A HISTORY OF MEDICAL ULTRASOUND

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The history of ultrasound lacks the dramatic appearance of radiology that resulted from Rontgen's discovery of x-rays. Ultrasound infiltrated medical imaging by stealth, beginning to emerge a full fifty years after its first scientific apprearance and taking the whole of the **second half of the twentieth century** to become established. This is a very brief account of the slow emergence of this **now omnipresent imaging** method in modern diagnostic medicine.

Ultrasound refers to any **physical wave of a frequency above the limit of human hearing,** 20 kHz (20,000 cycles a second). This limit was investigated towards the end of the 1800s, using very small tuning forks, whistles and electrical sparks to generate sound waves up to about 100 kHz.

Ultrasound can travel in liquids and solids as well as in air. Seeking a means to detect submarines during WWI, the eminent French physicist **Paul Langevin** required a new, more powerful, source of ultrasound and a more sensitive detector. He realised that a slice of a natural quartz crystal could be used, but only if it was cut along a particular angle. In 1880, brothers Pierre and Jacques Curie had shown that quartz was piezoelectric: applied pressure generated an electric voltage and, conversely, an applied voltage caused the crystal to expand or contract. Langevin mounted **X-cut quartz crystals** between plates of steel. When the correct, resonant, electrical frequency was applied (he used 40 kHz) the face oscillated strongly, **like a loudspeaker**, causing **a beam of ultrasound** to be emitted. Conversely, an ultrasound wave arriving at the surface generated an electrical signal that could be detected and amplified, **like a microphone**. These X-cut quartz transducers could be used therefore to send pulses and receive echoes. The **time taken** for the pulse to return gave the distance of a target, submarine, iceberg or sea floor, knowing the speed of sound in sea-water, about 1500 m/s.

During the 1920s and 1930s, quartz and other piezoelectric crystals were used as sources of ultrasound to investigate its **physical, chemical and biological properties**. Thinner crystal cuts led to higher ultrasonic frequencies, 1 MHz or more. Exposure caused **heating,** and high intensities caused violent mechanical agitation and **cavitation**, which was thought to be the cause of the observed destruction of biological cells. By 1950, ultrasound was in widespread use for therapy, the **therapeutic heating** enhanced, it was believed, by '**micro-massage**'.

Ultrasound Imaging

In the 1940s, the first tentative steps were taken to use ultrasound as an alternative to x-rays to image internal body structures. The Austrian Dussik brothers created **transmission images of the head** using a pair of transducers, scanned backwards and forwards. **Those who are first are not necessarily right**. They picked the wrong approach (transmission) and the wrong part of the body. Even today, ultrasound is not used to scan the brain because the beam is distorted too much as it passes through the skull.

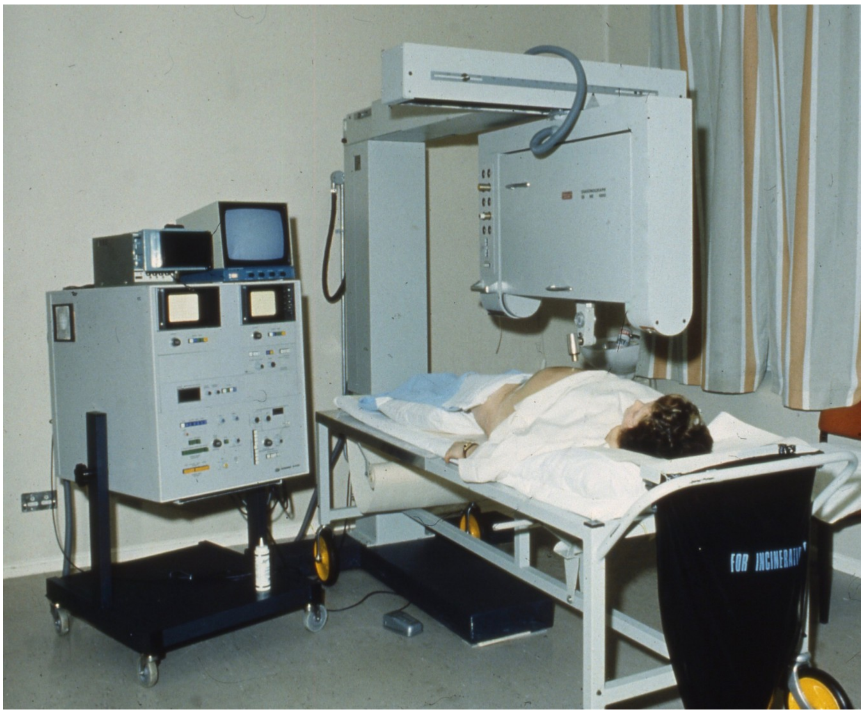
Pulse-echo ultrasound

Two industrial developments had emerged by 1950 which, together, gave rise to the start of modern medical ultrasound imaging. **Pulses of ultrasound** were used to test for defects in metal parts by **detecting their echoes**, a scaled version of underwater detection, but over shorter ranges and at higher frequencies. And certain micro-crystalline mixtures, which had been developed for improved capacitors during the war, were discovered to be piezoelectric. Quartz was soon replaced by the **ferro-electric ceramic lead zirconate titanate**, which could be shaped and cut at will, opening the way to a future of arrays and focussed beams.

No-one knew then how best to use ultrasound, and for which clinical purposes.The earliest workers often started with a **borrowed industrial flaw detector**. Coupling the beam into the body was challenging, and many early experimental systems used **water baths** into which the person or body part was placed. The most successful progress emerged from partnerships between a **specialist medical doctor and an engineer**, such as the obstetrician **Ian Donald** and engineer **Tom Brown** in Glasgow, the cardiologist **Inge Edler** and the physicist **Helmuth Hertz** in Lund and the doctor **John Wild** and the engineer **John Reid** in Minneapolis. In this last partnership, one of the earliest, a **modified radar simulator** working at 15 MHz was adapted to create ultrasound breast images, **looking for cancer**. This diagnostic challenge was too great at this stage, but they showed how easy it was to **distinguish cystic from solid lesions** using ultrasound. But the **unusual images** created by these pioneers using ultrasound, showing slices through the body instead of projections, were **unfamiliar** to doctors who were used to looking at radiographs, and were **difficult to read**. In addition to showing little structural detail, these were **sectional images**, or tomographs, and this format would only find general acceptance with the advent of the x-ray CT scanner 20 years later.

Commercial scanners

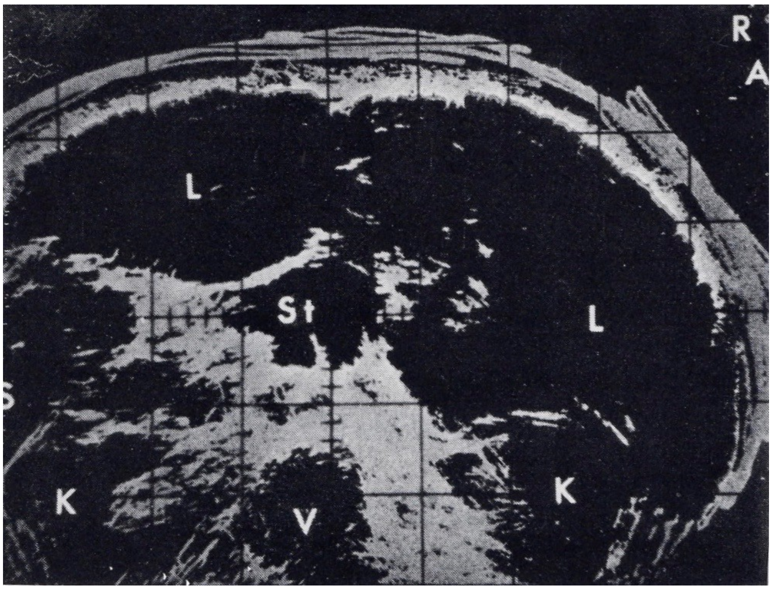
A wide variety of different ultrasound scanners were designed and offered for sale during the 1960s and 1970s. The majority used **contact scanning** instead of a water-bath. The skin was **coated with oil** as a coupling and lubricant. The pulse-echo transducer was then **slid and rocked** across the skin, constrained to move in one plane, and its position and direction automatically registered. The received **repetitive echo trains (A-scans)** were **written into an image (a B-scan)** as lines of bright spots. One version was the **Diasonograph,** with its unique, rugged overcouch gantry, developed in Scotland from Tom Brown's design for Ian Donald. Most other manufacturers used a simpler, more flimsy, articulated arm to hold the transducer. The high-contrast images were built up as the operator moved and rotated the transducer on the patient's skin, recorded on film or a storage oscilloscope. **Compound scanning** was widely used, the image built up from many directions. Later, with improved means of focussing and image processing, compound scanning became less important. By the end of the 1960s, most large hospitals were equipped with a scanner of some sort. Some attempts to **automate the scan** were made, most successfully in the **Octoson**, developed by the Commonwealth Acoustics Laboratory in Sydney.



The Nuclear Enterprises Diasonograph. C. 1975

Early clinical uses

Obstetrics and gynaecology proved a major area of use. Contrast between the developing fetal skeleton, the amniotic fluid and the uterine wall created images that could be understood. Ultrasound had the additional advantage of safety, in comparison with x-rays. In **cardiology** a new technique, echocardiography, allowed the movement of valves and heart wall to be tracked using M-mode, which recorded the motion of the echoes over a few cardiac cycles. **Ophthalmology** applications were soon successful, the short range allowing high frequency, high resolution images of, for example, retinal detachment.



Abdominal B-scan c. 1972, L, liver: S, spleen: K, kidney: V, vena cava.

Abdominal scanning was much slower to evolve, requiring some important developments in electronics. The most important produced '**grey-scale'** images, compressing the echo amplitudes so that both strong and weak echoes could be included, filling spaces with structural detail. This paved the way for soft-tissue imaging of the liver, kidneys, muscles and breast. Adjustable **swept gain** corrected for varying attenuation.

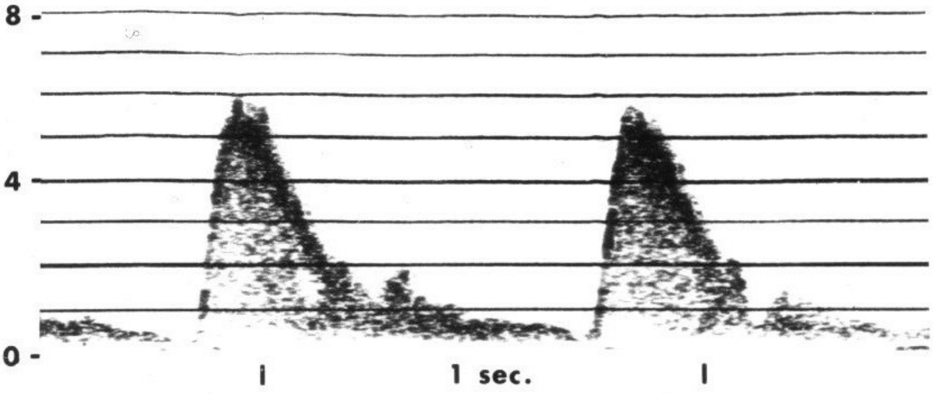
Real-time imaging

Early scans took **several seconds** to complete. During the 1970s several approaches were introduced to **move a transducer mechanically**, so creating a **real-time sequence of 2D scans** many times a second. Up to five transducers were mounted within a scan head, which were scanned automatically in turn over the skin surface. An alternative, electronically **switched linear arrays**, quickly followed. Using phase control on the amplifiers on each array element it was possible to sweep the focus over each pulse-echo cycle. During the 1980s, arrays, of a variety of sizes and shapes, replaced mechanical scanners. **Phased arrays**, with steered beams, were particularly used in cardiology. Eventually, 2D arrays enabled the fixed focus in the scan plane to be adjusted also. Miniature mechanical scan-heads and probe arrays were designed to image the **heart** from the oesophagus, the **prostate** from the rectum and the **uterus** from the vagina. By the early 1980s, real-time scanners had replaced the older static B-scanners for most applications. The first portable scanners, such as the Minivisor, became available.

The portable Minivisor, c 1980, with integrated linear array and display

Doppler

Detection of the **Doppler frequency shift** of the received wave made it possible to observe the speed of movement of body structures and blood, demonstrated first by Satomura in Japan in 1959. At first, this effect was used for **fetal heart detection**, and to observe **blood flow in peripheral arteries**, using continuous wave ultrasound. The Doppler-shifted frequencies, in the audio range, could be either listened to or displayed using **spectrum analysis**, at first by replaying the recorded sound off-line and later by fast digital frequency analysis. **Pulsed Doppler** required higher acoustic powers and more sensitive receivers. By the 1990s, pulsed Doppler imaging became an integral part of real-time scanning, displaying local regions of arterial and venous flow in **colour overlay**, leading to a rapid expansion in the use of ultrasound in peripheral vascular disease.



Off-line spectrogram of the Doppler waveform from canine aorta c. 1974

More recent developments

In due course, **digital electronics** completely replaced the old analogue systems, giving cleaner signals and improved processing, and opening new technical possibilities. Notable recent developments include: **harmonic imaging**, using harmonics generated by propagation in tissue to de-clutter the image: **elastography,** by recording strain in response to a force, applied either at the surface or caused by the acoustic radiation pressure within tissue: **very fast frame rates**, forming a whole image by parallel processing of echoes following a single emitted pulse from a large array: **cheaper, portable scanners** resulting from miniaturization, improved batteries and new transducer technology.

Current status

Ultrasound scanning now probably **contributes at least 30% of all medical imaging** worldwide. By 2014, the year that the UK NHS stopped gathering imaging statistics, the number of ultrasound scans in England was approaching ten million, well exceeding the combined totals of CT and MRI at that date. Uses outside obstetrics now constitute the majority, and also extend outside the confines of departments of imaging and radiology. Many new medical technologies never emerge beyond the headline-grabbing launch phase, and others only find permanent homes in niche areas of medicine. Not only has ultrasound scanning found extensive clinical application, it is **cost-effective, safe, small-scale** and, in particular, it is **kind to the patient**.