after this low attenuation structure (Gorgas, 2011; Nyland et al., 2002). This artifact is especially useful in differentiating fluid-filled structures from solid structures of low echogenicity (Nyland et al., 2002).

12.1.5.3. Reverberation

Reverberation occurs when the ultrasound beam reflects repeatedly between two interfaces. This artifact was initially described in equine thoracic ultrasonography and occurs more commonly between the transducer and tissue interfaces, but also sometimes internally between two highly reflecting interfaces (Gorgas, 2011). Each reflection detected by the transducer is depicted as a bright line, forming an image with several concentric lines regularly spaced (Ziegler, 2007). Comet-tail artifact, a special form of reverberation, is characterized by regular bright continuous echoes, being frequently encountered in the gastrointestinal tract, at the boundary of the diaphragm, and with metallic objects such as foreign bodies (e.g., pellets) or a biopsy needle (Mannion, 2006; Boon, 2011).

12.1.5.4. Mirror image

Mirror image occurs when a strongly reflective, obliquely oriented surface reflects the sound beam distally instead of returning it to the transducer (Gorgas, 2011). This happens, for instance, with the diaphragm-lung interface: the primary pulse is reflected into adjacent organs such as the liver, which in its turn reflects it back to the diaphragm-lung interface where, eventually, is reflected back again to the transducer (Mannion, 2006). Because this echo has taken longer to return to the transducer, the computer assumes that it came from a deeper location, and so a copy (mirror image) of the liver is placed erroneously cranial to the diaphragm, which can lead to a wrong diagnosis of diaphragmatic hernia or lung consolidation. (Gorgas, 2011).

12.1.5.5. Side-lobe Artifact

Side lobes are unwanted parts of the ultrasound beam, traveling laterally, in different directions from the main ultrasound beam (Barthez, Léveillé & Scrivani, 1996; Boon, 2011). Although having a much lower intensity than the main beam, side lobes may create significant artifacts when they interact with highly reflective acoustic surfaces, generating echoes that will be erroneously displayed as having originated from within the main beam (Scanlan, 1991; Feldman, Katyal & Blackwood, 2009). This occurs in imaging of the gallbladder or urinary bladder, where side lobes produce artefactual 'pseudosludge' in an otherwise echo-free structure (Gorgas, 2011). A variant of the side-lobe artifact is slice-thickness artifact, which occurs when part of the ultrasound beam includes a cystic structure and the other part includes surrounding tissues. The echoes from the tissue are displayed within the cystic structure, mimicking the presence of sediment (Mannion, 2006).