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Development, Functions, Design-features of Ultrasound Machine and Future Improvement Strategies

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ABSTRACT

Ultrasound machines are essentials tools in the field of medical imaging. They are used to create images of internal organs, tissues, and liquids in the human body. The use ultrasound technology in diagnostics and treatment has significantly increased in recent years due to its non-invasive nature and accurate results. This work on medical ultrasound machine explores the, historical development, functions, design-features and future improvement strategies.

Keywords: Ultrasound, history, functions, human, development, imaging, diagnostic, therapeutic, medicine, frequency, diagnosis, probe

1. Introduction

Ultrasound machine as a medical equipment directs high-frequency sound waves at the internal body structures being examined (Aladin et al., 2011). Ultrasound according to the Physicist is the acoustic energy with ultrasonic frequency above the human hearing (20 hertz to 20,000 hertz) (Moyano et al., 2022). A typical ultrasound diagnostic operates in the frequency as high as 2 to 18 megahertz which is by far greater than the human limit (Health et al., 2010). Frequency and intensity are the main characteristics of ultrasound and they are common to all kinds of waves. Ultrasound also has wavelength that restricts the quality of detail it can detect and this is peculiar to different kinds of waves. It is practically impossible to observe details significantly smaller than the wavelength of our probe; for example, one cannot observe individual atoms with visible light due to its relative size compared to the wavelength of light. Ultrasound as a diagnostic imaging machine is used to visualize the internal organs of the body for examination and diagnostic purposes (Grogan et al., 2023). The common uses of ultrasound are for probing the uterus and ovaries during pregnancy to monitor the health of a developing baby, diagnosing gallbladder disease, evaluating blood flow of internal organs, for guiding a needle for biopsy, examination of breast lump, thyroid gland, and joint inflammations. These diagnoses are handled by sonographers and carried out using a transducer, a hand probe that is placed on and moved over the patient. A water-based gel is used to couple the ultrasound between the transducer and the patient (Aladin et al., 2011) and (Masic2010). Ultrasound can be used for therapeutic purposes to interact with tissues in the body such that they are either modified or destroyed.

2. Historical Review

The usage of ultrasound in medicine began during the World War I(Donald et al., 1958) and it was used in detecting submarines. Shortly after, different centers around the world introduced it in general diagnosis (Newman et al., 1998). Dr Karl Theodore Dussik's work on transmission ultrasound investigation of the brain in the year 1942 and was the first published work on medical ultrasound before the research by the likes of Prof Donald Ian in mid 1950s leading to the wider use of ultrasound in medical practice owing to its noninvasive, good visualization characteristics, and relative ease of management (Campbell et al., 2013) and (Newman et al., 1998).

Figure1. Showing the first ultrasound machine used in diagnosis.(Donald et al., 1958)

In the mid-sixties, due to more discoveries of piezoelectric materials, further improvements were made on ultrasound images, from bistable to grayscale, from still images to moving images which led to increase in its applications (Donald et al., 1958).Ultrasound has undergone rapid changes since its origination three decades ago; the original cumbersome B-mode gantry system has evolved into a portable, user-friendly and sophisticated high resolution real-time imaging system (Lanza et al., 2020). Such rapid progression was brought by the combined efforts of medicine, physics, engineering, physiology, and government. Also, the improvement on transducers has led to higher resolution of images (Hussain et al., 2022)

Ultrasound diagnostics can be differentiated into transmission and reflection technology (Masic I et al., 2010). Transmission technology is based on distinguishing the tissues with various absorbance of ultrasound. This technology has been abandoned due to uneven absorption of ultrasound images providing internal structure that comprise of a collage of darkness and light (Aladin et al., 2011).

Aladin et al. (2011) opined on reflection technology (echo) that occurs when the wave passes between two tissues of different acoustic impedances and a fraction of the wave bounces back. Their technique was based on the principle of functioning sonar, where a sound wave is produced by a ceramic piezoelectric transducer encased in a probe. Strong, short electric pulses from the ultrasound machine make the transducer ring at the desired frequency between 2 to 18 Megahertz. A complex set of control pulses from ultrasound machine, the lens attached to the transducer, and the shape of the transducer make the sound focused which gives rise to an arc shaped sound wave from the face of the transducer. The wave travels into the body and comes into focus at a desired depth. Recent transducers make use of phased array techniques that aids the sonographic machine to change the direction and depth of focus (Aladin et al., 2011).

2.1 Modes of Ultrasound

Modern day ultrasounds come with several features and various modes which can be used in medical imaging. These include:

2.1.1 A-mode (Amplitude)

This is the earliest ultrasound mode which shows returning echoes in one dimensional, graphical format. A single transducer scans a line through the body and the echoes are plotted on the screen. This information is used to measure depth/thickness of tissues. This mode is used in examining the lens, cornea and chambers of the eye. However, this mode has been superseded by other modes but still directly relative (Christian 2016)

2.1.2 B-mode (Brightness)

This represents the amplitude peaks in A-mode as dots of varying brightness. In B-mode ultrasound systems can send out successive ultrasound pulses in different directions to form multiple image lines (Christian 2016)

2.1.3 M-mode (Motion)

Here, a rapid sequence of B-mode scans whose images should follow which. M-mode is used in assessing distance between tissue planes as they move. This application is commonly seen in echocardiography for assessing chambers and valves(Christian 2016).

2.1.4 Doppler Mode

Doppler mode utilizes Doppler Effect (the frequency alterations from an ultrasound interaction with moving objects) in measuring and analyzing blood flow in most modern ultrasound systems. This is very important in medicine as it helps to visualize the direction and speed of blood flow in the body, for example, to determine reverse blood flow in the liver vasculature (Harvey et al., 2002). There are generally two ways the Doppler data can be collected (pulsed wave and continuous wave) and displayed (spectra and color). In pulsed wave doppler, the transducer alternates between emitting a single pulse of ultrasound and waiting to receive the returning echoes while in continuous wave doppler, a continuous wave of ultrasound is produced and returning echoes are interpreted simultaneously by the ultrasound machine. For display of doppler data, spectral doppler displays in graphical format while color doppler displays as colored pixels and it is the most widely used form of doppler ultrasound.

Human tissues are heterogeneous in terms of the ultrasonic waves, and the passage of waves through the tissue leads to refraction, reflection, scattering and absorption of energy.

Reflection of ultrasound relies on the characteristic acoustic impedance of the funds on whose border is reflected, whereas, the absorption and refraction of ultrasound increases with frequency. Example, abdominal examinations (kidneys, pancreas, and liver) uses a frequency of about 3 MHz, examination of children, neck, breast, and the similar uses a frequency of around 5 MHz, and sometimes even 7 MHz. The higher frequency allows better discernment of detail in the picture, and is being used by the highest frequencies that are sufficiently prevalent (Aladin et al., 2011).

Another major use of ultrasound in medical diagnostics is to detect motion and determine velocity through the Doppler shift of an echo. Doppler Effect, described in 1842 by Christian Andreas Doppler, is the change or shift in the frequency or wavelength of a wave due to relative movement between an emitting or reflected sound source and the receiver. This change in frequency is called Doppler frequency shift (DFS), which equals the difference between the transmitted and the received frequencies (Katsi et al., 2013).This technique is used to monitor fetal heartbeat, measure blood velocity, and detect occlusions in blood vessels, for example. The magnitude of the Doppler shift in an echo is directly proportional to the velocity of whatever reflects the sound. There is a double shift due to the presence of an echo. The first doppler shift occurs because the reflector (say a fetal heart) is a moving observer and receives a Doppler-shifted frequency. The reflector then acts as a moving source, producing a second Doppler shift.

2.2 Basic Components of an Ultrasound

The basic components of an ultrasound consist of a transducer, transducer pulse control, central processing unit, display, keyboard with control knobs, printer.

2.2.1 Transducer

This is the most important part of an ultrasound machine. The ultrasound linear probe is responsible for sending and receiving the sound waves that create the image. It does this through piezoelectric effect, a phenomenon that causes quartz crystals within the probe to vibrate rapidly and send out sound waves. This is done by using an application of an electrical current. These waves then bounce off objects and are reflected to the probe. After the probe sends out the waves, the front-end processor combines and amplifies them. This signal is then sent to the CPU.

Transducer probes come in many shapes and sizes, as shown in the photo below. The shape of the probe determines its field of view, and the frequency of emitted sound waves determines how deep the sound waves penetrate and the resolution of the image. Transducer probes may contain one or more crystal elements; in multiple-element probes, each crystal has its own circuit. Multiple-element probes have the advantage that the ultrasound beam can be "steered" by changing the timing in which each element gets pulsed; steering the beam is especially important for cardiac ultrasound. In addition to probes that can be moved across the surface of the body, some probes are designed to be inserted through various openings of the body (vagina, rectum, esophagus) so that they can get closer to the organ being examined (uterus, prostate gland, stomach); getting closer to the organ can allow for more detailed views (Hijazi).

Figure 2. Showing various transducer probes in their various shapes and sizes used in different fields. (Tudor et al., 2019)

2.2.2 Transducer pulse control

The transducer pulse controls allow the operator, called the ultrasonographer, to set and change the frequency and duration of the ultrasound pulses, as well as the scan mode of the machine. The commands from the operator are translated into changing electric currents that are applied to the piezoelectric crystals in the transducer probe.

Figure 3. Showing controls used by a sonographer to send commands (Hijazi, 2011)

2.2.3 Central Processing Unit (CPU)

The CPU is the brain of the ultrasound machine. The CPU is a computer that contains thememory, amplifiers and power supplies for the microprocessor and transducer probe. The CPU sends electrical currents to the transducer probe to emit sound waves, and also receives the electrical pulses from the probes that were created from the returning echoes. The CPU does all of the calculations involved in processing the data. Once the raw data are processed, the CPU forms the image on the monitor. The CPU can also store the processed data and/or image on disk *(Hijazi, 2011)*

2.2.4 Display

This the screen that shows the data collected from the CPU. This display can be either black and white or colored depending on the model of the ultrasound used.

2.2.5 Keyboard

This comes with control knobs which helps the sonographer adjust the image on screen to make it crisp. The keyboard is used for inputting details of a patient such as name, weight, height, age, and purpose of visit; to add notes, and take measurements.

2.2.6 Printer

A printer in ultrasound system is used to capture the hardcopy of the data on display

3. Functions of Ultrasound Machine

Ultrasound scans are one of the most common medical procedures today and its applications are needed in almost every medical department. Deeper imaging is possible with ultrasounds than with X-rays, without any harmful health concerns. Ultrasounds perform 2 major functions which are Diagnosis and Therapy (Palmer, 1988).

3.1 Diagnostic ultrasound

Diagnostic ultrasound is able to non-invasively image internal organs within the body, although it is not good for imaging bones or tissues that contain air such as lungs, with exception fetus and infants or lungs and lining around the lungs when they are partially filled with fluids. Most diagnostic ultrasound probes are placed on the skin. However, to optimize image quality, probes may be placed inside the body via the gastrointestinal tract, vagina, or blood vessels. Ultrasound images are displayed in 2D, 3D, or 4D (which is 3D in motion) (Quarato et al., 2023)

The following are the applications of diagnostic ultrasound:

1. One of the best-known uses for ultrasound imaging is fetal ultrasound, which is used to examine a baby during pregnancy. It’s also used to view the ovaries and uterus during pregnancy.
2. An abdominal ultrasound examines abdominal tissues and organs.
3. Bone sonometry is a type of ultrasound imaging that examines bone density and assesses risk for osteoporosis.
4. Breast ultrasound screening can help detect breast cancer in women with dense breasts.
5. An echocardiogram, an ultrasound of the heart, allows assessment of the overall function of the heart. Echocardiograms are often combined with Doppler ultrasound, which visualizes blood flow through blood vessels and organs.
6. Ophthalmic ultrasound examines the structures of the eye.

7. Ultrasound can help assess joint inflammation.
8. Ultrasound imaging can help diagnose causes of pain, swelling, and infection inside the body.
9. Physicians use ultrasound imaging to examine the structures of internal organs for damage after illness.
10. Ultrasound can help detect genital and prostate problems.
11. To guide interventional procedures such as biopsies or to drain collections of fluid, this can be both diagnostic and therapeutic (Quarato et al., 2023).

3.2 Therapeutic ultrasound

Therapeutic ultrasound produces high levels of acoustic output that can be focused on specific targets for the purpose of heating, ablating, or breaking up tissue. Its purpose is to interact with tissues in the body such that they are either modified or destroyed. Among the modifications possible are dissolving blood clots, or delivering drugs to specific locations in the body. These destructive, or ablative, functions are made possible by use of very high-intensity beams that can destroy diseased or abnormal tissues such as tumors. The advantage of using ultrasound therapies is that, in most cases, they are non-invasive. No incisions or cuts need to be made to the skin, leaving no wounds or scars with a technique known as High Intensity Focused Ultrasound (HIFU).

HIFU is a method for modifying or destroying diseased or abnormal tissues inside the body (e.g., tumors) without having to open or tear the skin or cause damage to the surrounding tissue. HIFU is currently FDA approved for the treatment of uterine fibroids, to alleviate pain from bone metastases, to close wounds, open the blood brain barrier to allow medications to pass through, and most recently for the ablation of prostate tissue. Also, research is now being carried out in the treatment of certain types of cancer by local heating, since focusing intense ultrasonic waves can heat the area of a tumor while not significantly affecting surrounding tissue.

Trackless surgery—that is, surgery that does not require an incision or track from the skin to the affected area—has been developed for several conditions. Focused ultrasound has been used for the treatment of Parkinson’s disease by creating brain lesions in areas that are inaccessible to traditional surgery. A common application of this technique is the destruction of kidney stones with shock waves formed by bursts of focused ultrasound. In some cases, a device called an ultrasonic lithotripter focuses the ultrasound with the help of X-ray guidance, but a more common technique for destruction of kidney stones, known as endoscopic ultrasonic disintegration, uses a small metal rod inserted through the skin to deliver ultrasound in the 22- to 30-kilohertz frequency region (Haar, 2009).

4. Design-Features of Ultrasound

The inverter is a device that converts electrical signals into mechanical (ultrasonic vibrations), and vice versa. When activated inverter is leaned on the body, it emits an ultrasonic beam. Ultrasonic waves are focused by lenses, ultrasonic mirrors and by electronic means. These ultrasonic waves during imaging are emitted from a transducer, a crystal exhibiting the piezoelectric effect. Piezoelectric effect is the expansion and contraction of a substance with the application of voltage thereby causing a vibration of the crystal. Tissues that come in contact with the transducer absorb these high-frequency vibrations. Similarly, if pressure is applied to the crystal which appears as a wave reflected off tissue layers, a voltage is released which can be recorded. The crystal therefore acts as both a transmitter and a receiver of sound. Ultrasound, on its journey away from the transducer and on its return journey is absorbed by tissues on its path. The nature and position of boundaries between tissues and organs are ascertained from the time between when the initial signal is sent and when the reflections from different boundaries between media are received, (as well as a measure of the intensity loss of the signal) (Aladin et al., 2011) and (Palmer, 1988).

Reflections at boundaries between two different media occur due to differences in a characteristic known as the *acoustic impedance* Z of each substance. Impedance is defined as $Z = \rho v$, where ρ is the density of the medium (in kg/m^3) and v is the speed of sound through the medium (in m/s). The units for Z are therefore kg/(m$^2 \cdot$ s).Table 1 below presents the speed, density, and their associated acoustic impedances of sound through various media (including various soft tissues). There is a huge difference between the acoustic impedance of air and soft tissues and that of soft tissue and bone but the acoustic impedances of soft tissues vary with a small gap.

Table 1 showing the ultrasound properties of various media including tissues in the body(Tole et al., 2005)

Medium	**Density (kg/m^3)**	**Speed of Ultrasound (m/s)**	**Acoustic Impedance (kg/(m^2.s))**
Air	1.3	330	429
Water	1000	1500	1.5×10^6
Blood	1060	1570	1.66×10^6
Fat	925	1450	1.34×10^6
Muscle (average)	1075	1590	1.7×10^6
Bone (varies)	1400-1900	4080	5.7×10^6 to 7.8×10^6
Barium titanate (transducer material)	5600	5500	30.8×10^6

Some wave energy is being reflected while some are transmitted at the boundary between media of different acoustic impedances, some of the wave energy is reflected and some is transmitted. The greater the *difference* in acoustic impedance between the two media, the greater the reflection and the smaller the transmission.

The *intensity reflection coefficient a* is defined as the ratio of the intensity of the reflected wave relative to the incident (transmitted) wave. This statement can be written mathematically

$a = \frac{(Z_2 - Z_1)^2}{(Z_1 + Z_2)^2}$, (1) (Feng et al., 2008)

where Z_1 and Z_2 are the acoustic impedances of the two media making up the boundary. When the acoustic impedances of the two media are the same, there will be a reflection coefficient of zero (i.e., no reflection). An impedance "match" provides an effective coupling of sound energy from one medium to another. The image formed in an ultrasound is made by tracking reflections (as shown in Figure 3) and mapping the intensity of the reflected sound waves in a two-dimensional plane.

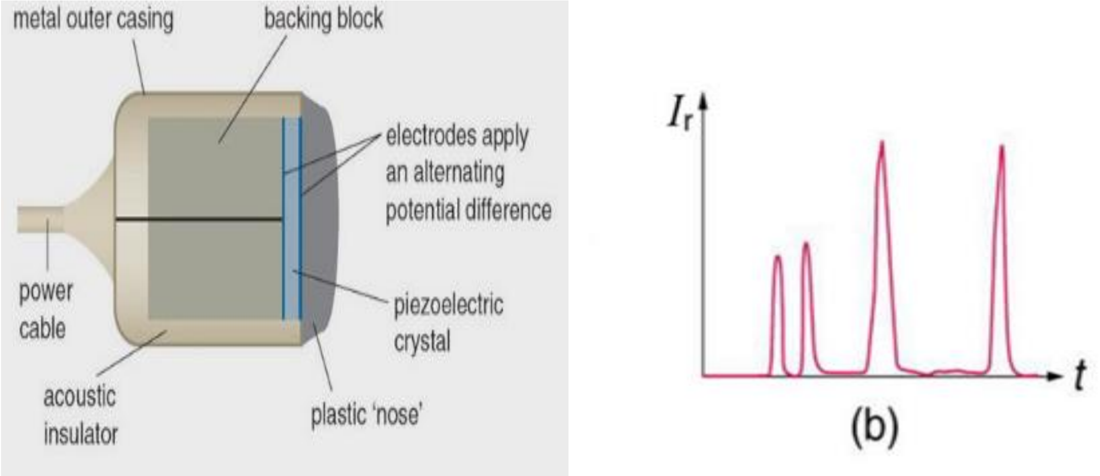

Figure 4. (a) A transducer probe showing its design (b) Graph of echo intensity against time showing the proportionality of the distance of a reflector to the time for echoes to return (Tole et al., 2005)***.***

5. Future Improvement Strategies

There is high drive for low cost and high-quality imaging services due to the growth of healthcare costs in developed countries, and the desire to access care in developing countries. Due to demand and technology, research has proven that miniaturization of signal processing electronics reduces the size and cost of ultrasound devices and has invariably led to the rise of portable ultrasound devices that function with mobile devices. This has proven to be a threat to the multi-modality imaging companies as new companies continue to come up with innovative portable products and low-cost devices to satisfy local demand. Some companies have gone ahead to create pocket size ultrasound devices such as hand-held visual stethoscope although with no proven success as a development tool and yet to be embraced globally.

In this age of rapid expansion of artificial intelligence (AI) with its large number of conquered tasks such as agile-legged locomotive robot, object recognition in images, machine translation, speech recognition, self-driving cars, and so on; the conversation about the impending and potential impact of AI on our clinical practice within the medical imaging community cannot be averted. A notable example of potential AI development in medicine is mammography. There had been shortages of skills and staff affecting the National Breast Screening Programme but with the AI tools, the resource use reduces; and the same development is needed in ultrasound imaging.

Ultrasound poses some specific engineering needs such as the need for broad, standardized datasets of complete and routinely gathered ultrasound clinical image data; knowledge of differing local imaging procedures; robust handling of variations in image quality; and the need for algorithms that are generalisable among equipment manufacturers.

There are however other ultrasound AI tools needs such as the need for persistent optimization of 2D and 3D volume sonography, the improvement of real-time intuitive user guidance, human factors research connected to ease of AI tool usage, and generalisability by manufacturers to create room to utilize multiple vendors for best solutions. Notably, global acceptance of these technologies depends on appropriate authorization measures and clinical infrastructure, including cloud-based solutions and incorporation of plug-in-based solutions —standardisation and certainly adequate staff training

6. Conclusion

The applications of ultrasound in medical diagnostics have produced manifold benefits with no known recorded risks. These machines are essentials tools in the field of medical imaging as they are used to creating images of internal organs, tissues, and liquids in the human body. The usage of ultrasound technology in diagnostics and treatment has significantly increase in recent years due to its non-invasive nature and accurate results even as the technology of ultrasound machine continue to evolve progressively so does the accuracy and accessibility of this diagnostic tool.

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