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(ARTICLE)

The Role of Ultrasound in Diagnostic and Therapeutic Applications in Medical Sciences. A Comprehensive Literature Review

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دور الموجات فوق الصوتية في التطبيقات التشخيصية والعلاجية في العلوم الطبية. مراجعة شاملة للأدبيات

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Abstract:

Background: Ultrasound is a non-invasive imaging technique that employs high-frequency sound waves to visualize structures within the body. Its lack of ionizing radiation, ability to produce images in real time, broad accessibility, and suitability for repeated examinations have made it an important tool in clinical practice. **Objective/Aim**: This review summarizes the basic principles of medical ultrasound and examines its principal diagnostic and therapeutic uses. It also considers advanced ultrasound techniques, major benefits and limitations, safety aspects, and emerging developments in clinical practice. **Review Content**: The review covers the basic principles of ultrasound imaging, the historical development of technology, and its applications in abdominal, pelvic, obstetric, cardiac, and vascular imaging. Advanced techniques, including Doppler ultrasound, three-dimensional imaging, contrast-enhanced ultrasound, and elastography, are also considered. Therapeutic applications such as physical therapy, lithotripsy, phacoemulsification, and High-Intensity Focused Ultrasound (HIFU) are reviewed, together with the advantages, limitations, safety considerations, and current and future clinical roles of ultrasound. **Conclusion**: Ultrasound is a versatile modality with important diagnostic and therapeutic applications across a wide range of clinical specialties. Advances in transducer technology, digital signal processing, three-dimensional imaging, contrast-enhanced methods, tissue characterization, and image-guided treatment continue to broaden its capabilities. Although operator dependence and acoustic barriers remain important limitations, ultrasound continues to have a significant role in modern clinical practice.

Keywords: Ultrasound, Diagnostic applications, Therapeutic applications, Clinical practice.

الملخص:

الخلفية: يُعدّ التصوير بالموجات فوق الصوتية تقنية تصوير غير جراحية تستخدم موجات صوتية عالية التردد لتصوير التراكيب داخل الجسم. وقد جعلها انعدام الإشعاع المؤين، وقدرتها على إنتاج صور فورية، وسهولة استخدامها، وملاءمتها للفحوصات المتكررة، أداةً مهمة في الممارسة السريرية. الهدف: تُقدّم هذه المراجعة ملخصًا للمبادئ الأساسية للتصوير الطبي بالموجات فوق الصوتية، وتدرس استخداماتها التشخيصية والعلاجية الرئيسية. كما تتناول تقنيات الموجات فوق الصوتية المتقدمة، ومزاياها وعيوبها الرئيسية، وجوانب السلامة، والتطورات الحديثة في الممارسة السريرية. محتوى المراجعة: تغطي المراجعة المبادئ الأساسية للتصوير بالموجات فوق الصوتية، والتطور التاريخي لهذه التقنية، وتطبيقاتها في تصوير البطن، والحوض، والتوليد، والقلب، والأوعية الدموية. كما تتناول التقنيات المتقدمة، بما في ذلك الموجات فوق الصوتية دوبلر، والتصوير ثلاثي الأبعاد، والموجات فوق الصوتية المعززة بالتباين، والتصوير المرن. تُستعرض التطبيقات العلاجية للموجات فوق الصوتية، مثل العلاج الطبيعي، وتفتيت الحصى، واستحلاب العدسة، والموجات فوق الصوتية المركزة عالية الكثافة (HIFU)، إلى جانب

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مزاياها، وقيودها، واعتبارات السلامة المتعلقة بها، وأدوارها السريرية الحالية والمستقبلية. الخلاصة: تُعدّ الموجات فوق الصوتية تقنية متعددة الاستخدامات ذات تطبيقات تشخيصية وعلاجية هامة في طيف واسع من التخصصات السريرية. وتستمر التطورات في تكنولوجيا المحولات، ومعالجة الإشارات الرقمية، والتصوير ثلاثي الأبعاد، والأساليب المحسّنة للتباين، وتوصيف الأنسجة، والعلاج الموجه بالصور، في توسيع نطاق إمكانياتها. وعلى الرغم من أن اعتمادها على مهارة المُشغّل والحواجز الصوتية لا يزالان من القيود الهامة، إلا أن للموجات فوق الصوتية دورًا بارزًا في الممارسة السريرية الحديثة.

الكلمات المفتاحية: الموجات فوق الصوتية، التطبيقات التشخيصية، التطبيقات العلاجية، الممارسة السريرية.

1- Introduction

Introduction to Ultrasound:

Ultrasound is a non-invasive imaging method that uses high-frequency acoustic waves to generate images of internal anatomical structures. A transducer produces acoustic waves, while echoes reflected from interfaces between tissues are detected and processed by a computer to create diagnostic images as shown in Figure 1. In contrast to X-ray and computed tomography (CT), ultrasound does not involve ionizing radiation, which makes it particularly suitable for examinations that may need to be repeated. Its accessibility, real-time imaging capability, and capacity to provide high-resolution images have supported its widespread clinical application [1,2].

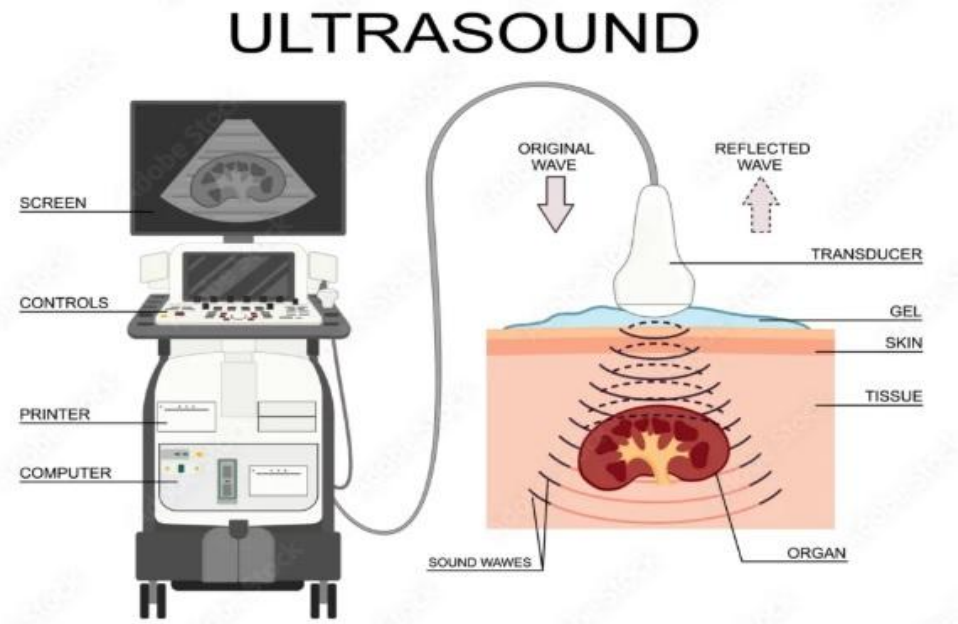

Figure 1. Schematic representation of ultrasound imaging.

Principles of Ultrasound Imaging:

Medical ultrasound primarily functions according to the pulse-echo principle. Piezoelectric elements within the transducer convert electrical energy into acoustic energy and subsequently convert returning echoes into electrical signals. Transducer frequency affects both image quality and penetration. Higher frequencies generally produce improved spatial resolution but penetrate less deeply, whereas lower frequencies provide greater penetration and are therefore useful for deeper anatomical structures [1,2].

Development and Evolution of Ultrasound Technology:

Ultrasound technology has progressed substantially from its early applications to contemporary digital systems that generate high-quality images in real time. Advances in transducer design and digital signal processing have improved image quality and enabled specialized imaging methods. Current ultrasound systems incorporate conventional B-mode imaging together with Doppler techniques, three-dimensional imaging, contrast-enhanced ultrasound, and other advanced applications [1,2].

History of Medical Ultrasound in Diagnosis and Therapy:

The origins of ultrasound can be traced to the use of sound waves in underwater navigation and investigations of sound transmission and propagation. Medical applications began to develop in the 1940s, when Karl Theodore Dussik investigated ultrasound transmission through the brain, one of the earliest published medical applications of the technique. In the 1950s, researchers explored ultrasound for both diagnostic and therapeutic purposes, including physical therapy and rehabilitation, and early studies also investigated the possibility of using focused ultrasound for tumor ablation [3,4].

History continuation

As scientific and technological progress continued, ultrasound imaging advanced from static images to dynamic, real-time visualization. The introduction of microprocessors and improved image-processing methods later facilitated color Doppler imaging, which made blood-flow visualization possible, as well as three-dimensional ultrasound imaging. Because ultrasound relies on sound waves rather than ionizing radiation, it offers a non-invasive approach for examining soft tissues and anatomical structures. These characteristics, together with its safety, effectiveness, non-invasive nature, and comparatively low cost, have contributed to its widespread adoption [3,4].

2- Diagnostic Applications of Ultrasound:

Diagnostic ultrasound utilizes short pulses produced by piezoelectric crystals, usually operating at frequencies of 2-12MHz. The frequency is mostly determined by the thickness of the piezoelectric crystal, which affects the ultrasound's imaging properties [5]. Additionally, the majority of biological tissues absorb ultrasound waves at a rate of roughly $1\ dB\ cm^{-1}\ MHz^{-1}$, and travel through tissues at a speed of about 1500 m/s. Thermal effects may result from this absorption, but mechanical effects such as cavitation and acoustic streaming may also happen, especially at lower frequencies [1]. Due to its physical characteristics and non-invasive nature, ultrasound has a wide range of diagnostic applications and is frequently used to assess several organs and tissues throughout the body.

Abdominal ultrasound: The solid organs of the abdomen, including the aorta, inferior vena cava, the pancreas, liver, gallbladder, bile ducts, and spleen, are imaged. Sound waves are blocked by gas in the bowel; consequently, there are limited diagnostic options in this location [1].

Obstetric ultrasound: Intrauterine pregnancy confirmation, fetal viability assessment, gestational age estimation, fetal anatomy assessment, monitoring of fetal development, and assessment of the placenta and amniotic fluid [6].

Neurosonography: Views the brain, involving the fetal brain, evaluates blood flow and stenosis in the carotid arteries and the large intracerebral arteries using transcranial ultrasound [1].

Echocardiography: Evaluation of cardiac chambers, ventricular function, wall motion, cardiac valves, intracardiac blood flow, and congenital abnormalities [1].

Doppler ultrasonography: The assessment of deep vein thrombosis, carotid artery stenosis, arterial blockage, and other vascular problems can be achieved through the measurement of blood flow direction and velocity [7]. Additionally, it is frequently utilized in high-risk pregnancies, particularly during the third trimester. It can also be combined with transvaginal ultrasonography to assess ovarian cysts and assist in the diagnosis of ectopic pregnancy [1]

Musculoskeletal ultrasound: Examining of muscles, ligaments, tendons, joints, bursae, and peripheral nerves. It is useful in detecting inflammation, joint effusions, tendon tears, and soft tissue abnormalities [5,7].

Pelvic, gynecological, and urological ultrasound: Evaluation of the uterus and ovaries or urinary bladder, prostate, and tests. Performing a pelvic Sonography through either an external or internal method (transrectal in males or transvaginal in females). Internal pelvic floor imaging by providing accurate anatomical information about the relationship between abnormal structures and adjacent organs, helps treat double incontinence, pelvic prolapse, and obstructed defecation [1]

Elastography: Characterization of selected thyroid, breast, and musculoskeletal lesions as well as evaluation of tissue stiffness, especially liver stiffness in chronic liver disease [7,8].

Contrast-enhanced ultrasound: Assessment of vascularity and tissue perfusion, particularly in the identification of localized liver lesions and cardiovascular abnormalities [8].

Image-guided and interventional ultrasound procedures: Real-time guidance for a range of minimally invasive procedures, involving biopsies, abscess drainage, fluid aspiration, vascular access, catheter placement, and therapeutic injections. Additionally, it is employed in interventional applications that provide accurate visualization and guidance throughout the intervention, such as intrauterine transfusion and other image-guided procedures [1].

Ultrasound in dermatology: Initially utilized to measure skin thickness, to include the detecting of foreign bodies in soft-tissue wounds, the evaluation of benign and malignant tumors, inflammatory and infectious diseases, and cosmetic dermatologic conditions, as well as the assessment of inflammatory response to patch tests and the estimation of the volume and extent of nonmelanoma skin cancers. Additionally, it helps with surgical planning by offering additional information about the size, lesion depth, and tissue involvement of lesions [1].

3- Therapeutic Applications of Ultrasound:

Over the past few decades, therapeutic ultrasound has evolved significantly, expanding from its initial use, which was primarily focused on tissue heating, to a variety of therapeutic applications. Improvements in ultrasound technology have enabled more accurate, effective, and, targeted treatment methods for several medical conditions. These advancement have established ultrasonography a significant therapeutic tool in modern medicine, with applications extending across different clinical fields [5]

High-intensity focused ultrasound (HIFU): Tissue ablation and localized thermal coagulation are caused by concentrated acoustic energy. Clinical uses include palliation of pain from bone metastases, essential tremor, prostate cancer, and selected uterine fibroids [8]. These processes typically employ much higher energy but lower frequencies (between 250 and 2000 kHz) than medical diagnostic ultrasonography. Additionally, HIFU is also being investigated as a relatively new therapeutic technique for the treatment of cancer, especially prostate cancer, which allows the ultrasound probe to be placed in close proximity to the target tissue [1].

Extracorporeal shock-wave lithotripsy: According to Ranganayakulu et al. [1] focused acoustic shock waves fragment selected renal and urinary tract stones into smaller fragments that the urinary system can remove.

Drug delivery: High-intensity focused ultrasound (HIFU) can improve targeted drug delivery by increasing tissue permeability, encouraging localized drug release, and enhancing the accumulation of therapeutic agent at the designated site, such as in tumors [9].

Tumor ablation: Is intimately associated with ultrasound-based therapy, especially high-intensity focused ultrasound (HIFU), which concentrates acoustic energy at a specific focal point to enable noninvasive, image-guided tumor tissue destruction. In this situation, ultrasound can be used as a guided tool and a therapeutic modality to selectively ablate cancerous tissue while minimizing damage to surrounding tissues [10].

Therapeutic ultrasound in rehabilitation: Creates mechanical and thermal effects in biological tissues by using acoustic energy. It may produce mechanical changes and localized heating, which makes it beneficial for cancer treatment as well as physiotherapy and rehabilitation. Therapeutic applications may also include dental applications such as ultrasonic cleaning [1].

Phacoemulsification: is a technique that uses ultrasound to treat cataracts. This procedure essentially, high-frequency ultrasonic energy is utilized to fragment the cloudy lens. After aspirating the lens fragments, and replaced with an intraocular lens [1].

Other physiological impacts: Low-intensity ultrasound has also been shown to have additional physiological effects, such as promoting bone growth and potential disrupting the blood-brain barrier for drug delivery [1].

Bone-healing ultrasound applications: Low-intensity pulsed ultrasound (LIPUS) has been investigated and applied in certain protocols to promote healing in specific fractures, including nonunions and delayed unions [11].

4- Advantages and Limitations of Ultrasound:

Major advantages of ultrasound include the absence of ionizing radiation, real-time imaging, broad availability, low cost, and suitability for repeated examinations. Different transducers can also be selected according to the anatomical region under investigation. Nevertheless, ultrasound has limitations; image quality and diagnostic accuracy can depend on operator expertise and appropriate probe selection. Limited imaging depth, dependence on transducer characteristics and examination technique. Air, bowel gas, bone, and calcified tissues may interfere with transmission of the ultrasound beam and decrease visualization of deeper structures [12].

5- Safety and Clinical Considerations:

Because diagnostic ultrasound does not involve ionizing radiation, it provides an important alternative to imaging techniques associated with radiation exposure. However, ultrasound energy can cause thermal and mechanical effects in biological tissues, particularly when higher intensities are used. Clinical applications should therefore be appropriately controlled, with acoustic settings and exposure conditions selected according to the intended diagnostic or therapeutic purpose [1].

6- Current and Future Applications of Ultrasound:

Ongoing technological development continues to expand the role of ultrasound in clinical medicine. Improvements in transducer technology, digital signal processing, three-dimensional imaging, contrast-enhanced techniques, and tissue characterization are increasing its diagnostic potential. The integration of ultrasound with image-guided interventions and therapeutic approaches such as HIFU further demonstrates its capacity to function as both a diagnostic modality and a tool supporting treatment [1,2].

7- Conclusion:

Ultrasound has become an important diagnostic and therapeutic modality because it is non-invasive, does not use ionizing radiation, provides real-time imaging, is widely accessible, and has applications across many areas of clinical medicine. Technological progress has enhanced ultrasound through Doppler imaging, three-dimensional techniques, contrast-enhanced methods, and elastography, while therapeutic approaches such as HIFU have extended its role beyond diagnosis. Despite persistent limitations associated with operator experience and acoustic barriers, continued advances in ultrasound technology are strengthening its diagnostic and therapeutic capabilities. Ultrasound therefore remains a versatile imaging modality with an increasingly important role in modern clinical practice.

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