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Ultrasound device: An overview

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Abstract
Ultrasound refers to sound waves that operate at frequencies exceeding 20 kHz. In atmospheric conditions, ultrasonic waves in air possess wavelengths of 1.9 cm or shorter. These ultrasonic devices are employed for object detection and distance measurement. Ultrasound imaging stands out as one of the most rapidly evolving techniques in medical diagnostics and treatment. Advancements such as elastography and contrast-enhanced ultrasonography have greatly enhanced tissue characterization and vascular evaluation, while super-resolution and molecular imaging methods provide new perspectives on tissue microvasculature, inflammation, and angiogenesis. The integration of these functional and molecular insights with radiomics improves the diagnostic and prognostic capabilities of ultrasound. In addition to its diagnostic applications, ultrasound demonstrates significant therapeutic potential, with high-intensity focused ultrasound (HIFU) currently under investigation for tumor ablation, and microbubble-mediated sonoporation facilitating targeted drug and gene delivery. Technological advancements have broadened the application of ultrasound into various industrial and scientific fields, including non-destructive testing, cleaning, and even the generation of sonoluminescence for experimental physics. Despite its non-invasive, non-ionizing, and widely available characteristics, the reproducibility of ultrasonographic examinations is still constrained by operator variability, a challenge that can be mitigated through standardization and automated image analysis. This review offers a thorough examination of contemporary trends and translational innovations in diagnostic and therapeutic ultrasound, highlighting their clinical importance and the prospective future of this vital modality.

Keywords: Ultrasound, ultrasonography, diagnostic imaging, Radiomics, TVS

Introduction
Ultrasound technology has been established as a crucial tool in various scientific and industrial fields, especially in medical diagnostics and therapeutic applications. The American National Standards Institute defines ultrasound as "sound waves with frequencies exceeding 20 kilohertz (kHz)," which is a frequency that is considerably higher than the upper limit of human hearing, approximately 20,000 Hertz, with minor variations among individuals (Fig 1). When these high-frequency waves propagate through air at standard atmospheric pressure, they produce wavelengths of 1.9 centimeters or less, enabling ultrasonic devices to possess the extraordinary ability to detect objects, accurately gauge distances, and evaluate the characteristics of materials or tissues through non-invasive methods. Figure 2 depicts the basic structure of an ultrasound device.

Definition: Ultrasound is defined by the American National Standards Institute as "sound at frequencies greater than 20 kHz". In air at atmospheric pressure, ultrasonic waves have wavelengths of 1.9 cm or less.

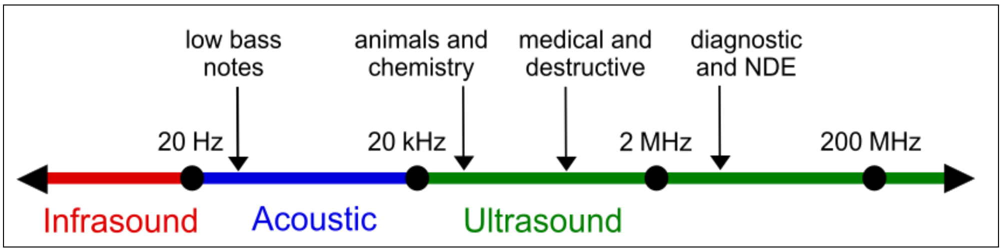


Fig 1: Ultrasound frequency (>20kHz)

Fig 2: Ultrasound device

In the field of clinical practice, ultrasound has emerged as one of the most commonly employed imaging techniques, due to its adaptability, safety, and ability to provide real-time images.

Working Principle: An ultrasound machine produces images that facilitate the assessment of internal organs. It emits high-frequency sound waves that reflect off bodily structures. A computer receives these waves and processes them to create an image. Figure 3 demonstrates the operational principle of ultrasound devices employed in medical diagnostics.

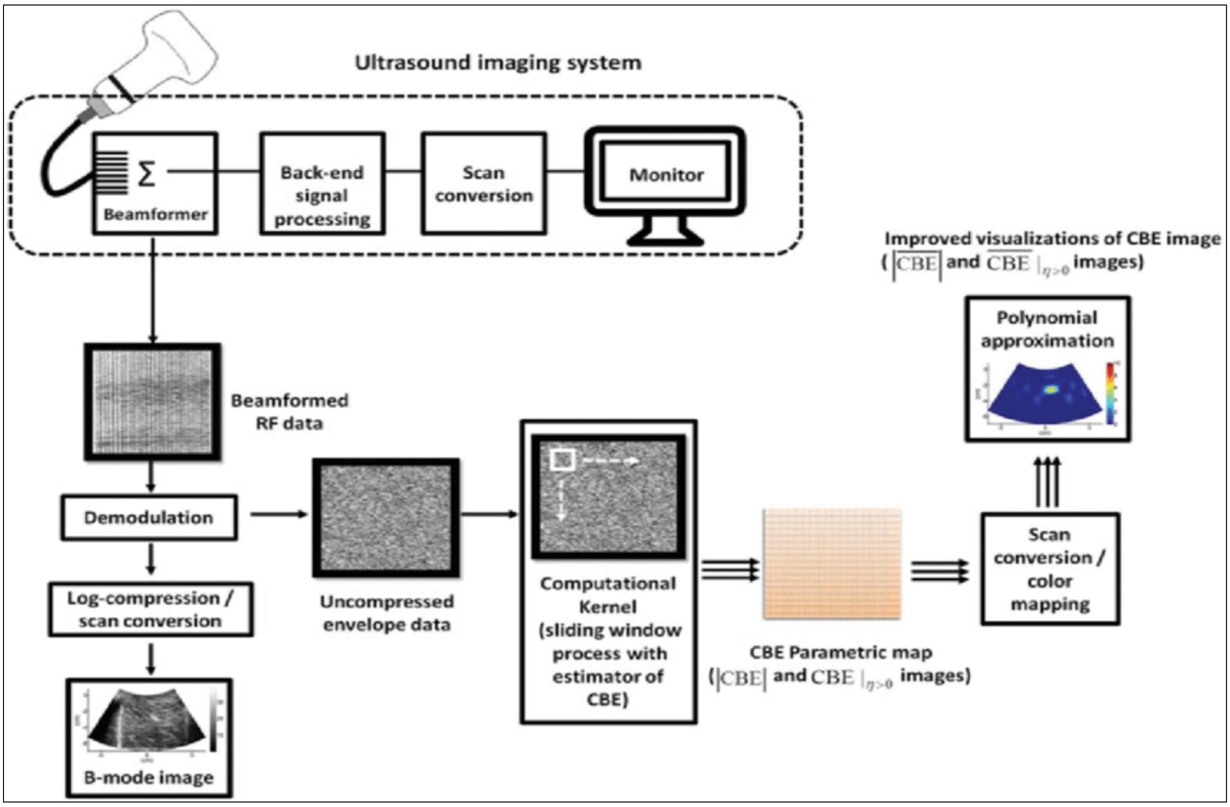


Fig 3: Working principle of ultrasound device

Wave frequency: When an ultrasound scanner is employed, the transducer assumes a pivotal function by generating a concentrated beam of high-frequency sound waves directed into the body. These sound waves navigate through diverse biological substances, such as air, water, bodily fluids, soft tissue, blood, and bone, each exhibiting distinct acoustic characteristics.

Wave attenuation: The fundamental physical parameters involved consist of frequency, propagation speed, pulse characteristics, the interaction of the wave with tissue, angle of incidence, and attenuation. Sound is fundamentally a type of mechanical energy that travels through a medium in alternating phases of high and low pressure, known as compression and rarefaction.

Wave reflection: Ultrasound transducers are generally designed using piezoelectric ceramic crystals that possess distinctive electromechanical characteristics. When an electric field is applied to these crystals, they vibrate and emit ultrasonic sound waves at specific frequencies.

Image formation

Once generated, the sound waves travel through the body's tissues, consistently meeting tissue interfaces where differing acoustic impedance results in partial reflection of the wave. The returning echoes are received by the transducer and converted into electrical signals.

Types of clinical ultrasound techniques

Diagnostic Ultrasound: Diagnostic ultrasound is a non-invasive imaging technique that is widely used to visualize the internal organs of the body. One of the most common applications of ultrasound occurs during pregnancy, where it is used to carefully monitor the growth and development of the fetus. Beyond obstetrics, ultrasound is extensively utilized for imaging various structures including the heart, blood vessels, eyes, thyroid, brain, breast, abdominal organs, skin, and muscles. The images produced can be in two-dimensional (2D), three-dimensional (3D), or four-dimensional (4D) formats, with 4D representing 3D imaging in motion.

Functional Ultrasound: Functional ultrasound includes sophisticated techniques like Doppler and color Doppler imaging, which are utilized to measure and visualize blood flow within vessels or the heart. These techniques quantify both the velocity and direction of blood flow through the use of color-coded maps. Doppler ultrasound is especially beneficial for evaluating the presence of plaque in carotid arteries, which helps assess potential blockages that may restrict blood flow to the brain. Another significant functional application is elastography, which estimates and maps the stiffness of tissues. This technique aids in distinguishing tumors from normal tissues by producing either color-coded stiffness maps, high-contrast grayscale images, or overlays that integrate stiffness data with anatomical images.

Therapeutic or Interventional Ultrasound: Therapeutic ultrasound utilizes high-intensity sound waves directed at particular tissue areas for the purposes of heating, ablating, or disrupting abnormal tissues. A notable technique known as High Intensity Focused Ultrasound (HIFU) employs precisely focused beams to selectively address diseased tissues, such as tumors, while avoiding surgical cuts or harm to surrounding healthy tissues. The guidance and monitoring of treatment can be conducted using either ultrasound or magnetic resonance imaging (MRI), thereby guaranteeing accuracy and effectiveness throughout the therapy.

Ultrasound procedure

Scope of clinical applications: Ultrasound is widely utilized in clinical environments for purposes such as screening, diagnostic assessment, and procedural support. It facilitates the examination of various organs, including the thyroid, breast, prostate, and liver.

During most ultrasound examinations, such as an upper abdominal scan, patients are positioned on an examination table while a sonographer applies a conductive gel to their skin. This gel enhances the contact between the ultrasound probe and the skin, thereby facilitating the transmission of sound waves. The hand-held transducer is maneuvered over the examination area, transmitting real-time 2D or 3D images to a monitor for immediate viewing.

Transvaginal sonography (TVS)

Normal anatomy and variants: Transvaginal ultrasound (TVS) facilitates comprehensive imaging of pelvic organs across a minimum of two planes, taking into consideration variations due to age and the menstrual cycle. The evaluation encompasses the dimensions, contours, echotexture, and echogenicity of the organs.

- **Bladder:** Evaluation of size, shape, and contents.
- **Cervix:** Internal and external os, cervical canal, continuity with uterus, size, outline, and echotexture.
- **Vagina:** Outline and echotexture.
- **Recto-uterine Pouch (Pouch of Douglas):** Assessment of presence and volume of fluid.

Uterus is evaluated for

Position (anteversion, retroversion, anteflexion, retroflexion). - Dimensions in accordance with age-specific normative ranges. - Form and outline, recognizing irregularities such as a bicornuate or septated uterus, or masses that interfere with the normal contour. - Endometrial thickness and echo pattern assessed based on menstrual phase and menopausal condition. - The myometrium is analyzed for echotexture and the existence of hypo- or hyperechoic regions.

Ovaries are examined for size, shape, position, follicle count and appearance, and echogenicity.

Adnexae evaluations encompass fallopian tubes, broad ligaments, pelvic muscles, and pelvic vasculature.

Table 1. Summarizes the ultrasound sonographic features of common uterine and ovarian pathologies.

Table 1: Ultrasonographic features of pathologies

Anatomical structure	Pathology and their Ultrasound features
Uterine Myometrium	**Fibroids (Leiomyoma/Myoma):** Benign tumors comprised of fibrous and smooth muscle tissue; can be intramural, subserosal, submucosal, pedunculated, or cervical in location. Multiple or single fibroids of varying sizes; characterized by well-defined masses with altered echogenicity. May contain fibrous tissue, calcification, or necrosis. Color Doppler may show vascularity and adjacent vessels; vascular patterns vary and may not be definitive for diagnosis.
	Adenomyosis: Presence of diffuse or nodular endometrial tissue deposits within the myometrium. Typically affects multiparous women in their mid-40s with menorrhagia and dysmenorrhea. Ultrasound shows enlarged uterine fundus and body, particularly the posterior myometrium, acoustic linear striations, indistinct endometrial-myometrial interface, and coarse heterogeneous myometrial echotexture.
	Uterine Sarcoma: Malignant carcinoma of uterine muscle; rare (<5% uterine malignancies). Appears as a very heterogeneous myometrium with possible cystic spaces. Can mimic fibroids or endometrial carcinoma but suspected when rapid size increase occurs.
Endometrium	**Carcinoma:** Presents primarily as abnormal uterine bleeding, especially unscheduled post-menopausal bleeding. There is a 50% association with polyps or submucosal myomas. Normal ultrasound endometrial thickness is ≤5 mm, with some

	protocols using 4 mm. Drug effects (e.g., hormone therapy, tamoxifen) can alter appearance.
	Polyps: Common in pre- and post-menopausal women with thickened endometrium, often asymptomatic but may cause intermenstrual or postmenopausal bleeding. Appear as focal endometrial thickening or echogenic masses with feeder vessel visible on color Doppler.
	Asherman's Syndrome: Characterized by increased echogenicity at the junctional zone of the endometrium and myometrium, associated with uterine adhesions usually post dilation and curettage.
	Haematometrocolpos: Accumulation of menstrual blood in vagina and uterus, often due to imperforate hymen, cervical stenosis, or post-surgical obstruction.
Ovary	**Simple Cyst:** Common benign finding, especially in premenopausal women; well-defined, echo-free, unilocular with thin smooth walls and good acoustic transmission. Most resolve without intervention.
	Ovarian Torsion: Ultrasound shows an enlarged, congested, and edematous ovary, often with complex adnexal mass and free pelvic fluid. Perfusion is reduced or absent due to vascular occlusion.
	Hemorrhagic Cyst: Initially homogeneous echogenicity that becomes heterogeneous as blood clots form; may cause pain or rupture inducing peritoneal irritation. Echoes vary from low-level homogeneous to septated clot formations.
	Endometrioma: Smooth, thick-walled cysts filled with old blood, homogeneous echotexture, with acoustic enhancement and no loculations or solid elements. Often coexists with other pelvic endometriotic deposits.
	Polycystic Ovarian Syndrome (PCOS): Syndrome characterized by ovarian dysfunction with hyperandrogenism and polycystic ovary morphology. Diagnostic criteria include oligo/anovulation, clinical or biochemical hyperandrogenism, and specific ovarian ultrasound features (≥12 follicles sized 2-9 mm and/or ovarian volume >10 mL). Clinical manifestations include menstrual irregularities, hirsutism, acne, and obesity.

Table 2: Ultrasound in dentistry

Specialty	Clinical Applications
Periodontology	Measuring and visualizing gingival thickness Detecting and mapping periodontal pockets Identification of subgingival calculus Monitoring response to periodontal therapy
Endodontics	Detection and monitoring of periapical lesions Identification of root fractures and canal obstructions Monitoring healing after root canal therapy Assessing root morphology
Oral and Maxillofacial Surgery	Preoperative localization of impacted teeth, cysts, and tumors Intraoperative guidance for implant placement Real-time soft tissue assessment Postoperative evaluation of healing
Salivary Gland Disorders	Evaluation of glandular structure Diagnosis of sialolithiasis, obstructions, and inflammation Guidance for minimally invasive procedures
Caries Detection	Experimental use in identifying enamel and dentin demineralization Non-ionizing, real-time screening (future/adjunct tool)
TMJ and Adjunctive Uses	Dynamic imaging of TMJ function and disorders Assessment in muscle and orthodontic therapies Peri-implant tissue evaluation

Sonication: Ultrasonication presents significant opportunities in the treatment of liquids and slurries, enhancing mixing and chemical reactions across a range of applications and industries. It produces alternating low-pressure and high-pressure waves within liquids, resulting in the creation and explosive collapse of tiny vacuum bubbles.

Sonochemistry: Power ultrasound operating within the 20-100 kHz frequency range finds application in the field of chemistry. The ultrasound does not directly engage with molecules to facilitate chemical alterations, as its usual wavelength, which is in the millimeter range, is excessively long in comparison to the size of the molecules.

Ultrasonic manipulation and characterization of particles

A researcher from the Industrial Materials Research Institute, Alessandro Malutta, developed an experiment that showcased the trapping effect of ultrasonic standing waves on wood pulp fibers suspended in water, leading to their alignment into equidistant pressure planes. The duration required to align the fibers within these equidistant planes is assessed using a laser and an electro-optical sensor.

Echolocation: Echolocation refers to the method by which sound waves and their echoes are utilized to identify objects in the environment. Bats employ echolocation to navigate and locate food in darkness.The characteristics of the echo enable them to ascertain the size, shape, and distance of the object.

Motion sensors and flow measurement: A prevalent use of ultrasound technology is in automatic door openers, where an ultrasonic sensor identifies an individual's approach and activates the door mechanism. Additionally, ultrasonic sensors serve the purpose of intruder detection, as they can monitor a broad area from a single location. Ultrasonic flowmeters are employed to gauge the flow in pipes or open channels by measuring the average velocity of the liquid in motion.

Sonoporation: Microbubble-enhanced ultrasound is being utilized more frequently to enhance drug delivery to pathological locations. In this regard, various strategies can be considered, pertaining either to direct drug delivery (i.e., encapsulating the drug within the microbubble core or shell) or to indirect drug delivery (i.e., the simultaneous administration of drugs and microbubbles). Clinically, the most advancements have been achieved with the latter method, where oscillating microbubbles generate stable or inertial cavitation to facilitate vascular perfusion, increase vascular permeability, or enhance tissue penetration.

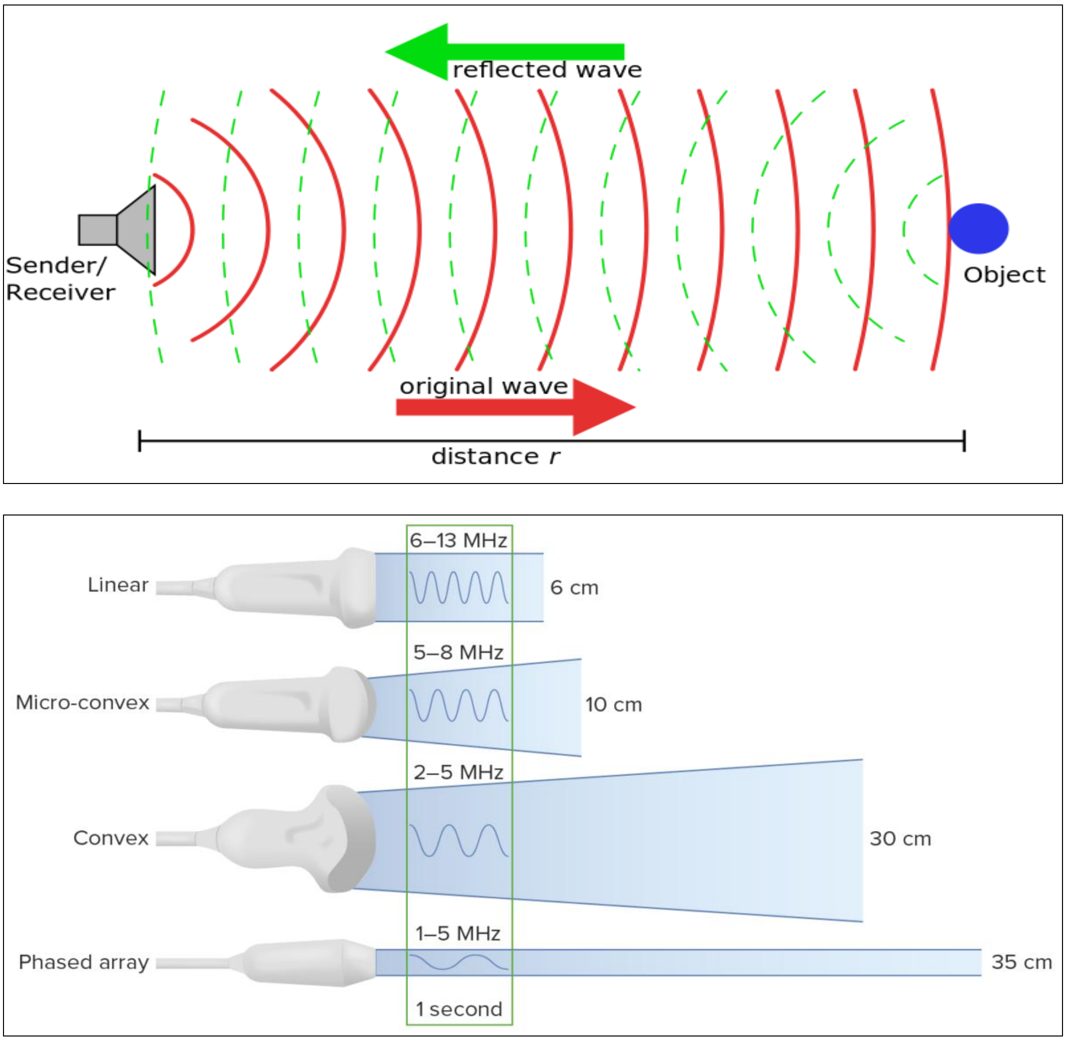


Fig 4: Sonoporation - principle

Ultrasound Identification (USID): Ultrasound Identification (USID) is a technology that falls under the category of Real-Time Locating Systems (RTLS) or Indoor Positioning Systems (IPS). It is designed to automatically monitor and determine the location of objects in real time by utilizing straightforward and cost-effective nodes (badges/tags) that are either affixed to or integrated within objects and devices. These nodes subsequently emit an ultrasound signal to relay their location to microphone sensors.

1) **Ultrasonic cleaning:** Ultrasonic cleaners, sometimes mistakenly called supersonic cleaners, are used at frequencies from 20 to 40 kHz for jewellery, lenses and other optical parts, watches, dental instruments, surgical instruments, diving regulators and industrial parts.
2) **Ultrasonic disintegration:** In a manner akin to ultrasonic cleaning, biological cells, such as bacteria, can be broken down. High-intensity ultrasound generates cavitation, which aids in the disintegration of particles or the occurrence of reactions. This technique finds applications in biological sciences for both analytical and chemical objectives (including sonication and sonoporation) as well as in the eradication of bacteria in sewage.
3) **Ultrasonic humidifier:** The ultrasonic humidifier, one type of nebulizer (a device that creates a very fine spray), is a popular type of humidifier. It works by vibrating a metal plate at ultrasonic frequencies to nebulize (sometimes incorrectly called "atomize") the water. Because the water is not heated for evaporation, it produces a cool mist.

Contrast-enhanced ultrasound imaging (CEUS)

For numerous years, CEUS has been integrated into clinical practice for the characterization of suspected lesions across various organs, particularly the liver, as well as for identifying cardiovascular abnormalities (for instance, through echocardiography). In the realm of cardiovascular imaging, microbubbles are primarily utilized to amplify the signal within the vessel lumen and to depict stenoses and aneurysms.

Super-resolution ultrasound imaging

In a manner akin to the 2014 Nobel Prize in Chemistry, which recognized advancements in overcoming the diffraction barrier to produce super-resolution microscopy images, ultrasound imaging is also pursuing super-resolution techniques to examine the microvasculature of tissues. Subsequently, additional research demonstrated that this approach can enhance the resolution of a clinical ultrasound system by a factor ranging from 2.2 to 5.5. In 2015, Eckersley's team published the inaugural *in vivo* data pertaining to functional super-resolution ultrasound. Their image post-processing algorithm facilitated the extraction of flow direction and velocity data from the microvasculature of a mouse ear.

Fig 6: Super-resolution Ultrasound imaging

Ultrasound imaging utilizing targeted microbubbles has been effectively employed in preclinical studies to explore molecular changes in the endothelium that take place during pathophysiological processes associated with cancer, cardiovascular diseases, and gastrointestinal disorders, as well as in reaction to therapeutic treatments. In the field of oncology, in particular, microbubbles that target the vascular endothelial growth factor receptor 2 (VEGFR2) have demonstrated significant sensitivity for the *in vivo* characterization of tumor angiogenesis and the evaluation of therapeutic response.

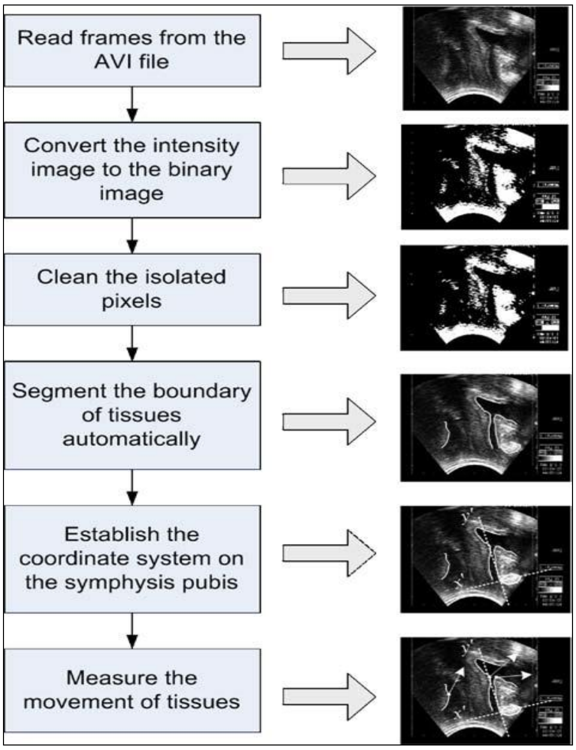


Fig 5: Workflow of CEUS

Molecular ultrasound imaging

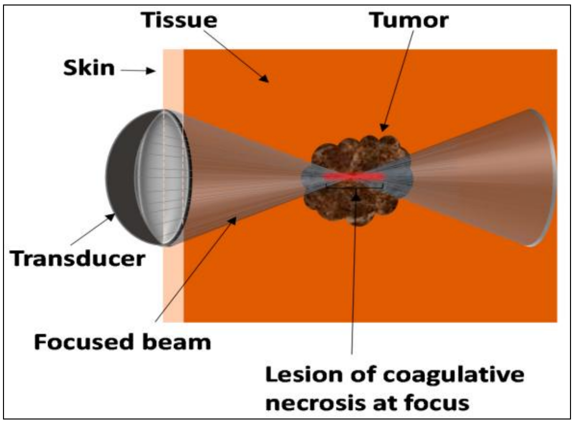


Fig 7: Molecular Ultrasound imaging in oncology

Radiomic ultrasound analysis: While radiomic studies are becoming more prevalent for CT and MRI data, there are very few publications that discuss its use in ultrasound data. This is likely due to the challenges associated with standardizing data acquisition and extracting quantitative data.

High-intensity focused ultrasound (HIFU)

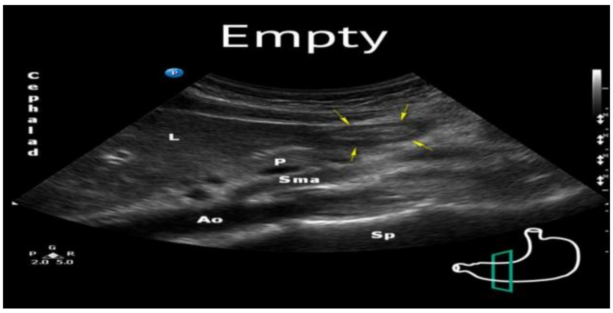


Fig 8: HIFU image

HIFU can result in localized tissue heating, cavitation, and radiation forces, which may be utilized for various therapies including tissue ablation, image-guided drug delivery, sensitization to radiation therapy, and immune stimulation. Recent technological advancements in MR HIFU have enabled applications within the human brain. Aberrations caused by the passage of ultrasound waves through the human skull are corrected using phased-array HIFU transducers informed by high-resolution CT scans. For instance, in the treatment of essential tremor, a portion of the subthalamus is ablated using MR HIFU. The patient remains awake throughout the procedure, and the therapeutic effect is immediate.

Processing of ultrasound-signals

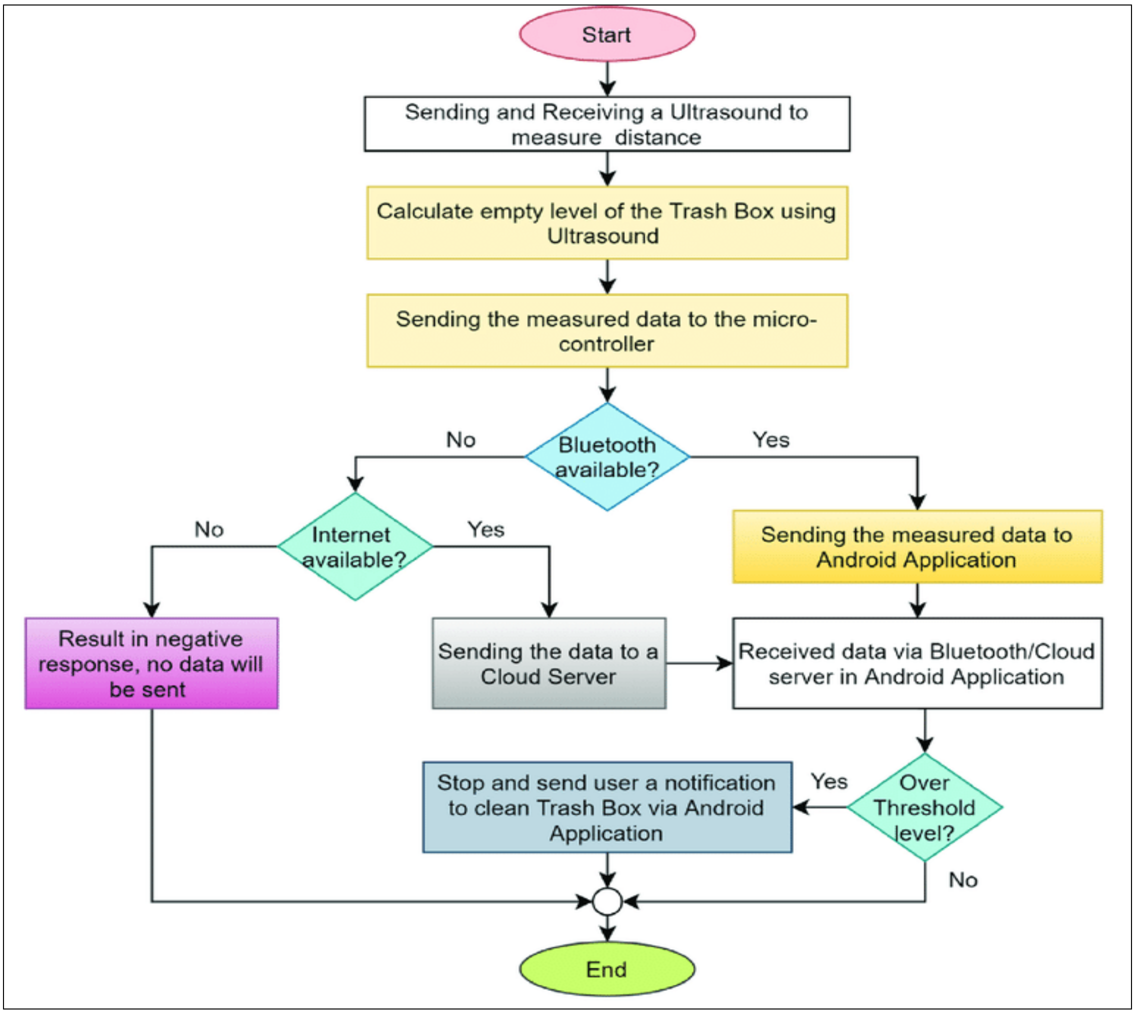


Fig 9: How the Ultrasound signals are processed?

Types of Ultrasound scans in clinical practice

The common types of ultrasound scan are:

1) Abdominal ultrasound, which examines the internal organs of the abdomen, such as the liver, gallbladder, pancreas and spleen.
2) Obstetric/pregnancy ultrasound, which is a routine scan to assess the growth and health of the baby.
3) Female pelvis ultrasound, which may use transvaginal ultrasound (with the transducer in the vagina) or external pelvic ultrasound to look at the female pelvis, uterus, cervix, fallopian tubes and ovaries.
4) Breast ultrasound, which is used to assess breast symptoms such as lumps, and also to screen for breast cancer in women with dense breast tissue.
5) Renal ultrasound, which is used to scan the urinary tract including the kidneys and bladder.
6) Transrectal ultrasound, which provides images of the prostate gland.
7) Doppler ultrasound, which monitors blood flow in the major arteries and veins
8) Echocardiogram, which examines the heart
9) 3D ultrasound, which shows a three-dimensional picture of the inside of the body
10) 4D ultrasound, which creates a three-dimensional picture in motion

What to Expect During an Ultrasound?

Comfort and Safety:

External ultrasounds are typically painless, and patients do not sense the high-frequency sound waves utilized in the imaging process. Certain procedures, such as those necessitating a full bladder, may induce temporary discomfort or a feeling of pressure. Remaining still on the examination table, particularly during pregnancy, may also lead to mild discomfort. In instances where the ultrasound probe is inserted into a body cavity (for example, trans vaginal or transrectal scans), there may be slight discomfort during the procedure; however, significant pain is not anticipated.

Safety Considerations

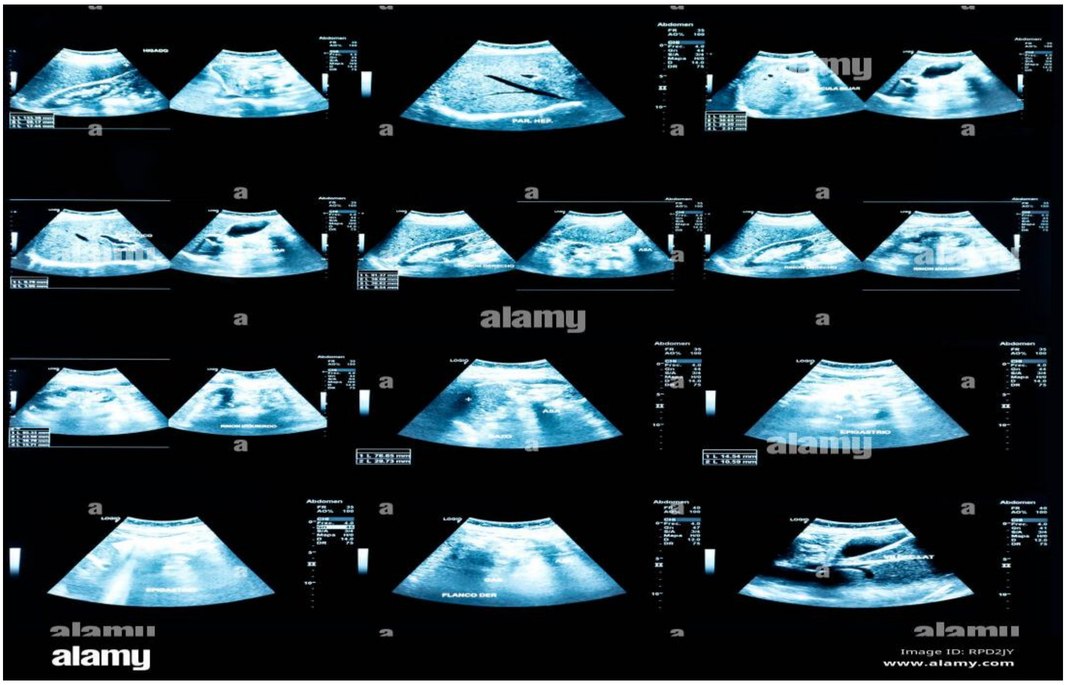
Years of clinical experience and research have demonstrated that ultrasound is a safe imaging technique, devoid of the ionizing radiation risks linked to X-rays and CT scans. However, it is essential that all ultrasound procedures are conducted by qualified professionals to guarantee patient safety and achieve the best possible image quality.

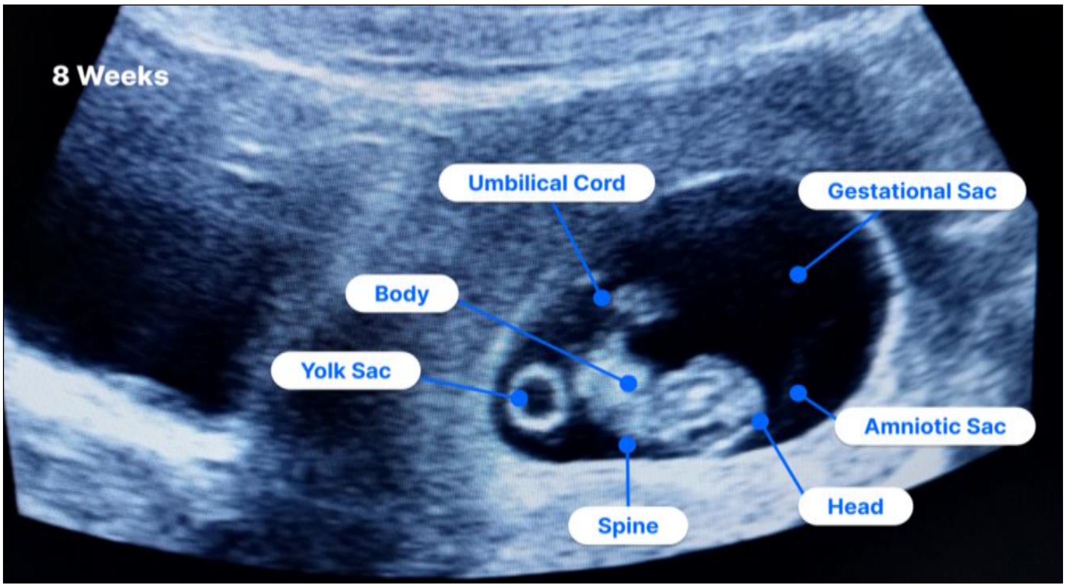
Report content

It is recommended that an ultrasound report be divided into the following sections:

- **Type of examination performed**
  The specific type of ultrasound examination conducted must be indicated at the beginning of the report to guarantee an accurate record.

Examples: Ultrasound examination of the upper abdomen Transvaginal ultrasound examination of the pelvis





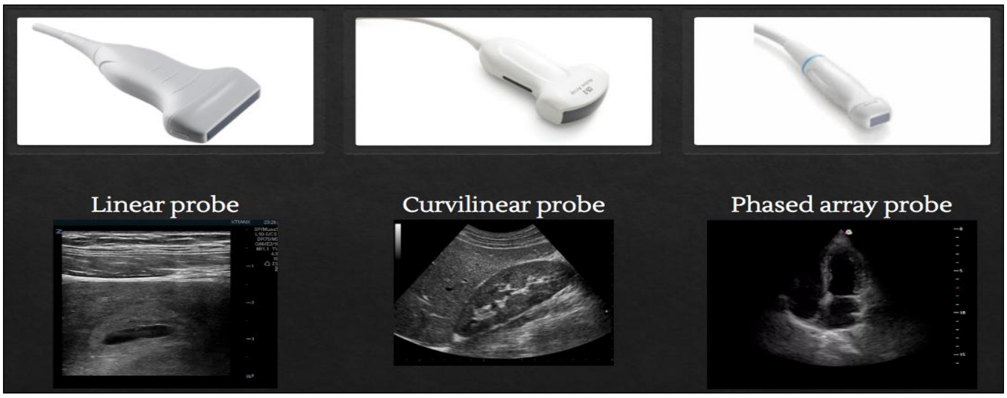
Written report

The report ought to be definitive whenever feasible, specifying instances where the findings align with a particular diagnosis. In cases where a conclusion cannot be drawn, alternative interpretations of the ultrasound findings may be provided.

Any relevant actions undertaken should be reported.

For example: I have notified the patient regarding the presence of an ovarian cyst that necessitates follow-up. I have scheduled a follow-up scan to take place in six weeks. The patient is cognizant of this appointment. Considering the findings, I have personally communicated these results to the referring clinician, Dr. XXX, via telephone.

Probes Optional With Specification (Standard Kit Include 6.5Mhz Rectal Linear Probe)		
	Type	Rectal Linear Probe
	Center Frequency	6.5Mhz
	Frequency Adjustment	5.5 - 9.0Mhz
	Scan Depth Range	62 - 173mm
	Type	Back-Fat Probe
	Center Frequency	3.5Mhz
	Frequency Adjustment	2.0 - 5.0Mhz
	Scan Depth Range	111 - 270mm
	Type	Convex Probe
	Center Frequency	3.5Mhz
	Frequency Adjustment	2.0 - 5.0Mhz
	Scan Depth Range	111 - 270mm
	Type	Sheep / Goat Rectal Probe
	Center Frequency	6.5Mhz
	Frequency Adjustment	5.5 - 9.0Mhz
	Scan Depth Range	62 - 173mm



Perception

Humans: The maximum frequency threshold in humans, which is around 20 kHz, is attributed to the constraints of the middle ear. Auditory perception can take place when high-intensity ultrasound is directly transmitted into the human skull, allowing it to reach the cochlea via bone conduction, bypassing the middle ear entirely.

Conclusion

Historically, ultrasound has not received the recognition it deserves in clinical practice; however, recent developments have started to uncover its extensive diagnostic and therapeutic capabilities. Cutting-edge ultrasound methods, including advanced image postprocessing, are facilitating thorough quantitative multiparametric evaluations. Additionally, the incorporation of enhanced contrast agents allows for the exploration of intricate vascular features that were mainly accessible through imaging techniques such as CT and MRI.

Conflict of Interest:
The authors affirm that there are no conflicts of interest associated with this manuscript.

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