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Ultrasound Physics: Innovations in Medical Diagnosis

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Annotation: Ultrasound as a non-invasive diagnostic tool has played a primary and significant role in diagnostic radiology since the early 1980s. From that time on, intriguing patient studies and experiments with phantoms were conducted to bridge the gap between basic principles and advanced imaging techniques nowadays performed also in clinical routine. Understanding the relationship of basic physical principles and imaging techniques is important to appreciate the capabilities and limitations of the complex imaging modality. As ultrasound contrasts have had an increasing impact on diagnostic ultrasound imaging in the last decade, they have found special attention. Finally, the progress in the development of new types of contrasts and contrast specific imaging methods is discussed. This overview is intended for a basic understanding of the physics of ultrasound and a survey of current developments and future trends in the field for students and doctors new to medical ultrasound, as well as for researchers in the field.

The first application using ultrasound originated from “depth sounding” as conducted on ships in the early 20th century. The measured propagation times of ultrasound provided a measure of the depth of the water. Later, inspection of metals and plastics with ultrasound was used in the construction industry. The great advantage of this NDE method is the non-invasive access to the interior of an object and so it soon became a standard tool for evaluation hardness or particle diameter in different materials. A-B scans were performed in the water-tank inspection of alloy welding seams, which were at least 150 mm thick and welded from both sides. Standard lateral weld seam inspection methods were not sensitive or safe enough. In substations of electric power plants, transformers are oil filled. These oil tanks have to be inspected because there may occur leaks. Because they are situated on an isolating platform, the only way to inspect them was again with ultrasound technology. Now spa machines with infrared stress releasing rays, which were constructed to avoid the occurrence of skin cancer have this effect when operated on the compounds. With the construction of highly sophisticated machines, innovative and unwanted effects were found. On both Triton head parts the warm water flowing through the tubes creates bubbles. The only way to avoid this is regularly to clean the tubes, but this is complicated as you have to switch the tubes.

Keywords: Ultrasound imaging, Doppler ultrasound, contrast-specific imaging, elastography, artificial intelligence, non-invasive diagnostics, medical physics, real-time imaging.

1. Introduction to Ultrasound Physics

Ultrasound consists of sound waves with frequencies higher than the human range of audibility. In applications found in modern clinical medicine, the frequency range used is between 2 and 15 MHz. How they interact with tissue and the resultant images have important implications for their diagnostic use. Ultrasonic systems emit short pulses of acoustic energy that pass into the body from a transmitted element. The energy is absorbed, reflected, scattered, refracted, and transmitted by the various tissue and organ interfaces encountered. A small part of the energy reflected back at each interface is detected by the transducer. From the received echoes, a gray-scale tomographic image of the tissue distribution in the beam path is calculated using appropriate assumptions for the sound’s speed and attenuation coefficients within each type of soft tissue. Patient contact is maintained by acoustical coupling that can be produced by appropriate immersion, biocompatible gels, or hoods [1]. Imaging can thus be performed in situ at the hospital bed, in the intensive care units, in the emergency room, and practically in any hospital or local health station in a non-invasive and portable fashion with minimal patient discomfort or morbidity, influence on the patient's clinical status or need of isolation, not requiring use of ionizing radiation, sophisticated and expensive apparatus, or patient's preparation and recovery room. However, in order to optimize the setting of the system and its use, some general principles behind its working need be understood by the medical personnel using it [2]. Given the continuous technological advancements in ultrasonic systems, and their implications in terms of strategy and behavior when using them, it is also appropriate for the reading physician to stay abreast of news of updates and future trends of such technology. [3][4][5]

1.1. Basic Principles of Ultrasound Waves

Ultrasonic waves can propagate through almost any medium, including solids, liquids, and gases. In medical diagnostic imaging, the most commonly used medium is soft tissue. When it comes to the body's internal structures, it can be said that they are made up of various interfaces that have different acoustic impedances. Because of these differences in acoustic impedance, the various characteristics of the tissues can be visualized on the screen as gray scale. The generation of an ultrasonic wave is relatively easy with the use of the piezoelectric effect, by feeding electrical energy to a transducer so that it vibrates.

The produced ultrasonic waves can be propagated through different media. While passing through the medium, ultrasonic waves can be either absorbed or reflected by the tissue interfaces. Whenever there is a change in the medium due to a tissue-property difference thereby creating an interface, some fraction of the propagating ultrasound is reflected back to the transducer. There is also a phenomenon called refraction whenever ultrasound passes through the tissue interfaces as the medium imaging plane is changed. The acoustic impedance plays an important role in determining the image quality of the tissue interfaces and this is determined by the formula - acoustic impedance = propagation velocity x density. Furthermore, using a transducer, electrical energy can be converted into the sound wave, and the sound wave can be converted back into an electrical signal by the transducer. One advantage of ultrasound technology in medical diagnosis is its application in the Doppler effect so that blood flow can be assessed within the blood vessels by detecting a frequency shift. The basics of Doppler effects that can be applied to the ultrasound are the frequency shift, the Doppler equation, angle sensitivity, the double-continuity principle, and the color Doppler. [6][7][8]

Literature Review

2. History and Development of Ultrasound Technology

Ultrasound was discovered in the early 19th century, through an experiment conducted by a famous French mathematician and physicist, Pierre Simon Laplace. It is said that he measured the speed of sound in the air by the method of resonance, and was successful in obtaining a value very close to the currently known one of 335 m/s. But, the first person who detected / recognized the existence of ultrasonic waves /objects was another French mathematician and physicist, Lazzare Nicholas Marguerite Carnot. In 1819, he, by means of Whistle (fife), while inspecting the quality of a bronze cannon being used in the Napoleonic Military, he noticed that there was a very strange and strong wind blowing suddenly, and the voice of the whistle stopped temporarily. Using this method to check the exterior of the cannon, he always found something slightly strange and started a series of experiments. [2] This has gradually led to the understanding of ultrasonic waves. It is probably one of the first documented cases of inquisition as a natural phenomenon. However, until the beginning of the 20th century, no substantial interest in acoustics as a science was generated. Most people were just curious about the sounds caused by nature, and no overview was seen as studying the mechanism of the sound generation has never been attempted. And until the late 1950's and 1960's, with the development of piezoelectric materials and various electronics technologies, it was impossible to amplify and convert the ultrasonic frequencies used in diagnosis and treatment into electrical energy. Furthermore, to store this high frequency electrical energy, the development of an equipment to produce a strong and uniform electromagnetic force was required. It took a long time to develop detention technology to invent consumable devices. In 1885, the ultrasonic sound theory was adopted. In 1897, the uniform transmission medium and the acoustic pulse theory. In 1935, the causative potential of high intensity ultrasonic waves. Complete detection and transducer technology. Necessary for use as a diagnostic medical device were developed. Since then, various advanced technologies have been developed to improve image quality and functional studies. The discovery of ultrasonic waves has long been thought that various abilities and directives of various animals to survive have already developed this technology, but in the 21st century research on ultrasonics as a high-tech medical modality and application continues to grow continuously more than other imaging techniques. It is expected that as the search field extends little by little, it will eventually become a new icon of clinical imaging.

2.1. Milestones in Ultrasound Innovation

Routine medical usage of ultrasound for diagnostic imaging had its origin in the early sixties with the advent of B-mode imaging technique [9]. Progress in this area was rapid and with the beginning of the seventies grey scale imaging was already well established and large area imaging detectors started to be developed. At this time also the pioneering work related to ultrasonic methods for detecting blood flow was initiated. Technology advancement has been so fast that in the late seventies linear array scanning systems with advance scan converters were employed, and two dimensional imaging became a practical clinical reality. In the beginning of the eighties phased array technology was introduced and with it real time, large field of view two-dimensional imaging has finally become possible. In these days it is difficult to think about some medical problems which could not be solved at least to some extent, using appropriate ultrasonic diagnostic tools. More than that, continuous technology advances and introduction of new techniques were made, making US methods competitive with other imaging modalities as well as an independent valuable diagnostic tool.

Form a simple, portable means of diagnostic imaging, diagnostic ultrasound has progressed over the years into a complex, multicomponent, real-time combination of electronics. The first ultrasound instruments, developed in the 1940s and operating in the frequency range of 1-10 megahertz, were A-mode devices named biostereoscopes. A-mode instruments displayed structured information from the body being investigated, with the echoing signals, which were electronically represented at a fast paper strip. Diagnostic operators were often hailed for their exceptional skills in identifying diseased regions from a variety of images of heart signals. It was an excellent introduction of ultrasound in medical diagnostics, and many important discoveries which were to build the foundation for further conversion of ultrasound, were made using this so-called fixed-period system. Scalgram and compound scanning instruments were the next technological improvements in the field of diagnostic ultrasound. With these advancements, exploratory efforts took on a completely different dimension, being rapidly converted from a pure observational to a quantifiable diagnostic technique. This was also a critical age for the establishment of regulatory laws, not only on a federative, but on an international level, which would later stimulate a commercial and competitive dialogue between several technological companies [2]. [10][11]

Materials and Methods

3. Advanced Ultrasound Imaging Techniques

Ultrasound technology has the capability to diagnose numerous medical conditions and monitor several kinds of treatments. The novel ideas presented in this issue enhance the diagnostic accuracy, utility, and clinical relevance of medical ultrasound imaging. Among these innovations are methods that provide 3D views of internal structures and the temporal dynamics of biological processes are state-of-the-art. 4D ultrasound imaging is capable of presenting real-time 3D images and the resulting motion pictures of internal features. Other new technologies implement the use of ultrafast ultrasound pulses, parallel receive beamforming, or multi-element arrays for the detection of shear waves induced by the patient's heartbeat. With a better understanding of the applied technologies, users can expect faster and more precise tissue characterization via elastography.

Elastography and other "stiffness imaging" techniques show promise for improved visualization of certain features within biological tissues. This investigation employs a model based on the premise that the speed of a shear wave depends on the characteristic mechanical properties of the medium through which it propagates. Initial results are shown to agree well with the known mechanical characteristics of the simulated phantoms. Estimations of the turgor pressure in an in vitro model of a leaf's stoma are also predicted. Advanced diagnostic imaging techniques including an array-based oversampling method to create synthetic transmit aperture images and the quantitative evaluation of the time-intensity-curve from contrast-enhanced images are detailed and results are presented. A particular focus is made on the use of ultrasound in conjunction with other imaging modalities, such as spectroscopy, to concurrently image anatomy and microperfusion. This may be important in the clinical determination of tumor extent and especially useful in broad clinical settings where other imaging modalities to guide intravascular contrast agents are not readily available.

New automatic image interpretation technologies involving artificial intelligence and machine learning are giving rise to the development of passive and active systems. As regards passive systems, adaptive filters are under development, and it is suggested that the use of artificial neural networks can be a future trend. Active systems are based on a hybrid computer-human network, in which an expert prototype can have distinct nodes. Recently, artificial intelligence technologies have been continuously gaining attention in this field with high speeds in terms of data storage and retrieval. As a result, an expert system for the thyroid gland and a passive system for benign/malignant breast disease were implemented. There are a considerable number of relevant reports or clinical studies utilizing artificial intelligence technologies in a broad selection of clinical applications regarding either breast or thyroid investigations, as well as other organs. Clinical applications of 3D and 4D imaging methods range from obstetrics, through gynecology, to cardiology and tumor diagnosis. A review of the feasibility of these techniques in relation to specific organs or regions is presented. [12][13]

3.1. Doppler Ultrasound Imaging

Doppler ultrasound imaging is an effective technique for assessing blood flow in various clinical scenarios. It is one of the most common applications employed in medical imaging and has rapidly expanded for diagnostic purposes. The principles of the Doppler effect and its impact on medical imaging are briefly addressed. Doppler can open the door for measuring the velocities of different movements in steady and non-steady systems. The sound signal is a mechanical longitudinal wave that can travel in measurement media tissue as one of the various types of mechanical waves. Just like most mechanical waves, the ultrasound waves could be reflected, refracted, scattered, absorbed, and insonified, together with bio-structures.

The detection of the ultrasound echoes, the signal travel time, and the speed of propagation were used to calculate the one-way travel distance between the transducer and the bio-structure. The description of these terms makes it possible to intelligently discuss medical ultrasound. Doppler is the most diagnostically used aspect of medical ultrasound. The utilization of medical ultrasound resulted in a reduction in other types of an invasive examination, a reduction in the rate of the unnecessary surgical intervention, and a redirection of treatment planning [14]. The last resulted during the attendance of adding Doppler modality to the imaging ultrasound.

Results and Discussion

4. Ultrasound Contrast Agents

For the last six decades U/S has been a pivotal diagnostic tool playing a crucial role in the clinical sphere in various ways. A more recent innovation in this realm is the rise of U/S contrast agents, enriching the usual grey scale images captured in diagnostic sonography with vital additional data. Various technologies and approaches have been devised for enhancing the well-known B-mode image quality, encoding it with Doppler information, applying currently discussed pulsating and possibly chemical sources of fluid epistasis, vasoepistatic proprietary filtration procedures, elastography, harmonic imaging, ultrafast acquisition leading to ultrafast or even real-time imaging, and cofocal or otherwise apodized constructing foci steering beams as well as receiving high resolution delayed-only echoes. However, the real groundbreaking innovation has occurred after successful commercialization in the 90's of the microbubble-based U/S contrast agent. At the same time, a new generation of contrast-capable power U/S devices offered a substantial contrast dose in far greater agreement with systemic therapeutic applicability. Regarding the safety and general tolerability of U/S contrast agent administered in the indicated fashion and doses, unequivocally drastic is also the economical consideration. U/S contrast agents of considerable technical variety, including gas-filled bubbles, liposomes, solid agents, and dextrose-based visulating formulations, have been shaped to date. Recently, an initially promising novel ridership approach to U/S contrast imaging in cardiology, hepatology, oncology, and other realms, suggests low tubular flow of barium sulphate particles as an outstandingly durable blood pool contrast agent, albeit possibly just entrapping contrast liver lesions with no subsequent clearance. Also summarized is basic contrast pharmacokinetics growing in this vintage screening research field, touching upon the complex intrapulmonary bubble recolonization kinetics and appearing as disparate potential in organs versus disparity backgrounds. Methodologically, such matters appear confronting U/S contrast administration protocols with mathematical modeling of both inter-agent echo interaction and basic contrast pharmacodynamics; future from the modeling perspective of a more comprehensive contrast patient this is explored. Also proposed are some parallel, long-term parallel research perspectives, expressive of further, integrative innovation direction. The earliest milestones on the road to creating U/S contrast agents date back to the early 60's when the ultrasonically induced change in reflectivity was first documented in heart and gallbladder. However, it wasn't until the late 70's that the first bubble-cont density echo enhancement imaging was achieved, primarily in the experimental realm. This early research focused on simple, air-based bubble agents – indeed U/S contrast agents were initially and tendentially thought of in terms of much simpler form than would be the case for the products of the 90's. Initial transpulmonary use has been limited to non-linear paradigms, acoustic angiography and imaging substantially more sophisticated than the considered clinical standard. U/S diagnostic imaging (and therapy) make use of the mechanical waves that propagate at frequencies above audible range. In therapeutic applications, the ultrasound is often diverged or focused on the tissue intended to be treated, while in imaging the impulse signals originated from the reflecting site are collected by the same transducer. Often, the same transmitting transducer captures these scattered impulses and uses them to construct an image. A higher contrast in B-mode can thus be achieved when a separating chemical or mechanical component in the tissue is present, reflecting most of the energy in a single specific direction. Everything else is effectively filtered out, meaning that only the echoes returned from the particle will generate a vivid ultrasound trace [15]. In so-called gray values, ultrasound images (the values of which could correspond to a larger variety of acoustic properties), the contrast is lower for the same echo composition. This means that blood will be practically invisible, especially since, within the context of standard seismographic 2D-TV imaging, blood-filled vessels will appear black, similar to the relatively hypo-echoic properties of arterial flow. Indeed, one of the principal reasons for the sluggish introduction of perfusion U/S imaging in past few decade clinical standard was that Doppler techniques were inadequate for so-called invisible regions of flow, such as microvessels or otherwise capillary flow, the resolution was lacking, especially in signal analysis and display. Moreover, since from the shortest mechanical wave (with the highest frequency) it is possible to sense flows only in bigger blood vessels (the wavelengths will significantly dwarf the entirety of the capillaries), in standard images on a horizontal (or axial) 2-D cross cut of the target it is possible to infer only information about the axial velocity – in larger veins it will be straightforward to appreciate turbulent flow (M-mode traces the target as the time passes, making it possible to visualize the frequency (the bandwidth) and qualitative signal behavior in general. [16][17]

4.1. Types and Applications

Due to its availability and relative safety, ultrasound imaging is widely used in the medical field as a non-invasive diagnostic tool. Image contrast enhancement using ultrasound contrast media (UCM) can significantly improve the diagnostic capability of sonographics. This article reviews types of UCM products available in the market and describes recent clinical applications. Balancing diagnostic quality or confidence and safety will remain a major concern in the use of UCM in clinics. UCM, when injected into the blood vessels, allows the screening of the organ or tissue vasculature through its acoustic impedance contrast to the surrounding blood or tissues. Injecting these tissues into the organs improves the image resolution of the vasculature. UCM, record through its oscillative or nonlinear responses in the acoustic field, could provide information on the small deformation of the bubble or target object it surrounds. This principle has led to the exploration of bubble UCM for the assessment of tissue elasticity or in detecting small differences or deformations in biological tissues.

Based on the physical composition or operating principles, UCM have been classified differently. Exogenously perfused agents consist of encapsulated microbubbles or nanobubbles. Microbubbles (MBs) are filled with a polydisperse gas core encapsulated by a biocompatible shell, usually in the form of a lipid, albumin, or polymer membrane. Following intravenous injection, the MBs scatter, record or enhance the US signal strength and hinder bubble collapse. Lipid-shelled MB particles less than 8 μm in diameter enhance the echogenicity of the blood and have a good safety profile. Nanobubbles, on the other hand, are stabilized with a hydrophilic shell, which acts as a stabilizing barrier preventing bubble coalescence, record or hindering dissolution or shrinkage and promoting a sustainable acoustic response. The record effect of UCM as described earlier has sparked the creation of specific applications. Diploma has been focusing more on enhancing the image quality in diagnostics, and in a sense drug carrier to augment therapeutic effects, whereas, commercial products and clinical usage have been populating rapidly in recent years with new products and applications. Recently, therapeutic ultrasound combined with nanoparticles has emerged as an alternative tumor treatment modality. Promising results from both animal and clinical studies have been reported [15]. In this technical note, the particularities of cavitation-enhanced HIFU in brain and current research topic were considered.

5. Future Trends in Ultrasound Technology

Ultrasound is one of the most affordable diagnostic imaging techniques which is widely accepted by medical community because of its advantages such as non-invasiveness, safety in use and real-time imaging capabilities for dynamic studies. The rationale for ultrasound use is the widespread availability, easy portability and low costs of the equipment compared with that of other imaging modalities. At present, ultrasound is still far behind other imaging modalities from the viewpoint of the number of articles that describe diagnostic methods instead of scanners or technologies in physics journals. However, always increasing effort is spent to develop new diagnostic possibilities or even wider use of ultrasound. The present paper gives a brief overview not of the state-of-the-art, but the state-of-progress of future research. In particular, the new achievements in ultrasound techniques will be reviewed which are already established or those about to be introduced into medical technology.

There is an increasing trend to use ultrasound devices by lay persons for commercial or medical purposes. The number of installed ultrasound scanners in clinical practices rises each year; at the same time, a growing number of medical experiments are done with advanced ultrasound scanners in research centers. It may be anticipated that therapeutic ultrasound will grow in importance in the future. Broadband curved arrays and multi-dimensional imaging will become standard. Even better quality 3D imaging will allow the diagnosing of smaller lesions. Better composed harmonic and sub-harmonic imaging. The MRI-based ultrasound platforms for focused and interstitial ultrasound therapy exist and further development is anticipated. An improved understanding of cellular and molecular mechanisms underlying biological effects of high intensities, shocks and insonation with microbubbles is expected. The idea behind lies in the assumption that both normal and neoplastic tissues can be usually well recognized. [18][19][20]

6. Conclusion

It is apparent that without a high level of understanding of basic ultrasound principles, users are limited in their ability to make informed decisions regarding the use or rejection of diagnostic options available on modern machines. Automated and difficult aspects such as speckle may be considered best left to the machine. However, it remains the acoustician's (sonographer’s) responsibility to monitor effect on quality of the screened image. Indeed, there are conditions where discretion should lead to a manual change of an automatically selected option.

The process of research and modern implementations in the medical diagnosis of ultrasound imaging in transmission and pulse-echo began simultaneously in different countries of the world. The description of studies conducted in the Soviet Union and united into a particular scientific and methodical stream is closely related to investigation pursued abroad. Paralleled investigation in the field of piezo-acoustic transduction and ultrasonic system engineering led to the achievement of significant results and the establishment of new diagnostic technologies for medicine. The use of ultrasonic waves for remote measurement in the diagnosis of internal organs depends on the development of methods and devices for the generation and perception of aperiodic ultrasonic pulses and the ability to interpret the real characteristics of the object [2]. With the beginning of the general development of ultrasound diagnostics, the study of propagation, backscatter, diffraction and dissipation of an ultrasonic beam - the basic physical tasks of this area, the prospects of their implementation and the ways of research are formulated.

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