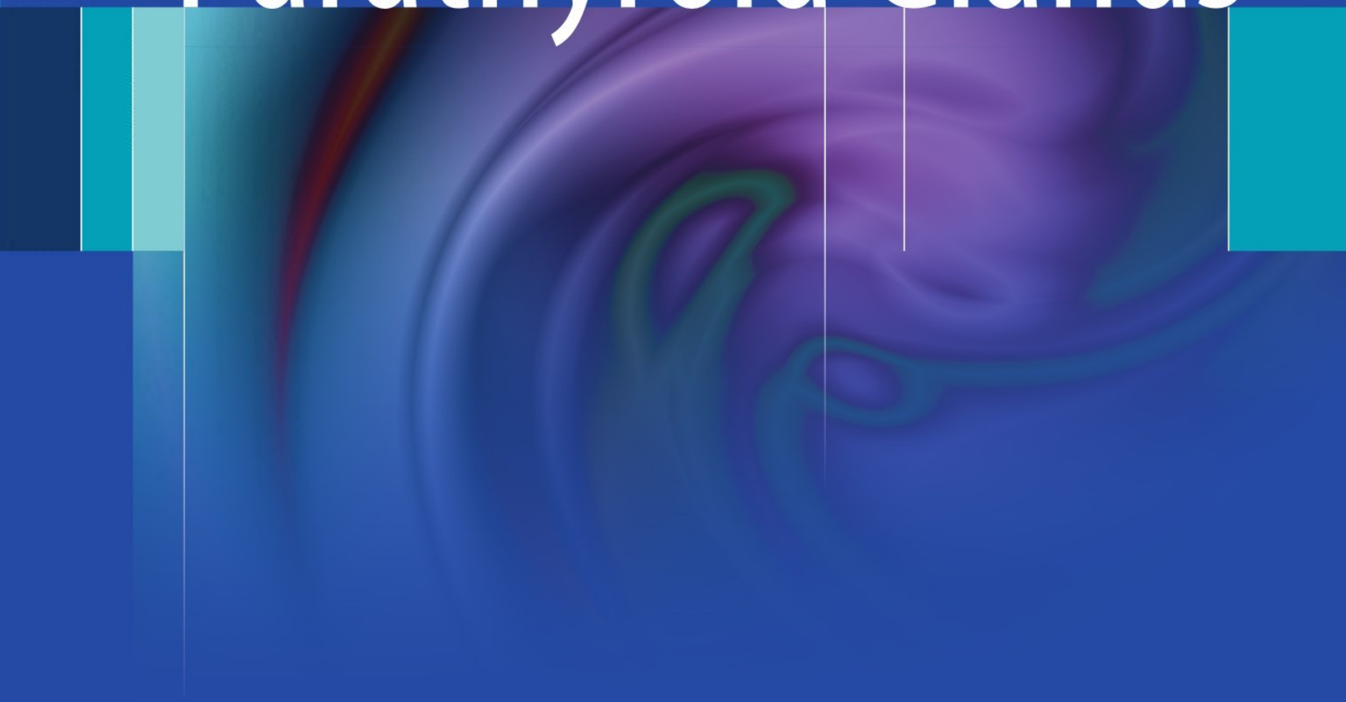
Robert A. Sofferman · Anil T. Ahuja *Editors*

Ultrasound of the Thyroid and Parathyroid Glands



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I wish to take an unusual precedent to dedicate this textbook to my co-author and editor, Dr. Anil T. Ahuja, who has been my ultrasound mentor, academic colleague, and special family friend for the past several years. He has a remarkable clinical knowledge of conditions of the head and neck and is perhaps the foremost comprehensive imaging expert of this special region of human anatomy. He has understood the relevance of ultrasound to the daily interpretation and management of diseases of the thyroid and parathyroid glands and in particular its office use by endocrinologists and surgeons to the benefit of their patients. It is his unselfish interest in educating me as a head and neck surgeon that has resulted in this collaborative effort. I hope that we are able to transfer this information to others with a similar passion for ultrasound through the text and electronic access to relevant cine loops.

– Robert A. Sofferman, MD, FACS

Preface

This textbook is devoted to comprehensive portrayal of high resolution ultrasound of the thyroid and parathyroid glands. This goal cannot be accomplished without addressing the entire cervical lymph node basins as well as other clinical conditions and anatomical areas which may be misinterpreted as being of thyroid origin. Ultrasound technology is not specific to any single medical discipline and as such the authors represent an objective merger of both radiologic and clinical specialties devoted to study of this fascinating endocrine region. In fact, the text attempts to extend beyond the simple dry presentation of groups of images to apply sufficient clinical information concerning function of the thyroid and parathyroid glands in a variety of disease states. The reader may recognize some redundancy in discussion of ultrasound physics, scanning techniques, and application of fine needle aspiration. By design, this concept emphasizes certain important details and illustrates that there are multiple ways to apply variations in technology to arrive at the same endpoint. The images included in the text are a result of decades of experience with head and neck imaging and frequently both CT and MRI are included in parallel with ultrasound to enhance the presentation. The one process which cannot be demonstrated in a written text is dynamic cine loop imaging. Thus, an on-line link to a variety of carefully selected cine loops is included as an adjunct to provide the reader with the most comprehensive understanding of this technology and its relevance to radiologists, endocrinologists, endocrine, and head and neck surgeons. In fact, the cine loop may be the most important tool to adequately portray the pathology of interest and to allow sharing of imagery with other clinicians in a simple and brief overview. This concept is analogous to the realm of photography where black and white, color, and movie renditions all have a creative role in properly capturing a scene.

In discussion of the history of ultrasound and its modern day application, several American societies which have a vested interest in clinical ultrasound of the thyroid and parathyroid glands are mentioned to barely scratch the surface of modern day issues. It is apparent that there will be omissions from various parts of the world where ultrasound is the primary imaging tool and is performed to excellent clinical advantage. These countries from Asia, Europe, South America, Australia, and Africa each have their own specialty societies and contributions to the understanding of this marvelous imaging tool. Finally, with the advent of both changes in technology, reduction in its market cost, and clinical relevance ultrasound has in part become an office-based procedure. This has allowed clinicians to serve their patients with efficiency and convenience and to become more involved in the direct observation of the anatomy and pathology of the condition under study. In fact, it has presented the clinician with an opportunity to better enjoy the outpatient experience since so much detailed information can be accrued simply and beautifully in the examining room. There are a few economic and political hurdles to overcome, but establishment of an office-based use of ultrasound can easily be accomplished if the commitment is present on the clinical side [1]. The authors hope that this comprehensive investigation of cervical ultrasound will both assist the clinician to better understand images of interest and develop new initiatives in its use.

Internet Access To Cine Loops

Cine loops are dynamic movie clips which compliment the static text images and explanations. During routine ultrasound examination of the thyroid and parathyroid glands it is necessary to evaluate the entire cervical lymph node basins. In the process of this examination, salivary glands, muscles, vessels, nerves and potential congenital abnormalities may be encountered. For this reason, no discussion of the thyroid and parathyroid glands would be complete without addressing in some way these other relevant areas and structures. Although a single ultrasound image transfers some information, the cine loop is a more complete rendition of the pathologic condition under study. These dynamic movies are collated into the following categories: 1-general 2-lymph nodes 3-parathyroid glands 4-thyroid gland 5- FNA and sampling. The owner of this text will be able to access these cine loops through Springer with the following Internet link: http://www.springerimages.com/videos/978-1-4614-0973-1.

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Shatin, Hong Kong Anil T. Ahuja, MD

Reference

1. Nagarkatti S, Mekel M, Sofferman R, Parangi S. Overcoming obstacles to setting up office-based ultrasound for evaluation of thyroid and parathyroid disorders. Laryngoscope. 2011;121:1–7.

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Section I

History and Basic Concepts

1 The History of Clinical Ultrasound

Robert A. Sofferman

Introduction

No text devoted to the application of ultrasound to medicine would be complete without at least a brief review of the remarkable events which have preceded its current uses. In fact, one review of musculoskeletal ultrasound includes “From bats and ships to babies and hips” in its formal title [1]. Although this is clearly an oversimplification, it emphasizes the presence of ultrahigh-frequency sound in our natural environment and its scientific adaptation to more practical matters.

Perhaps the earliest documented experiments concerning sound waves about our audible registry did occur with bats during the lifetime of an Italian priest and physiologist, Lazzaro Spallanzani who lived from 1729 to 1799 [2]. He was fascinated by the ability of bats to navigate in complete darkness. He proved that these animals could continue to fly effectively while being blindfolded but could not do so when their ears were occluded. In spite of the fact that this suggested that audition is critical to the bat in its rapid flight maneuvers, the true foundation of these special navigational aptitudes remained elusive until 1938. Two Harvard students, Donald Griffin and Robert Galambos, recorded directional ultrasonic noises emitted from bats during flight, and the theory of echolocalization was confirmed [3].

Of course, clinical ultrasound is intimately connected to an understanding of the physics of sound transmission. Jean Colladon was a Swiss mathematician and scientist who fortunately redirected his interests from law. In 1826, he designed a clever experiment to determine the relative ability of air and water to support sound waves [4]. With the help of another co-scientist positioned in a boat exactly 10 miles away, he struck a church bell underwater at the same time a gunpowder explosion was initiated above the water surface. The distant boat was equipped with a trumpet-type instrument to receive sound waves placed beneath the boat. The bell sound was subsequently appreciated well in advance of the recognition of the gunpowder report which proved that sound waves travel more efficiently in a fluid medium. In addition, he calculated the velocity of sound in water during the experiment and arrived at a value of 1,435 m/s which is remarkably close to the modern accepted standard in spite of the relative simplicity of the experimental design.

Perhaps no greater advance in the development of ultrasound can be argued above the identification of the piezoelectric effect. In 1881, the physicist Gabriel Lippmann deduced mathematically that an electric charge could produce a mechanical stress [5]. Pierre Curie and his brother Jacques began to study various crystals concurrent to the work of Lippmann [6]. They demonstrated that

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several crystals (quartz, tourmaline, topaz, cane sugar, and Rochelle salt) emitted an electrical charge when subjected to mechanical deformation. This was the inverse of the practical application of Lippmann, and together, these are fundamental to transducer transmission and reception of ultrasound waves. Synthetic piezoelectric crystals (lead zirconate titanate (PZT) were developed in 1954 and serve as the most widely used materials for sound transduction [5, 6].

Echolocalization (the application of directional sound and reflection to detect objects and measure distances to them) is the term initially applied to nautical circumstances. When the Titanic sank in the northern Atlantic Ocean, a Canadian inventor submitted a patent in 1912 for devices to locate icebergs. Reginald A. Fessenden thus developed the first sonar apparatus (the acronym SONAR from "SOund NAvigation and Ranging" immediately evolved), and it was put to practical use 2 years later with the ability to detect an iceberg 2 miles away [7]. Since this occurred in the midst of World War I with threats to Allied shipping from German submarines, the adaptation of this technology to its military advantage became a pressing necessity. Paul Langevin and Constantin Chilowsky developed an underwater quartz generator sandwiched between two steel plates, which is credited as the first modern ultrasound transducer prototype [7].

The very first recorded successful sinking of a German U-boat using this echolocalization was on April 23, 1916, and refinements of the device became widely employed during World War II for protection of North Atlantic convoys [4]. In fact, in conjunction with the use of depth charges, these sonar devices were responsible for leveling the playing field in the deterrence of submarine effectiveness. Further applied use of ultrasound in the shipping and aeronautical industry occurred after World War II for the detection of flaws in metal. These reflectoscopes were the indirect precursors of diagnostic ultrasound in medicine [8].

Karl Dussik, a neurologist at the University of Vienna, is credited with the first medical use of diagnostic ultrasound in the attempt to use transcranial ultrasound beams to locate and characterize brain tumors and adjacent ventricles [9]. In the late 1940s, George Ludwig was enrolled at the Naval Medical Research Institute in Bethesda and applied his experiments to detect foreign bodies in animal tissues and to study gallstone reflectance using pulse-echo principles [10–13]. He explored the attenuation of ultrasound in tissues, the concepts of impedance mismatch, and the ideal frequencies to allow penetration of sound waves into tissues without producing excessive heat and injury. His insight was one of the important foundations for future clinical use of ultrasound.

A University of Colorado radiologist, Douglas Howry, became interested in the development of B-mode ultrasound to allow interpretation of cross-sectional anatomy [14]. He was one of the earliest radiologists to embrace ultrasound and its imaging capabilities, performing a significant amount of his research in the basement of his home. A University of Cambridge student, John Julian Wild, reported on the use of A-mode ultrasound in the examination of malignancies of the breast and intestinal tract and the development of a linear handheld device which was B-mode in design [15]. He also described A-mode ultrasound for transvaginal and transrectal scanning. Wild then met Professor Ian Donald, who was working at the Hammersmith Hospital in London, and a natural cross-fertilization of mutual interests evolved. Donald had experience with sonar techniques while serving in the Royal Air Force during World War II and became very enthusiastic about the application of ultrasound to obstetrics and gynecology. In collaboration with an English engineering firm, his group developed instrumentation which allowed the differentiation of cystic from solid abdominal masses [16]. Perhaps the sentinel ultrasound event at that time surrounded a patient with a pelvic mass presumed to be inoperable cancer on clinical grounds. Ultrasound suggested that it was a cyst, and this fortunate pathology was eventually confirmed at successful surgery. This event was published in a 1958 edition of Lancet and marked a major success for diagnostic ultrasound [16]. Subsequent development of an "automatic" scanner in 1960 led to several clinically relevant advances in obstetrics: (1) first antepartum diagnosis of placenta previa using ultrasound, (2) measurement of biparietal diameter of the fetal head, and (3) utilization of the full bladder transmission to allow detection of early pregnancy at 6–7 weeks gestation in 1963 [17].

In spite of these selected diagnostic processes concerning ultrasound, in fact, its initial uses for medicine were in the realm of therapeutics. The destructive qualities of high-intensity ultrasound were recognized in the 1920s to the point where it was used therapeutically in neurosurgery. At the Universities of Iowa and Illinois, during craniotomy, ultrasound was employed to ablate parts of the basal ganglia in patients with Parkinson's disease [18].

It was employed extensively for physical therapy and rehabilitation medicine for its ability to produce deep heat in tissues of patients with rheumatoid arthritis [14]. In fact, during the 1940s, it became a panacea for many conditions without good controlled evidence-based studies with conditions such as arthritic pain, gastric ulcers, eczema, asthma, thyrotoxicosis, hemorrhoids, urinary incontinence, elephantiasis, and even angina. In fact, its tissue-disruptive qualities were of such concern that the evolution of diagnostic ultrasound was curtailed for several years.

B-mode ultrasound continued with examination of the heart. Helmuth Hertz, a physicist at the University of Lund, Sweden, and Inge Edler, a cardiologist, allegedly met over a lunch in 1953 and decided to pursue the development of echocardiography [14]. In the United States 3 years later, Robert Rushmer, pediatrician and physiologist, and two engineers collaborated to design instruments which allowed the examination of the dog's cardiovascular system in the conscious state. Their work allowed the development of handheld Doppler devices [14].

Several relevant historical elements about modern thyroid ultrasound are nicely reviewed by Robert A. Levine in the text by Baskin, Duick, and Levine entitled "Thyroid Ultrasound and Ultrasound-Guided FNA" [19]. Thyroid ultrasound received its impetus with a study in 1967 by Fujimoto of 184 patients [20]. The B-mode ultrasound required that the patient be immersed in water bath and examined the characteristic echoes within the thyroid gland and contained nodules. Although the thrust of this paper was to demonstrate that ultrasound was capable of differentiating benign from malignant lesions, 25–35% of nodules were incorrectly classified [28].

A 1971 paper by Blum described the ability of A-mode ultrasound to distinguish cystic from solid thyroid nodules [21]. A 1974 paper by Ernest Crocker described the findings of "low-amplitude, sparse, and disordered echoes" seen in thyroid cancer which, in today's descriptive terminology, would be hypoechoic and heterogeneous in pattern [22]. In their series, all six definitive preoperative cancer diagnoses anticipated on ultrasound were confirmed at surgery.

In 1977, Wallfish reported on experience with ultrasound-guided fine needle aspiration [23]. Although cytology was not as well developed and accepted as it is today, this concept set the stage for providing more accuracy in sampling specific lesions within the thyroid gland. In fact, there is no current ultrasonographic characteristic which determines malignancy with certainty, but the addition of guided aspiration cytology comes the closest. This early paper was prophetic in its message.

Advances in ultrasound technology continued to receive major contributions from Austria, Germany, Japan, United States, Denmark, Finland, Italy, Hungary, Spain, Belgium, Union of Soviet Socialist Republics, China, England, France, Poland, Holland, and Australia. In 1972, Kossoff and Garrett from Australia employed gray scale imaging for the differentiation of tissue type and density by combining A-scan sonography with B-mode display [24]. The fine single echoes of A-scan ultrasonography were combined sequentially side by side to arrive at a composite gray scale image.

Christian Doppler was a mathematician and physicist at the University of Vienna and published a paper at the Royal Bohemian Society in Prague in 1841 entitled "On the coloured light of double stars and certain other stars of the heaven" [25]. The astronomical principles in that publication were said to be the foundation for certain wave principles, most notably, that wave frequencies change as moving objects approach and depart from a static point of reception [26, 27]. Since those early theoretical interests in the alteration of sound waves with movement, Doppler principles have been applied in virtually every area of clinical medicine. The development of color flow imaging has been a critical element in interpretation of the character of lymph nodes of the head and neck and identification of vascular structures. A paper by Lagalla and coworkers in 1992 was one of the initial attempts to differentiate benign from malignant thyroid nodules [28]. They demonstrated that absence of flow (type I) within a nodule is useful in identifying the innocent nodule. Type II with perinodular flow is generally an indicator of the benign lesion, whereas type III with chaotic intranodular flow is usually associated with malignancy. These findings have been consistently similar to modern thyroid ultrasound interpretation.

In fact, Doppler has become so sophisticated in its anatomical performance that the typical color Doppler techniques employed to assess blood flow velocity and volume in large vessel assessment are not as preferred as its related methodology, power Doppler. Because neither the direction of flow or volume is critical to thyroid, parathyroid, and lymph node assessment, power Doppler was recognized as a better tool as it demonstrates less distortion and shows small vessels with low flow to better advantage [29].

The development of the transistor and integrated circuitry allowed miniaturization of electronics and thus smaller consoles. Probes then became smaller, and the era of portability of equipment became a reality. The larger expensive consoles continued to reside within radiology departments in hospitals and universities, and the resolution evolved slowly but progressively through the 1990s. With the portability of ultrasound units and their accessibility to Emergency Room physicians and surgeons, abdominal ultrasound became a convenient method of determining cavitary hemorrhage. The clinical development of determining cholelithiasis and the assessment of breast masses are but a few examples of the transition of ultrasound to an office-based procedure in general surgery. As well, ultrasound-guided fine needle aspiration cytology has become as much a clinician-associated office procedure as one performed by radiologists. Endocrinologists, otolaryngologists, and surgeons interested in thyroid disorders have embraced the technology in spite of its potential conflict with the efficiencies of office scheduling.

Ultrasound Education and Administration

As ultrasound advanced and became a commonly performed procedure in radiology departments, technicians performed most of the actual examinations and were supervised by radiologists and residents. Striving to achieve recognition, in 1970 the sonographers organized, and this group eventually became the Society of Diagnostic Medical Sonography [14]. 3 years later, the US Office of Education determined that ultrasonography should be worthy of an occupational designation. This membership has grown significantly to the point where 20,000 members were listed as of 2007 [14].

While these sonographers represent the nucleus of the American Institute of Ultrasound in Medicine, there are now 54 professional societies represented in the AIUM from a broad segment of medical, radiological, surgical, and allied health-care disciplines.

The American Association of Clinical Endocrinologists has developed a training/credentialing postgraduate program for its members, which allows clinicians to perform office-based ultrasound and FNA of requisite lesions [Baskin, Jack. Personal communication, 2010]. The first course on ultrasound for endocrinologists was established in 1998 under the direction of Jack Baskin, M.D., who became the undisputed father of ultrasound education for his specialty. In fact, he was instrumental in developing and maintaining the Endocrine University devoted in large measure to the further development of ultrasound for endocrinology fellows. A special certificate of excellence has been developed by AACE, which requires individuals who are interested to prove significant experience by submission of cases to a panel of experts, take a written examination, and accommodate to recertification every 10 years (Endocrinology Certification of Neck Ultrasound). To date, approximately 150 endocrinologists have completed full validation through this process [30].

The American College of Surgeons has developed postgraduate ultrasound courses in multiple surgical disciplines. The history of this development and the breadth of this educational project have been elucidated in a manuscript published by the surgeon leaders who have been instrumental in the application of ultrasound to clinical surgical practice [31]. Breast, abdominal, thyroid and parathyroid, biliary, vascular, and FAST examinations are areas covered at the Annual Congress in these courses. These consist of didactic lectures, hands-on skill sessions with formal ultrasound examination of patient volunteers, practice FNA on phantoms, and faculty observation and written examination. The ACS has developed a mechanism for these courses to be exported to sites outside of the Annual Congress. In fact, the American Academy of Otolaryngology–Head and Neck Surgery has been the recipient of this opportunity such that each year, interested head and neck surgeons can receive identical training and certification to that presented at the ACS Congress.

In 1984, Wolfgang Mann published the first textbook in Germany devoted to clinical ultrasound of the head and neck [32]. In fact, by the mid-1990s, ultrasound experience was a requirement for board certification for otolaryngology in Germany [32]. While ultrasound education can be obtained through postgraduate courses, the foundation for the future will be in the development of formal residency training in ultrasound history, physics, and hands-on experience. Whereas general surgical training encompasses the use of ultrasound in central line placement, FAST examination in trauma, assessment of both gallbladder and appendix in abdominal pain, and breast examination and biopsy, to mention a few areas of interest, other specialties have been slower to become formally aligned with this technology. With the profusion of exposure to thyroid and parathyroid surgery, otolaryngology has come to understand the relevance of ultrasound and its application to the head and neck well beyond this small central organ. The time for formal curricula and courses within residency just for residents in training has arrived.

The multitude of postgraduate courses has mirrored the profusion of office-based ultrasound in clinical medicine. Its application to thyroid and parathyroid assessment is highly relevant and carries efficiencies for patients and referring physicians. Beside the reduction in size of ultrasound units and portability, they have now become affordable for purchase. The companies which manufacture these machines have realized that the market outside of radiology departments is quite substantial. In addition, the systems can be tailored to individual needs, depending on the specialty or even pooled resources of multiple clinicians. Ultrasound of the breast and head and neck can be accommodated by a single linear transducer, whereas abdominal ultrasound requires a convex probe. However, all other settings and variations can be managed through dials and changes which the sonographer does at the console.

In summary, the application of clinical ultrasound in medicine has proceeded through nearly a century of evolution along with military and industrial interests. In countries which have not been able to provide broad-reaching, sophisticated imaging technology such as CT scanning, ultrasound has been used to clinical advantage. This has occurred in spite of the fact that comparative resolution with earlier systems of even a decade ago cannot equate to what exists in today's market. The historical overview of ultrasound demonstrates that multiple individuals of diverse scientific backgrounds have collaborated in the eventual development of a remarkable product which crosses medical specialty applications. This text is designed to cover the comprehensive use of ultrasound for anatomic study and, to some degree, therapeutic management of thyroid and parathyroid disorders. It has been prepared to appeal to radiologists with a special interest in this area and clinicians who can now image this anatomic region in an outpatient, office-based setting expecting a sophisticated degree of image resolution.

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Physics and Principles of Ultrasound

2

Robert A. Sofferman

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

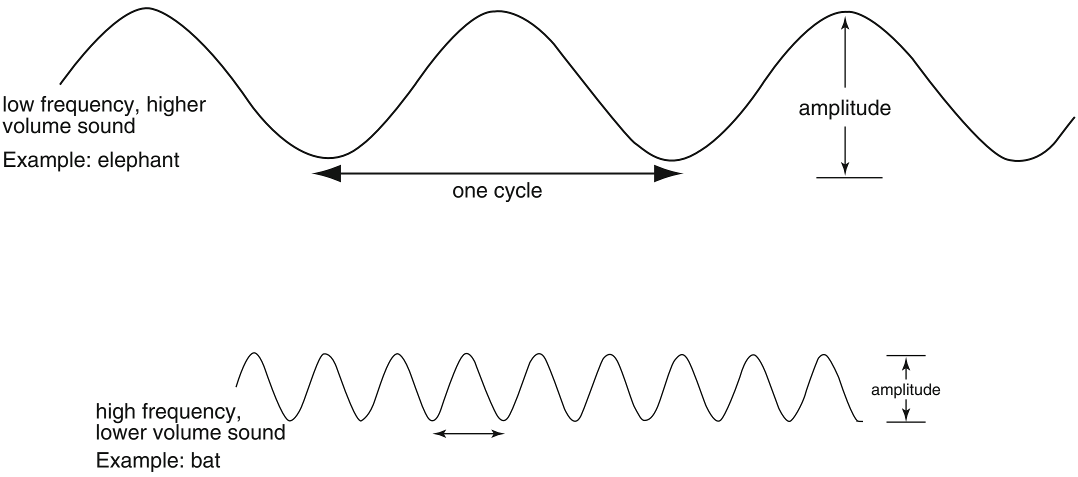

Fig. 2.1 Sound travels as linked sine waves. The frequency is determined by the number of cycles per unit of time and loudness by the amplitude. Sound travels at varying speeds through tissues depending on tissue density and properties

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.

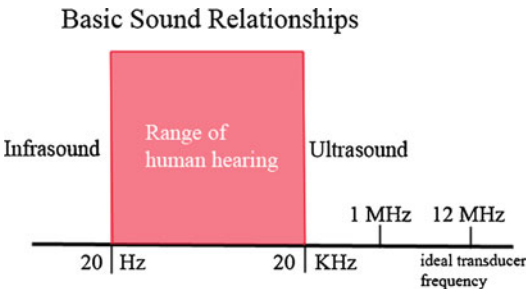

Fig. 2.2 Humans hear frequencies from 20 to 20,000 cycles/s. Ultrasound is above 20 kHz and infrasound below 20 Hz

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).

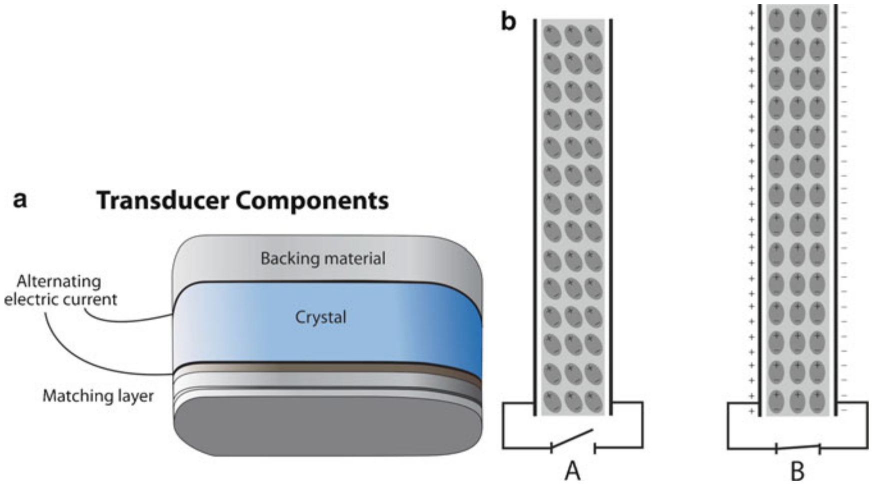

Fig. 2.3 (**a**) The transducer is comprised of piezoelectric crystals surrounded by insulating material and matching layers at the exit port which allow ideal transmission of the sound waves through the skin into the tissues. (**b**) Piezoelectric crystals elongate and shorten with realignment of the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

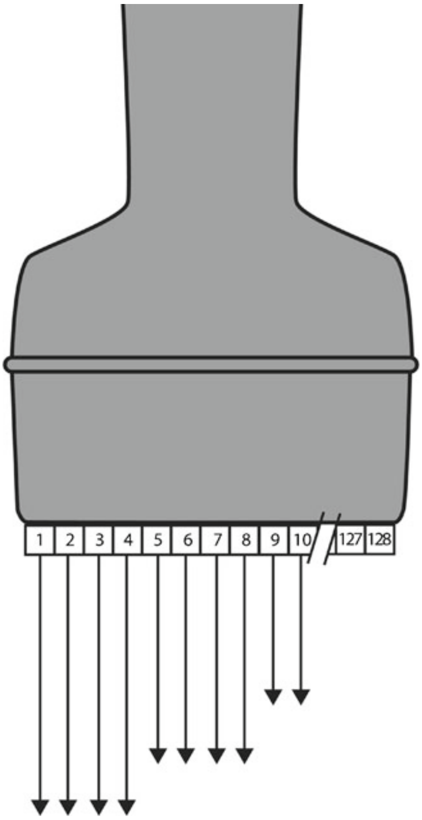

Fig. 2.4 Each crystal resides in its own sectored compartment adjacent to others which will send waves into the tissues upon command

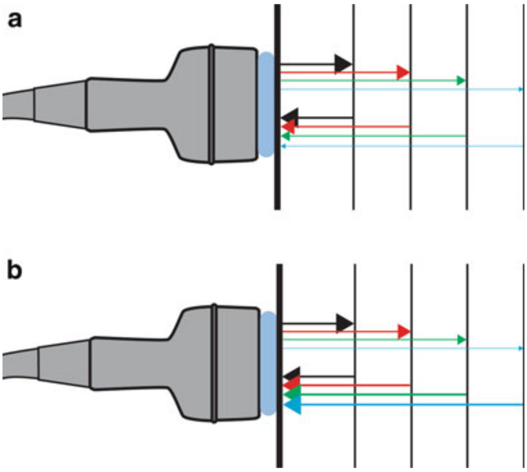

Fig. 2.5 (**a**) As ultrasound waves enter tissues, they attenuate with depth from the surface. High-frequency waves attenuate more than those of low frequency. (**b**) Time-gain compensation allows selective amplification of the weaker deep and intermediate returning echoes

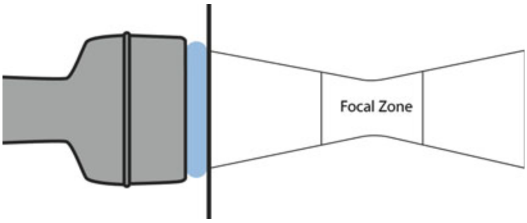

Fig. 2.6 The focused penetrating sound waves do not have a rectangular or linear pattern. The hourglass shape is typical, and the focal zone is the narrowest portion of this configuration

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."

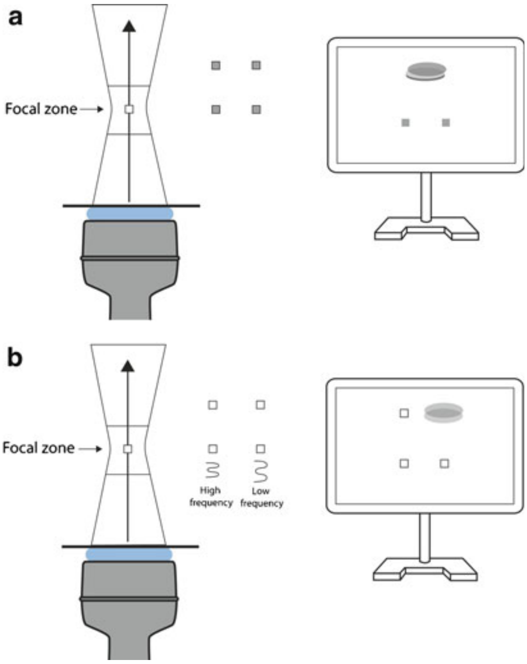

Fig. 2.7 (**a**) Lateral resolution depends more on alignment of the ideal focal zone to the region in question. Those points near or within the focal zone will be discerned as separate and better resolved. (**b**) Linear resolution depends on the frequency of the emitting ultrasound wave with higher 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

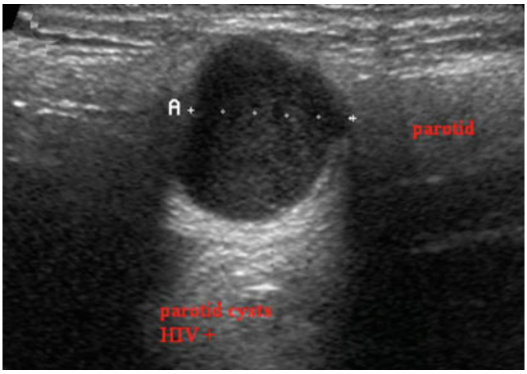

Fig. 2.8 Posterior enhancement deep to the posterior capsule of a cyst

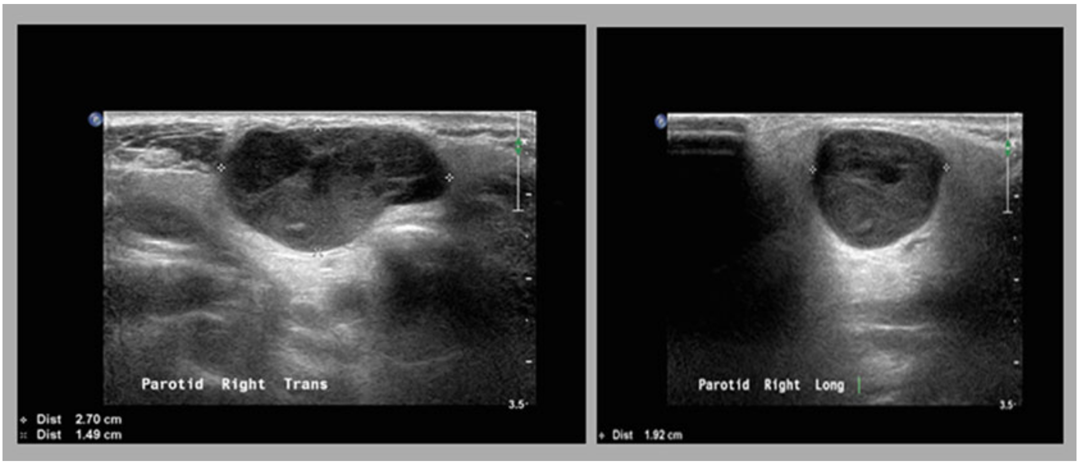

Fig. 2.9 Similar posterior enhancement deep to a pleomorphic adenoma, a testimony to the uniform character of its tissues and even transmission of sound waves with little attenuation

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).

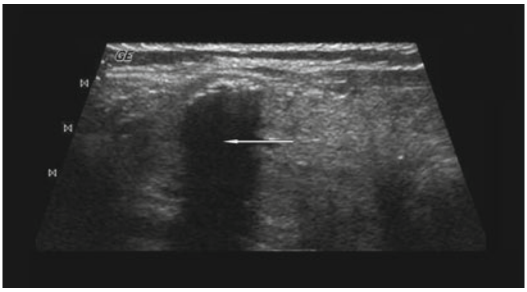

Fig. 2.10 Dense calcification prevents penetration of sound beyond the lesion resulting in posterior shadowing artifact (demonstrated by *arrow*)

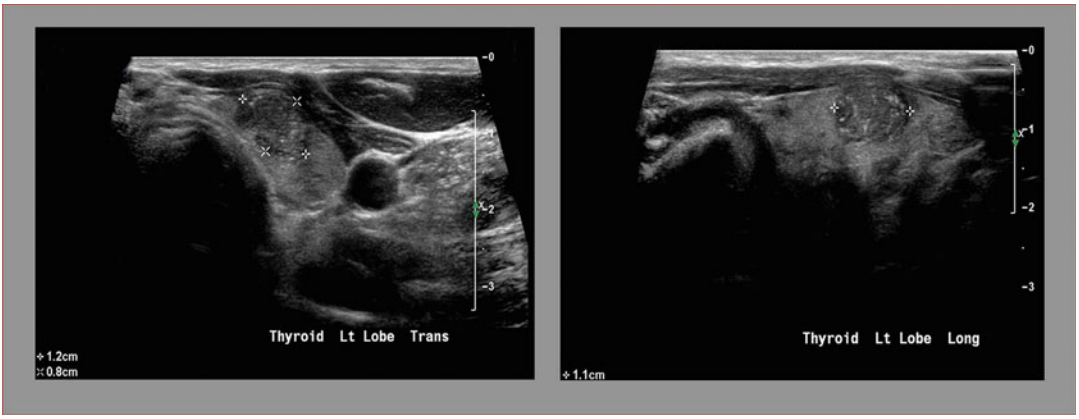

Fig. 2.11 Microcalcifications do not produce posterior shadowing artifact

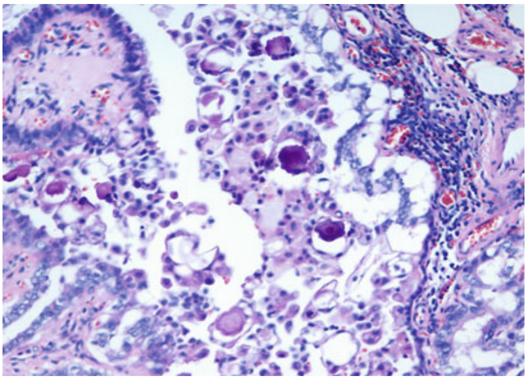

Fig. 2.12 Psammoma bodies are small, discrete calcifications commonly found in papillary carcinoma

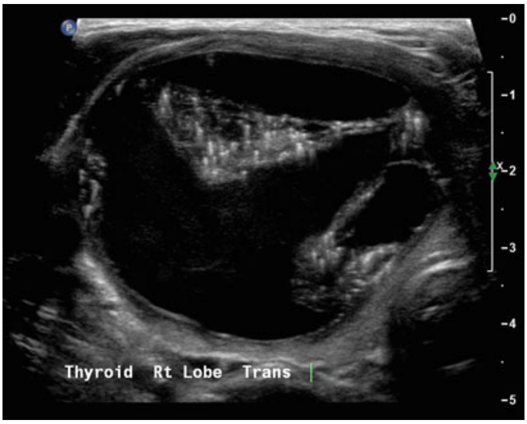

Fig. 2.13 Comet tail artifact is similar in appearance to microcalcifications, but the comet tail clearly differentiates it from the representations of psammoma bodies

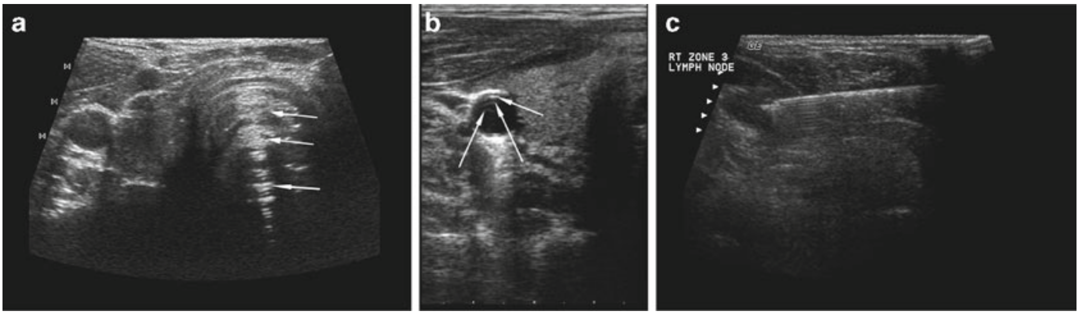

Fig. 2.14 Reverberation artifact can be seen in the following: (**a**) Anterior tracheal wall. (**b**) Anterior wall of the carotid artery. (**c**) Biopsy needles in the long axis. *Arrows* demonstrate the reverberating artifacts

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).

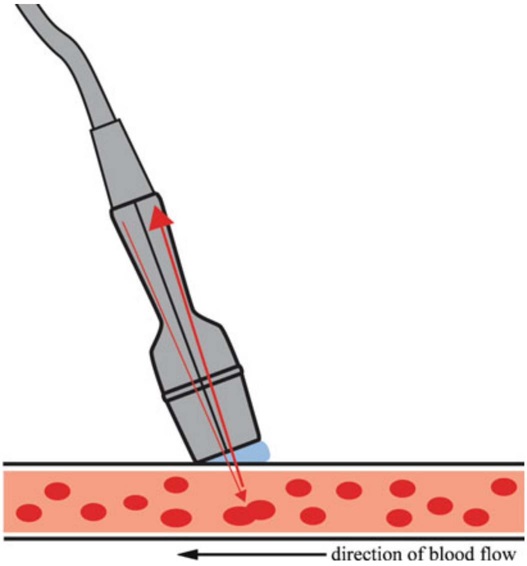

Fig. 2.15 Doppler waves reflect differentially off moving red cells. Depending on whether these cells are moving toward or away from the transducer, direction of flow and its velocity can be determined by the Doppler system

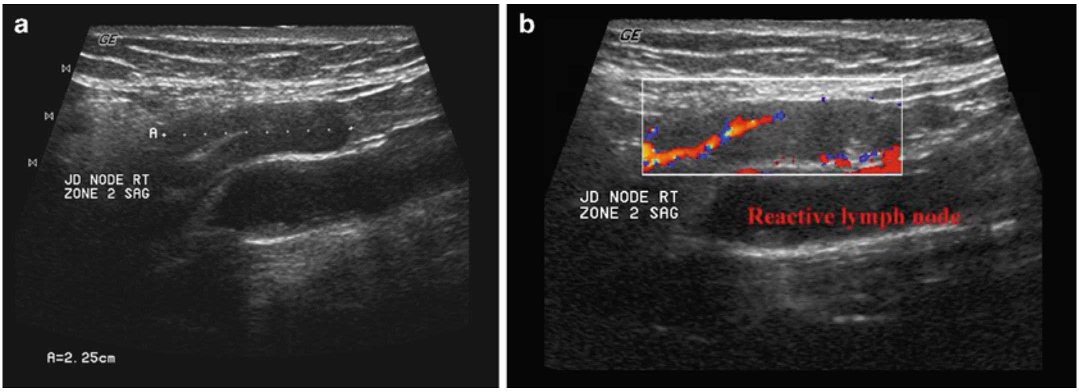

Fig. 2.16 Gray scale image of a hyperplastic lymph node with a typical “hilar line” (**a**). Power Doppler demonstrates the axial vessel penetrating the hilum of the node and representing the “hilar line” (**b**)

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.

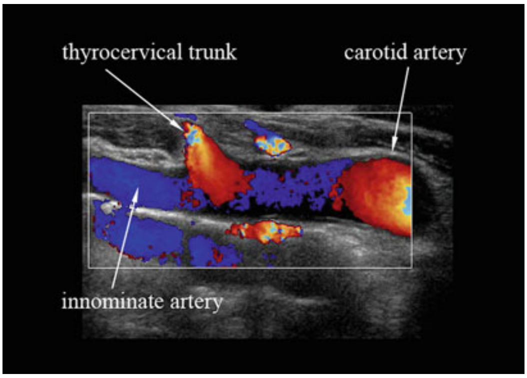

Fig. 2.17 Color Doppler demonstrates the innominate, thyrocervical trunk, and carotid artery relationships

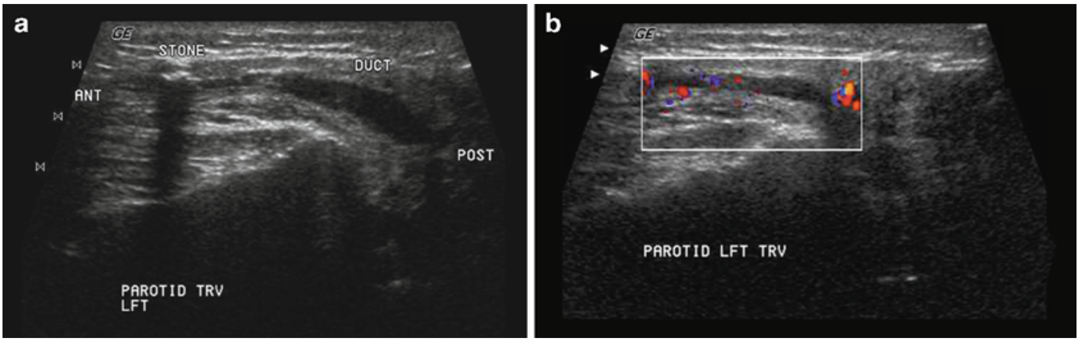

Fig. 2.18 (**a**, **b**) The use of Doppler to distinguish a vessel from duct is demonstrated in this salivary duct calculus producing obstruction and duct ectasia. The gray scale image alone cannot easily make that determination, but the addition of Doppler confirms that the widened anechoic structure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