HISTORY OF MEDICAL ULTRASOUND

WN McDicken and CM Moran

Medical Physics, Centre for Cardiovascular Sciences, University of Edinburgh, Edinburgh, Scotland, UK

I. INTRODUCTION

This section deals with the technology that used single piezoelectric ceramic transducers to obtain information on soft tissues. It also seeks to identify lessons learned from applications as techniques advanced to multi-element array transducers. In the early days, engineering and clinical projects were pursued in universities and companies throughout the world. It is worth remembering that ultrasound technology was developed at the end of the vacuum tube valve era. Stability and reliability were problematic with valve circuitry as was the shear bulk of the instruments. Not surprisingly, digital technology impacted the field in an ever- increasing way.

To explore the very large output of scientific work, use has been made of bibliographies in text books and international conferences proceedings. Several text books with a historical content provide extensive bibliographies of medical ultrasound [1-7]. Reference 3 is a very large cumulative bibliography with 19,453 entries from pre-1950 up to 1978 [3]. These publications also give an appreciation of the large amount of biological research which was a feature of that era. International conferences, although they are selective in content, convey the range and enthusiasm of participants around the world and a flavour of early research both technical and clinical [4]. The internet also provides many scientific papers and excellent reviews but the amount can be over-whelming, but usually worth pursuing. All figures are reproduced from McDicken (1991) [8].

II. A-MODE AND M-MODE SCANNERS

A basic instrument used initially in medical ultrasound was called an A-scanner. With this type of unit, a single piezoelectric ceramic transducer was employed to transmit a short pulse of ultrasound, typically 2 or 3 cycles in length, along a narrow directional beam into the body. After transmission, this unit then quickly switched to a reception mode using the same transducer to detect echoes from targets of interest. The very high speed of ultrasound in tissue resulted in a rapid collection of echo data e.g. in 130 microseconds for a target at a depth in tissue of 10 cm. This rapid data collection is central to all pulse imaging techniques which can therefore operate at high frame rates. High frame rates are a very valuable feature of medical ultrasound. Using an average speed of sound in soft tissue of 1540 m/sec to calibrate scanners gives acceptable errors for range measurement in virtually all clinical applications.

There were a large number of A-scan instruments available in the 1960s since in the engineering industry they were manufactured for detecting echoes from flaws in engineering components – they often went by the name of 'flaw detectors'. They were basically oscilloscopes with a pulse generator and receiver added. Part of the folklore of ultrasound is that engineering apprentices immersed their feet in buckets of water and used the flaw detectors to detect their bones. A few clinical applications were developed for example measurement of shift of the brain midline due to head injury or measurement of eye-ball length (Figure 1**).**

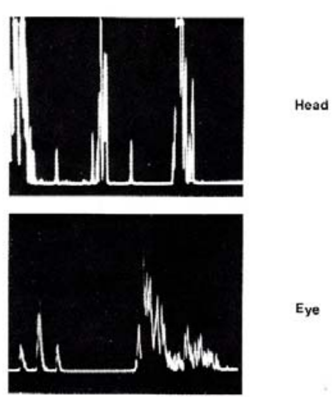

Fig. 1 An A-scan trace from the head. The echoes from the midbrain are positioned between the strong echoes from the skull. An A-scan trace from the eye shows cornea and lens echoes on the left and orbital echoes on the right.

A-scanners are no longer purchased as stand-alone clinical instruments. Pioneering applications of engineering in medicine were often not complex but were difficult to interpret. The A-scan facility remained a feature of imaging machines for around 30 years and were widely used to make biparietal diameter measurements in obstetrics. It was felt that greater accuracy of measurement could be obtained with it rather than with a B-scan image. High quality image storage displays had still to be incorporated into scanners.

The A-scan mode was considered to be safe for both the operator and the patient since MHz frequencies are rapidly attenuated in air and there had been no reports of harmful effects. Studies of bio-effects of ultrasound ran in parallel with development of imaging technology.

Early A-scan applications showed that it was essential to exclude even a very thin film of air at the transducer/tissue interface. Exclusion was readily achieved with oil or gel in the interface. This simple means of exclusion permitted good acoustic coupling of single element or array transducers. Ease of coupling made contact scanning possible even when the transducer was moved across the skin. Stand-alone A-scan units never found much routine clinical application but they did provide a means of gaining experience of the use of ultrasound in tissue. Echoes from static structures remain fixed on a display. Motion of structures such as heart walls and valves could be observed and recorded (Figure 2**).** The latter technique, known as an 'M-mode', is fast and is still a feature of modern echocardiography. M-mode traces can be presented simultaneously with other physiological signals such as an ECG, phonocardiogram and Doppler ultrasound flow spectrograms (Figure 3).

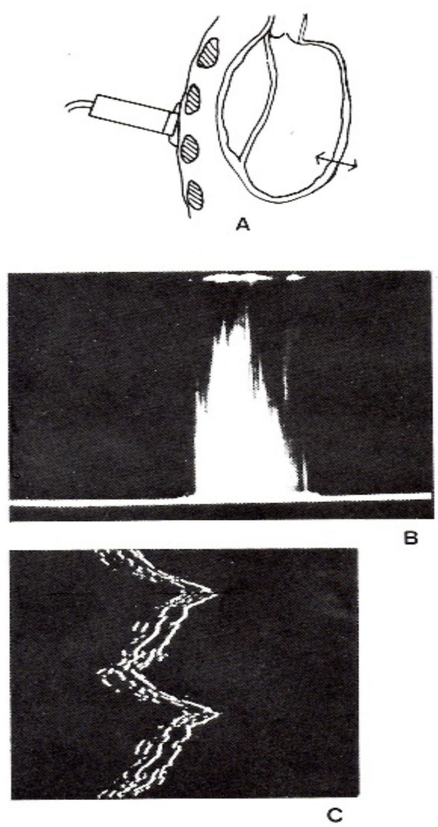

Fig. 2 Principle of M-scanning. (a) Transducer directed at moving structure of interest and held fixed, (b) echoes may be observed on an A-scan display but this does not give a record of motion, (c) echo dots sweep up the screen to provide a trace of position versus time.

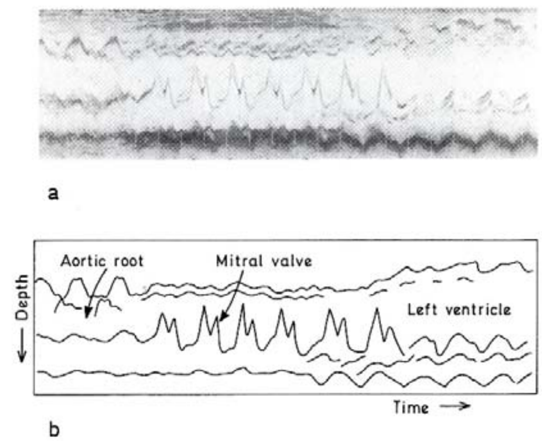

Fig. 3 Adult heart action recorded by M-scanning: write-out on a fibre-optic chart recorder. The direction of the beam was slowly altered during the recording.

III. Water-bath B-mode scanners

Early ultrasound imaging scanners often employed water-baths to couple the machines to the patient. In a water-bath scanner, a depth of water was interposed between the transducer and the patient either by immersion of the patient or by enabling access via a thin membrane on the side of the tank (Figure 4).

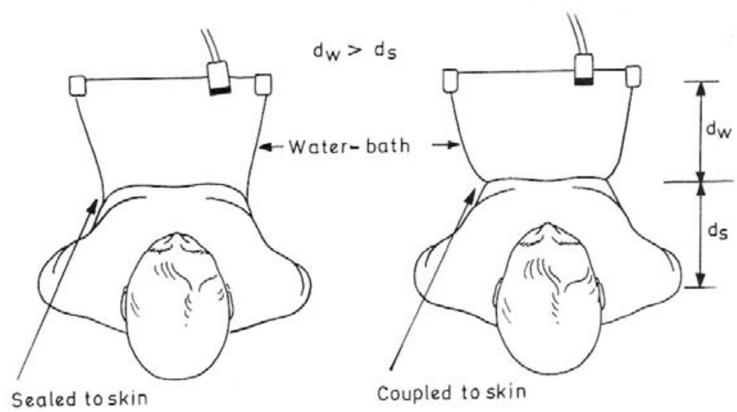

Fig. 4 Water-bath coupling techniques.

To avoid multiple reflection echoes in the water overlapping in time with echoes from tissue, the depth of water had to be greater than the depth in tissue of the structures of interest. The walls of the bath were often lined with rubber which was an excellent acoustic absorber reducing weak background multiple reflection signals. Water is a uniform low attenuation medium in which a transmitted field could form with good focusing. The velocity of ultrasound in water at room temperature is close to the average velocity of ultrasound in soft tissue i.e. 1540 m/s. It is easy to appreciate why water was used as the coupling medium in the first imaging machines. Water-bath scanners were popular for scanning soft tissues which were mobile such as breasts, eyes, testicles and infants.

As technology developed, lessons were learned which benefitted the next generation of scanners. A water-bath scanner, known as the 'Octoson' is a particularly good example of this process (Figure 5). In this machine, 8 large saucer-shaped transducers, each of diameter 7 cm, were mounted on a cradle in a water-bath. The position of the cradle could be altered by a drive mechanism to select the scan-plane. The 8 transducers could oscillate singly or collectively to perform a simple or compound scan. In a later version of this machine, the single-element transducers were replaced by annular array transducers to give an extended focal range. The large aperture transducers provided well-focused beams. The patient lay on a membrane across the top of the water-bath (Figure 6).

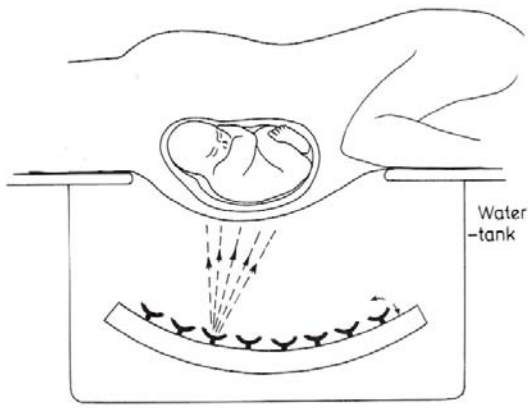

Fig. 5 Basic structure of the UI Octoson scanner.

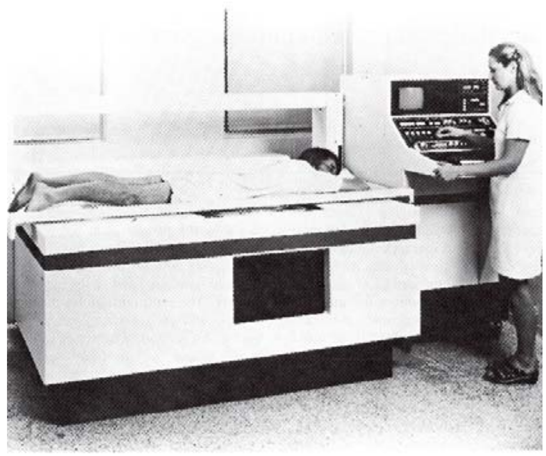

Fig. 6 The UI Octoson scanner (courtesy of Ausonics).

A large part of the success of the Octoson was due to the grey-scale images resulting from the electronic processing of the echo signals. This grey-scale processing preserved the weak echoes which had been removed as noise in most scanners. The preservation of weak echoes in an image demonstrated that they were generated by weakly scattering targets in the parenchyma of tissue. As a result of this preservation, the images looked like slices through tissue and did not just show boundaries (Figure 7).

Fig. 7 Image from UI Octoson scanner (courtesy of Kossoff G).

These images improved the reputation of ultrasound imaging when X-ray CT and MRI imaging were making a significant impact. Compound scanning had been developed to accurately show distinct tissue boundaries and anatomical boundaries such as the fetal head and the liver/kidney interface. Simple sweep grey-scale images demonstrated that it was often better to have a small amount of local image distortion rather than blurring due to misregistration in compound scanning. The importance of well-focused beams, both on transmission and reception, was illustrated by the clarity of small liquid-filled structures (e.g. cysts and blood vessels). Improved transducers and grey-scale signal processing handled boundary and parenchymal echoes well. In other words, full use was made of the dynamic range of the echo signals. The speckle pattern of the weak echoes gave some information on the nature of the scanned tissue but it is probably of more value for assessing tissue motion such as that of the myocardium. Complete images produced by single sweep scans showed that compound scanning is not essential. This had major implications for hand-held, real-time scanners which were starting to be developed.

Grey-scale images were initially recorded using photographic film which did not allow the build-up of the image to be observed as the echoes were received and was therefore inconvenient to use. The advent of grey-scale scan converters, with which the build-up of the echoes in the image could be observed, provided the technology that ultrasound imaging required. Today echo signals are stored in digital memory which permits imaging processing. For a few years bi-stable display cathode ray tubes had been employed since they presented the large structures clearly but they were essentially a blind alley.

IV. Real-time mechanical scanners

It became obvious in the early 1970's that if fleeting structures like heart valves could be presented in an image to the operator, interpretation of cardiac echoes would be greatly facilitated. The simplest approaches were to make a single-element transducer rotate (Figure 8), rock (Figure 9) or oscillate (Figure 10) with the transducer closely coupled to the skin surface. With a careful choice of casing plastic, oil and structural design, the transmitted pulse was not degraded compared to an M-mode or B-mode and hence image resolution was preserved. The image sector angle of a rocking transducer was usually kept below 90^0 to minimise vibrations. Rotating transducers could readily produce a large 180^0 field-of-view with a high line density at low frame rates, giving a quality of image similar to that of a B-scanner. This was a goal of real-time scanners since, understandably, there was a reluctance to accept lower quality images. Oscillating transducers, angular or linear, performed well up to about 30 frames/sec, above which vibrations became problematic. The rotating transducer approach was therefore preferred at higher frame rates. An example of a commercially produced transducer consisting of four transducers on a rotating wheel is presented in Figure 11. A linear oscillation with a rectangular field-of-view suited some applications and a number of elegant devices were produced.

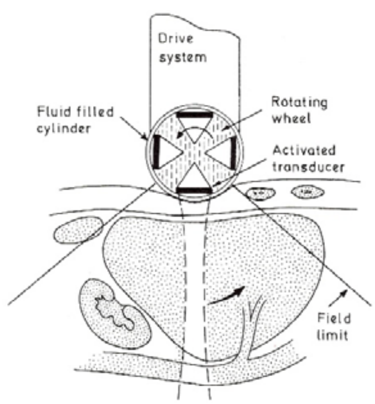

Fig. 8 A schematic diagram of a rotating transducer, real-time B-scanner.

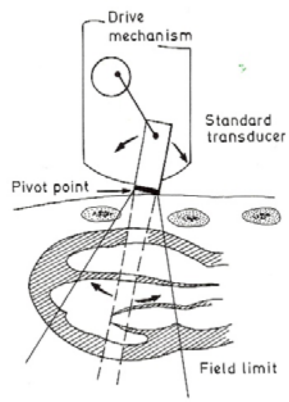

Fig. 9 A schematic diagram of an oscillating transducer, real-time B-scanner. The oscillations produce a sector scan.

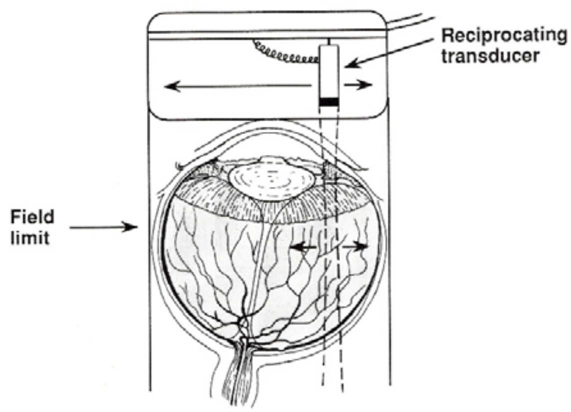

Fig. 10 A schematic diagram of an oscillating transducer, real-time B-scanner. The oscillations produce a linear scan.

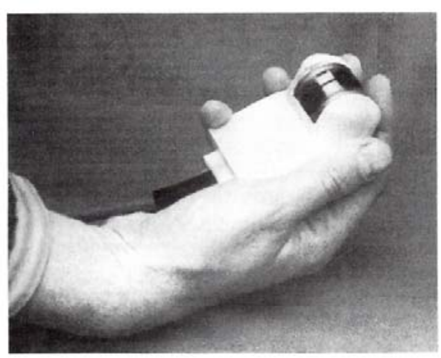

Fig. 11 A mechanical transducer assembly in which four transducers rotate in a thin-walled oil-bath (courtesy of BCF).

The advent of hand-held imaging transducers, which gave good image quality, made scanning quicker and easier. Imaging moving structures and changing scan-planes meant that the sensitivity controls (Gain, Time-gain-compensation – TGC, Power) were difficult to optimise with manual controls. Approaches to automatic control were introduced whereby information, related to echo signal magnitudes and rates of attenuation, was used to set the sensitivity in different regions of the image. After some initial concerns about loss of control, expressed by clinical users, it was demonstrated that well-balanced reliable images could be quickly produced.

There were attempts at mechanical 3D imaging at this time. However clinical operators with hand-held transducers developed skills in mentally imaging 3D anatomy as they viewed changing planes of scan. This removed the immediate need for 3D real-time imaging. The latter awaited the demands of heart scanning where changing volumes are of interest and these demands were accommodated by 2D phased arrays.

The versatility of real-time ultrasound technology is amply exhibited by a range of special invasive devices which have been developed. Over the history of medical ultrasound both real-time mechanical and electronic array technologies have been used. This versatility continues to be exploited in Doppler duplex, tissue biopsy and contrast agent applications. The new equipment remains relatively inexpensive.

IV. PLAN POSITION INDICATOR (PPI) IMAGING

In PPI, a transducer rotates and scans through 360^0 at right angles to the axis of a rod which is inserted into the body (Figure 12). Since the transducer can be placed close to the site of interest, high frequencies can be used. The transducer is contained in a shallow oil bath or balloon to avoid friction at the tissue. The transducers are often labelled 'transrectal', 'transvaginal', 'transuretheral' or 'transoesophageal'. Transoesophageal probes give good access to the heart by avoiding lung and bone. As for rotating element B-mode scanners, careful choice of oil and window plastic results in little distortion of the transmitted ultrasound pulse. Rotating transducers are also employed in flexible endoscopes.

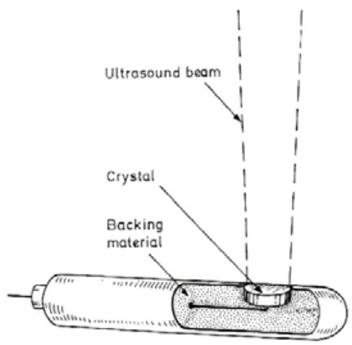

Fig. 12 Transducer for 360º radial invasive scanning.

V. CATHETER SCANNERS

Reducing the diameter size of PPI endoscopes from say 15 mm to 2 mm and increasing the frequency from 3 MHz to 30 MHz gave rotating element catheters a 360^0 field-of-view. Such catheters continue to be applied to the study of artery walls. Again liquid-filled balloons are used to make good acoustic coupling. This catheter technique is known as intravascular ultrasound (IVUS) [9]. Due to the risk of infection, catheters are required to be disposable and hence inexpensive. A concern using catheters which viewed only sideways and not forwards was that they may block a stenosed artery. Forward-viewing oscillating-transducer catheters were produced which demonstrated that easily understood images, pulse-echo and Doppler, could be produced of structures ahead of the catheter tip.

VI. BIOPSY NEEDLE GUIDANCE

A big attraction of real-time ultrasonic imaging was that the tip of a fine needle could be observed and followed to the tissue site of interest. The needle may or may not be passed through a guide channel or attached to the transducer. Again sterility must be retained. This continues to be a very valuable technique since a collected tissue sample can then be passed to the pathology laboratory. This method of getting an accurate diagnosis has in many cases removed the need to try to interpret ultrasound signals from tissue.

It is possible to attach a small piezoelectric element to the tip of the needle and get a signal which identifies it accurately in the real-time image. To avoid expense, most operators work with a normal needle and rely on identifying the tip echo signal. However there can be ambiguity as to the exact source of the tip echo.

REFERENCES

1, Gordon D. Ultrasound as diagnostic and surgical tool. E & S Livingston Ltd, Edinburgh & London. 1964

2, Wells PNT. Physical principles of ultrasonic diagnosis. Academic Press London & New York. 1964

3. White D, Clark G, Carson J, White E. Ultrasound in biomedicine. Cumulative bibliography of the world literature in ultrasound in medicine and biology to 1978. Pergamon Press, Oxford. 1982.

4. Bock J and Ossoinig K. Ultrasono Graphia Medica Vols 1,2,3. 1st World Congress on Ultrasonic Diagnostics in Medicine and SIDUO III, Vienna. 1960

5. Holm HH and Kristensen JK. Ultrasonically guided puncture techniques. Munksgaard, Copenhagen. 1980

6. Nicolson M and Fleming JEE. Imaging and Imagining the Fetus. The John Hopkins University Press, Baltimore. 2013

7. Cobbold RSC. Foundations of biomedical ultrasound. Oxford University Press, Toronto, 2007.

8. McDicken WN. Diagnostic ultrasonics. Principles and use of instruments. Churchill Livingstone. 3rd edition. 1991

9. Intravascular Ultrasound. Techniques, developments and clinical perspectives. Eds: Bom N and Roelandt JR. Kluwer Academic Publishers. Amsterdam, The Netherlands, 1989.

AUTHOR BIOGRAPHY

Professor William Norman McDicken graduated from University of Glasgow with a BSc in physics in 1962 and a PhD in nuclear physics in 1965. He was an assistant lecturer for one year at University of Glasgow before becoming a medical physicist for the West Regional Hospital Board in Glasgow (1966-1974). During this time he organised and ran a new course on medical ultrasound. In 1974 he became a medical physicist in Lothian Regional Hospital Board, Edinburgh becoming the Professor of Medical Physics and Medical Engineering at University of Edinburgh in 1988. He held this role until 2005 whereupon he became Emeritus Professor of Medical Physics and Medical Engineering, University of Edinburgh, a post he still retains. Professor McDicken is a past president of British Medical Ultrasound Society and a winner of the Hospital Physicists' Association's Manufacturers' prize.

Professor Carmel Mary Moran BSc MSc PhD FInstP FIPEM graduated in Physics and Applied Maths from Queen's University Belfast in 1986, MSc from University of Aberdeen in 1988 and PhD from Institute of Cancer Research, University of London in 1991. From 1991, she has worked at the University of Edinburgh, formerly in Medical Physics and latterly in the Centre for Cardiovascular Science. Her research interests include the development and characterisation of ultrasonic contrast agents for diagnosis and therapy and the applications of high frequency ultrasound. She established, and currently directs, the preclinical ultrasound imaging facility at the University of Edinburgh. She is a member of the EFSUMB safety committee and is a Past-President of the British Medical Ultrasound Society.