Physics and Principles of Ultrasound

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Ultrasound has a storied history which achieved reality during World War II in finding German submarines in the protection of North Atlantic convoys. It was initially employed for its therapeutic benefits in physical therapy to produce deep heat and ablation of brain lesions for Parkinson's disease. The wave characteristics have been altered in diagnostic ultrasound to the point where energy transfer is limited, and deep tissue heat is virtually nonexistent. Ultrasound systems are comprised of a transducer, console (which contains the computer software, electrical components, Doppler technology, and storage), and the display. The physics of ultrasound waves and the means of their delivery are important to meld into this discussion. Artifacts which are demonstrated in the display of clinical ultrasound can be used to advantage in understanding what is actually portrayed.

Before delving into the applied physics of ultrasound, it is helpful to turn attention to the natural world and some of the creatures which use sound waves to remarkable advantage. As will become apparent in the formal discussion to follow, sound waves depend on a support transport medium. Liquids and animal soft tissues transmit sound waves efficiently and to nearly the same velocity since the aggregated molecules are compact and noncompressible. Bone transmits sound waves even better due to its even compact nature, but bone reflectivity obviates the practical use of ultrasound. On the other hand, air is a poor supporter of sound waves due to the compressibility of the molecules and their reduced concentration. In the ocean, dolphins and odontocetes such as toothed whales emit very-high-pitched single-frequency clicks to communicate with others of their species [1]. It is also used for echolocalization of schools of fish upon which they prey. In contrast, baleen whales which feed on plankton do not transmit in the high-frequency range but more on the order of 10–30 Hz. These sound waves travel extreme distances due to both their low frequency and the medium of transport which has important communication advantages. Above ground, elephants also transmit in this approximate low-frequency range with a volume level which may reach 117 dB [2, 3]. These transmissions can be identified as far as 10 km from the source and may also be sensed by the broad elephant's feet or the trunk which it may place along the ground to "hear" in this unique way. Once again, the sound transmission through a more solid medium is more effective than through air. Bats [2, 4] emit sounds in the ultrasound range to identify insects and obstructions, but the waves are disadvantaged by having to travel in air. As will be noted in the subsequent discussion of sound wave physics, high-frequency sound attenuates rapidly with reduction in returning wave energy. The massive

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ears of the bat relative to its body are critical to reception of the returning waves. Since their emitted sounds have high frequency in an air medium, the distances the sound must travel are short to overcome these disadvantages of acoustic physics.

Physics of Ultrasound

As just illustrated, sound waves travel readily through fluid medium and very ineffectively through air. In contrast with light which can travel in a vacuum, sound requires a support medium. The sound waves travel effectively through liquids which are comprised of closely compacted molecules. In fact, water and soft tissues have approximately the same transmission velocity with the latter averaging 1,540 m/s. In addition, the attenuation or loss of sound wave amplitude occurs rapidly in an air medium. Thus, structures which are retrotracheal or retroesophageal are difficult or impossible to visualize.

The principles of ultrasound are complex, relying on sophisticated physics and mathematics. Many of these applied concepts to be described have been simplified from the comprehensive text by Kremkau [5] entitled "Diagnostic Ultrasound, Principles and Instruments." Sound is transmitted as sequential sine waves whose height represents amplitude or loudness (Fig. 2.1). A single full cycle is measured from peak to peak, and the number of these cycles per one second represents the frequency. The frequency (cps) is also described in Hertz (Hz) which by convention is in honor of the German physicist Heinrich Hertz for his work on electromagnetic transmission [6]. It is of interest that the son of Heinrich Hertz's nephew, Carl Hellmuth Hertz, is said to be credited with invention of medical ultrasound [6]. The human ear can recognize sounds as low as 20 Hz and as high as 20,000 Hz (Fig. 2.2), and ultrasound is so named because its frequency emission is in the range of more than a million cycles per second or in the megahertz (mHz) range. An ultrasound wave is transmitted to human tissues through the transducer by physical deformation of the tissue surface. This is accomplished through piezoelectric crystals which elongate and shorten in response to applied alternating electrical current (Fig. 2.3). These crystals are organized in 128 parallel channels which emit sound waves of equal frequency into the tissues (Fig. 2.4). Besides containing the vibrating crystals, the transducer at the contact interface with the skin contains a structure of matching layers which permits better energy transfer. Piezoelectric crystals employed for

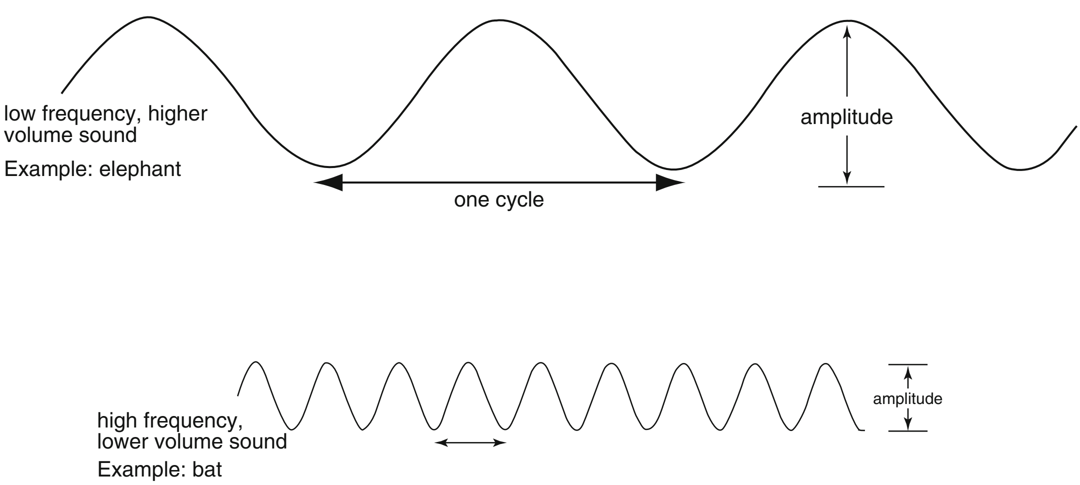

Fig. 2.1 Sound travels as linked sine waves. The frequency is determined by the number of cycles per unit of time and loudness by the amplitude. Sound travels at varying speeds through tissues depending on tissue density and properties

ultrasound are synthetic (PZT=lead zirconate titanate) as opposed to naturally existing crystals such as quartz.

As these emitted sound waves enter the skin and deeper structures, they are reflected back toward the transducer by a variety of tissue elements. Most waves either reflect at angles from these reflectors or pass through without returning directly to the transducer. Only 1% of entering sound is reflected directly back, but it is these waves which are responsible for presenting the eventual images. The tissues contain structures which are of varying density, and these adjacent contrasting elements produce an acoustical mismatch. This mismatch or interface acts as a reflector. When the tissues or fluid through which the sound waves travel is of even consistency and the reflector is broadly uniform such as the posterior wall of a cyst, a bright evident, hyperechoic signal just deep to the entire posterior wall is produced. This artifact is consistently helpful in diagnosing a cystic structure and occasionally a mass lesion such as a pleomorphic adenoma. This solid mass can be noted in the submaxillary or parotid gland, is comprised in large part by a diffuse myxoid stroma, and with ultrasound often demonstrates the same posterior enhancement identified with cysts.

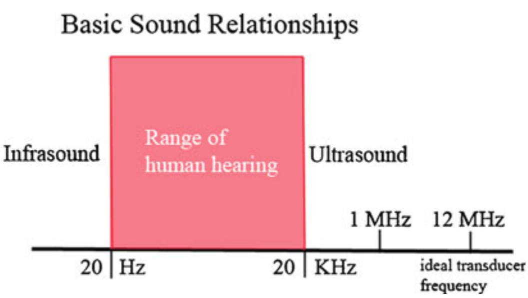

Fig. 2.2 Humans hear frequencies from 20 to 20,000 cycles/s. Ultrasound is above 20 kHz and infrasound below 20 Hz

Sound waves are emitted in packets of pulsed cycles and then stop for one frequency cycle to allow the same transducer to receive these reflected impulses and convert them into electrical energy. This is accomplished by the same emitting piezoelectric crystals which are set into vibration on the mechanical return. Acoustic waves progressively lose amplitude as they pass through tissues, a phenomenon known as attenuation. The extent of this attenuation depends on the tissue density and depth required for sound waves to reach the visual desired target (Fig. 2.5).

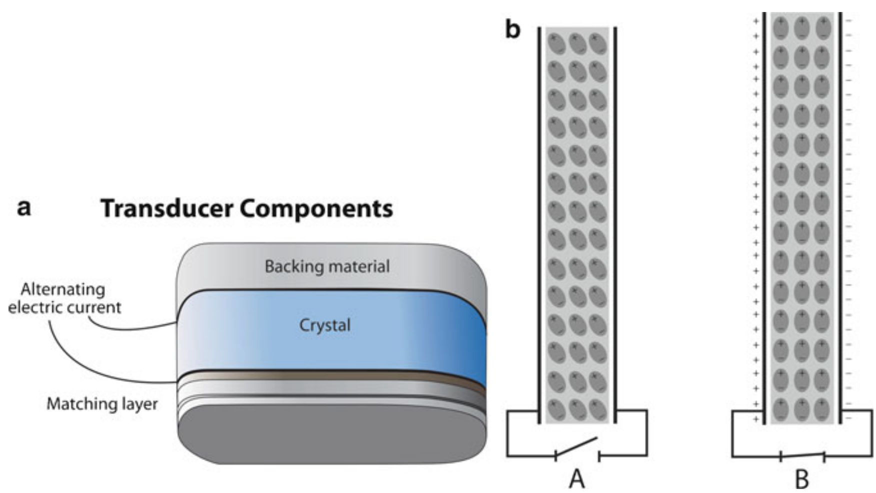

Fig. 2.3 (**a**) The transducer is comprised of piezoelectric crystals surrounded by insulating material and matching layers at the exit port which allow ideal transmission of the sound waves through the skin into the tissues. (**b**) Piezoelectric crystals elongate and shorten with realignment of the crystal dipoles in response to applied alternating current

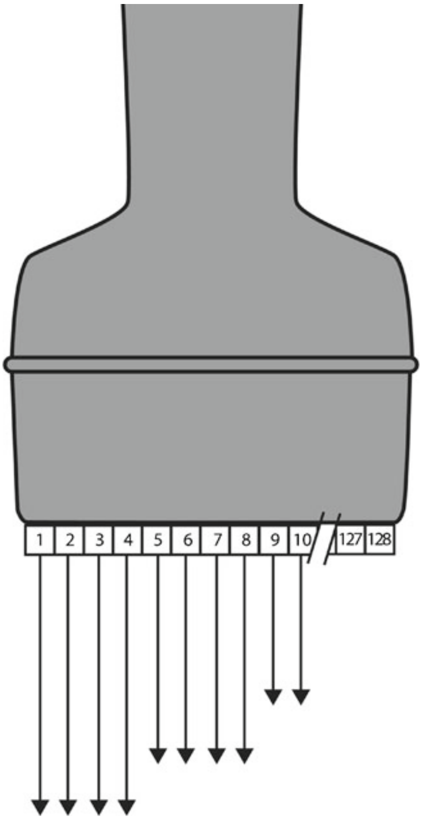

Fig. 2.4 Each crystal resides in its own sectored compartment adjacent to others which will send waves into the tissues upon command

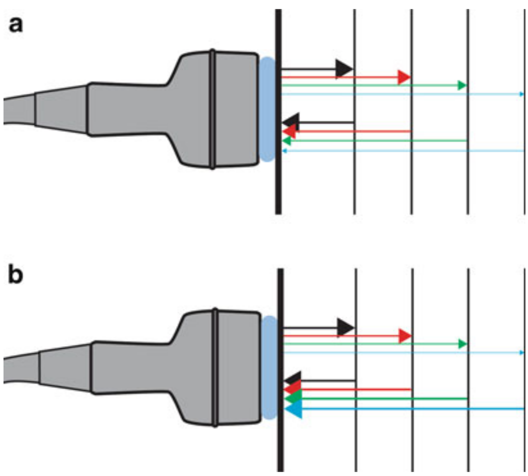

Fig. 2.5 (**a**) As ultrasound waves enter tissues, they attenuate with depth from the surface. High-frequency waves attenuate more than those of low frequency. (**b**) Time-gain compensation allows selective amplification of the weaker deep and intermediate returning echoes

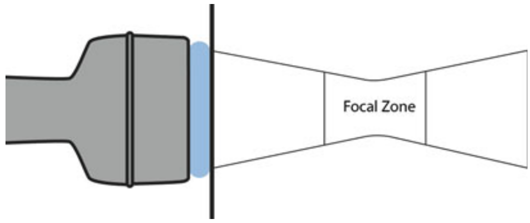

Fig. 2.6 The focused penetrating sound waves do not have a rectangular or linear pattern. The hourglass shape is typical, and the focal zone is the narrowest portion of this configuration

Another critical consideration in attenuation is the frequency of the penetrating sound waves. Low-frequency waves do not attenuate until arriving at a deeper level than those of high-frequency ultrasound. Thus, abdominal ultrasound utilizes frequencies in the 3–5-MHz range to achieve adequate penetration with retention of adequate reflection. This low frequency comes at a cost as there is a reduction in resolution. In contrast, high-frequency sound waves produce greater resolution which if possible is always desirable to achieve. Structures in the head and neck are relatively superficial in location and do not require the lower-frequency deep penetrating waves. A 10–12-MHz transducer readily demonstrates all of the relevant anatomy of the thyroid gland, parathyroid glands, and adjacent lymph nodes.

In addition to frequency, other characteristics of sound waves are highly relevant to attainment of ideal resolution. Sound waves emit and do not maintain a purely linear shape. Its physical form becomes centrally narrowed ("focal point") as it passes through tissue in the approximate shape of an hourglass (Fig. 2.6). If one examines the reflected images, there is an optimum depth at which they are sharpest in resolution. The structures superficial and deep to this narrowed area of each wave are reasonably well resolved but not to the ideal level as noted at the focal point. This ideal area or "focal zone" can be adjusted on the console to a preferred shallow or deeper depth. The image clarity at the focal zone is designated its "lateral resolution" (Fig. 2.7). The frequency of the transmitted wave determines another type of clarity-designated "axial resolution."

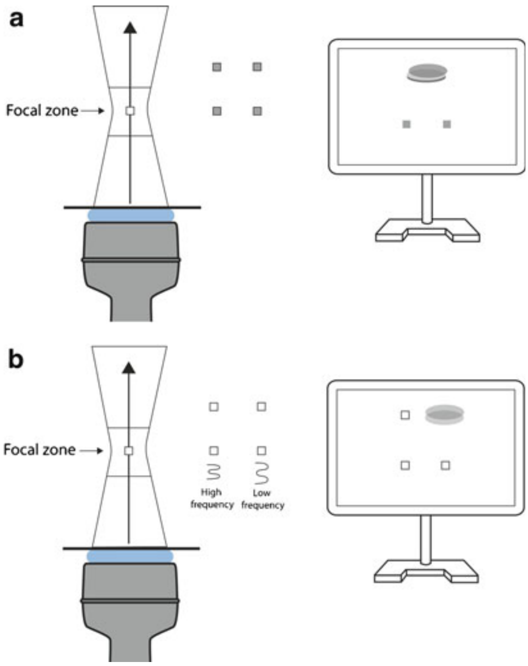

Fig. 2.7 (**a**) Lateral resolution depends more on alignment of the ideal focal zone to the region in question. Those points near or within the focal zone will be discerned as separate and better resolved. (**b**) Linear resolution depends on the frequency of the emitting ultrasound wave with higher frequencies permitting better definition of adjacent points. As well, this image demonstrates that both linear and lateral resolution work together to provide the optimum resolution

As indicated above, high-frequency sound waves produce a profile of resolution which is superior to that produced by low-frequency waves. The ability to separate adjacent points of interest into their individual components is what produces both contrast and clarity. High-frequency waves produce better ability to resolve adjacent tissue elements in the direct path of the sound wave, and this “axial resolution” in concert with a preferred level of “lateral resolution” allows the sonographer to achieve the best image quality. In summary, where depth of penetration is the most important priority such as a thick multinodular or substernal goiter, the lower-frequency waves must be utilized with some sacrifice in resolution. In most other circumstances involving the neck tissues, high-frequency waves may be selected since only a 3–4-cm tissue depth is under study.

Besides these frequency issues, other manipulations of the image can be performed from the console. The overall image brightness can be adjusted by a turn of the gain control knob, but this is not selective and affects all structures on the display. As previously described, ultrasound waves attenuate at greater depth from surface entry. The attenuation is especially problematic when higher frequencies are employed as in thyroid and parathyroid imaging. When the deeper aspects of a large goiter with 6–7 cm of A–P dimension are difficult to see, the time-gain compensation knob can be manipulated to brighten the attenuating structures. The deeper attenuated waves can be selectively amplified with time-gain compensation by increasing the gain of these waves while leaving unaltered the more superficial waves which have never lost their image brightness. Thus, the overall image has a more even distribution of brightness. There are other proprietary methods of improving image quality. SonoCT [7] changes the way sound waves are delivered from the transducer. Adjacent channels send divergent waves from a central point which then intersect with several adjacent waves which similarly have been modified. The intersections of these waves produce an image which has better contrast and sharpness. Electronic noise is an undesirable but unavoidable element in amplification systems. This noise can be reduced by band pass filtering which eliminates the frequencies above and below the ideal selected frequency. Harmonic imaging is a common refinement which manipulates both the fundamental and second harmonic frequency echo reception. The fundamental frequency is filtered while allowing passage of the second harmonic, a postprocessing method which improves image quality. Modern ultrasound units have employed several unique methods beyond the traditional elements of acoustic physics to refine image quality which were simply unimaginable less than a decade ago.

Artifacts

Artifacts are images which appear on the display and do not represent actual physical structures. These shadows or enhanced representation of tissue elements tell a story. Pure thyroid or parathyroid cysts have a thin capsule and are fluid-filled without significant solid components. Sound enters the cyst as strong signals penetrating the anterior capsule. Since the interior of the cyst is fluid which readily transmits sound without interruption, the parallel sound waves then strike the posterior capsule which through the acoustical mismatch acts as a reflector. A large proportion of these waves penetrate just beyond this capsule and concentrate as uniform returning reflecting signals. This produces a relatively broad area which is hyperechoic to adjacent tissues and the cyst itself. "Posterior enhancement" is the designated artifact invariably diagnostic of a cyst (Fig. 2.8). As described above, the unique tissue characteristics of a pleomorphic adenoma also produce posterior enhancement due to the uniform tissue matrix (Fig. 2.9). In contradistinction to this permissive transmission, coarse calcifications or close aggregates of microcalcifications block transmission of the sound waves to deeper tissue planes. This produces a dark rectangular area deep to the densely hyperechoic structure. Known as posterior shadowing artifact (Fig. 2.10), this particular image is representative of a consolidation of calcium. In contrast, microcalcifications (Fig. 2.11) generally seen in papillary carcinoma of the thyroid gland do not produce posterior shadowing artifact as a result of their small size. These microcalcifications are small points of hyperechoic signal and represent either psammoma bodies defined histologically in papillary

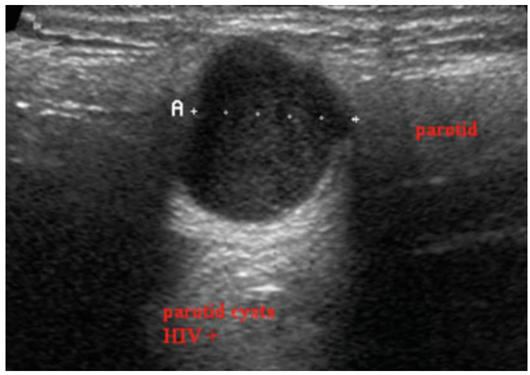

Fig. 2.8 Posterior enhancement deep to the posterior capsule of a cyst

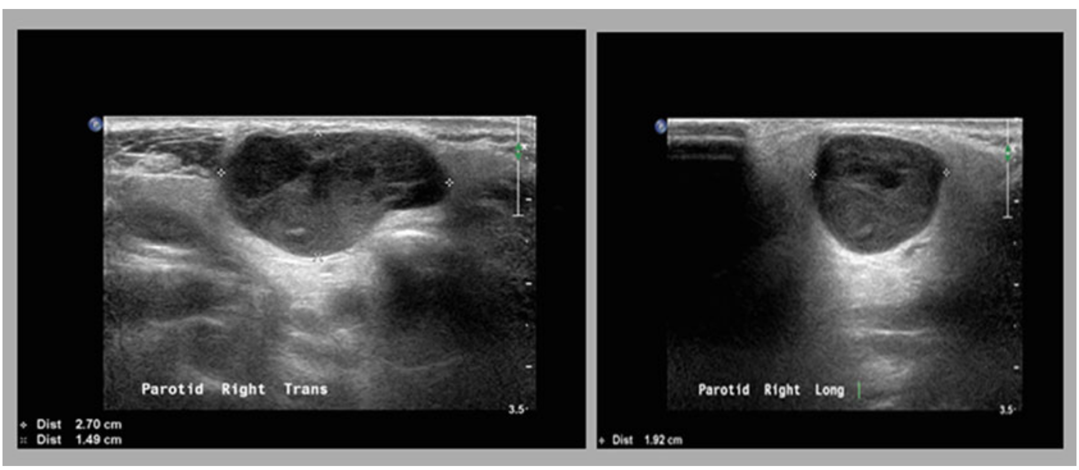

Fig. 2.9 Similar posterior enhancement deep to a pleomorphic adenoma, a testimony to the uniform character of its tissues and even transmission of sound waves with little attenuation

carcinoma or aggregates of amyloid or fibrosis noted in some medullary carcinomas. Microcalcifications may be identified in either the primary thyroid carcinoma or metastatic adenopathy (Fig. 2.12). When planning fine needle aspiration cytology, the areas selected for sampling under ultrasound guidance are often those with a large proportion of microcalcification. Other artifacts may be confused with microcalcifications. "Comet tail" artifacts (Fig. 2.13) are hyperechoic points with a tapering image of hyperlucency extending from and deep to the circular dot. The "tail" portion of this hyperechoic artifact is actually a form of reverberation. Small areas of colloid within the nodule crystallize and serve both as finite obstructions to transmission and deeper reverberation of the ultrasound waves in typical comet tails. Ahuja has studied comet tail artifacts in a large number of thyroid conditions and invariably has found that this is a marker for an underlying benign process [8]. Reverberation artifact is more of a curiosity than one which defines an important anatomic correlation. Reverberation suggests that the sound waves are reflected one or more times deeper into the tissues than the actual target but retain the same pattern and echogenicity. Some of the initial primary waves pass alongside the target but deep to it and on the return are redirected back into the tissues from the deepest aspect of the lesion. When they finally make their way back to the transducer after one or more of these delays, the signal processor incorrectly assumes and displays them as deeper structures rather than the delayed secondary echoes they really are. The anterior wall of the trachea, anterior wall of the carotid artery, biopsy needles in their long axis, and the trailing tapering region of comet tails are all examples of reverberation artifact (Fig. 2.14).

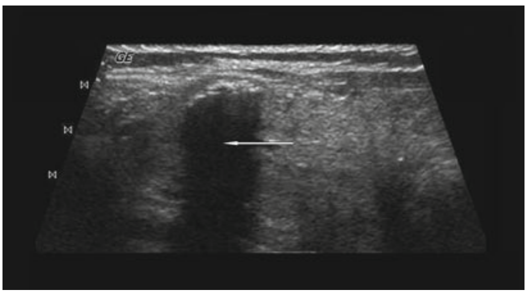

Fig. 2.10 Dense calcification prevents penetration of sound beyond the lesion resulting in posterior shadowing artifact (demonstrated by *arrow*)

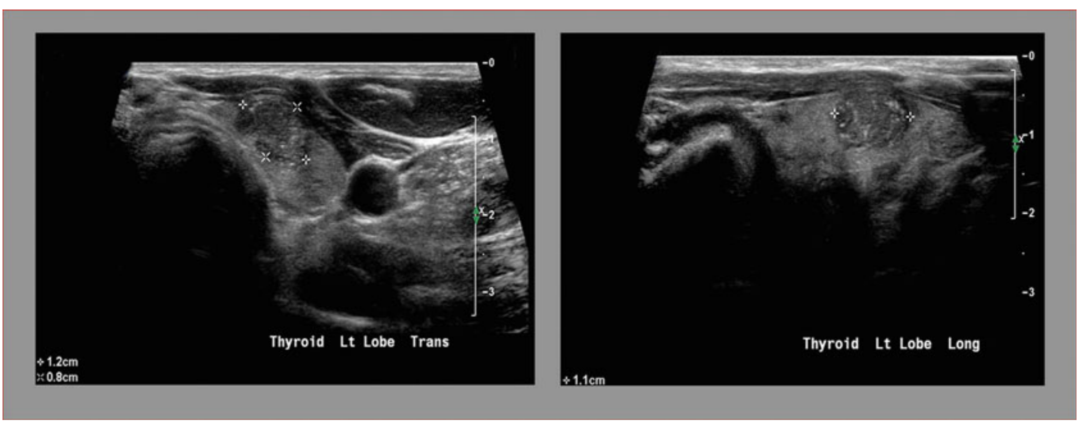

Fig. 2.11 Microcalcifications do not produce posterior shadowing artifact

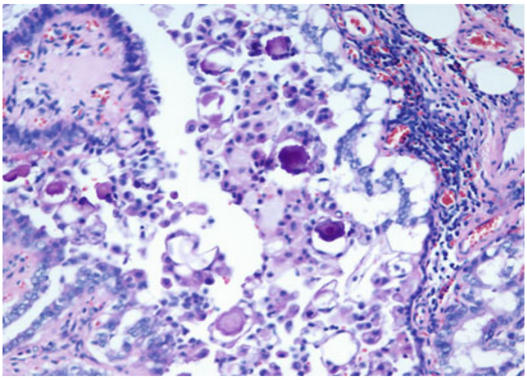

Fig. 2.12 Psammoma bodies are small, discrete calcifications commonly found in papillary carcinoma

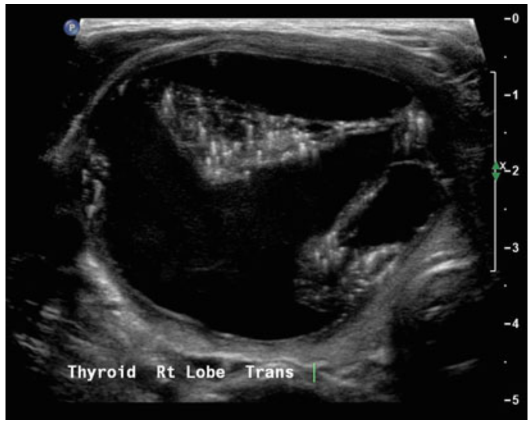

Fig. 2.13 Comet tail artifact is similar in appearance to microcalcifications, but the comet tail clearly differentiates it from the representations of psammoma bodies

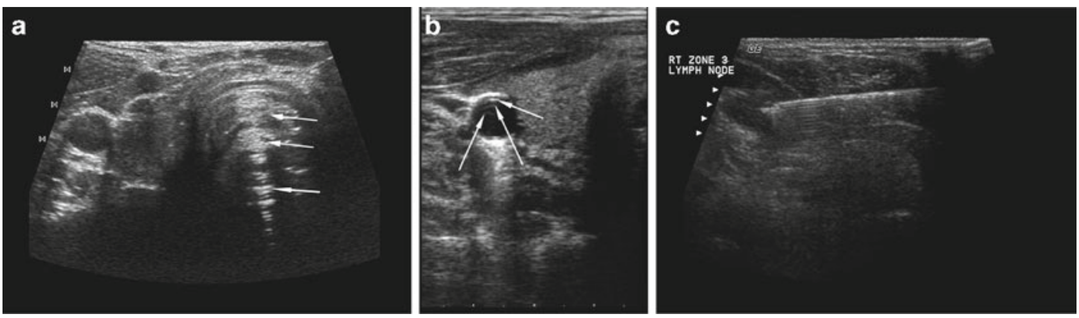

Fig. 2.14 Reverberation artifact can be seen in the following: (**a**) Anterior tracheal wall. (**b**) Anterior wall of the carotid artery. (**c**) Biopsy needles in the long axis. *Arrows* demonstrate the reverberating artifacts

Doppler

Doppler is a unique and technically different process than gray scale ultrasound. This methodology can assess the vascularity of anatomical and pathological elements. [9] The Doppler shift of sound waves occurs when waves imparted at an angle to a blood vessel penetrate the wall and strike directionally moving red blood cells. These waves are then reflected by the flowing red cells, and the reflected sound is either augmented or reduced in intensity depending on both the direction and velocity of this movement (Fig. 2.15). This velocity of red cell movement can be calculated and directional flow given a color designation, i.e., flow toward the transducer is red and away from it blue by convention. The mathematical Doppler equation can be transformed into a visual graph where systolic and diastolic velocity can be measured over a unit of time to compute actual blood flow through vessels large enough in caliber to be measured. The system then determines the exact color image and coordinates this with a matched gray scale representation of the same view. The corresponding B mode image is then alternated so rapidly with its twin Doppler representation that a moving rendition is the end product. The eye sees this as a moving color video or cine loop.

This color Doppler imaging and flow interpolation produces not only a representative image but also a quantification of the vascular activity. Although this feature is highly relevant to the study of carotid and peripheral vascular anatomy and restriction of flow, the clinician interested in Doppler application for thyroid and parathyroid work has little need of this exact realm of the technology. Power Doppler is a separate console setting which ignores these calculations and directional relationships. Power Doppler is more sensitive to low-flow states and produces a sharp image of even the smallest blood vessel. Through their sensitivity and resolution capabilities, good power Doppler systems may display a discrete blood supply through the hilum of a lymph node or vascular pattern of a hyperplastic parathyroid adenoma (Fig. 2.16). In fact, power Doppler can often be used as a differentiating tool between these two structures in the clinical setting. Color rather than power may still be used to identify a large vessel in the neck, but the quantitative issues have little clinical relevance (Fig. 2.17). Of course, one can still identify a vessel as such without any Doppler technology by observing the persistence of a rounded structure as the transducer is moved up or down over the target. The sagittal view demonstrates the vessel as well by confirming it as a long continuous structure. However, the Doppler button produces a level of efficiency in identifying a vascular structure without changing planes or leaving the area of interest. In salivary duct ectasia, where there may be confusion over whether a tubular anechoic structure is a vessel or obstructed duct, Doppler can answer this question and store the imaged result (Fig. 2.18).

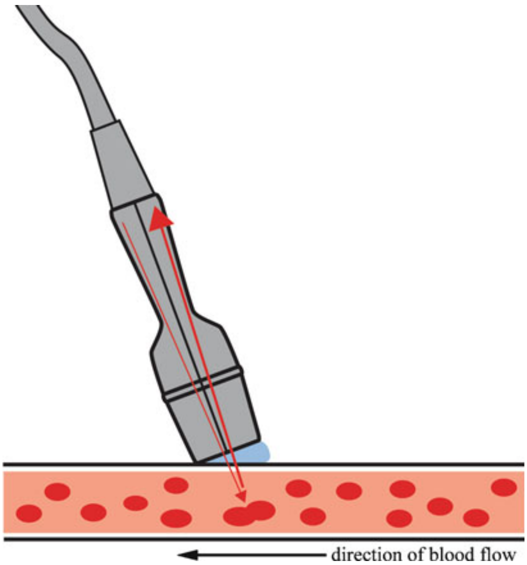

Fig. 2.15 Doppler waves reflect differentially off moving red cells. Depending on whether these cells are moving toward or away from the transducer, direction of flow and its velocity can be determined by the Doppler system

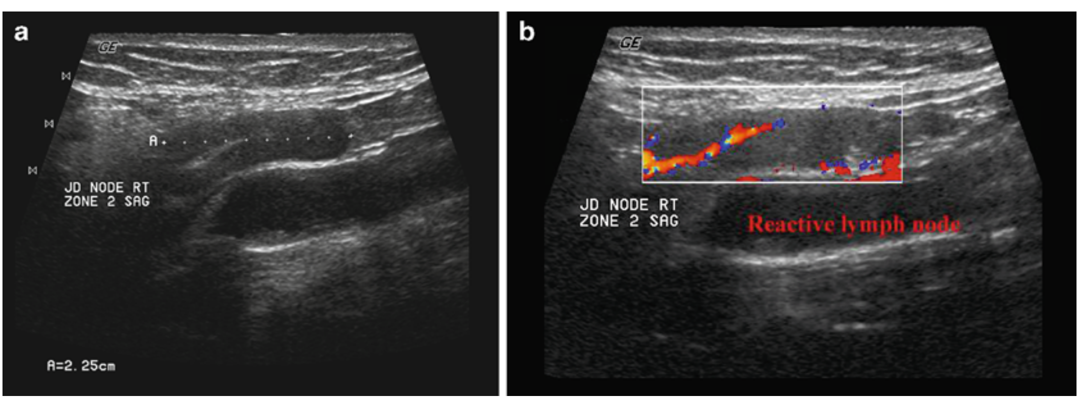

Fig. 2.16 Gray scale image of a hyperplastic lymph node with a typical "hilar line" (**a**). Power Doppler demonstrates the axial vessel penetrating the hilum of the node and representing the "hilar line" (**b**)

In summary, the modern ultrasound system is based on the physics of sound energy and transmission/reflection in tissues. It is not critical to understand in detail these principles and mathematical relationships, but a general working knowledge does provide the clinician with tools to better apply this technology to his or her clinical craft. A full understanding of artifacts with gray scale imaging is pivotal to proper ultrasound interpretation, and there are certain subtle tricks which involve manipulating the technology. As an example, there is often confusion between microcalcifications and other less important punctate hyperlucencies. It is possible to apply Doppler to these areas, turn down the color gain to a negligible degree, and demonstrate very small posterior shadowing in true microcalcifications. Another method is to eliminate harmonic imaging or SonoCT and only employ the fundamental frequency, once again to bring out the fine posterior shadowing artifact which may have been eliminated by the modern system refinements [Ahuja AT, personal communication, 2011]. In fact, there is a significant difference between reviewing the static images which someone else has obtained and the real-time study either in static or cine loop form by the treating clinician. Cine loops are the best means of reviewing an ultrasound case on referral since the study seems dynamic and as if the reviewing physician is doing the actual procedure. In the hands of the clinician, ultrasound will provide opportunities to better understand pathologic conditions and obtain more information at the time of the patient encounter than has ever before been possible.

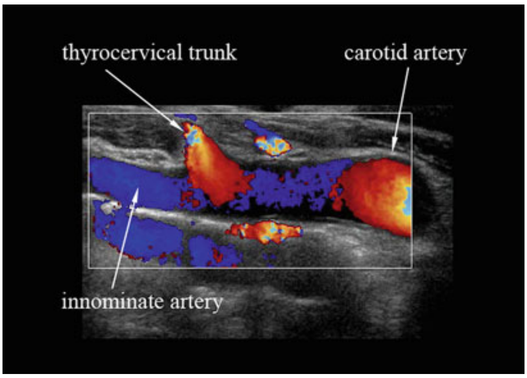

Fig. 2.17 Color Doppler demonstrates the innominate, thyrocervical trunk, and carotid artery relationships

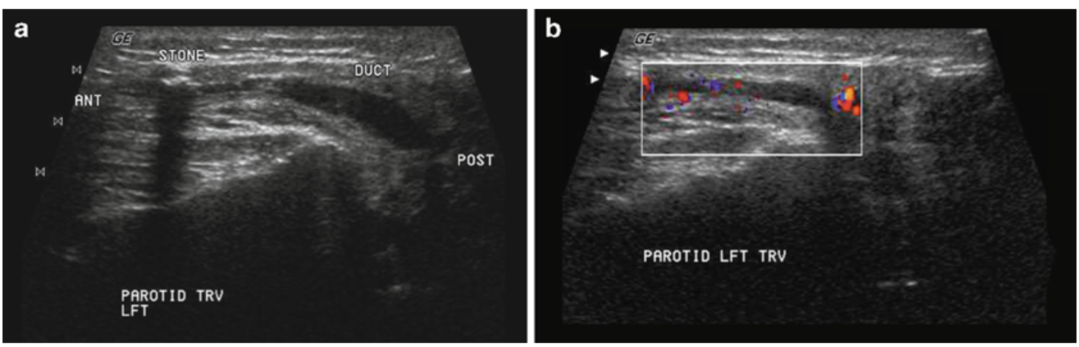

Fig. 2.18 (**a**, **b**) The use of Doppler to distinguish a vessel from duct is demonstrated in this salivary duct calculus producing obstruction and duct ectasia. The gray scale image alone cannot easily make that determination, but the addition of Doppler confirms that the widened anechoic structure is not a vessel

References

1. Au W, Popper A, Fay R. Hearing by Whales and Dolphins. Springer handbook of auditory research Vol. 12, pp. 72, 85, 89, 2000.
2. Simmons JA et al. Echolocation and hearing in the mouse-tailed bat, *Rhinopoma hardwickei*: acoustic evolution of echolocation in bats. J Comp Physiol. 1984;154:347–56.
3. Reuter T, Nummela S. Elephant hearing. J Acoustic Soc Am. 1998;104:1122–3.
4. Payne K. Silent thunder: in the presence of elephants. New York: Penguin Group; 1998. p. 121.
5. Kremkau FW. Diagnostic ultrasound. 6th ed. Philadelphia: WB Saunders; 2002. 18–37, 62–64, 71–76, 86–92, 167–194, 273–318.
6. Hertz H. Wikipedia, en.wikipedia.org. Accessed January 3, 2011.
7. Freedman MT, et al. Ultrasound images of implanted tumors in nude mice using Sono-CT correlated with MRI appearance. In: Chin-Tu Chen, Anne V. Clough (eds) Medical Imaging 2001: Physiology and Function from Multidimensional Images; 2001. pp.163–167.
8. Ahuja A, Evans R. Practical head and neck ultrasound. London: Greenwich Medical Media Ltd; 2000. p. 41.
9. Deane C. Doppler ultrasound: principles and practice. In: Nicolaides K, Rizzo G, Hecker K, and Ximines R. (eds) Doppler in Obstetrics. http://www.centrus.com/commonultrasoundcases/principlesofultrasound.html. Accessed January 15, 2011.

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