The Role of Ultrasound in Medical Diagnostics and Treatment

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Abstract

The ultrasound machine generates images to examine various parts of the human body. It emits high-frequency sound waves that are reflected off bodily structures, and a computer receives these reflected waves to create images. Unlike X-rays or CT scans, ultrasound does not utilize ionizing radiation. Ultrasound has gained popularity due to its widespread availability and the ability of modern devices to produce high-resolution images, offering exceptional clarity, which in turn provides precision, accuracy, sensitivity, and specificity. A major advantage of ultrasound is that it allows frequent examinations without causing harm to the patient, as it does not emit radiation. As the name suggests, ultrasound typically refers to high-frequency sound waves. These waves pass through body tissues and are converted into electrical signals. The accuracy of ultrasound diagnostics depends on the operator's expertise in handling the equipment, selecting the appropriate probe, identifying artifacts, and interpreting the results. There are several ultrasound techniques, including A-mode, B-mode, M-mode, Doppler, contrast-enhanced ultrasound, and other techniques. In medicine, ultrasound is also used for interventional procedures, such as guiding biopsies. Ultrasound can visualize nearly all organ systems within the human body without causing harm to the patient, making it the gold standard in diagnostic imaging.

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Introduction

The ultrasound machine generates images by emitting high-frequency sound waves that reflect off bodily structures. A computer captures these waves to create images. Unlike X-rays or CT scans, ultrasound does not use ionizing radiation. Modern diagnostic equipment, including ultrasound, is widely available, in contrast to other imaging techniques like MRI or CT scans (Birnholz, 1977). Ultrasound devices now provide high-resolution images, ensuring reliability in terms of sensitivity, accuracy, and specificity. A key advantage is that ultrasound enables repeated examinations without patient harm, as it does not involve radiation. Ultrasound is used in a variety of clinical applications, from organ imaging to minimally invasive surgeries under ultrasound guidance. It is commonly used for screenings, diagnosing medical conditions, and monitoring heart and vascular health, including detecting conditions like atherosclerosis and blood clots.

Additionally, during pregnancy, ultrasound can identify fetal malformations and predict pregnancy outcomes. Transvaginal ultrasound is particularly informative in such cases, offering clearer insight than abdominal methods. Though using only ultrasound is not sufficient for a definitive diagnosis, it is vital for a comprehensive diagnostic approach and is often used alongside other tests like lab investigations. In some cases, ultrasound has 100% diagnostic reliability, particularly for urolithiasis, genitourinary tumors, and kidney pathologies. Transrectal ultrasound, for example, can detect prostate abnormalities, including enlarged adenomas. Overall, ultrasound remains one of the most comfortable and widely accepted diagnostic methods (Birnholz, 1977).

Ultrasound properties

Contrast resolution is primarily determined by the sensitivity of the ultrasound system, which depends on the ratio of useful signals to noise. The sensitivity of the scanner sensitivity depends on its ability to distinguish useful acoustic signals from noise in the presence of interference. Filters are used to separate signals from noise by setting a threshold that eliminates weak signals, which are likely noise. However, this does not guarantee complete noise elimination, as some signals may still fall within the threshold range. The dynamic range of the system defines the threshold for useful signals, representing the ratio of the maximum to minimum signal levels the system can display.

A larger dynamic range allows the system to present both high and low-intensity signals, enhancing sensitivity and image quality. The main component ensuring ultrasound vibration generation and echo signal detection is the transducer, typically containing 32, 64, or 128 piezoelectric elements. The sensor is designed to limit the spread of ultrasound vibrations and is coated with a polymer material that matches the acoustic impedance of biological tissues (McDicken & Anderson, 2011).

Optimal results are achieved by selecting the correct probe and setting the equipment properly to improve image resolution and minimize common artifacts. Modern ultrasound systems, similar to digital cameras, require minimal setting up to obtain and store images, with user adjustments often limited to brightness and contrast settings. Advanced systems offer adjustable parameters such as depth and power, allowing customization for specific surgical needs. Once the appropriate probe is selected, the system is configured accordingly (McDicken & Anderson, 2011).

One of the key goals of ultrasound is to obtain clear, focused images. By electronically focusing and controlling the ultrasound beam within a limited scanning area, sonographers achieve high-resolution images. The focus zone, located closest to the sensor, collects ultrasound waves in a narrow beam, providing the clearest image. Areas outside this zone experience rapid beam dispersion, leading to lower image quality. The focus zone can be adjusted to align with the diagnostic area, similar to how camera lenses focus on specific areas. Advanced ultrasound systems, such as linear and phased array sensors, allow the focus zone to be electronically adjusted at varying depths, even creating multiple focus zones. This feature improves image quality by narrowing the beam. While general ultrasound settings are adjusted to the scanning depth, sonographers often adjust parameters based on patient-specific factors, such as body composition or age. Changes to the scanning depth or area affect the frame rate, which is the speed at which the ultrasound image is updated. Multiple focus zones can reduce the frame rate, as each zone requires a narrow beam. These adjustments optimize visualization for clear tissue imaging (Henč-Bartolič, 2004).

Resolution of the ultrasound machine

Lateral resolution is determined by the width of the ultrasound beam, which must be smaller than the distance between two points for them to be perceived as separate. Beam width is limited by focusing capabilities but always exceeds the wavelength. Sagittal resolution refers to the minimal distance between two points aligned along the sagittal plane, influencing the thickness of the tissue slice. Thinner slices improve sagittal resolution, which depends on piezoelectric element parameters and acoustic lens characteristics. The spatial resolution of a scanner is defined by the axial, lateral, and sagittal resolution, collectively referred to as the resolution volume.

The focal point, where the beam width is minimal, is achieved using a spherical transducer surface. A smaller curvature radius results in better focusing. Dynamic focusing, using different curvature radii across multiple transducers, improves lateral resolution at various depths. In electronic sensors, dynamic focusing is achieved by delaying the excitation of piezoelectric elements and creating focal zones at desired depths. However, dynamic electronic focusing adjusts only lateral resolution, not sagittal resolution, which is improved by using an acoustic cylindrical lens (Henč-Bartolič, 2004).

Artifacts on ultrasound

Various artifacts affect the interpretation of ultrasound results. While some are unavoidable and enhance diagnostic accuracy, others, such as color gain set too high, create interference. Motion artifacts, including heart pulsations and aortic pulse, complicate imaging, especially when the color scale does not match the examined blood flow velocity, leading to color inversion. The confetti artifact, seen as small colored pixels, is indicative of post-stenotic turbulent flow, while flicker artifacts provide important diagnostic information, such as kidney stone detection. Artifacts like beam thickness or acoustic shadowing can also affect image interpretation, with the latter being valuable diagnostically. Reverberations, caused by multiple reflections between highly reflective surfaces, appear as linear artifacts and are interpreted as increased distance to the transmitter by the ultrasound system (Breyer, 1991).

Ultrasound probes, also known as transducers, vary in design to suit different diagnostic needs. The main types include:

- Linear Probes: These consist of a linear array of piezoelectric elements (up to 512), which are activated in groups when exposed to an electric signal. They produce a geometrically accurate image using parallel waves but may be limited in cases with large image sizes, such as gas in the intestines. Linear probes are ideal for visualizing superficial structures.

- Convex probes: Similar to linear probes but equipped with piezoelectric elements arranged along a convex surface, creating a fan-shaped wave pattern, allowing for a broader field of view.
- Sector probes: These are mechanical or electronic. In mechanical sector scanners, the sensor position changes to adjust the direction of the sound beam. In electronic scanners, phase differences in the electrical signal shift the sound beam while the sensor remains stationary. Sector probes are compact, making them suitable for scanning areas near barriers like ribs or bowel gas, especially when visualizing deeper structures.

Traditional ultrasound scanning is increasingly supplemented by digital signal processing, enabling billions of operations per second. Technological improvements, such as transitioning from single-row to multi-row (matrix) transducers with a wide frequency range, allow for signal frequency selection over a broad spectrum. Combined with digital processing and fast echo speeds, these advancements enable high-contrast, high-resolution imaging and the study of slow blood flow dynamics in small vessels (Jurilj, 2007).

Echo-contrast agents: Used to enhance harmonic frequency components, these agents aid in differentiating blood flow echoes from tissue echoes.

3D echography: High volumes of visual data are stored using high-speed signal processing. 3D images are reconstructed using echographic data from adjacent image slices without requiring a positioning transducer. B-mode and Doppler images can be displayed separately or combined (Jurilj, 2007).

The transducer core is a piezoelectric element that changes dimensions under an electric field or generates an electric field when deformed by vibrations. Most medical probes use polycrystalline lead titanate or lead zirconate materials. The transducer components include ceramic elements, a protective housing, and wiring connecting internal contacts to electronics. Auxiliary materials enhance the transducer's durability, extend the frequency range, or focus the sound beam.

The frequency of the transducer influences the shape and penetration depth of the ultrasound beam. Lower frequencies penetrate deeper but reduce resolution and Doppler shift, while higher frequencies offer improved resolution but limited tissue penetration. Most Doppler systems operate between 3-10 MHz, with lower frequencies favored for deeper structures like the heart and higher frequencies for vascular imaging (Breyer, 1991).

Properties of the ultrasonic wave

Sound waves propagate through air, liquids, and tissues as elastic waves, with molecules of the medium alternating between compression and rarefaction. Sound cannot travel in a vacuum. The speed of sound in tissue is approximately 1540 m/s, allowing precise measurement of travel time and distance using the time-distance principle.

Reflection of sound waves: The degree of reflection depends on acoustic impedance, which is the ratio of the intensity of the incident wave to the portion transmitted through the medium. Impedance is the product of the density and sound velocity of the medium, characterizing the scattering of wave energy (Planinić, 2005). According to the Doppler effect (Fig. 1), the frequency of a reflected sound wave changes as the source moves relative to the receiver. Frequency shifts from moving erythrocytes allow the analysis of blood flow velocity and direction in vessels and the heart.

Ultrasound quality: This depends on two factors: the highest possible resolution (linked to the transducer frequency) and the appropriate penetration depth (related to the lowest frequency). Shorter waves provide higher resolution but lower penetration, with the optimal frequency range for ultrasound diagnostics in the range of 1-10 MHz and an optimal wavelength range of 0.15-1.5 mm.

Sound speed varies based on medium density: approximately 1500-1600 m/s in soft tissues, 331 m/s in air, and 3500 m/s in bones. Most ultrasound instruments are calibrated for a speed of 1540 m/s. The sound pulse consists of two or three waves emitted axially. The maximum resolution in the axial direction is half the pulse length, approximately equal to one sound wavelength. For instance, at a frequency of 3.5 MHz, the axial resolution is about 0.5-1 mm. As depth increases, the ultrasound beam narrows and then widens, reducing intensity and resolution. The focal zone has a width of 3-4 wavelengths and provides maximum lateral resolution, approximately 2 mm at 3.5 MHz (Planinić, 2005).

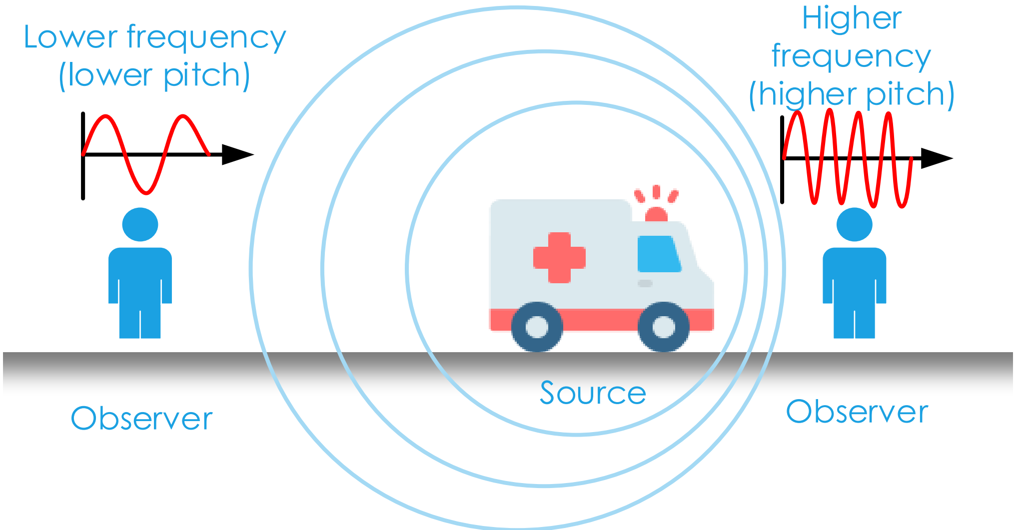

Figure 1. Doppler effect. Source: Author's illustration according to https://scienceready.com.au/pages/dopplers-effect

In echography, focusing the ultrasound beam improves resolution and detail recognition. Concave transducers create a converging beam due to reflection, and high-quality systems show clear resolution changes as the focal area shifts. Sound waves are partially reflected and transmitted through tissues, with greater impedance differences leading to stronger reflections, such as between soft tissue and bone or air.

High-impedance surfaces (e.g., gallstones) produce acoustic shadows, while scattering helps visualize organ contours. Refraction occurs when sound waves hit smooth, high-impedance surfaces at an angle. Absorption and attenuation convert sound energy into heat, remaining within safe limits according to the WHO, though lower energy is recommended for children and pregnant women.

Ultrasound frequencies range from 20 Hz to 20 kHz, and diagnostic ultrasound typically operates at around 106 Hz for visualizing tissues and gas bubbles (Jurilj, 2007; Planinić, 2005).

Reflected or scattered ultrasound waves are critical in medical diagnostics, with the strongest reflections occurring at boundaries between tissues with differing mechanical properties, such as soft tissue and bone or air-filled structures (e.g., lungs). The intensity of these reflections depends on the reflection coefficient, which compares the incident and reflected energy. Due to significant differences in acoustic impedance, gas pockets and bubbles strongly reflect ultrasound waves.

Ultrasound diagnostic systems consist of a transmitter that generates ultrasound frequencies, a transducer that converts ultrasound into electrical signals (and vice versa), and a display system for interpreting these signals. The interaction of tissues with ultrasound determines system performance. Frequencies used range from 1 MHz to 10 MHz, requiring specialized electronic devices to generate and amplify signals.

In Doppler systems, the transducer is vital for measuring blood flow velocities and is selected based on operating frequency, penetration depth, beam width, and Doppler shift frequency. Composite crystal transducers, commonly used in blood flow measurement, allow precise localization of flow measurement areas (Planinić, 2005).

Ultrasound techniques

A-mode

In A-mode, the amplitude of returning echoes from tissue boundaries is displayed as peaks along a horizontal axis, similar to an oscilloscope (Allan et al., 2011).

B-mode (brightness mode)

B-mode displays reflected ultrasound pulses as points with varying brightness proportional to their intensity, creating a two-dimensional image. About 120 scan lines are collected to form the image, with varying shades of gray representing different echo intensities. This mode is widely used in medical diagnostics and is critical for imaging organs and tissues, functioning similarly to sonar. Despite minor differences in the speed of sound in different tissues, it is generally considered constant in practice (Elias et al., 1987).

M-mode (motion mode)

M-mode captures the motion of structures like heart valves over time, creating a time-motion trace. It is commonly used in echocardiography to assess the dynamic movement of the heart and arteries. B-mode serves as the basis for M-mode and 2D imaging, displaying echo amplitude as brightness on the screen. This method allows continuous imaging for real-time observation of anatomical structures (Testa et al., 2011).

Continuous wave Doppler

Two piezoelectric crystals are used in Doppler ultrasound: one continuously transmits ultrasound waves, while the other receives the reflected signals. Frequency changes in the echoes are analyzed acoustically or visually to determine blood flow speed and direction, though depth information is lacking. In some Doppler probes, such as blood bubble detectors, transmission and reception elements are separate, allowing for better localization of the sensitive area within tissues (Shostak et al., 2022).

The Doppler effect, which alters wave frequency based on relative motion, applies to ultrasound as well. Reflected signals from moving objects, like red blood cells or gas bubbles, exhibit frequency shifts, known as Doppler shifts. Doppler flow meters respond only to these shifted signals, ignoring static structures without frequency variation. The magnitude of the Doppler shift correlates with the speed of the object, with higher speeds producing higher frequency signals. This effect is proportional to the ultrasound frequency, meaning a 10 MHz probe will yield twice the frequency shift of a 5 MHz one. Both continuous and pulsed Doppler systems emit ultrasound waves and receive the reflected signals. The frequency difference between the transmitted and reflected waves is the Doppler signal, which is only generated by moving structures (Shostak et al., 2022).

The output of the receiver can be evaluated audibly or as a waveform representing flow velocity. Selecting the correct Doppler receiver bandwidth is essential to minimize interference and accurately capture signals.

The Doppler signal from gas bubbles in the bloodstream produces a characteristic chirping or whistling sound. If the bubble speed is high, it becomes a clicking noise. Gas bubbles scatter ultrasound more effectively than solid or viscous particles of similar size, with Doppler signal amplitudes exceeding blood flow signals by over 10 dB, and up to 20 dB in some cases. Despite advances in electronic signal processing, the human ear remains a highly sensitive tool for detecting these chirps, especially in the precordial region where signals can be difficult to discern.

The Doppler effect in ultrasound refers to the frequency shift of reflected signals caused by the motion of an object, proportional to its speed. This effect allows for non-invasive measurement of blood flow direction and velocity, using ultrasound reflections from blood cells (Shostak et al., 2022). In A-mode (amplitude mode), ultrasound intensity is displayed as oscillation amplitude on a screen, without recording movement, making it useful in neurology, ophthalmology, and ENT diagnostics (Jurilj, 2007). Echoencephalography (Echo-EG), used for detecting intracranial abnormalities, records ultrasound reflections from brain structures, showing distinct patterns on an oscilloscope.

Recent advancements in continuous wave Doppler ultrasound have significantly broadened its applications in clinical practice, particularly in cardiology and obstetrics. For instance, continuous wave Doppler is now integral in assessing fetal heart rate and blood flow in the umbilical artery, allowing clinicians to monitor fetal well-being during pregnancy and detect potential complications early (Muglu et al., 2019). Furthermore, enhanced Doppler imaging techniques, such as color Doppler and power Doppler, have emerged, providing more detailed visualization of blood flow patterns and vascular structures. These technologies allow for the assessment of both the direction and velocity of blood flow in real-time, improving diagnostic accuracy for conditions like vascular occlusions and cardiac abnormalities. Additionally, ongoing research is focusing on integrating artificial intelligence with Doppler ultrasound to automate and enhance the interpretation of blood flow patterns, which may streamline clinical workflows and reduce the potential for human error in complex cases. As the field progresses, continuous wave Doppler ultrasound is set to play an increasingly pivotal role in non-invasive diagnostics and monitoring across various medical specialties (Micucci and Iula, 2022).

Pulse Doppler

This technique uses a single piezoelectric crystal that alternates between transmitting and receiving pulse wave echoes, enabling the measurement of depth and width in a target volume, as well as blood flow analysis in a localized area (11). The position of the sample volume is controlled by adjusting the pulse repetition frequency (PRF). Increasing PRF moves the sample to a shallower depth, while decreasing PRF shifts it to a greater depth. On ultrasound devices, PRF automatically adjusts based on the selected depth setting in millimeters (Mjolstad et al., 2012).

Duplex sonography

Doppler is combined with B-mode imaging to position the Doppler beam and select the area of interest under visual control. Synonyms include CDE, color flowmetry (CFM), and color Doppler mapping (CDC) (12). Color duplex ultrasonography merges grayscale imaging with Doppler flowmetry. Doppler readings are placed within the B-mode sector, with frequency shifts recorded and color-coded: red for flow toward and blue for flow from the transducer. Depth penetration and flow velocity depend on the transducer and frequency used. Power should be minimized to prevent artifacts such as false turbulence. Receiver gain (PWR) and filtering are adjusted to optimize frequency detection, with settings depending on the expected flow range (e.g., lower frequencies for parenchymal vessels). The detected Doppler shift is affected by the angle of incidence, with more accurate velocity measurements at smaller angles. Correct conversion of frequency shifts to velocity requires a known incidence angle, marked using the angle indicator for blood flow direction (Jurilj, 2007).

Power Doppler

This technique displays the spatial distribution of blood flow but does not indicate its direction. It is primarily used to confirm the presence or absence of flow and quantify it. Power Doppler is particularly effective for detecting areas of increased vascularization, such as inflammation. Unlike color Doppler, it measures the energy of ultrasound reflected from blood flow rather than its velocity, making it less dependent on the angle between the ultrasound beam and blood flow. It is more sensitive to slow flows and resistant to noise, making it ideal for assessing organ vascularization and blood flow. Some scanners combine both technologies for enhanced flow analysis (Yao et al., 2020).

Ultrasound with contrast

Current ultrasound technology can detect lesions as small as 4 mm in diameter. However, some formations are difficult to detect due to patient factors (e.g., obesity, intestinal gas, inability to take deep breaths) or acoustic properties of iso-echoic tumors. In such cases, echo contrast agents (echogenic particles injected intravenously) help localize and characterize lesions using the Doppler effect (Erlichman et al., 2017).

A key advantage of phased-array sector scanners is their high resolution and large field of view. By adjusting the delay times in each receiver channel, the focus can be synchronized with returning echoes, ensuring that all targets within the field are in focus. This feature overcomes the limitations of fixed-focus probes (Erlichman et al., 2017).

To enhance acoustic contrast in standard M-mode imaging, indocyanine green is injected, but the actual contrast is generated by gas microbubbles formed during injection. This has been confirmed in similar studies using isotonic calcium chloride. Contrast-enhanced ultrasound has been used for visualizing right atrioventricular valve insufficiency and septal defects. Gas microbubbles create a significant acoustic impedance difference, making the reflected energy easily detectable (Erlichman et al., 2017).

Temporal resolution refers to the number of frames per second provided by the scanner. It is limited by the scanning process, as the ultrasound beam sequentially examines the area and displays information only after the scan is complete. Processor speed is another limiting factor, especially when combining modes, such as black-and-white and color images. The faster the system, the better the temporal resolution. High frame rates, typically above 70 Hz on computer monitors, ensure smooth image display, reducing eye strain and diagnostic errors, especially in dynamic studies like echocardiography.

Contrast resolution indicates the ability of the scanner to differentiate minimal intensity differences in reflected signals. In B-mode, contrast is displayed as varying brightness levels, with each pixel capable of showing up to 256 shades of gray, enhancing diagnostic accuracy. However, the human eye can only distinguish 30 to 50 shades, so increasing gradation beyond 256 does not improve visualization, while reducing it can hinder diagnostic quality (Erlichman et al., 2017).

3D ultrasound

Tissue Doppler imaging (TDI) is a Doppler technique used to study tissue motion, primarily for diagnosing myocardial contractility issues. More recently, it has been applied to assess vascular wall motion. TDI operates in three main modes: 2D color, color M-mode, and pulsed wave mode. Like color Doppler blood flow mapping, the color mode encodes the velocity and direction of myocardial motion rather than blood particles. Color M-mode captures myocardial motion with higher resolution and allows for phase analysis of cardiac activity. Pulsed wave TDI provides segmental and layer-specific information about myocardial movement, similar to traditional Doppler (16).

Additionally, advanced modes, such as myocardial strain, tissue tracking, and 3D imaging, provide volumetric insights by encoding reflected ultrasound in three dimensions. This 3D approach combines 2D scans in frontal and sagittal planes to produce a volumetric representation, streamlining the process with modern electronic advancements (16).

4D ultrasound

Using a conventional 2D sensor and a specialized scanning algorithm, 3D images are created by mechanically moving the sensor along the examined body area. Free-hand 3D reconstruction requires significant time and expertise, limiting its use in routine ultrasound exams (Obruchkov, 2008). In contrast, real-time 3D (or 4D) imaging, which relies on a high-performance processor and advanced image-processing algorithms, provides dynamic 3D visualization with a virtual time axis. This technology relies on specialized volumetric electronic matrix sensors equipped with around 3,000 elements. Notably, 3D scanning terminology is still evolving, and the same techniques are often designated differently, such as dynamic 3D (or 4D) (Obruchkov, 2008).

4D ultrasound technology has significantly advanced prenatal imaging by providing real-time visualization of fetal movements and anatomical structures. This dynamic imaging capability enhances the ability to assess fetal development, including the detection of congenital anomalies and assessing organ function. For instance, studies have shown that 4D ultrasound improves the visualization of facial features, allowing for better evaluations of conditions like cleft lip and palate (Bashir et al., 2015).

Furthermore, the incorporation of 4D imaging in obstetrics has been associated with increased parental bonding, as expectant parents can observe their baby's movements and behaviors, making the experience more engaging .

In addition to obstetric applications, 4D ultrasound is also being explored in areas such as cardiology and musculoskeletal imaging, offering insights into cardiac function and joint dynamics.

As this technology continues to evolve, ongoing research focuses on enhancing image quality, reducing acquisition times, and improving the diagnostic utility of 4D ultrasound across various medical specialties (Daoud et al., 2022).

Ultrasound in clinical practice

In clinical practice, ultrasound of the head and neck primarily assesses the thyroid and cervical lymph nodes, differentiating them from other neck masses, salivary glands, and parathyroid glands. Due to their superficial location, these structures are ideally suited for high-resolution ultrasound, which is non-ionizing, accessible, and relatively inexpensive. While ultrasound offers excellent sensitivity for detecting small pathological changes, it has lower specificity. This issue is resolved by combining ultrasound with guided fine-needle aspiration biopsy, enhancing diagnostic accuracy. Routine ultrasound-guided biopsy allows lesion identification, characterization, monitoring of benign processes, and assessment of potential complications. Portable ultrasound devices are widely used by surgeons and endocrinologists in outpatient settings.

Ultrasound is primarily employed for thyroid examination, often requiring no additional imaging. However, limitations include difficulty in assessing large lesions, deep structures, and multiple lesions, as well as challenges caused by gas and bone interference. For example, ultrasound may struggle with evaluating tumor spread beyond the thyroid or assessing deep parotid gland lesions, salivary gland tumors, or perineural metastases. Doppler ultrasound with contrast evaluates blood flow within pathological formations, including resistance, flow speed, and patterns, though power Doppler is more sensitive than color Doppler for detecting blood flow (Birnholz, 1997).

Elastography, when combined with sonography, uses tissue compression or focused ultrasound to create real-time elastograms, which are superimposed on grayscale sonograms.

Ultrasound of the gallbladder and biliary tract

The gallbladder, filled with bile and easily visualized on ultrasound, closely adheres to the liver and is examined alongside it. It lies along the middle hepatic vein and interlobar sulcus. Due to its small diameter, the cystic duct and intrahepatic ducts can only be seen when dilated. The common hepatic duct is typically visible at the hepatic hilum, while the common bile duct may be obscured by gas in the stomach or duodenum. After cholecystectomy, the common bile duct may slightly enlarge. The gallbladder and bile ducts are susceptible to various inflammatory conditions and neoplasms, along with cholelithiasis and associated complications, such as acute and chronic cholecystitis, being the most common.

Ultrasound is frequently used to diagnose cholecystitis, one of the most common indications for abdominal ultrasound. Fasting for 6-8 hours is required before scanning. Gallbladder imaging is performed in multiple planes and patient positions, including subcostal and intercostal windows, with static images taken in longitudinal, transverse, and oblique planes. Different patient positions, such as supine or left lateral, may enhance visualization, and patient movement helps assess mobility within the gallbladder lumen, distinguishing stones from polyps. In cases where the patient is immobile, slight adjustments, such as elevating the bed head or using a forward-leaning position, can aid visualization.

Gas in the stomach or duodenum may obscure the distal bile duct, but color Doppler sonography evaluates masses and wall thickening. Doppler artifacts may indicate the presence of stones or adenomyomas. Spectral Doppler assesses blood flow dynamics and direction (Popescu & Sporea, 2010).

Ultrasound of the pancreas

Fasting for 6-8 hours before ultrasound enhances image quality by reducing gas in the stomach and intestines. The scan is performed using a convex transducer at the highest frequency, typically up to 5 MHz, though advanced sensors can operate up to 9 MHz without losing acoustic clarity. Tissue harmonic ultrasound improves image quality, especially for fluid-filled structures such as cystic neoplasms, the pancreatic duct, and vasculature. Doppler ultrasound assesses vascularity, including tumor vascularization.

The pancreas should be examined in both transverse and longitudinal planes. For improved visualization, patients may be positioned in various ways, such as supine, standing, or while holding their breath. Pressure applied to the abdomen can help collapse gas-filled loops for better imaging, although it may be uncomfortable. A small amount of water or contrast medium (100-300 ml) can also enhance visualization, particularly for the pancreatic tail, though this technique is rarely used due to potential artifact formation.

The spleen serves as an acoustic window for viewing the pancreatic tail. Contrast-enhanced ultrasound using second-generation microbubble contrast agents allows better differentiation between solid and cystic masses. It also aids in differentiating focal pancreatitis from neoplasms. Special software may be needed to suppress signals from surrounding tissues, allowing the visualization of vascularized structures. This technique can detect conditions like chronic pancreatitis, pancreatic ductal carcinoma, cystic lesions, and various pancreatic tumors (Zamboni et al., 2012).

Ultrasound of muscles, ligaments, tendons, cartilage

Healthy muscle tissue appears relatively hypoechoic, while bone surfaces and calcifications are highly echogenic with distal acoustic shadowing and possible reverberation if the bone surface is smooth. Hyaline cartilage covering joint surfaces is hypoechoic and homogeneous, whereas fibrocartilage, such as the labrum of the hip and shoulder joints or menisci of the knee, appears hyperechoic. Ligaments are hyperechoic with a fibrous, denser structure compared to tendons.

Advanced ultrasound techniques, such as multi-beam compounding, improve scanning and diagnostic capabilities. This method directs multiple ultrasound beams at different angles, creating a single image with enhanced spatial resolution, though it may reduce image sharpness and cause blurring during movement due to frame summation. Foreign body artifacts can also change during multi-beam scanning, potentially affecting visualization.

Unlike static imaging techniques such as X-rays, CT, and MRI, ultrasound offers a significant advantage—real-time dynamic imaging. The scanning process is guided by the patient's history, symptoms, and physical examination, with each stage focused on areas of pain or other symptoms, allowing targeted imaging and confirmation of pathology when needed (Graberski Matasović, 2003).

Ultrasound-guided puncture biopsy

Ultrasound-guided percutaneous interventions offer several advantages, including continuous visualization and precise needle placement, minimizing the risk of complications by avoiding vital structures. Compared to blind techniques, ultrasound guidance enhances accuracy, efficiency, and cost-effectiveness. It is particularly beneficial in locating superficial masses, reducing procedure time, and overcoming the limitations of standard imaging methods like CT. Other benefits include accessibility, mobility, absence of ionizing radiation, and lower costs.

This chapter focuses on ultrasound-guided interventions, particularly those involving joints, bursae, tendon sheaths, and other anatomical structures. While ultrasound navigation is widely used across diagnostic and therapeutic procedures, the emphasis is on ultrasound control rather than the effectiveness of individual interventions. Accurate targeting requires knowledge of normal anatomy and pathological echographic signs (Khati et al., 2011).

Techniques for ultrasound-guided percutaneous punctures include indirect and direct methods. The indirect method identifies the target and marks its location on the skin, but lacks continuous needle visualization, limiting its application. The direct method allows real-time needle visualization, offering superior accuracy and lower complication rates. This can be achieved using free-hand techniques or biopsy needle guides, though the latter is less common for musculoskeletal interventions due to added complexity. The n-plane technique introduces the needle along the scan plane, ensuring full visualization of the needle tip and tissues (Khati et al., 2011).

Conclusion

An ultrasound machine creates images allowing the examination of different parts of the human body. The device sends high-frequency sound waves that bounce off body structures. The computer receives the waves and uses them to create an image. Ultrasound, as the name implies, is an ordinary high-frequency sound wave. As the wave passes through body tissues, it is converted into an electrical signal. The accuracy of ultrasound diagnostics depends on the operator's skill in handling the device, choosing an adequate probe, perceiving artifacts and reading the findings.

The popularity of ultrasound is primarily due to its availability, and today, ultrasound devices provide visualization in the form of high-resolution images, meaning very clear images. This ensures reliability in terms of accuracy, specificity and sensitivity. The ultrasound method allows multiple examinations to be carried out without harm to the patient, as there is no radiation.

There are several ultrasound techniques, such as A-mode, B-mode, M-mode, Doppler, and ultrasound with contrast.

In medicine, ultrasound is widely used in diagnostics, as well as in interventional applications, such as biopsies guided by ultrasound. Ultrasound can visualize almost any organ in the human body and does not harm the patient, which is why it is the gold standard in diagnostic tests.

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