HEAD AND NECK ULTRASONOGRAPHY

ESSENTIAL AND EXTENDED APPLICATIONS

Second Edition

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PREFACE

Head and Neck Ultrasonography: Essential and Extended Applications, Second Edition is a comprehensive textbook of office-based and intraoperative ultrasonography for clinicians, and especially surgeons, who manage patients with head and neck disorders. Since the first edition of this book was published, ultrasonography has continued to experience an explosion in interest and application within nearly every medical subspecialty. The anatomy of the head and neck is particularly accessible and amenable to ultrasound examination, and otolaryngologists/head and neck surgeons and endocrine surgeons are increasingly incorporating ultrasonography into their clinical practices. There is an ever expanding body of journal literature citing the utility and advantages of neck ultrasonography, especially in the management of thyroid disease, head and neck cancer, and benign neoplasms and masses in the head and neck. There are evolving applications to active processes such as swallowing, sleep dynamics, and speech. The publication of this complete textbook of head and neck ultrasonography is the ideal complement to this surge in appreciation and utilization of ultrasonography.

Head and Neck Ultrasonography covers the fundamentals of ultrasound physics, equipment, normal head and neck ultrasound anatomy, and technique. Individual chapters cover specific anatomy and pathology. Interventional ultrasonography and dynamic ultrasonography are included. New chapters since the first edition focus on ultrasound in airway management, global health, pediatrics, endobronchial procedures, plus special chapters on fine-needle aspiration, documentation, and accreditation.

This textbook is unique both in its thoroughness and in its relevance to the clinical setting, where ultrasonographic examination is a dynamic and interactive process between physician and patient. Although numerous examples of still ultrasound images are necessary and invaluable (and are the traditional format of ultrasound textbooks), this book also takes advantage of dynamic video clips that can be viewed online to best illustrate both the process and the interpretation of specific examinations and procedures. Both standard B-mode (gray-scale) and color Doppler sonography images are included.

Head and Neck Ultrasonography is organized into chapters written by individuals with particular expertise in the given topic. Contributors include predominantly surgeons but also authorities from the fields of radiology, endocrinology, gastroenterology, neurology, anesthesiology, pulmonology, and pathology. I have had the privilege of learning from and collaborating with these experts in head and neck ultrasonography who are helping to move the applications of this powerful tool forward. To the clinician caring for head and neck disorders, I hope that this book will be a useful resource for trainees and experienced practitioners alike and will provide stimulation for new applications of ultrasonography within the region.

ACKNOWLEDGMENTS

As a true sign that rightness can prevail, one of the chapters herein was contributed by an author from the very department that rejected my incorporating ultrasound into my practice when I was first getting started. Thankfully, the wisdom of utilizing ultrasonography in the office to provide optimal care for patients with diseases of the head and neck speaks for itself. Since the first edition of this textbook was published, there has evolved a critical mass of authorities who are eager to practice, demonstrate, teach, and write about the benefits of ultrasound, ensuring that head and neck ultrasonography in the clinical realm is here to stay. There is ever-growing demand and interest in ultrasound education. Hence this updated second edition, which features more numerous, more accessible, and more high-resolution images and video clips than in the first edition, representing the next best thing to real-time, interactive ultrasonography.

Many people have contributed to bringing this second edition to fruition, and I can never thank each of them sufficiently. I know that they derive the same gratification I do from sharing their ultrasonography passion and insights with others. Still, I would like to give special thanks to the following individuals: to all of my contributing authors for their hard work and commitment to educating the readers of this book about the infinite benefits of clinical ultrasonography; to Hans Welkoborsky, Urban Geisthoff, and Jens Meyer, my enduring partners who have co-taught annual introductory ultrasound courses, creating that epiphany for the newly exposed, year after year; to my patients, who recognized long before the medical community did that point-of-care ultrasound had obvious advantages over ultrasound dissociated from clinical care; and to the late Senator J. William Fulbright for having established a program that sponsors cultural and scientific exchange and mutual understanding, enabling individuals like me to meet and learn about amazing people and ideas such as those represented by this book.

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To my family: Paul, Stuart, and Eric
Who have patiently and lovingly shared, and endured, the many hours, adventures, and miles
traveled in the course of acquiring and passing on the knowledge contained herein

To my parents
Who have always taught by example and will forever be my mentors

And to my late colleague, dear friend, and ultrasound enthusiast, Bob Sofferman, whose
passion for and commitment to ultrasound education will never be forgotten

1

THE HISTORY OF HEAD AND NECK ULTRASONOGRAPHY

William B. Armstrong and Yarah M. Haidar

Ultrasound use has expanded as a clinical modality over the past 50 years, with increasing applications in the head and neck. While diagnostic medical ultrasound has a relatively brief history, discovery of the concepts that enabled development of ultrasound dates back to at least the 1700s. This chapter reviews the history of ultrasonography and discusses advances in acoustics, physics, electrical engineering, materials science engineering, and computer science married with medicine to produce the high-quality instrumentation available today.

Historical Development of the Ultrasound

Understanding of the concept of ultrasound can be traced back to the Italian naturalist Lazzaro Spallanzani (1729–1799) in his study of bats.[1] In 1793, he discovered that when the eyes of bats were covered or removed, their ability to detect and avoid obstacles during flight was not impaired. He observed several bats that he caught for studies and noted that the bats were able to navigate in complete darkness while a barn owl could navigate by the light of a single candle but crashed into the walls when the candle was extinguished. Later, Louis Jurine of Geneva found that covering the ears of bats impaired their ability to avoid obstacles, which Spallazini later confirmed. This suggested that sound localization was essential in bats' ability to navigate. This theory was opposed by many naturalists of the period in favor of the theory that tactile receptors on the skin were responsible for guiding navigation. This work was largely forgotten and not confirmed until a series of experiments by Donald Griffin and Robert Galambos published in 1941 demonstrated conclusively that binaural hearing was required for successful navigation.[2] They recorded the ability of a large number of bats to navigate through a path obstructed by thin vertical wires after impairing vision or hearing by unilaterally or bilaterally covering the ears. They also demonstrated impaired flight when the mouths were covered, preventing production of high-frequency sounds for echolocation.

A discovery fundamental to understanding the properties of sound was recognition that sound traveled at different velocities in different media. In 1826, Jean-Daniel Colladon, a Swiss physicist, inaugurated the birth of modern underwater acoustics by striking an underwater bell in Lake Geneva and determining when the sound was heard by his colleague on a boat 10 miles away.[3] His measurement of the speed of sound in water was remarkably accurate. Bonnycastle's experiments in 1838 measuring the transit of sound in water for depth sounding were largely unsuccessful, and traditional lead line depth sounding was used until the 20th century. In 1877, John William Strutt (Lord Rayleigh) published "The Theory of Sound," which comprehensively described the mechanics of vibration and sound wave propagation and formed the basis of future work in acoustics and ultrasound.[4] During the same period, Francis Galton conducted research on hearing ability of humans. He developed a brass whistle that could be tuned to very high frequencies, producing the first ultrasonic sound generator. After testing the upper frequency limits of human hearing and demonstrating that the maximum hearing frequency decreased with age, he conducted experiments demonstrating a number of animals had sound perception at much higher frequencies than humans.[4]

The most important breakthrough that made medical ultrasound possible was the discovery of the *piezoelectric effect*.[5] In 1880, Pierre Curie and Jacques Curie made an important discovery that eventually led to the development of the modern-day ultrasound transducer (Figure 1–1). The Curie brothers observed that an electric charge was generated when pressure was applied to crystals of quartz or Rochelle salt (sodium potassium tartrate tetrahydrate). This effect was called "piezoelectricity" from the Greek word *piezo*, meaning "to press."[5,6] Gabriel Lippman mathematically deduced the reciprocal behavior, and the Curie brothers subsequently demonstrated mechanical vibration in response to a voltage potential across the crystal.[5] The technology remained a curiosity without a significant application for the next 30 years.

On April 15, 1912, the sinking of the *Titanic* produced a public outcry to develop iceberg detection methods and served as a catalyst for utilizing underwater acoustics to develop practical devices.[6] Five days after the *Titanic* sinking, Lewis Richardson, an English physicist, filed his first of two patents for an "Apparatus for Warning

Figure 1–1. The brothers Pierre (*top right*) and Jacques Curie (*top left*) with their parents.

a Ship of its Approach to Large Objects in a Fog" in England.[7] Similarly, in Vienna, Alexander Behm described an underwater ultrasound device that same year. Neither produced a working device, and it was not until April 1914 that iceberg detection was possible using Reginald Fessenden's electromagnetic moving-coil apparatus.[3] The oscillator emitted a low-frequency (1 kHz) sound wave and then switched to a receiver to listen for echoes. It was able to detect an iceberg underwater from 2 miles away. The device could also transmit in Morse code for ship-to-ship communication. However, because of the low frequency, it could not precisely identify the direction of the returning signal. Although this technology was well accepted, its use focused on underwater signaling and detection of World War I submarines.[3]

In 1915, Constanin Chilowsky, a Russian electrical engineer, in conjunction with Paul Langevin, a French physicist, developed a working hydrophone with a piezoelectric transducer. The hydrophone transducer consisted of a mosaic of thin quartz crystals between two steel plates with a resonant frequency of 150 kHz, making it the first piezoelectric ultrasound transducer.[3] This work occurred with many contributors on the eve of and during World War I and became known during World War II as *Sound Navigation and Ranging (SONAR)*.

In 1928, Soviet physicist Sergei Sokolov suggested using ultrasonic energy for industrial purposes, including detection of flaws in metals. Prior to the development of ultrasound, the integrity of ships' metal hulls was verified by standard x-rays.[8] To detect millimeter flaws in metal, the transducer frequency had to be increased to the megahertz range. In 1941, Floyd Firestone, at the University of Michigan, developed the "supersonic reflectoscope," to detect flaws in metal for industrial purposes.[8–10] Donald Sproule in England independently developed the earliest pulse-echo metal flaw detectors. Although Sproule and Firestone manufactured these instruments concurrently in 1941, their results were not made public until 1946 following World War II.

Early ultrasound transducers used quartz crystals, but during World War II, limitations in sources for natural piezoelectric crystals spurred a search for artificial piezoelectric materials. Ferroelectric ceramic materials were discovered that had significantly better piezoelectric properties compared to natural crystals. Barium titanate ($BaTiO_3$) was the first ferroelectric ceramic material to be produced, in 1946. Subsequent research resulted in production of *lead zirconate-titanate (PZT)* discovered by researchers at the Tokyo Institute of Technology around 1952.[11] Use of PZT allowed development of smaller and more sensitive ultrasound transducers.

Often overlooked when discussing the development of ultrasound is the evolution of computing power, which enabled advances in probe design, instrument miniaturization, and data processing. The vacuum tube invented in 1907 made modern electronics possible. However, vacuum tubes are bulky, generate considerable heat, and have significant power requirements. The Electronic Numerical Integrator and Computer (ENIAC computer) developed in 1945 had over 17,000 vacuum tubes, occupied 1800 square feet of space, weighed 30 tons, and had a clock speed of 100,000 cycles per second.[12] The transistor was developed at Bell Labs in 1947. The transistor replaced the vacuum tube with a smaller, very reliable, long-lasting device that consumed much less power. In 1959, the first integrated circuit (IC) containing multiple transistors linked on a silicon or germanium wafer was produced. The first commercial ICs were developed independently by Robert Noyce at Fairchild Electronics and Jack Kilby at Texas Instruments in 1961. These ICs greatly miniaturized the electronic components, had much lower power consumption, and increased reliability. They could be mass produced and made cheaply. The computing power on ICs has consistently doubled roughly every 2 years. The initial chips had the equivalent of a handful of transistors. The Intel 8080 processor produced in 1974 had 6000 transistors. Contrast this to current chips used in microcomputers with clock speeds of 3 GHz, containing over 2 billion transistors. These advances in computing power provided enabling technology to produce modern ultrasound devices that became progressively smaller and less expensive. Today, portable and even handheld ultrasound devices are available, and they can be used in the office setting or in remote settings for management of emergencies in the field with transmission of images via cellphone.[13]

Development of Medical Ultrasound

The earliest medical applications of ultrasound were for therapeutic, not diagnostic, purposes. It was recognized early on that high-power ultrasound produced tissue destruction. Langevin observed that a school of fish in the path of his ultrasound device were killed and placing his hand in front of a transducer in water caused significant pain.[6] Lynn and Putnam attempted to use ultrasound for the destruction of brain tissue in experimental animals. Ultrasound caused considerable tissue damage to the scalp and brain, resulting in a wide variety of neurologic sequelae. In the 1950s, Fry and Meyers reported performing ablation on parts of the basal ganglia after exposure with a craniotomy in humans to treat Parkinson disease.[14,15] Therapeutic ultrasound was used in physical and rehabilitation medicine for rheumatic arthritis and other disorders. Its use expanded with enthusiastic results published on trials with substandard design and implementation.[16] Patients were treated for a wide range of disorders ranging from eczema to cancer to otosclerosis and Meniere disease.[16] Many of these enthusiastic initial findings were discredited, and the reputation of ultrasound also suffered, curtailing development for at least a decade.

Karl Theodore Dussik, a psychiatrist and neurologist, and his brother Friedrich, a physicist, began studying ultrasonography in the late 1930s. In 1937, the brothers used a 1.5-MHz transmitter to scan the brain and noticed areas with decreased wave transmission, which they called "hyperphonograms," thought to be the lateral ventricles.[8] The brothers initially proposed that ultrasound might be able to detect brain tumors. It was later determined by Guttner, in 1952, that the images produced by the Dussiks were variations in bone thickness and not the lateral ventricles. However, their work stimulated interest in use of ultrasound for medical diagnostic purposes.

George Ludwig, working at the Naval Medical Research Institute, was among the first investigators to report on the use of the pulse-echo technique in biologic tissue, using ultrasound waves on slabs of beef and human extremities. They also demonstrated that ultrasound could visualize gallstones in dogs. He carried out extensive experiments on various tissues, studying signal impedance and optimized frequency and energy output to achieve optimal tissue penetration and resolution without causing tissue damage. He is credited with demonstrating the sound velocity in animal soft tissues to have a mean of 1540 m/s.[17]

John Julian Wild, an English-trained surgeon who immigrated to the United States in the post–World War II era, was able to demonstrate the diagnostic utility of ultrasound. He used ultrasound clinically to distinguish between bowel obstruction and ileus. Using *A-mode* (amplitude mode) imaging and a 15-MHz transducer, Wild was able to visualize the three distinct layers of the bowel wall and to visualize malignant tissue.[18] Wild's early experiments were conducted with A-mode scanning, but he made contributions that led to the development of *B-mode* ultrasonography. In 1952, with B-mode ultrasound, Wild was able to identify a recurrent thigh tumor and breast cancer.[19]

In the 1940s, Douglass Howry became interested in ultrasound during his radiology internship. He partnered with W. Roderic Bliss, an electrical engineer, to develop the first B-mode scanner in 1949. Working with Joseph Holmes, a nephrologist at the Denver VA facility, and Gerald Posakony, an engineer, they developed the first linear contact scanner using surplus radar equipment.[6] Howry continued to develop improved scanning equipment, and in 1962, he and colleagues left the University of Colorado to form Physionics Engineering, Inc, where they produced the first commercial, articulated arm, handheld contact B-mode scanner in the United States.[20]

Around the same time in 1954, Ian Donald joined the faculty at The University of Glasgow. He had knowledge of RADAR from his time in the Royal Air Force. After meeting Julian Wild, he partnered with engineering colleagues to use a metal flaw detector to examine gynecologic pathology specimens. With this A-mode ultrasound machine, he was able to differentiate various types of tissue in recently excised fibroids and ovarian cysts. He, along with Tom Brown, an engineer from Kelvin & Hughes Scientific Instrument Company, developed the first contact compound scanner.[21] Donald then commenced evaluation of abdominal masses. A turning point occurred when ultrasound was used to evaluate the abdomen of a woman with massive ascites from portal vein obstruction, initially diagnosed as advanced gastric cancer. Ultrasound imaging demonstrated findings consistent with a cyst, and the patient subsequently underwent laparotomy to remove a massive mucinous ovarian cyst, thereby saving this woman's life. His work to date was published in 1958 in the *Lancet*[22] and is considered one of the most influential articles in clinical ultrasound ever published. Donald contributed enormous amounts of research to the field of ultrasound, demonstrating measurement of biparietal diameter of the head to chart fetal growth, reporting the fortuitous discovery of full bladder scanning to detect early pregnancy and uterine abnormalities, and reporting antepartum diagnosis of placenta previa.

The next turning point in ultrasonography was the development of real-time imaging, which allowed for acquisition and display of images to occur nearly simultaneously. Real-time imaging was pioneered in the mid-1950s by J. J. Wild, but the first commercially available real-time ultrasound machine was the *Videoson* produced by the Siemens corporation in the 1960s (Figure 1–2). This machine had a rotating transducer in a water bag and was first used by Hoffman in 1966 and Hollander in 1968 to image the pelvis.[23]

Early ultrasound produced still images with data points displayed as black and white dots on an oscilloscope screen. Polaroid or 35-mm photographs could be taken of the images for recording, but the ability to process and display information was a major technical limitation. Signals above a certain threshold were recorded, but signals below the set threshold were not displayed.

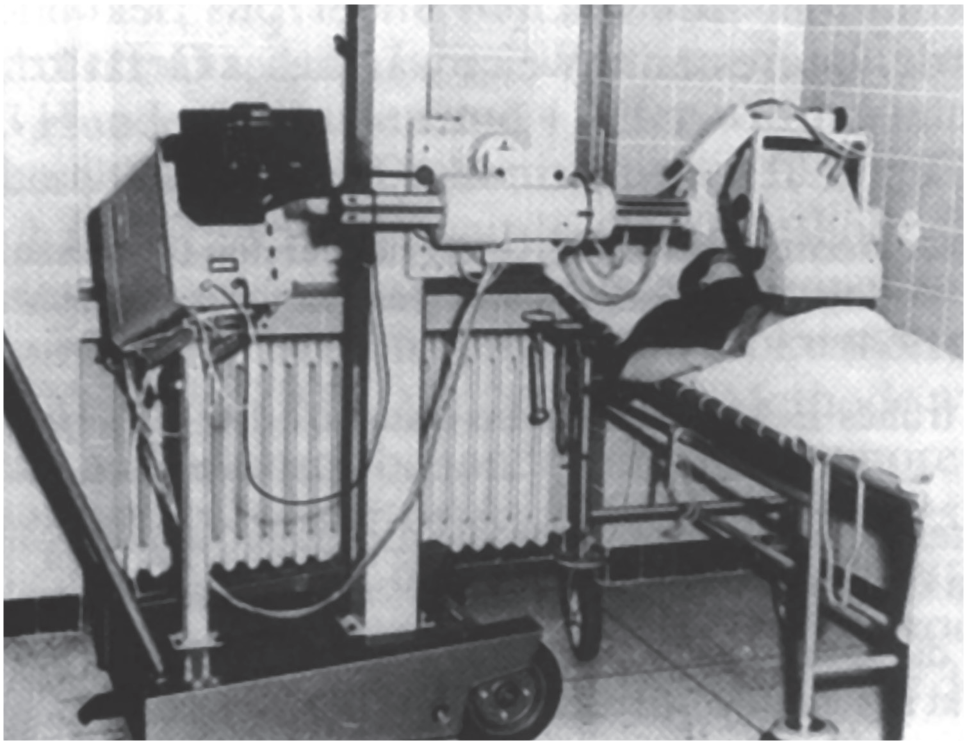

Figure 1–2. First real-time scanner (Videoson) with bulky transducer for B-mode ultrasound examination of the abdomen.

These bistable images were difficult to interpret and provided no information about the amplitude of the echo, necessary for delineating soft tissues. George Kossoff and William Garrett at the Ultrasonic Institute in Sydney, Australia, pioneered the development of gray-scale imaging and demonstrated improved resolution and tissue discrimination abilities by improving signal processing methods, transducer design, and display techniques.[24]

Early ultrasound probes were very bulky and cumbersome, requiring patient immersion, use of water bags, and/or use of mechanical translating arms to produce interpretable B-mode images. Transducer design was a major limitation to be overcome. Development of a probe with multiple crystals aligned in a linear array was first accomplished by Wernar Buschmann in East Germany in 1964. He produced a six-crystal linear array probe for use in ophthalmology. Nicholas Bomm followed with the creation of a 20-crystal linear array probe measuring 66 mm × 10 mm. This design evolved into the Multiscan system, which was the first commercially available real-time linear scanner. This probe had significant limitations but served as a model for further design improvements.[25]

In the 1970s and 1980s, advances were made in transducer design. Early mechanical transducers that physically translated the crystal in space gave way to linear and curved array probes (described in the previous paragraph) consisting of multiple crystal elements that are sequentially fired to produce B-mode images. *Phased array transducers*, consisting of multiple crystals fired as a group with slight delay across the array that allowed steering and focusing of the beam, were also developed. The phased array transducers allowed production of a small transducer that could image with a narrow footprint (eg, between ribs). Improved transducer design, incorporation of real-time scanning to allow detection of movement, incorporation of gray-scale imaging, plus advances in display technology produced images that began to resemble true anatomic structures.[25]

Lastly, it is important to discuss the development of power Doppler when evaluating the history of ultrasound. Christian Andreas Doppler, an Austrian mathematician and physicist, in 1842, first proposed the Doppler effect, which described the observed changes in frequency of transmitted waves when motion exists between the source of the wave and an observer. The first application of the *Doppler effect* in medicine involved the measurement of differences in the transit time of ultrasonic waves in the body between two transducers, performed in the 1950s by Shigeo Satomura, a physicist from Osaka University.[8] Eventually, this technology was adopted in the United States and a coupled real-time mechanical sector scanner to a pulsed Doppler machine was developed in the 1960s. *Color Doppler* is based on the mean Doppler frequency shift and results in a color display of the directional movement of velocity. *Power Doppler* was developed in the 1980s and early 1990s and allowed for display of the total integrated Doppler power spectrum. Summation of the signals removed the directional dependence and allowed visualization of blood flow in soft tissues so that tissue or tumor vascularity could be characterized and was not dependent on the angle of blood flow.[26]

Incorporation of Ultrasonography in the Head and Neck

In the late 1940s, Keidel reported the use of ultrasound for the diagnosis of paranasal sinus disease. A-mode ultrasound was initially used (Figure 1–3), but before long, compound scanners were introduced for two-dimensional diagnosis of paranasal sinus disease (Figure 1–4).[27] Holms and Howry, in their study of ultrasound in 1963, examined its utility in the head and neck, in addition to the abdomen. In the late 1960s and early 1970s, ultrasound was then further explored for the diagnosis of head and neck tumors[28] and for assessment of motion of the lateral pharyngeal wall.[29] Kitamura et al[28] used ultrasound for recording vocal fold motions and Abramson et al[30] used ultrasound for diagnosis of middle ear effusions. Ultrasound eventually was applied to examining the thyroid gland. This was first described by Fujimoto in 1967 based on evaluation of 184 patients with B-mode ultrasonography.[31] After this initial

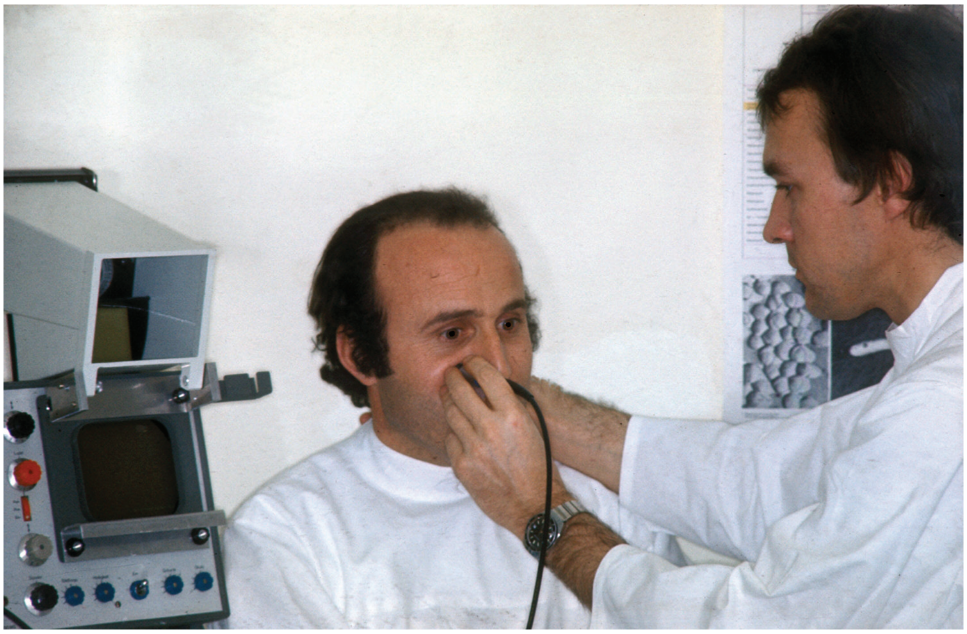

Figure 1–3. A-mode ultrasonography of the maxillary sinus in 1974.

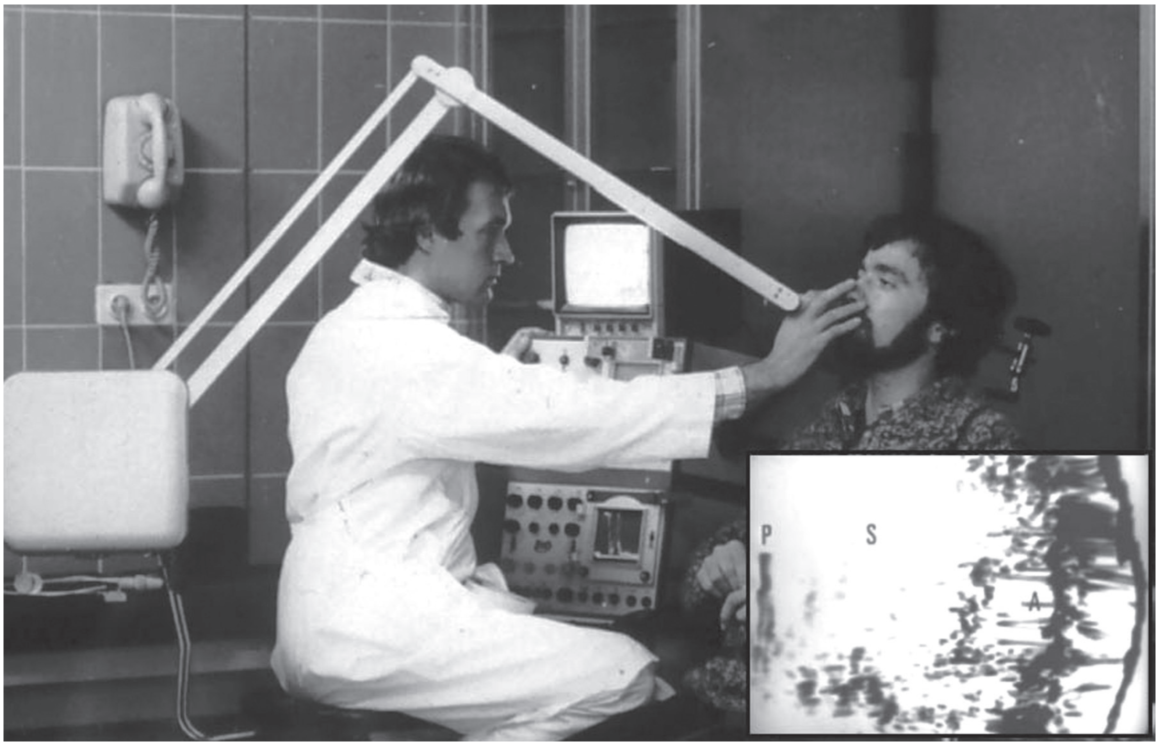

Figure 1–4. First compound scanner of the maxillary sinus in 1974 using the Combison (Kretz, Zipf, Austria). Inset: gray-scale image of maxillary sinus in a vertical plane for a patient with acute maxillary sinusitis. A = anterior wall of the sinus; P = posterior wall; S = sinus lumen with secretion.