THE DIASONOGRAPH STORY

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I. BACKGROUND.

Up to the time when Ian Donald started to experiment with ultrasound in Glasgow there had already been many significant developments in diagnostic applications of ultrasound around the world. A number of researchers had managed to acquire industrial flaw detectors and publish the results of their A-mode investigations of tissues. In 1949, R P McLaughlin and G N Guastavino at the Argentinian laboratory of the American electronics company RCA, published a paper describing their own pulse echo instrument for detecting foreign objects in tissue, including the example of a stone embedded in an excised kidney [1]. In the same year, George Ludwig, a medical officer, and Francis Struthers, a physicist, both at the Naval Medical Research Institute in Bethseda, Maryland, measured the acoustic properties of a range of tissues and demonstrated gallstones implanted in dogs [2]. Also in 1949, John Wild, an English surgeon working at the University of Minnesota in the USA, measured changes in bowel wall thickness [3]. In 1953, cardiologist Inge Edler and physicist Hellmuth Hertz, in Lund, Sweden, experimented with an industrial flaw detector, borrowed from a shipyard, and interpreted moving echoes from within the heart. By 1954, they had invented the M-mode technique for recording and measuring echo movements and had published M-mode echo recordings of the hearts of living patients, establishing what was to become the diagnostic technique of echocardiography [4]. In 1956, G Mundt and W Hughes described their use of a flaw detector for A-mode examination of in vitro enucleated eyes and patients with intraocular tumours [5].

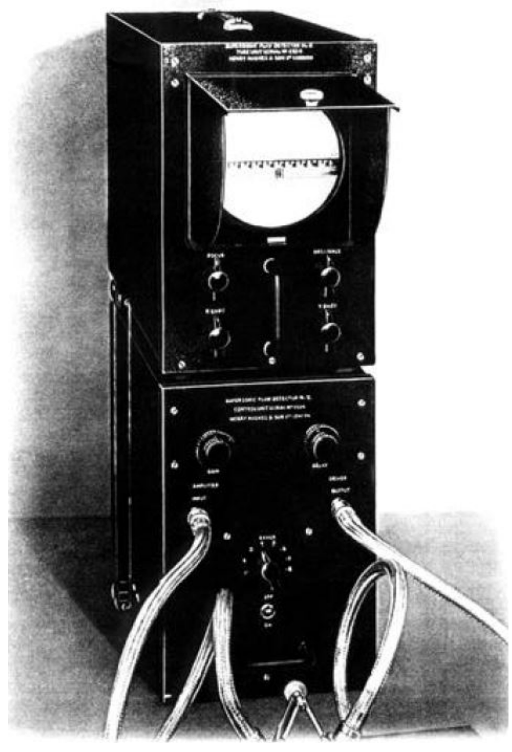

Fig. 1 The Kelvin and Hughes Mark IIb Flaw Detector.

In the late 1940s, Valentine Mayneord, Professor of Physics as Applied to Medicine, at the Royal Cancer (later Marsden) Hospital in London, picked up on Wild's early work and started to investigate the application of ultrasound A-scans to the brain, a very challenging organ to study with ultrasound due to attenuation, reflection and refraction by the skull. R C Turner, an electronic engineer in Mayneord's department, using a Kelvin and Hughes Mark IIb industrial flaw detector (Figure 1), was sometimes able to show that an echo from the midline of the brain could be displaced towards or away from the probe if there was a space occupying lesion in either hemisphere [6]. Turner demonstrated his findings to Swedish neurosurgeon Lars Leksell during a visit by the latter to Mayneord's department [7][8]. Later, in 1950, Leksell borrowed a similar Kelvin and Hughes Mk IIb flaw detector but failed to improve much on Turner's patchy success [9]. However, when he replaced the Kelvin and Hughes instrument with the Siemens flaw detector that his cardiologist colleague Elder had used, he found

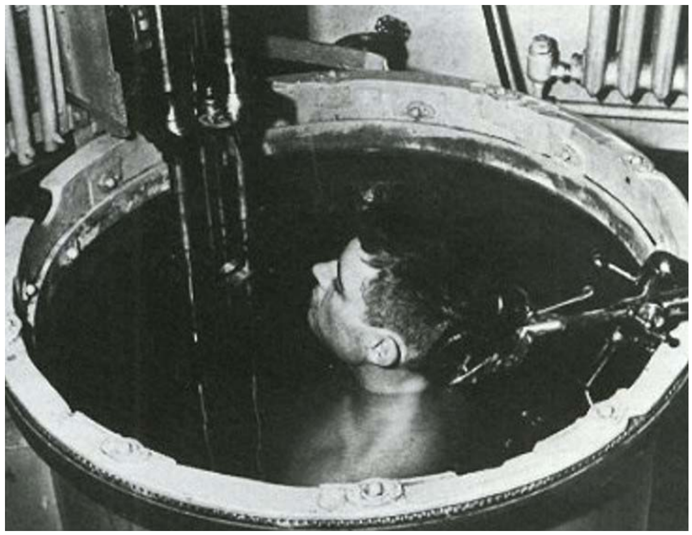

Fig. 2 Water bath compound scanning system of Howry et al., c 1957. This water-bath was based on the gun turret of a WW2 B-29 bomber. Photo courtesy of AIUM.

he could demonstrate shifts of the midline echo more clearly. His results, published in 1955 [10], led to the establishment of echoencephalography as a valuable diagnostic tool.

Cross-sectional (B-mode) images of human subjects were first achieved by two groups in the USA. One group was led by radiologist Douglass Howry, in Denver, USA, while the other consisted of Wild, mentioned above, and his electronic engineer colleague, John Reid, in Minneapolis. Between 1949 and 1954, Howry's group constructed a number of 'Somascope' instruments which required the subject to sit in a water bath, across or around which an ultrasound transducer was automatically scanned [11]. In the later versions, the direction of the ultrasound beam was changed between passes of the transducer, producing 'spatially compounded' images in

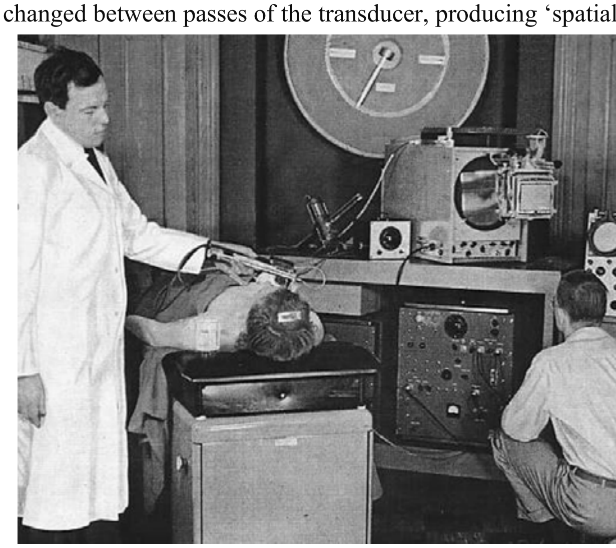

Fig. 3 John Wild (left) demonstrating the hand-held 15 MHz contact scanner developed by himself and John Reid (right) c 1953. From the front cover of Electronics magazine, March 1955.

which each anatomical target was insonated from several directions and the echoes summed [12] (Figure 2). This resulted in improved spatial resolution and better delineation of specularly reflecting tissue interfaces. The need for immersion was avoided by Wild and Reid who, in 1953, built the world's first hand-held ultrasound contact scanner, which they used successfully to produce grey-scale images of breast tumours [13]. This 'Two-dimensional Echoscope', as Wild called it, had a small water-filled chamber with a flexible rubber membrane forming its base, mounted beneath it (Figure 3). A 15 MHz transducer was driven back and forth within this chamber by an electric motor and worm screw drive.

II. IAN DONALD.

Before his move to Glasgow, Ian Donald (Figure 4) held the post of Reader at the Institute of Obstetrics and Gynaecology at the Royal Postgraduate Medical School, Hammersmith Hospital, London. During his previous clinical career, he had demonstrated a talent and enthusiasm for innovation by developing improved mechanical devices for the diagnosis and treatment of respiratory problems in neonates. Donald had read Wild's 1951 paper in the Lancet [14] and was able to speak with him directly when Wild visited the Royal Postgraduate Medical School during an extended visit to London to deliver the University Lecture in Medicine. Wild showed Donald slides of some of his A-mode and cross-sectional (B-scan) ultrasound images. They also discussed [15] the possibility of using ultrasound to image the gravid uterus, Wild indicating that, in view of its cystic nature, a lower frequency would be more appropriate than the 15 MHz that he had been using. Wild had also visited Mayneord to hear of his work with the brain, so he knew of the Kelvin and Hughes flaw detector and suggested something similar might be suitable if Donald wanted to take further the possibility of obstetric applications. Donald was unable to attend Wild's lecture himself, but Mayneord, who Donald knew through his interest in his work, gave him an account of it [15]. Apart from describing his ultrasound breast imaging work in his lecture, Wild had included a discussion of how ultrasound might be applied to the lower abdomen. He had also commented on the safety of using ultrasound on live subjects, advising that a positive but cautious approach to safety was justified, given the absence of evidence of tissue damage at the ultrasound intensities used.

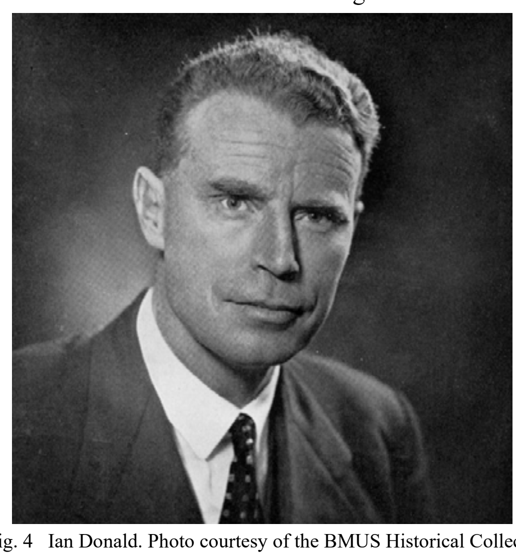

Fig. 4 Ian Donald. Photo courtesy of the BMUS Historical Collection. Photograph held in NHS Greater Glasgow and Clyde Archives.

In September 1954, Ian Donald took up his post as the Regius Professor in Obstetrics and Gynaecology at the University of Glasgow. For a while he collaborated with John Lenihan, of the Western Hospital Board's Regional Department of Medical Physics, and in particular with physicist and engineer Ronald Greer, continuing his efforts to develop novel respiratory equipment and to investigate the respiratory changes during the first breath of the newborn. However, it proved difficult to make further substantial progress into the problem of neonatal respiratory distress [16] and Donald realized a change to a new project might be timely. He was aware that differentiation between ovarian cysts and fibroids was an important clinical problem, with potentially life-threatening consequences for the patient, so he decided to experiment with ultrasound to see if it could help.

One of the first things he did was to borrow a powerful ultrasound generator “from a friend of a friend in a scientific instrument factory near Paisley” [17] and noted that red cell destruction depended on exposure time. He concluded that the degree of cell damage was directly proportional to the heat generated [18] and considered that the use of ultrasound would be safe as long as no significant heating occurred. In the spring of 1955, through an introduction by a grateful patient, he was invited to the Renfrew factory of the boiler making company, Babcock and Wilcox, where he was given a demonstration of a flaw detector, made by Kelvin Hughes Ltd [18]. Although Donald was probably not aware of the significance, this was their latest, much improved, Mark IV model with a single hand-held probe containing two piezoelectric transducers, one for pulse transmission and one for echo reception; these were arranged in a shallow ‘V’ configuration so the crossover region of their beams extended several centimetres from the probe [19]. He noticed that the technicians used their thumbs several times a day to check that the instrument was working satisfactorily, reinforcing his opinion that there was no significant hazard from ultrasound exposure. A technician also demonstrated that the echo from the bone could be identified and that its position along the time-base trace on the A-scan display shifted back and forth as the probe was pressed in and out against the thumb.

In July 1955, Donald arranged a second visit to Babcock and Wilcox, this time using the flaw detector himself to examine uterine fibroids and a large ovarian cyst, freshly removed from patients that morning. Donald reported that the results from the flaw detector were as he had expected from his reading of the published literature [18]. This gave him encouragement, although Fleming and Nicholson have since argued that his interpretation of the echo patterns may have involved a degree of wishful thinking and that he may have been lucky to find the controls already set appropriately [20]. Shortly afterwards, Donald visited Prof. Mayneord at the Marsden Hospital. He found the team somewhat discouraged by the difficulties they had encountered, to the extent that they had decided to replace their Kelvin and Hughes flaw detector with an A-scan machine they were building themselves. They were, therefore, in a position to offer their Kelvin and Hughes Mk IIb flaw detector as a loan to Donald [21].

On his return to the Western Infirmary, Donald enlisted the help of Greer and, together, they tried to reproduce the results that Donald had achieved during his second visit to Babcock and Wilcox and to move on to investigating the intact abdomen. Unfortunately, they had little success, largely because the Mk IIb flaw detector they were using was inferior to the later, Mk IV, model that Donald had used at Babcock and Wilcox. Its performance had been further compromised by a modification made by Turner, while working on the midline shift project in Mayneord’s Department. In its original form, the Mk IIb machine had separate transmit and receive probes in order to prevent the large excitation voltage applied to the transmit transducer from temporarily overloading and paralyzing the receiving amplifier. Unfortunately, it proved extremely difficult to hold these two probes close together on the curved skull of the patient. By replacing the two probes with a single probe for both transmission and reception, Turner had solved this ergonomic problem but in so doing he had reintroduced the paralysis problem, making it impossible to detect echoes from within 8 cm of the probe face. Donald and Greer tried introducing water offsets between the probe and the patient in order to overcome this serious limitation, both in the form of open-ended tubes with a rubber membrane at the patient end [22] and in the form of water-filled sealed condoms[18], but these did not prove to be suitable as a long term solution for clinical use. Despite further help when obstetrician John MacVicar (seen on the right in Figure 12), then a registrar in the Department of Midwifery, joined the team sometime in 1956, they still could not obtain consistent echo patterns from within the abdomen, nor reliably interpret them.

III. TOM BROWN AND KELVIN AND HUGHES LTD.

This rather unsatisfactory state of affairs continued until Tom Brown (Figure 5), a twenty-three-year-old engineer with Kelvin and Hughes Ltd, at Hillington, Glasgow, heard that a professor was using one of the company’s flaw detectors to examine patients. Brown had previously impressed his employers by his work in helping to develop a semi-automatic flaw detecting system to the extent that they had sponsored him for a course in applied physics at the Royal College for Science and Technology in Glasgow (now Strathclyde University). Unfortunately, the mathematical content of the course had proven too challenging for Brown and he had to drop out after one year [23]. As he said himself: “I spent too much time playing snooker and generally enjoying the student lifestyle” [24}. His employers took him back, but he was now looking for a way to redeem himself in their eyes. The idea of applying ultrasound to medical diagnosis appealed to him so, one evening in late 1956, he telephoned Donald; his boldness was rewarded by an invitation to visit Donald at the Western Infirmary. Despite what he called a “rather comical demonstration with the water stand-off and all the rest of it” [24], Brown could see there were echoes coming back from within the patient’s body, so he called his boss, Alex Rankin, Head of

Applications Engineering, to tell him of the potential new application. Rankin was already well disposed towards medical projects involving ultrasound, having provided support to Leksell in Sweden. He immediately arranged for a brand-new Mk IV flaw detector to be delivered to Donald [23].

Fig. 5 Tom Brown, pictured around the time he built the bed-table scanner. Photo courtesy of the BMUS Historical Collection.

The new instrument made all the difference to the success of Donald and MacVicar's A-scanning efforts (Figure 6). Probes were provided at ⅝ MHz, 1.25 MHz, 2.5 MHz and 5 MHz, but they soon established that a frequency of 2.5 MHz gave the best compromise between penetration and spatial resolution for obstetric patients. In addition, Brown's company was able to provide them with a Cossor oscilloscope camera to record the A-scans on 35 mm film [23]. Hitherto, their only means of recording A-scan traces had been by sketching them. Donald was very pleased, as the ability to produce accurate photographic records of the traces was important for publication of any noteworthy results.

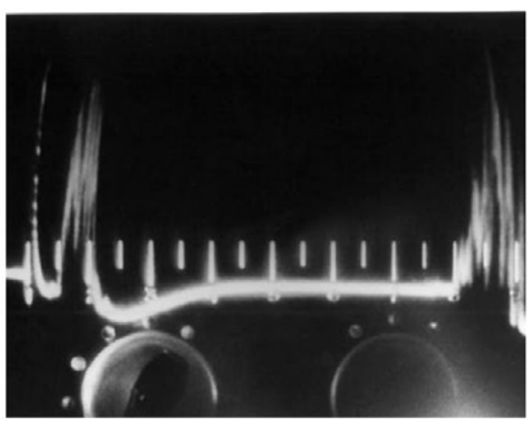

Fig. 6 A-scan of a simple ovarian cyst, c 1956. Photo courtesy of Tansey and Christie [24].

Donald also appreciated the involvement of an engineer with substantial practical experience of the most recent developments in industrial ultrasound technology. As a result, Brown was welcomed into the fold whilst Greer's involvement came to an end [23]. At first, Brown's involvement was purely informal, with him going to the Western Infirmary in the evenings, after his day's work at Kevin and Hughes at Hillington. There, he would perform any necessary maintenance and help MacVicar develop and analyse film from the day's clinical work. In order to learn how to interpret the echo traces, they would experiment by applying the probe to their own bodies, as well as to rubber membrane acoustic windows built into the walls of water tanks containing surgically removed cysts and tumours [25]. Donald, however, had little time for such in-vitro experimentation, preferring that the probe be applied directly to real patients [26].

Donald was happy to arrange an abundant supply of patients and he drove the project forward with characteristic energy. By mid-1957, with Brown's assistance, he and MacVicar were providing a clinically useful service to gynaecological patients and starting to look at obstetric patients. Through their hard-won and growing expertise in interpreting the A-scans, they had largely solved the original challenge of differentiating cysts from solid tumours and they could even differentiate between different types of cysts. There had been occasional mistakes, as when a highly vascular fibroid had been mistaken for a cyst [27], but this all contributed to the learning process; consequently, the initial scepticism amongst Donald's clinical colleagues at the Western Infirmary was disappearing. The much-quoted turning point in the acceptance of the technique was when a swollen abdomen, thought by the Regius Professor of Medicine to be due to ascites, secondary to inoperable and terminal cancer, was being ultrasonically examined by Donald. Looking over Donald's shoulder, MacVicar, commented that the trace looked like that of an ovarian cyst. Although MacVicar was rewarded by an unseen kick from Donald for contradicting the Professor of Medicine's diagnosis, Donald accepted that an ovarian cyst was a possibility and arranged for a laparotomy, which confirmed that the mass was indeed a very large ovarian cyst. This was duly removed and, instead of being allowed to die, the patient made a full recovery [24][28].

A. The Bed-table Scanner

Notwithstanding Donald and MacVicar's satisfaction and excitement with the clinical value of A-scanning using the Mk IV flaw detector, Brown was convinced that a display that showed the positions of each reflecting interface was needed to fully exploit the potential of the ultrasound pulse-echo technique. He felt that, ideally, since the human body was three dimensional there should be a 3D representation of the echo sources. This was to remain his ambition throughout his life [23] [24] but, for now, he accepted that an image of a 2D cross-sectional slice of the patient would have to suffice. According to Brown [23], Donald was initially less enthusiastic about what 2D imaging could offer. This was despite the interest Donald had shown in radar and sonar during his wartime military service and the 2D ultrasound images he had seen in the publications of Howry's team in Denver and of Wild and Reid in Minnesota. He had even attempted, unsuccessfully, to build a 2D ultrasound system himself in his early days in Glasgow, although very little is known about it [22]. He felt the detailed echo information from within organs and other body masses that he was now obtaining had more diagnostic value than knowing the position of a reflecting interface [29]. For whatever reason, Donald chose not to show Howry's or Wild's cross-sectional images to Brown. Years later, Brown said "I think that had we been aware of what Howry was doing and had set out our stall to improve on Howry's work, we would have been stuck with immersion scanning" [24]. Having seen the trouble caused by attempts to use water offsets when he first visited Donald, Brown was very keen to avoid using water, either for partial immersion of, or acoustic coupling to, the patient in a hospital environment. He also wanted a system that could be used at the patient's bedside, as was possible with the A-scan unit. It is a matter of conjecture what the outcome would have been if Brown had known of Wild and Reid's relatively compact hand-held contact scanning system: perhaps he might have been inspired to try to build a low frequency development of it.

From his knowledge of the radar work undertaken by Kelvin and Hughes, Brown was familiar with "True Motion" radar displays, in which the screen acted as a fixed map on which the position of the transmitting aircraft or ship, as well as the positions of echo-returning targets, were updated after every sweep of the beam. He considered applying the technology of this technique to the medical situation [23] but radar experts at Kelvin and Hughes quickly made him realize this approach would be unnecessarily complex. Whereas, in the case of radar, the position of the transmitting ship or aeroplane had to be calculated from the echo data returning from land-based targets, in the medical situation the position of the probe could be measured directly by mounting it on a support arm or mechanism from a fixed point. From the known transducer position, the positions of echo-producing targets could be plotted on the screen of a cathode ray tube (CRT) using the standard 'plan position indicator (PPI)' method of radar displays. Brown's proposal was supported by his managers at Kelvin and Hughes, including the company's Chief Scientist, Bill Halliday. However, the crucial move was made by Donald, who was keen to put Brown's input on a formal footing [23]. Donald arranged to meet William Slater, Deputy Managing Director of Kelvin and Hughes, impressing him with his account of the clinical value of the project and its potential. The result was that half a day per week of Brown's time was allocated to working with Donald, along with a budget of £500 to make the first machine. Brown later said this figure turned out to be very elastic [23].

During 1957, Brown designed and built his prototype system [30] [23] in the research department of the Kelvin and Hughes factory at Hillington. He felt that a system in which the probe was in direct contact with the patient was required, in the same way that the probe of a flaw detector was applied directly to the test piece in an industrial setting. Mindful of the convenience of being able to use the system on a patient in a hospital ward, he chose to build his prototype around a wheeled bed table. A photograph of the resulting 'Bed-table scanner' being used by MacVicar to scan Brown's abdomen is shown in Figure 7.

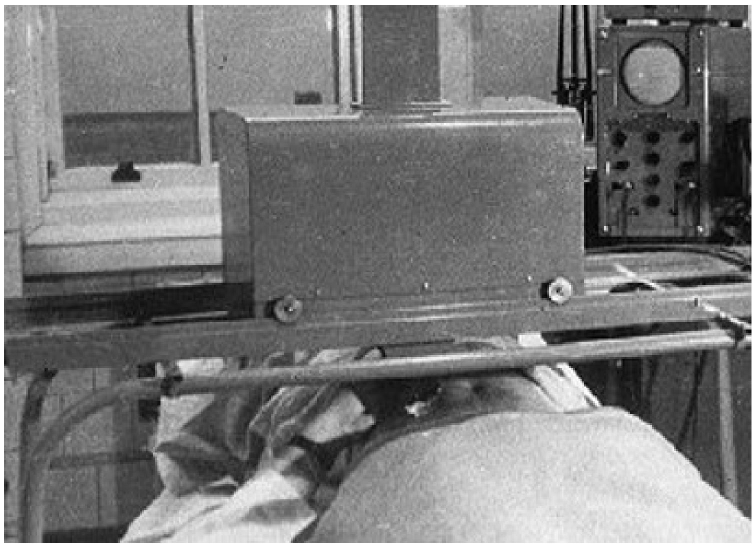

Fig. 7 Tom Brown's bed-table scanner, c 1957. Note the restricted room for the operator's forearm and hand (seen lower left). Photo courtesy of the BMUS Historical Collection

The user could move the transducer by hand anywhere within a fixed vertical transverse 'scan plane', keeping the transducer face lightly pressed against the patient's skin, which was kept lubricated with vegetable oil. The scan plane was defined by the position of a wheeled carriage that could be moved transversely on rails across the bed table. At any position within this plane, the transducer could be rotated or rocked through a large range of angles, thus giving the benefit of compound scanning, mentioned previously in connection with Howry's system. The scan plane could be moved longitudinally by simply moving the bed table above and along the bed on which the patient was lying. Three displays were provided: an A-mode display, at that time still considered essential by Donald and MacVicar: a B-mode display on a long persistence CRT screen, which the user could monitor as he moved the probe around in an exploratory fashion; a second B-mode display, this time on a short persistence CRT fitted with a camera for when the user had found a particular cross-sectional view that he wished to record. Figure 8 shows two of these displays: on the left is a Mark IV flaw detector used to display A-scans and, on the right, is a CRT with a Thompson-Polaroid Land camera attached for recording B-scans.

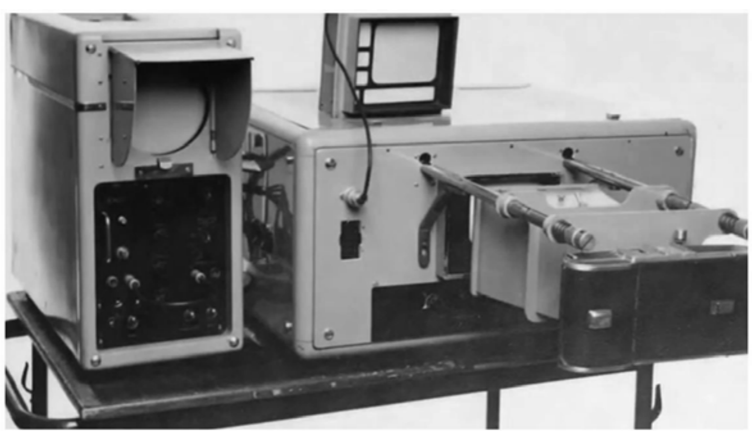

Fig. 8 Displays and camera from the bed-table scanner. Photo courtesy of the BMUS Historical Collection.

The hand-guided probe could be rotated about a horizontal spindle whose X and Y coordinates were measured by means of a system of wires and pulleys connected to the shafts of wire-wound X and Y linear potentiometers. The angle of the probe, and hence the ultrasound beam, to the Y axis of the measuring frame was measured by linking the rotation of the probe to the shaft of a sine-cosine potentiometer (Figure 9). By applying stable positive and negative voltages of equal magnitude (+v and -v) respectively to the diametrically opposite sides of the potentiometer's circular track, the resistance per unit length of which varied sinusoidally, the two wipers, arranged 90° apart on the potentiometer shaft, picked off voltages of v cosθ and v sinθ respectively, where θ was the angle of the probe to the Y axis of the measuring frame. Each of these voltages was applied to its own integrator circuit, producing two voltage ramps with slopes proportional to v cosθ and v sinθ respectively. A voltage proportional to the Y coordinate of the probe spindle was added to the v cosθ ramp and a voltage proportional to the X coordinate of the spindle was added to the v sinθ ramp. This provided vertical and horizontal voltage drives, respectively, for the time-base on the CRT used for the display. When the time-base had swept across the screen to reach a point corresponding to the probe face (with a correction to allow for the perspex block in front of the transducer) the transmitter was triggered. From this moment on, the position and orientation of the time-base trace on the CRT screen matched the position and orientation of the transmit-receive ultrasound beam within the scan plane. The speed at which the time-base spot of light was swept across the screen depended on the magnification required.

For unity magnification, for example, echoes from two targets a certain distance apart, both lying on the axis

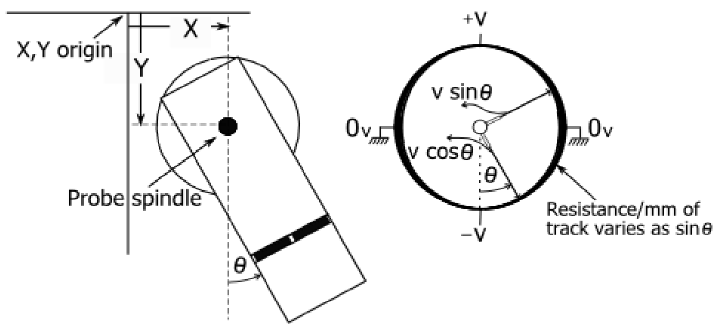

Fig. 9 Left: Measurement of probe angle Θ relative to the Y axis of the scan plane. Right: The 'cosine' wiper of the sine-cosine potentiometer is at the same angle as the principal axis of the probe.

of the beam, must be represented by echoes the same distance apart along the CRT time-base. In order to allow for the two-way travel of the sound pulse in the body, this requires the spot of light to be swept along the time-base trace at half the speed of sound in the body (approximately 1540 ms^{-1}). For a magnification of one half, the spot of light would have to be swept across the screen at one quarter of the speed of sound, and so on. This arrangement was similar to the measuring system used later in the Diasonograph machines. A then popular construction kit known as 'Meccano' was used to provide many of the smaller components, such as chains, sprockets and pulley wheels, but some of the larger and more critical components were manufactured by technicians in the model shop at the Hillington factory.

The probe was that of the Mark IV flaw detector. It housed two rectangular, 10 x 7 mm, unfocussed, air-backed barium titanate transducers, one for transmission and one for reception. They were mounted, side by side with their shorter sides adjacent, on one of the flat faces of a one inch (25.4 mm) thick cylindrical Perspex block, the opposite flat face being in contact with the patient [30]. As mentioned earlier, the use of separate transducers for transmission and reception avoided the problem of paralysis encountered in the modified Mk II flaw detector initially used by Donald. The transducer dimensions were chosen to give a compromise between beam width in the near field and angular divergence in the far field. Another consequence of using two transducer elements side by side was that the overlap of their beams increased with distance from the probe face, producing a two-way sensitivity that increased progressively with depth. This provided a degree of compensation for the effect of attenuation on echo strength from deeper targets and explained why swept gain (later often called TGC - time gain compensation) was not considered a high priority. A resonant frequency of 2.5 MHz was chosen for the transducers, corresponding to a transducer thickness of approximately 1 mm, as the earlier in-vitro experiments made by Brown and MacVicar had indicated that this frequency would give an optimum compromise between spatial resolution and penetration for use in the lower abdomen. The transmission pulse generator and receiver were those of the Mark IV flaw detector [31]. The transmission transducer was shock excited by a pulse of approximately 2 μs duration, generated by charging a 100 pF capacitor to about 1.4 kV through a high resistance and then triggering a thyratron to discharge it though the primary winding of a pulse transformer, across the secondary winding of which was connected the transducer in parallel with a 50 ohm damping resistor [30].

The other electronic circuits and components were also largely those used in the Mark IV instrument. Brown chose a pulse repetition frequency (PRF) of 50 Hz, partly because this was one of the standard PRFs of the Mark IV and partly because it represented what he considered to be a prudent compromise between safety and performance. A higher PRF would have allowed the probe to be scanned across the abdomen more quickly, without increasing the gaps between lines of echoes on the display, but it would also have meant that the patient would have received more ultrasound energy. On testing an early version of the apparatus by scanning a grapefruit suspended on a wire in a water tank, Brown realized the signal processor stage, the output of which was used to brightness modulate the time-base trace on a CRT, needed to be more sensitive. He described this circuit as being “where art and science tended to co-exist” [23], but he nevertheless managed to achieve a very acceptable dynamic range of the order of 60 dB.

The increased receiver sensitivity allowed him to introduce another safety feature in the form of a switched attenuator in the transmit voltage drive to the transducer. If the displayed echoes were too strong, the operator could reduce their amplitude by means of the attenuator, leaving the receiver sensitivity (gain) at its high level. He recommended that the operator should start with a high transmitter attenuation setting and, only if necessary, reduce it to the level needed to achieve a useful image, thus helping to ensure that the patient received no more ultrasound power or intensity than was necessary. Brown’s estimate of the maximum acoustic intensity that his scanner was capable of producing in the patient was 1.5 mW cm^{-2} and the maximum acoustic power was approximately 1.0 mW [30]. These values are tiny in comparison to the corresponding figures for obstetric ultrasound scanners post-1990 [32] and were considerably less than those of either Howry [33] or Wild [34].

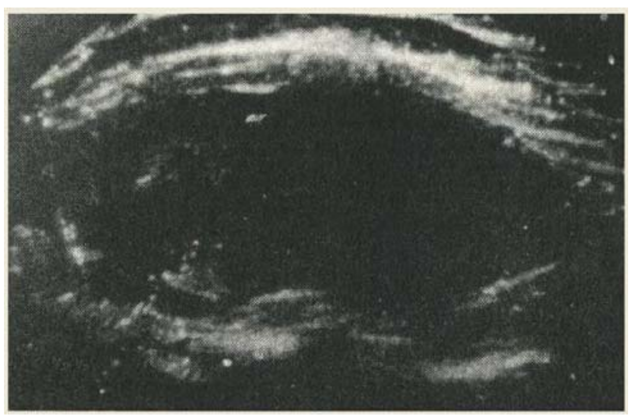

Fig. 10 Example of a scan produced by the bed table scanner. It shows a uterus containing a fetus (left) and a fibroid (right). Reproduced from Figure 17 of Donald, MacVicar and Brown, The Lancet, 1958 [30].

In late 1957, the machine was sufficiently developed to be put into use in the Western Infirmary, but Brown admitted to some disappointment at the quality of the images [35]. Figure 10 shows the scan of a uterus, obtained with the scanner, with barely recognizable echoes from an early stage fetus on the left and what was thought to be a fibroid on the right [30]. Brown and MacVicar frequently scanned each other to discover the limitations of the apparatus, how to get the best out of it, and which aspects of it required improvement. In observing clinicians using the system on patients, Brown recognized that the scanning technique varied considerably between operators and this had a large effect on image quality. Operator skill was not helped by the poor ergonomics of the system, which, Brown later admitted, had not been given much consideration during the design; in fact he described it as “ergonomically horrific”, but added “it was all done, after all, on a £500 budget” [24]. For example, the user had to reach into the narrow space between the table and the patient (Figure 7) to manipulate the probe whilst turning their head away to see the display screens. Brown was able to improve results by making further modifications, including the updating of the amplifier with one from his company’s new Mark V flaw detector which gave superior performance [31]. In order to overcome the restriction of being able to scan only in transverse vertical planes he later replaced the bed-table with another over-bed, structure, in the form of a wheeled steel framework. This allowed the operator to scan in planes perpendicular or parallel to the longitudinal axis of the patient’s body, and in planes inclined to the vertical, as desired [36]. Another later improvement was the replacement of the Cossor oscilloscope camera with a Thompson-Polaroid Land camera. This allowed photographic records of scans to be viewed in the scan room within minutes, rather than having to wait for a full roll of film to be exposed and then waiting a further period of hours for it to taken away, processed and returned. A potential disadvantage of Polaroid film was that it was less sensitive than conventional film. Initially, this resulted in the loss of weaker echoes but, after carefully reading Polaroid's technical literature, Brown solved the problem by designing an illumination box in which the Polaroid film could be briefly pre-exposed, increasing its sensitivity. These improvements all helped to foster marked and growing enthusiasm from Donald for the B-mode technique. By the time of submitting their June 1958 publication 'Investigation of abdominal masses by pulsed ultrasound' in The Lancet, Donald and MacVicar, with Brown's technical input, had used the bed-table scanner on 100 patients and had made 275 B-scan recordings [30].

In 1959, physicist Tom Duggan joined Donald's team to work on ultrasound, his salary being paid from a Scottish Hospital Endowment Research Trust grant that was intended to finance neonatal respiratory studies [31]. Between 1961 and 1962 he developed a fetal ultrasonic cephalometer, by means of which two bright 'pips' could be superimposed on the A-mode trace on a Kelvin and Hughes flaw detector [37]. The instrument was described as portable but it weighed 30 kg and had to be pushed about on a trolley [31]. The bright pips were placed at the leading edges of the two echoes from opposite sides of the fetal skull at the level of the parietal eminences. These echoes corresponded to the outside of the nearer side of the skull and the inside of the far side. The time elapsed between the generation of these two pips was measured electronically and converted to an estimate of the distance across the outside of the fetal head at this level, called the bi-parietal diameter (BPD). This was achieved by multiplying by a factor of 0.080 cm μs^{-1}, derived experimentally from measurements on neonates and post-mortem fetuses [38]. Because this conversion factor relates a distance to a (two-way) ultrasound time of flight, it is usually expressed by saying that the 'caliper velocity' is 1600 m s^{-1}.

The ultrasonic estimate of the BPD became an important index for monitoring fetal gestation and development, thanks to the efforts of John Willocks, a young doctor who had joined Donald's team about the same time as Duggan [37]. Later, Duggan joined Kelvin and Hughes, where he was involved with transducer developments, before moving on to an academic post at the University of Strathclyde and thence to the Regional Department of Medical Physics (now Clinical Physics and Bioengineering) at the West of Scotland Health Board. There, he was closely involved with the introduction of ultrasound teaching and development laboratories and with supervision of an ultrasound maintenance service [24].

Meanwhile, both Brown [23] and Donald [39] were frustrated by the variations between operators in probe manipulation, artefact avoidance and other scanning skills, as these were limiting the success of their cross-sectional imaging project. In Scotland in the mid-1950s, it was unthinkable that a young male engineer without any medical qualifications could be allowed to scan patients himself, particularly on gynaecology and obstetrics wards, so Brown was unable to demonstrate to others how to get more consistent results [23]. Mindful of his prior success in helping to develop an automatic industrial flaw detecting system, it seemed to Brown that an automatic clinical scanning system could provide the solution to the inconsistency problem as it would greatly reduce the influence of the operator on the scanning procedure. Even if it proved too complex and costly to consider as a prototype production machine, it would at least demonstrate the scanning action needed to produce good images. Donald agreed and asked Kelvin and Hughes if they could provide an "apparatus which automatically scanned the surface of the abdomen at a standard rate and rocking speed" [39].

B. The Automatic Scanner

Brown was aware that Kelvin and Hughes were investigating new probe designs in which the two rectangular transducer elements of the Mark IV design were replaced by a single disc-shaped transducer element, offering a much greater sensitivity than had been possible with the overlapping beam arrangement of the twin element probe. Also, by this time in the late 1950s, new, more sensitive, piezoelectrics such as lead zirconate titanate (PZT) were becoming available. Brown was keen to take advantage of these development as he was aware that attenuation, and hence signal loss, was very much more of a problem in tissues than in the metal structures for which flaw detecting technology had been developed. Not only would a higher sensitivity improve the dynamic range of the detected echo signals, but it would have safety implications as it would mean that pulses of lower energy could be transmitted. The large impedance mismatch between the transducer and the patient's tissue meant that the absorbing backing behind the transducer was more critical in suppressing 'ringing' than it was for industrial applications. This backing was normally made from epoxy resin in which dense metal particles were suspended but its performance could be degraded by gas bubbles trapped within it during the curing process. Brown and Clive Ross, a colleague at Kelvin and Hughes whom Brown described as "very gifted" [23], used a centrifuge to drive gas bubbles in the uncured epoxy resin away from the transducer as well as to give the backing an inclined rear surface. In Brown's own words, this allowed them to produce "some quite respectable single transducer probes" [40]. Brown was by now aware of the work of Howry's team, including their use of concave lenses to improve beam shape, so Ross experimented with different lens designs, finally settling on a conical design, having decided it gave better results than lenses with the more conventional spherical curvature. The new scanner was provided with a range of focused transducers, with the frequencies that were standard for Kelvin and Hughes flaw detectors, namely 1.5 MHz, 2.5 MHz and 5.0 MHz. Brown later said that perhaps a frequency of 3.5 MHz would have been optimum in terms of the compromise between spatial resolution and penetration for gynaecological and obstetric applications but that this omission was not too serious in view of the other limitations of the equipment at the time [40].

The electronics of the automatic machine were mostly identical to those of the updated bed-table scanner [40]. An important exception was that the receiver amplifier from the Mark IV flaw-detector could no longer be used as, following the change to single transducer element probes, the transmission pulse produced too much receiver paralysis. When developing the new Mark V flaw detector for Kelvin and Hughes, one of Brown's colleagues, John Woods, had found that the solution to this problem was to design a separate tuned RF amplifier for each probe frequency. Consequently, separate plug-in RF amplifiers were provided for use with each probe of the automatic scanner. A feature of the new amplifiers was that the amplifier gain could be made to increase with time after transmission at a rate set by the operator. Without this feature, attenuation due to scattering and absorption in tissue would mean that B-mode echoes produced by a single transducer element probe would exhibit a general trend to diminish in brightness with depth. The new feature, known as 'swept gain', meant that this attenuation could be compensated for in a controlled way by the operator. Previously, in the bed-table scanner, using probes containing two transducer elements, a fixed degree of such compensation had been provided by the increasing beam overlap with depth. Now, by judiciously adjusting the swept gain controls, the general brightness of echoes could now be made more uniform at all depths. (Note that swept gain did not affect the difference in brightness between a strong echo and a weak echo at similar depths).

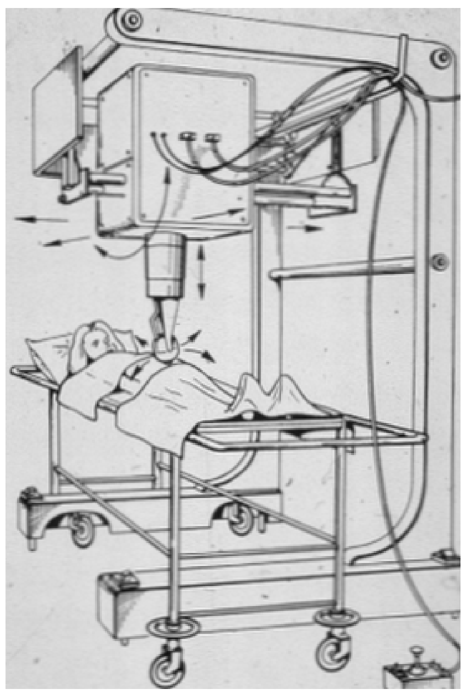

Fig. 11. Drawing of the automatic scanner from Brown [23], showing all the motorized movements. Courtesy of the BMUS Historical Collection

A diagram of the automatic scanner is shown in Figure 11. The finished machine, being used by Donald and MacVicar; is shown in Figure 12; a clearer view of the silver ball probe is inset. The ingenious way in which the probe was scanned and rocked automatically across the curved form of the patient is, perhaps, best described in Brown's own words [23]:

> "The 'business end' of the automatic scanner consisted of a probe holder in a 'silver ball' - which looked a little like the kind of soap dispenser once commonplace in public toilets. This was mounted on a vertical, telescoping motor-driven column, such that it moved up and down to keep

the probe face in contact with the patient's skin. It too was shiny chromium plate. A pressure sensing switch ensured that it maintained contact with the skin, but with minimal pressure.

The silver ball rocked to-and-fro on an axle, driven by a system of cranks and connecting rods. Slightly indelicate looking soft plastic "nipples" on either side of the ball touched the skin when the probe axis had moved about 30 degrees to the perpendicular to it, and - almost as sensitive as the real thing - caused the rotary motion to stop and then reverse its direction.

Each time the nipple touched the patient's skin, another set of relays and motors were activated to inch the vertical column sideways. This, when combined with the compensating up/down motion to keep the probe in contact with the skin, caused about a 15 mm tangential displacement between successive "sweeps" of the rotating probe.

In this way the probe gradually 'walked' across the abdominal surface, rocking to-and-fro as it went, carrying out what was actually quite a thorough, and highly consistent compound scan.

Of course, it was not quite as simple as that. To enable it to work properly on the steep flanks of the often rotund ladies being examined, an automatic changeover mechanism operated at about the 45 degree point on either side of the vertical, so that the horizontal drive then controlled the pressure, and the vertical drive did the 'inching'. The distance the machine 'inched' each time was regulated by a profiled cam system, so that it remained constant, irrespective of the average angle of the probe to the vertical. Nowadays it would all be done by microprocessor, but then it had to depend on cams, switches and relays - and I guess it was the sort of thing which would have delighted Heath Robinson.

There was a 'joystick' controller in a box on the end of a cable, by means of which the operator could position the probe for the start of the scan, but when he had done so, his task was over. He simply pressed the 'Auto' button, and the machine did the rest.

When it had finished, (about 90 seconds later on a big lady), it would switch itself off, and then ring a bell to summon him back. It may seem unlikely, but such was the confidence which developed in the machine, and the pressures of nicotine addition, that the bell became a necessity."

Fig. 12 The automatic scanner being operated by Donald (left) and MacVicar (right). The ball probe, viewed from another angle, is inset. Photo courtesy of the BMUS Historical Collection.

The large size of the somewhat intimidating box suspended above the patient was, in part, due to building-in the capability to scan transverse, longitudinal and all intermediate planes, as well in planes tilted away from the vertical. The tilt facility was little used, however, as users were not practised in the interpretation of the anatomy in such oblique views. The other reason for the bulk and complexity of the system was the incorporation of an optional facility for automatically stepping the scan plane in small increments perpendicular to itself in order to acquire a volume set of echo data. This reflected Brown's enduring ambition to produce a scanner incorporating both 3D echo acquisition and 3D display. In later years he was to work with Sonicaid Ltd, based in Bognor, UK, to produce the radical "3D Multiplanar Scanner", which produced three-dimensional stereoscopic virtual images of body tissue but met with little commercial success [41]. Conscious of the disastrous consequences if the heavy box ever were to fall onto a patient, Brown incorporated safety features such as ratchets and cams that would prevent it falling more than a few millimetres should its support chain break. As might be expected with such a complex mechanical system, malfunctions did sometimes occur. The most alarming being on one occasion while scanning a "very stout" patient. The silver ball "started to dig in because the soft flabby fat stopped progress across the abdomen and the probe oscillated on one spot, burrowing deeper into the six or eight inches of fat" [24]. This was attributed to the patient, understandably, drawing away from the advancing ball, thereby inviting it to advance further. A part may also have been played by congealed olive oil around the probe, inhibiting it from moving up and activating the pressure sensing switch [42]. A white nylon ring was fitted later around the ball, increasing its contact area and thus reducing the pressure experienced by the patient. Another problem was electrical 'snowstorm' interference over the screen, caused by sparking across the contacts in the DC electric motors. When this happened, somebody would be sent from Kelvin and Hughes to clean the contacts and to fit suppressors and electrical shielding, as necessary.

While work on the automatic scanner was proceeding, a financial crisis had to be overcome. The £500 budget Brown had been given by Kelvin and Hughes had already been spent many times over. In December 1959, without any immediate prospect of commercial sales, and in view of Donald's estimate that it could take a further 15 years for diagnostic ultrasound to become routine, Brown was told by his manager at Kelvin and Hughes that the company could not justify further financial backing for the project, although they had assured Donald that they would complete the automatic scanner. Donald promptly sought the support of the University of Glasgow and was immediately promised £750 towards the research project. Moreover, the University advised him to approach the Scottish Hospitals Endowments Research Trust, which he did with Slater, and was rewarded with a donation of £4,000. The Trust also advised him to apply to the National Research Development Corporation (NRDC), an organization set up to assist British industry to compete internationally. This resulted in the NRDC committing a total of £10,000 to Kelvin and Hughes towards the development of diagnostic ultrasonic scanning over several years [43]. The crisis was over.

In July 1960, the automatic scanner was exhibited at the Third International Conference of Medical Electronics, held at Olympia, London, but failed to attract any commercial interest. At this meeting, Donald and Brown met Howry for the first time, initiating a long lasting, mutually supportive collaboration. Despite there being no real hope of it being a marketable product, owing to its sheer complexity, Brown rightly described the automatic scanner as "a lovely machine" and felt it had established a benchmark in image quality. As he had hoped, it demonstrated effective scanning technique to trainee operators, helping to improve consistency of scanning expertise. It was the means by which Donald and MacVicar developed their image interpretation skills and understanding of the clinical role of diagnostic ultrasound, producing around 3,000 scans of reasonably

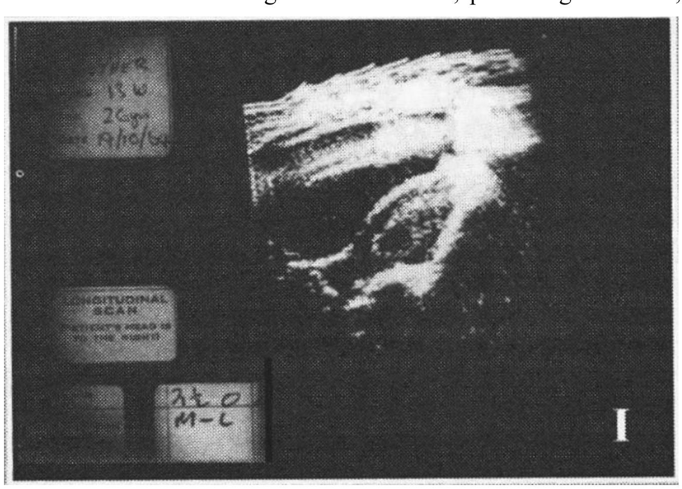

Fig. 13 Photographic record of the scan of an early pregnancy, obtained with the Automatic Scanner. Cards showing patient and scan details were included in the same exposure using an arrangement designed by Tom Brown. Photo courtesy of the BMUS Historical Collection.

consistent quality between 1959 and 1965 [24]. Figure 13 shows an example of an early pregnancy scan obtained using the automatic scanner, together with scan and patient information written on cards that were included in the photographic record, a technique devised by Brown. It was replaced by the first manually operated Diasonograph (see Section IV below), but it went on to do non-obstetric/gynaecological service in the hands of radiologists Ellis Barnett and Pat Morley in the Glasgow Western Infirmary.

C. The 'Sundén' (Lund) machine.

Since 1953, Lund University had pioneered diagnostic applications of ultrasound, both to the brain by Leksell [9], and to the heart by Edler and Hertz [4]. Professor Alf Sjövall, Head of Obstetrics and Gynaecology, had taken an interest in this work and in May 1958 he had instructed a young doctor, Bertil Sundén, to use Leksell's equipment (a Krautkrämer flaw detector) to investigate the potential of ultrasound for his own discipline [44]. Donald visited Sjövall in June of that year to learn about the upcoming technique of laparoscopy and during his visit he spoke about his own ultrasound work. On hearing of the achievements in Glasgow, Sjövall arranged for Sundén to spend three weeks with Donald to learn what he could of the new ultrasound B-scan technique, which at that time was based on the bed-table scanner. On his return, Sundén obtained a grant from the Swedish Medical Council to buy a similar scanner for use in Lund. Much to the delight of Kelvin and Hughes, an order was placed in 1959 for an agreed cost of £2,500. Although, by this time, the automatic scanner was well advanced [23], Sundén requested a copy of the bed-table scanner he had used. This was never intended to be anything but a prototype and so a replica was out of the question. However, there was no doubt that only a machine with a hand-guided probe would be acceptable. Consequently, Brown and his managers at Kelvin and Hughes turned away from the automatic scanning approach for this and any future orders and decided to design a more refined manual contact scanner, with improved performance and ergonomics.

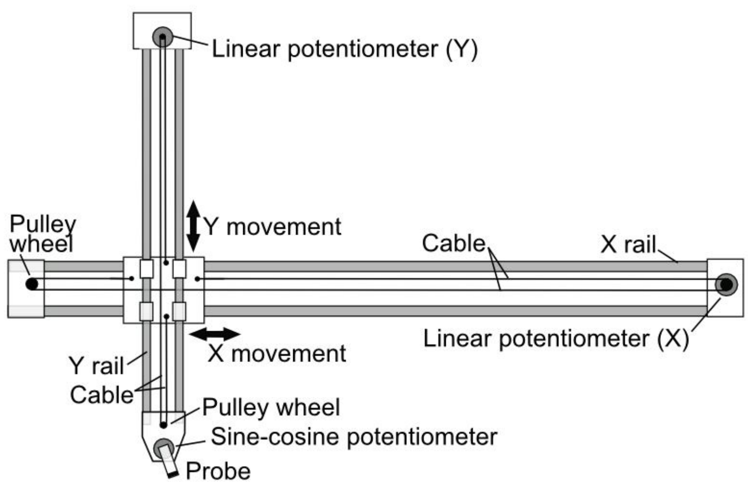

Fig. 14 Illustrating the principle of the system used to support and constrain the probe within the scan plane and to obtain the X,Y and angle coordinates of the probe relative to the scan plane.

Through his recent friendship with Howry, Brown was aware of the possibility of using an articulated arm (see section VIII *B*) to support the probe and measure its coordinates, but he continued to favour his original Cartesian coordinate method because of its intrinsically more rigid and accurate, albeit heavy and bulky, nature [23]. Figure 14 illustrates the general principle of the system of rails used to allow the probe free movement within a firmly defined scan plane and to measure the probe's X,Y coordinates and the angle of the probe to the Y axis. A photograph of the actual mechanics of a later version of the scanner (NE4102) is shown later in Figure 23b, but those in the Sundén scanner were basically similar. One of the designers at Kelvin and Hughes produced preliminary drawings of a machine to Brown's rough specification, but the company had a background in making equipment for industrial use and Brown felt the drawings did not suggest the kind of machine that would be appropriate for a clinical environment. Thanks to a mutual contact in the form of his sister in law, Brown met Dugald Cameron (Figure 15), a final year industrial design student at the Glasgow School of Art. Brown recognised that Cameron's talents and training could be just what was needed, so Cameron was commissioned to produce drawings showing how the aesthetics and the ergonomics of the design could be improved. Having first established that the machine should be planned around a single standing operator, Cameron set about making the design, as far as possible, both ergonomically convenient for the operator and non-intimidating to the patient. An initial sketch by Cameron for the design is shown in Figure 16.

As may be seen in the photograph of the completed machine (Figure 17), an inverted-U outer frame was

Fig. 15 Dugald Cameron, in the east basement of the Mackintosh Building of the Glasgow School of Art, using an air brush to produce presentation drawings for the Sundén scanner. Photo reproduced by the kind permission of Dugald Cameron.

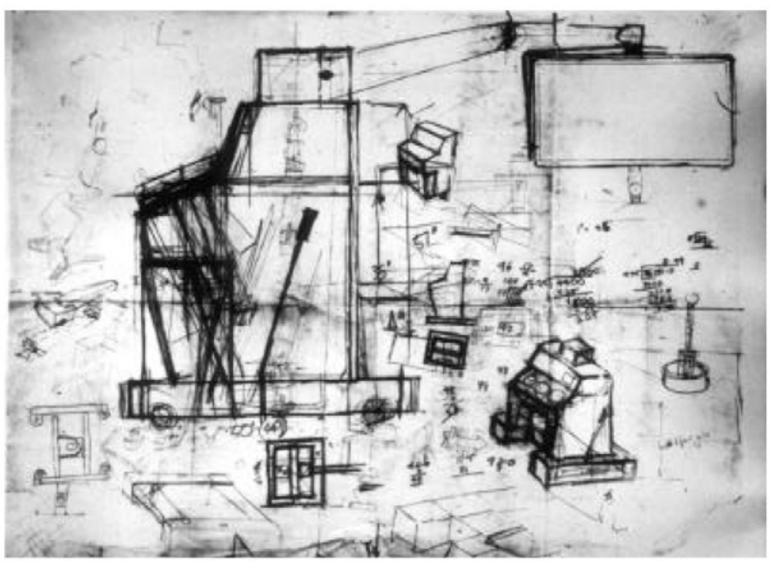

Fig. 16 Original sketch by Dugald Cameron of Kelvin and Hughes' concept for the Sundén machine. The Glasgow School of Art. By kind permission of Dugald Cameron.

supported over the patient by a hinged arm from a substantial column standing to the side of the patient. The arm, and all it supported, could be moved up or down, counterbalanced by a weight inside the support column [23]. This hinged arm allowed the outer frame to be positioned, as required, transversely or longitudinally with respect to the patient. The outer frame was free to rotate about a vertical axis at the end of the hinged arm, allowing the user to select a transverse, sagittal or intermediate scan plane orientation.

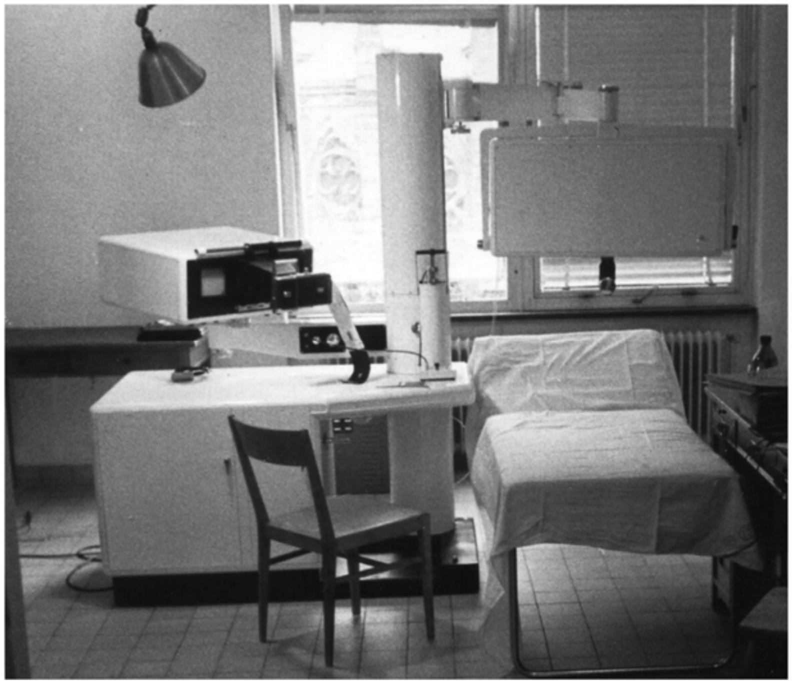

Fig. 17 The only known photograph of the original Sundén prototype in use in Lund in 1962. Photographed by Clive Ross, soon after he had installed it. Reproduced by kind permission of Mrs J Ross.

A chain system kept the angle of the outer frame constant with respect to the patient's longitudinal axis as it was moved transversely or longitudinally. Between the vertical arms of the outer frame, was a relatively slim rectangular box, enclosing the probe coordinate measurement frame and support arm. The position and orientation of this conspicuous 'probe support box' left the operator in little doubt as to the position and orientation of the scan plane. The box could be tilted about a horizontal axis to allow non-vertical planes to be scanned, for example in order to scan from the surface of the abdomen up into the rib cage or down into the pelvis. From the bottom of the box emerged the probe support arm, at the lower end of which was the probe holder. One of a range of probes could be easily inserted into this by means of a simple bayonet fitting. The probe could be rotated through ± 135° with respect to the 'Y' axis (scan plane vertical) within the scan plane by the operator, the rotation being transferred to, and measured by, a sine-cosine potentiometer located several centimetres above the probe on the same support arm. Separating the probe and the sine-cosine potentiometer in this way allowed the probe-holder to be smaller and neater, making it easier for the operator to grip and rotate the probe. The 'X' and 'Y' coordinates of the spindle, about which the probe rotated within the scan plane, were both measured by cable and pulley systems linking the spindle to linear potentiometers (Figure 14). The design also included the provision of accessible stowage for the range of probes and storage for the bottle of olive oil used for acoustic coupling. The job of overseeing the mechanical side of the project was entrusted to Brian Fraser, a senior development engineer within Kelvin & Hughes who had established a reputation as a practical designer in the field of marine instrumentation, leaving Brown free to concentrate on the electronics [23].

The electronics and their controls were housed in a console attached to the base of the support column on the side opposite the patient. A separate display console was suspended above the electronics console, on its own arm extending from the column. Although the structure was perfectly stable anyway, this gave the reassuring appearance of counterbalancing the heavy scanning frame suspended above the patient on the other side of the column. The display console accommodated two CRT screens for displaying B-mode scans, one with a long persistence phosphor for the operator to view and one with a short persistence phosphor for the Polaroid camera. This camera played a more fundamental role than simply providing a visual record of the images; it was intrinsic to the spatial compounding process since the final brightness of any target on the photograph was determined by the sum of several partial exposures, one for every time the ultrasound beam hit the target from a new direction [24]. It was, by now, considered that there was much less need for a dedicated A-mode display, although provision was made for an A-mode scan to be displayed on either of the B-mode screens if desired. As in the automatic scanner, Brown's continuing concern for safety meant that, as in the two previous scanners, the receiver gain was set as high as electrical noise would allow and a switchable attenuator was provided that enabled the user to progressively increase the voltage drive to the transducer until usefully large echoes could be detected. Perhaps because this scanner was going out onto a world stage, his caution over safety was even greater and the PRF was reduced to 25 Hz, half that used in the automatic scanner [23]. An undesirable effect of this was the creation of gaps between lines of echoes whenever the probe was moved too quickly across the patient's skin; such gaps are evident in the B-scan of twins shown in Figure 18.

Fig. 18 Scan of a twin pregnancy clearly showing the two fetal heads, obtained using the Sundén machine in 1956. Photo courtesy of the BMUS Historical Collection.

After extensive testing by Donald and MacVicar at the Western Infirmary, the 700 kg machine was delivered to Lund, Ross travelling with it to install it. According to MacVicar, the date of delivery was 10th March 1962 [45], although according to Maršál and Sundén in Lund, it was in the autumn of 1961 [46]. Whatever the date, Sundén made good use of the machine, achieving impressive results and promoting the use of obstetric and gynaecological ultrasound in Europe as well as gathering material for an MD thesis "On the diagnostic value of ultrasound in obstetrics and gynaecology", which was examined by Donald and published in 1964 [47]. General maintenance was carried out by local engineers but, in March, 1964, John Fleming, an electrical engineer who joined the staff of the Hillington factory in 1962 as a development engineer on medical ultrasound projects, was sent to Lund to carry out a major overhaul [48]. Amongst the jobs needed was the replacement of the sine-cosine potentiometer used to measure the probe angle to the scan plane vertical. Wear of the wire-wound track due to the constant use of the machine and, it was suspected, poor standards of potentiometer manufacture, meant that echoes were being increasingly misplaced on the scan. Intimate acquaintance with the electronics of the Sundén machine and its limitations was to prove valuable to Fleming when helping to develop improvements for future commercial machines. Notwithstanding minor problems, the Sundén machine was much more refined than its two predecessors but, sadly, unlike them it was not destined to a final resting place in the Historical Collection of the British Medical Ultrasound Society (BMUS) but was to end its days in the hands of a scrap merchant [23].

IV. SMITHS LTD.

Meanwhile, in the Hillington factory, gradual progress was being made towards a production version of the Sundén machine. Work was also proceeding towards the production of a portable A-scan instrument with electronic calipers, to meet an expected demand for fetal cephalometry arising from the work of Duggan and Willocks. For a while, progress was hindered by major organizational changes to the company. For several years, Smiths Group had held a controlling interest in the company. In 1961, this resulted in the name Kelvin and Hughes changing to Smiths Industries Ltd. Problems in other parts of the company were addressed at the same time and, in the words of Brown, "medical ultrasonics had to take a bit of back seat" [23] as he and his team were asked to spend most of their time working on the commercial version of the semi-automatic industrial testing system with which he had made his mark at the start of his career. However, overall, the takeover did bring improvements to the resources needed to develop the new ultrasound production machines. These included the recruitment of two engineers, John Fleming and Angus Hall, to join Brown in 1962.

A. The Smiths' Diasonograph.

In 1963, Brown tasked Fleming with revising the electronics for the new production machine while he oversaw the redesign of the mechanical side. Brown again invited Cameron to be involved, this time formerly as an industrial design consultant, working with one of the company's mechanical engineers, David McNair. The brief was to design a scanner that was physically safe for the patient and straightforward to manufacture. Possibly mindful of Donald's preference for the term 'sonar' rather than 'ultrasound', Brown suggested that the new diagnostic scanner might be called the 'Diasonic Scanner' and that the A-scan instrument might be called the 'Diasonic A-scope'. In the end, the names chosen were 'Diasonoscope for the A-scan instrument and 'Diasonograph' for the B-scanner.

Fig. 19 One of the first production Diasonographs in Smiths' factory, Hillington, Glasgow, c 1963. Also pictured is Arthur Johnson, a draughtsman involved in the project. Photo courtesy of the BMUS Historical Collection.

A major change to the mechanics of what was to be known as the Smiths' Diasonograph was the replacement of the elegant hinged 'elbow, shoulder and wrist-joint' arm that supported the measuring frame on the Sundén scanner with something that was less difficult and costly to manufacture. As may be seen in Figure 19, in the new design the probe support box and its outer frame, above the patient, were mounted at the end of a pair of substantial parallel steel tubes which could slide in and out of the side of a heavy and very stable, slab-sided cabinet. Inside this cabinet, the linear bearings through which the tubes passed were mounted on a counterbalanced slide, which could be driven up and down by an electric motor in order to adjust the height of the measuring frame above the patient. Brown still had in mind an ambition for 3D scanning at some future time so he ensured the counterbalancing would be sufficient to cope with the extra weight if the probe movements were to be motorized at some stage. The outer frame and probe support box were designed on similar lines to those in the Sundén machine, although they, and indeed the whole machine, which weighed nearly a ton, had a greater bulk and a less elegant look. It was not long before the machine acquired the nickname 'Dinosaurograph'. Reflecting the technical background of its makers, measuring scales were attached to the outer frame and box so that the coordinates and orientation of the scan plane could be recorded. In practice, little use was made of these, as operators preferred to use anatomical features on the patient, such as the umbilicus or symphysis pubis, to record the position of the scan plane. Brown's original intention was that the new machine would have a motorized couch that could move the patient longitudinally beneath the scanning frame [24]. Apart from being more convenient for the operator, a motorized couch would also have made it easier to modify the machine to automatically acquire sets of closely spaced transverse scans, should there ever be sufficient interest in 3D scanning. However, cost considerations meant that a simple modified hospital trolley was used in the production version of the scanner.

The electronics of the Sundén machine were based on thermionic valves (vacuum tube devices). Fleming was aware of the recent progress in semiconductor devices and their many advantages, including greater robustness, smaller size and lower power consumption. He therefore offered to transistorize everything, but Brown felt such an undertaking would be too expensive and time consuming and instructed him to stick with valve technology. Fraser later commented [49] that the decision as to whether or not to adopt solid state technology around that time was difficult since, although manufacturers were aware that valves would soon be obsolete, solid state technology was not quite adequately developed. Fleming redesigned the power supplies from scratch, but in revising the timing and transmitting circuits he made direct use of circuits from the company's latest (Mark VII) flaw detector. The probe frequencies chosen were the same as used in the Mark VII flaw detector, namely 1.5 MHz, 2.5 MHz and 5 MHz, as this allowed him to use the new switchable amplifier of the Mark VII to replace the three separate plug-in amplifiers used in the Sundén machine. Besides being more convenient for the operator, this meant there was no need to provide protective storage for the amplifiers that were not plugged in. The probes were quick and easy to change, thanks to their simple bayonet fitting. Similar probe fittings were used on all subsequent evolutions of the Diasonograph; Figure 20 shows a photograph of the probe holder on the next incarnation, the NE4101 discussed in Section V *A*, below.

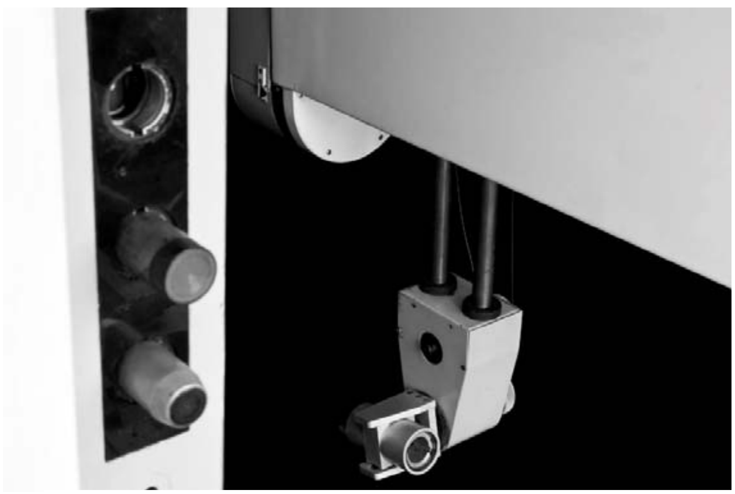

Fig. 20 The probe holder and probe storage facility on the NE 4101 Diasonograph. Photo courtesy of the Science Museum Group (https://collection.sciencemuseumgroup.org.uk/)

Cameron's original design for the Diasonograph was based on the assumption of a single operator, able to take advantage of a motorized couch. The decision not to incorporate a motorized couch meant that single-handed operation became difficult, although not impossible, and that, normally, two operators would be required - one to scan with the probe and another to operate the controls. In keeping with Brown's philosophy of trying to keep the scanning process as 'doctor-proof' as possible [24], there were three sets of controls on the electronic console, each requiring a different level of expertise (Figure 21) [50]. Covers were provided so that only the appropriate level controls could be revealed. The rightmost control panel housed the primary controls, consisting of the on/off switch, the sensitivity switch (in the form of a variable transmitter voltage attenuator) and the frequency selection switch (which changed the frequency band of the receiver RF amplifier). To the left of this panel was the panel containing the secondary controls, intended for more experienced operators. The main control was a switch to select either A-mode, M-mode (known then as 'Time-Position' (TP) mode) or B-mode (known then as 'Cross-sectional Display' or 'Section Scan'). There were also controls specific to each mode, such as 'scale', 'vertical shift' and 'horizontal shift' for B-mode, 'gain', 'reject' (suppression of weak echoes) and baseline time 'delay' and 'expansion' for A-mode, and 'sweep start' and 'sweep rate' for M-mode. The tertiary controls were less accessible, behind a fold down flap below the primary and secondary control panels. These were primarily for use by service engineers when calibrating the equipment and for technically advanced users, for example if engaged in experiments and research. Surprisingly, to users of modern diagnostic scanners, these tertiary controls included those for adjusting the swept gain.

A 'probe dispenser' was built into the outer frame, with a socket for storing each of the three probes (Fig. 20). An interlock mechanism between the frequency selection switch and the probe dispenser ensured that only the probe that matched the setting of the frequency selection switch could be released for use. Conversely, it ensured that the frequency selection switch could not be moved if the probe matching its current setting was absent from its socket on the probe dispenser.

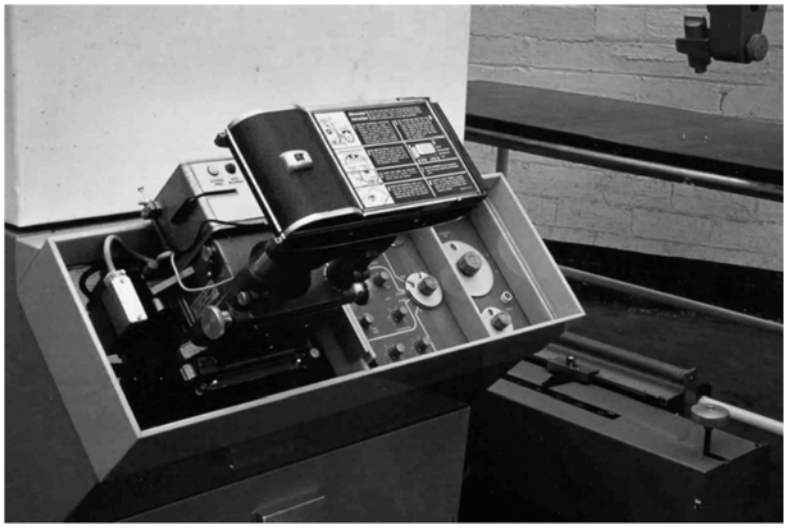

Figure 21. The controls on the console of the Smiths' Diasonograph, with the three levels of control and Polaroid camera, designed by Dugald Cameron. Photo reproduced by the kind permission of Dugald Cameron

The Smiths' Diasonograph was the world's first production model of an obstetric ultrasonic scanner, producing images that were superior to those of the Sundén machine and its predecessors. The Ministry of Health helped to stimulate the market by placing an order for four machines for research into the clinical application of ultrasound in UK centres. The first was installed in Glasgow's soon to be opened Queen Mother's Maternity Hospital in December 1963. Donald enjoyed experimenting with all the controls, including the tertiary ones, to the extent that he trained an assistant to scan patients with the machine, while he operated the controls. That assistant was Mrs Ida Miller, the "very efficient" wife of a local GP of Donald's acquaintance, recruited by Donald to help organize the scanning department [22] [51]. Over time, he allowed Miller to scan patients without his being present, thereby making her possibly the first sonographer in the UK, if not the world. In view of her lack of any formal medical qualification, he arranged later for a CCTV link between the scan room and his office so that he could exercise at least a nominal degree of supervision [52].

In 1965, Smiths Industries underwent internal organizational and management changes which did not suit Brown [23]. He left to work as Chief Engineer of Honeywell's Medical Equipment Division in Hemel Hempstead, working on equipment associated with heart surgery and coronary care, but no ultrasound. Fraser took over from him as leader of Smiths' ultrasound department, continuing to produce Diasonographs, of which twelve were sold by 1966.

Despite the sale of Diasonographs, by this time the Hillington factory of Smiths was losing money. It had also suffered a blow in losing a legal dispute with Automation Industries (USA) over global rights to patents concerning contact transducer systems, included some naming Brown as inventor [23]. The outcome was that, in 1967, Smiths decided to close their Hillington factory, giving up their investment in medical ultrasound. Determined to protect the British lead in obstetric and gynaecological ultrasound that he had done so much to establish, Donald turned again to the University of Glasgow, asking for permission to employ electronic engineers to maintain and develop the ultrasound equipment in Queen Mother's Hospital [53]. Much to Donald's amazement, the Principal, then Sir Charles Wilson, authorized him to set up the University Department of Ultrasonic Technology, complete with two full-time staff.

Fleming was pleased to accept a post as Research Technologist in the new department and encouraged his former colleague, Angus Hall, who had left Smiths two months earlier, to join him. The third member of the team was Jonathan Powell, a technician whom Willocks described as a "mechanical wizard" [53]. As a bonus, a large quantity of instruments and electronic components were acquired from Smiths for a nominal sum. They set to work correcting a variety of small but troublesome problems with their Diasonograph [54]. As on the Sundén machine, the wire-wound sine-cosine potentiometer was giving trouble. They found a permanent solution to this by sourcing, from the USA, a sine-cosine potentiometer with a plastic conductive track. Earthing problems were also addressed, thereby curing a problem of transient oscillation which had occasionally spoilt the images. This, in turn, allowed them to increase the receiver gain, resulting in improved penetration and sensitivity [55]. The Smiths' Diasonograph remained in service in Donald's department at the Queen Mother's Hospital until 1972, by which time an NE 4102 Diasonograph (see below) had been installed there [56]. About this time, Donald underwent a series of three major heart operations in a four-year period, retiring soon afterwards in 1976.

V. NUCLEAR ENTERPRISES LTD.

In 1967, after a period of competitive negotiations, during which Brown visited and briefed Sam Davis, Under-Secretary at the Ministry of Health in London [24], Smiths' interest in medical ultrasound was acquired by Nuclear Enterprises Ltd, a small but successful Edinburgh-based company that made gamma cameras, amongst other products. They immediately recruited Brown back from his position with Honeywell and also employed Fraser, who had been made redundant when Smiths had closed the Hillington factory. Donald was hired as a consultant.

A. The NE 4101.

The first Nuclear Enterprises version of the Smiths' Diasonograph was marketed as the NE 4101 [59]. Built with the help of stock inherited from Smiths, the mechanics and electronics were virtually identical to the Smiths' Diasonograph but the layout of the controls was different. There was no longer a distinction between 'primary' and 'secondary' controls, and the PRF was switchable between 50, 150 and 300 Hz. The NE 4101 had a superior performance to the Smith's Diasonograph, particularly in regard to registration (positional accuracy of targets on the B-scan image) when compounding (insonating from different directions). The improvement was due to the combination of many small factors, including the use of higher quality components and more careful assembly [57].

Around 1968, Brown started to go through what he described as "a difficult personal patch, probably reacting to past domestic problems and a very uncomfortable period with Honeywell", and for a time he was fairly incapacitated [23]. In 1970 he left Nuclear Enterprises to become a Research Fellow in Medical Physics at the University of Edinburgh [24]. In 1973 he joined Sonicaid Ltd. to pursue his ambition to develop a 3D ultrasound scanner, as mentioned in section III *B*. The resulting '3D Multiplanar Scanner' [41] did not enjoy much commercial success and production ended in 1979, when Brown gave up his medical ultrasound activities to work in the oil and gas industry. In 1999 he moved back into the medical world, becoming Quality Manager at the Radiological Protection Centre, St George's Hospital, London. He retired in 2002, setting up a small firm, NoStrain, in 2005 to help sonographers who suffered from musculoskeletal disorders as a result of scanning [58].

B. The NE 4102.

Brown's departure from Nuclear Enterprises meant that Fraser again became the main driving force for further development of the Diasonograph to what was to be the NE 4102 (Figures 22 and 23) [60]. The electronics console, previously forming the base of the support cabinet, now became a separate movable unit. This allowed the operator to sit closer to the patient whilst still viewing the screen and gave more freedom of choice in the layout of the scanning room. Instead of one display screen, serving whichever mode the operator selected, there were now two screens, one with a short persistence phosphor, particularly suitable for producing photographic records with a Polaroid camera, and one with a variable persistence phosphor. In place of cathode ray tubes with associated circuitry built in-house, fully assembled and tested display units were bought-in from Hewlett Packard. Push-button switches next to each screen determined whether that screen displayed A-mode, M-Mode or B-mode. An electronic caliper, as pioneered by Duggan, complete with a prominent digital display, could be used with either display screen. The caliper velocity could be set by the user - a facility which sometimes led to confusion when comparing successive BPD measurements of the same fetus at different hospitals [61]. Although A-mode scans were no longer used much to interpret echo patterns, they were sensitive indicators of rapid tissue movement. A valuable application of this was confirmation of fetal life by directing the probe onto the fetal or embryonic heart; M-mode could then be used to provide a photographic record.

Like the display units, the power supplies for the electronics were bought-in as ready-built and tested modules, in this case supplied by Standard Telephones and Cables Ltd. Using ready-built and tested components like these meant that the electronics were more tightly specified and reliable, leading to noticeable improvements to the images, including superior registration to that of the NE 4101. A signal processing option known as

'Differentiation' was introduced. As its name implies, this involved differentiating the rectified echo pulses, so that a very short spike was produced by the rapidly rising leading edge of each demodulated echo. This spike was mixed with the original demodulated echo signal, thereby improving axial resolution, albeit at the cost of a substantial loss of grey tone discrimination. Three controls were provided to set the swept gain characteristics,

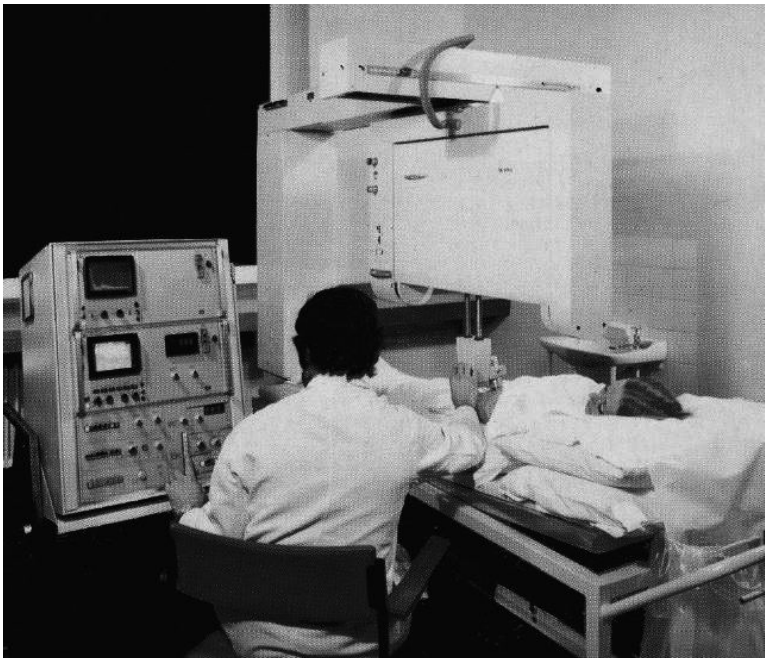

Fig.22. The NE 4102 Diasonograph. From Bulletin No. 64 - New Diasonograph NE4102 Diagnostic Ultrasonic Scanner. Nuclear Enterprises Ltd, 1972 [60].

arranged around a graphical representation of how the sensitivity increased with target depth. One control, labelled 'Initial attenuation (dB)' set the sensitivity close to the probe, a second, labelled 'Delay (mm)' set the depth range over which this initial sensitivity was maintained, and the third, labelled 'Slope (dB/cm)', set the rate at which the sensitivity increased with depth beyond the end of the delay.

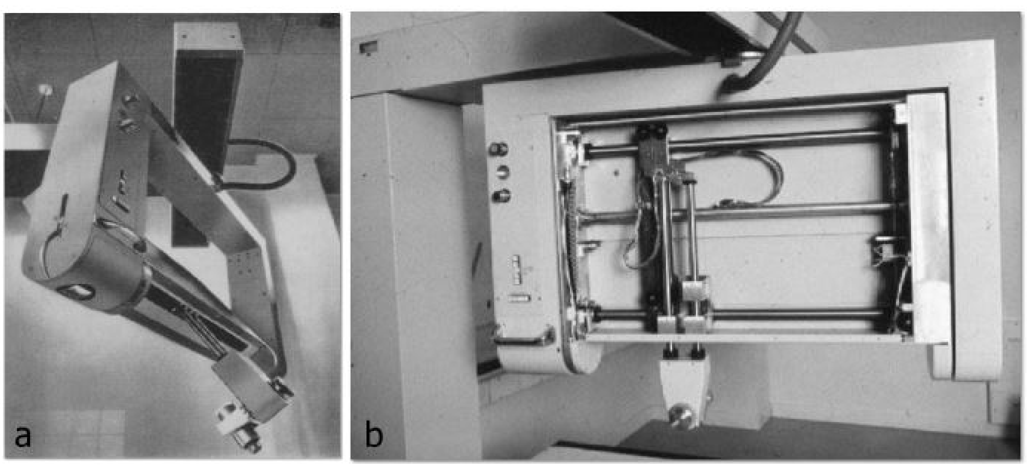

Fig. 23. a) Patient's view of the probe, the probe support box and the outer frame of the box, on an NE 4102. From Nuclear Enterprises Bulletin No. 64 [60]. b) View of the interior of the probe support box. The X and Y guide rails shown schematically in Figure 14 are prominent. Photo courtesy of the Design Council Slide Collection at Manchester Metropolitan University Special Collections.

As in previous Diasonographs, in order to minimise the ultrasound energy delivered to the patient, the sensitivity was varied by keeping the gain of the RF receiving amplifier as high as electronic noise would allow and using the sensitivity controls to vary the transmission excitation voltage In line with the growing confidence in the safety of diagnostic ultrasound, the standard PRF was increased to 600 Hz although a 'Velocity controlled' option was provided whereby the PRF varied between 60 and 1000 Hz according to the speed at which the probe was scanned across the patient, transmissions stopping altogether if the probe was held still in one position. The scanner's valve circuitry had been overdue for modernization and Fraser gave the task of re-designing the electronics using semiconductor technology to Alan Cole, described by Brown as "a very gifted electronics engineer" [23]. By the time the NE 4102 Diasonograph went on sale in 1972, the only valve remaining was a thyratron, a switch in the form of a gas-filled tube, used to discharge a capacitor across the transducer element. This was soon replaced by a newly developed solid-state switching device, the silicon controlled rectifier (aka thyristor) [57].

An example of a B-scan image of an early pregnancy obtained with this scanner, shown in Figure 24, illustrates the greater detail that could be seen as a result of the improved electronics. Combined with the rigidity and mechanical precision which had always been at the heart of the Diasonograph mechanics, this improvement in registration allowed more accurate size measurements to be made of anatomical structures. Hugh Robinson, First Assistant to Donald from 1972, took advantage of this to obtain accurate measurements of the crown-to-rump lengths of embryos and thereby establish a valuable method for assessing embryo growth [62]. The NE4102 was a marked advancement on the NE4101 and by November 1972 a hundred had been sold [63] in over forty countries around the world [64]. An NE 4102 installed in The Queen Mothers Hospital was in service until 1979 [56].

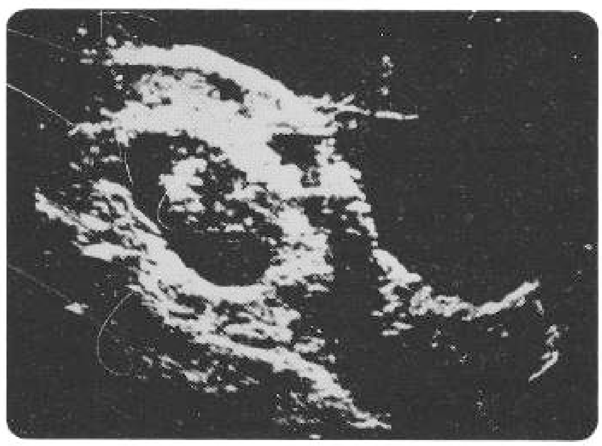

Fig. 24. B-scan of an early gestation sac, obtained with an NE 4102 Diasonograph. From Nuclear Enterprises Bulletin No. 64 [60].

C. Analogue Scan Converters.

In 1975, a major greyscale update was introduced for use with the NE 4102. Similar upgrades were being incorporated into scanners from other manufacturers at the same time, sometimes being retrofitted by medical physics departments [65]. These took advantage of the recent advances in image storage tubes, a popular example being the 'Lithocon' tube, as used in the PEP 400 and PEP 500 analogue scan converters from Princeton Electronic Products, USA [66]. At one end of an evacuated glass tube was a conducting 'target' consisting of a single crystal of silicon, on which was a mosaic of thousands of tiny non-conducting islands of silicon dioxide. There were three basic modes of operation: write, read and erase, carried out consecutively. In write mode, an electron beam emanating from a cathode, was accelerated and scanned across the target, using an X,Y timebase sweep, matching that of the CRT displays. By modulating the accelerating voltage of the electron beam with the amplified echo signal, negative charge was deposited onto the islands in proportions to that signal. By the end of each ultrasound scan, a charge pattern equivalent to the B-scan image had been painted onto the insulated mosaic. In read mode, this charge pattern could be read non-destructively and displayed on a TV monitor by scanning the same electron beam across the mosaic in a TV raster pattern. However, in this mode the voltage of the target was held only a few volts positive, so that the number of electrons reaching it was strongly influenced by the local negative charge on the island(s) immediately beneath the electron beam. The flow of these electrons from the target formed the output current used to modulate the brightness of the TV monitor. In erase mode, another raster scan of the electron beam was performed, with the target voltage raised to several volts positive, so that electrons from the beam could flood onto all the islands of the mosaic and raise all their voltages to that of the cathode.

When first introduced, the operator had to monitor the build-up of the B-scan image on a long persistence CRT, since the scan converter had to remain in write mode over this time. Only when the scan was complete, could he/she select read mode to see the greyscale image from the lithocon target on the TV monitor. This limitation was soon overcome by multiplexing between read and write every few lines of the TV raster scan. Gaps in the image during the intervals of reading were avoided by writing for the first (say) 2 ms of a TV field, reading for the next 2 ms, writing for the next 2 ms, and so on, but on the next field reading for the first 2 ms, writing for the next 2 ms , and so on. The brief transitions between reading and writing bands produced thin dark lines across the screen, giving a so-called ‘venetian blind’ effect, but this was a small price to pay for the ability to see the progressive build-up of the grey scale image as the probe was moved across the patient. Analogue scan converters revolutionized the display of ultrasonic images as they could produce bright images with about ten levels of grey, giving a huge improvement in grey level differentiation between tissues. They also improved spatial resolution on compounded images due to the more controlled build-up of charge on a given island when the corresponding tissue target was repeatedly scanned from different directions. The density of the insulated islands in the target mosaic was sufficiently high to allow four separate images to be written, stored, read and erased independently without noticeable loss of spatial resolution. Read-out using a raster that covered the whole mosaic presented the four images together on the viewing monitor, a facility known as ‘quad display’ that was incorporated into some later Diasonographs. The relatively bright screen of a TV monitor meant that users could, at last, be freed from the requirement of working in relatively dark scan rooms. The TV format also meant that video storage and multiple viewing screens could be used, for example in consulting rooms or lecture theatres. Notwithstanding its advantages, the advent of B-mode images having a good range of grey tones was not universally welcomed. It was not unknown for some ultrasound users, who had learned to interpret images with no, or very few discernible grey tones, to deliberately throw away the new greyscale information by adjusting the dynamic range controls to produce images with the high contrast appearance they were used to.

A special version of the NE 4102, marketed as the NE 4102B, incorporated this greyscale facility, including the ’quad’ display option, as standard, but a separate add-on package for existing NE 4102 scanners was made available as the NE 4104G Greyscale Storage Display [67]. An example of a greyscale B-scan image of an early pregnancy obtained with an NE 4102 equipped with an analogue scan converter is shown in Figure 25. Other accessories for use with the Greyscale Storage Display were introduced at the same time. These were: the NE 4106 Hard Copy Unit, based on a fibre optic recorder that produced approximately A4 sized (216 x 279 mm) grey scale images in just 12 seconds, the NE 4108 Video Cartridge Recorder and the NE 4210 Remote Photographic Facility, comprising a 6 inch (150 mm) TV monitor with a hinged adaptor to accept a Polaroid, or 70 mm, camera.

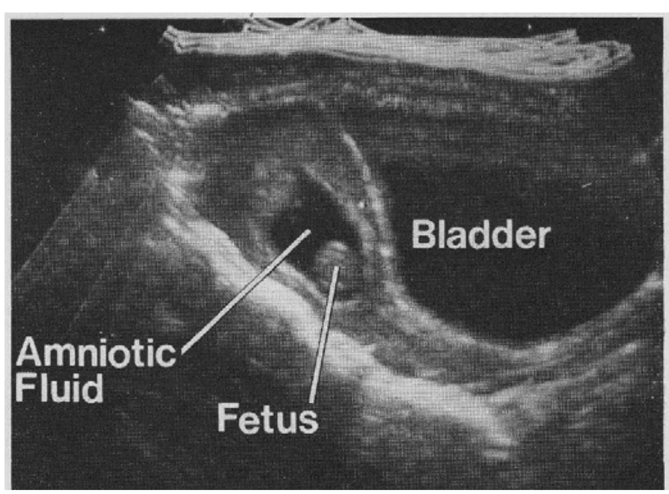

Fig. 25 Annotated greyscale B-scan of an early pregnancy obtained using an NE4102 fitted with an analogue scan converter. From Nuclear Enterprises Bulletin No. 434 [67].

D. The NE 4200.

In 1976, the NE 4200 was introduced [64]. Two high performance self-contained display units from Hewlett Packard were built into the electronic console, side by side. One was a short persistence HP 1332 for photography, but which could also display the TV image if required. The other was a variable persistence storage HP 1335, with a foot-operated erase switch. The NE 4200 could be ordered with greyscale imaging, based on a PEP 500 analogue scan converter and a separate TV monitor. The concept of greyscale enhancement of contrast resolution was taken further than on the NE 4102B, by providing an optional Colour Conversion Unit (NE 4204C). This comprised a 20-inch (508 mm) colour TV monitor and additional circuitry that added colour to the greyscale image. The signal amplitude range (window) over which the colour was applied could be varied by the operator to highlight subtle changes in echo amplitude, for example when looking for abnormal tissue, generating echo amplitudes that were only slightly different to echo amplitudes from surrounding normal tissue.

Different signal processing options could be selected by a row of four push buttons. One pair of push buttons selected between ‘Greyscale’ and ‘Non-Greyscale’. The latter option provided what the brochure described as “outline-type scans of important structures” [64], but this option also made the machine more acceptable to those users, mentioned above, who were, at least initially, happier with the high contrast images they had become accustomed to. Another pair of buttons selected between ‘Diff in’ and ‘Diff out’, where ‘Diff’ stood for ‘Differentiated’, as explained earlier for the NE 4102.

Bayonet fitting probes with frequencies of 0.5, 1.5, 2.5, 5 and10 MHz were available. There was also a 2.5 MHz biopsy probe (NE 4167), principally intended for amniocentesis, having a central aperture sufficient for needles up to 1.96 mm in diameter. A handheld 2.5 MHz probe, for cardiology applications, was also available, intended for use with an optional cardiac module (NE 4103C), built into the console. This module allowed simultaneous presentation of M-mode, then known as Time-Position (TP) mode, ECG and PCG traces. The PRF remained at 600 Hz, as in the NE 4102, but it was increased to 1800 Hz in M-Mode when using the cardiac module or at the upper limit of Velocity Controlled mode. An NE 4200 installed in Donald’s department in 1976 remained in service until 1985 [56], by which time real-time scanning was starting to become widely established, eventually to make so-called ‘static scanners’, including the Diasonographs, obsolete.

VI. EMI LTD.

By 1977, Nuclear Enterprises was producing fifteen Diasonographs every month, with a backlog of seven months of orders [68]. Production of ultrasound equipment was starting to dominate the company’s activities and this change to the company profile did not sit easily with the directors. EMI, a large international organization with a proven track record in manufacturing medical imaging systems, had increased its shareholding in Nuclear Enterprises to ninety percent in 1976 [69] and in 1977 the directors of Nuclear Enterprises decided to sell their ultrasound division to them.

A. The EMISONIC 4200.

Soon after this takeover, the EMISONIC 4200 Diasonograph was launched. A brochure [70] photograph is shown in Figure 26a. This machine was basically very similar to the NE 4200, although there were a few minor changes, including the layout and style of some of the controls on the console. The 0.5 MHz probe was dropped from the range and a 3.5 MHz probe was added, part of an extended range of over sixteen probes with frequencies of 1.5 MHz, 2.5 MHz, 3.5 MHz, 5.0 MHz and 10 MHz. For probes of all frequencies, a choice of either unfocused, medium or long focal length was offered. A 2.5 MHz, unfocused biopsy/aspiratory transducer was also offered, having a 13 mm diameter and a central 2.4 mm aperture to accommodate a 14 gauge (2.108 mm diameter) aspiratory or biopsy needle. The acoustic power output and PRFs of the EMI 4200 remained as they were in the NE4200, except for a reduction in PRF to 1200 Hz when using the cardiac facility. As in the earlier 4102B model, a ‘Quad’ option that allowed four greyscale scans to be displayed on the TV monitor at the same time, each being independently written and erased. A new patient safety feature was added in the form of proximity detectors, built into the lower faces of the outer frame to ensure that neither the outer frame nor the probe support box could press down onto the patient. This and other features are indicated in an annotated view of the mechanical system shown in Figure 26b. A greyscale B-scan, obtained with an EMI 4200, of a sagittal cross-section of a liver with metastases, is shown in Figure 27.

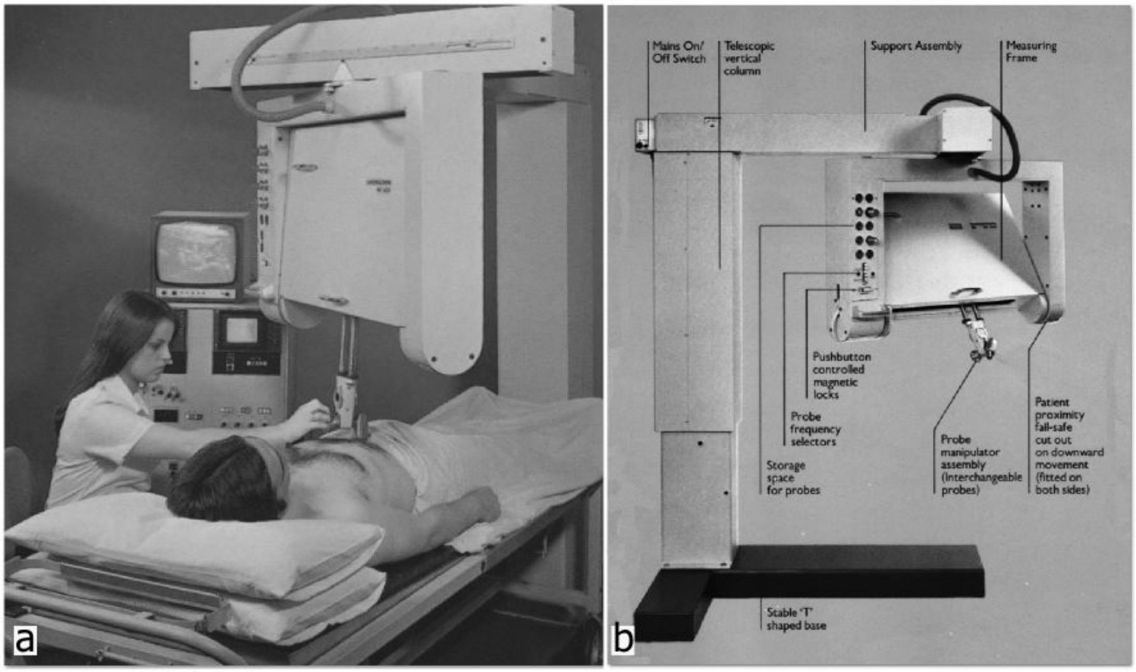

Fig. 26 a) The EMISONIC 4200 Diasonograph. b) Annotated image of the mechanical system. From Nuclear Enterprises Bulletin No. 112 (1977) [70].

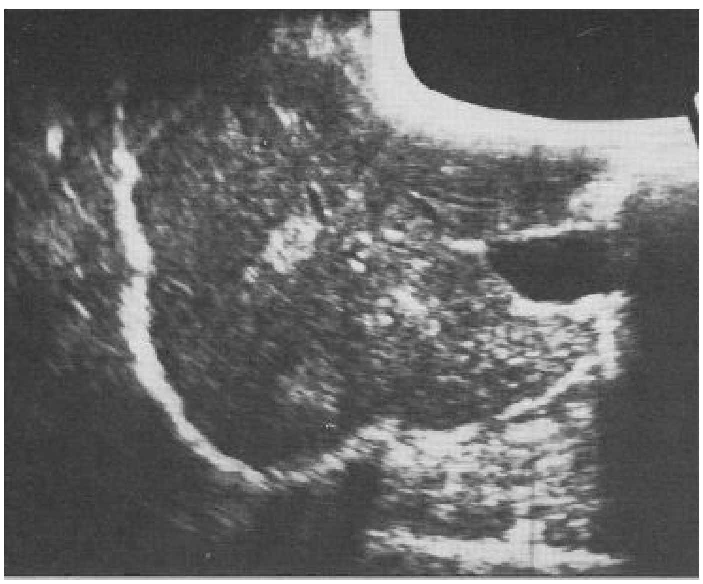

Fig. 27 B-scan of a liver with metastases, using the EMI 4200. From Nuclear Enterprises Bulletin No. 112 (1977) [70].

B. The EMISONIC 4201.

A second EMI Diasonograph, the EMISONIC 4201 (Figure 28) was launched in 1978 [71]. This machine had motorized movement of the outer frame and the probe support box, including automatic shifts (selectable between 2 mm and 40 mm) of the scan plane in a direction perpendicular to itself to facilitate acquisition of parallel sets of scans. A 9-inch (230 mm) TV monitor screen for greyscale images was built into the electronics console, alongside the short persistence and long persistence display modules. Every displayed and recorded scan could be automatically annotated with information such as the hospital name, patient number, scan serial number, scan plane coordinates and caliper reading. Potentially useful safety related information could also be included automatically in any of the displays, such as the probe frequency, transmission attenuation, and even the total number of pulses delivered to each patient. The quoted values for maximum temporal average output power were slightly greater than on the EMI 4200. For example, for the NE 4238 long focus, 13mm diameter 2.5 MHz probe, supplied as standard on both machines, the maximum temporal average output power was quoted as 6.92 mW for the NE 4200 and 10.8 mW for the NE4201. Although only a small increase, and quite insufficient to produce significant heating, even of bone [72], this was an early pointer towards a more dramatic trend over the coming two decades for acoustic outputs to be increased in order to improve image quality [73]. Provision was made for the console to interface with the EMISONIC 4264 'Spinner' real-time sector scanner (Figure 37b). An EMISONIC 4201 was in use in the Queen Mother's Hospital, Glasgow, until 1987 [56].

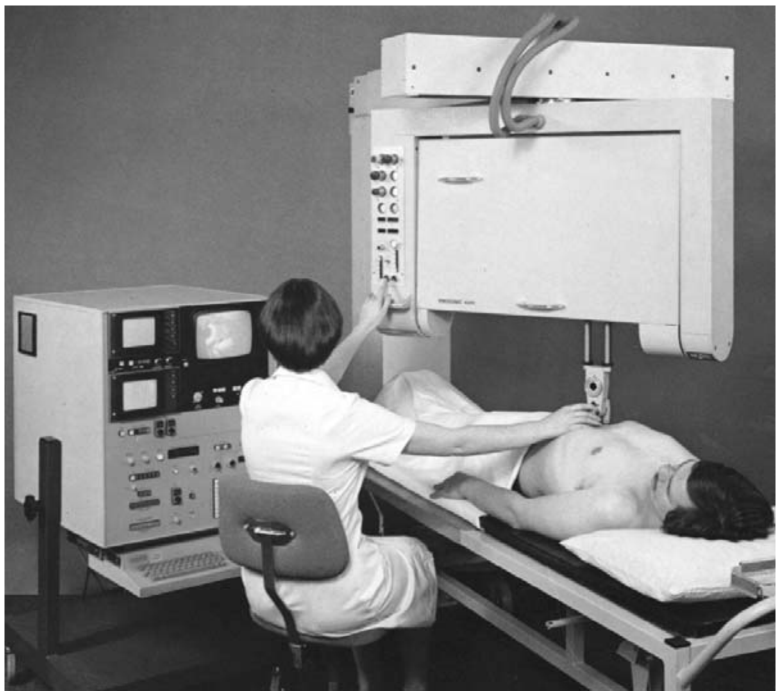

Fig. 28. The EMISONIC 4201. From Nuclear Enterprises Bulletin No. 116 (1978) [71]

VII. FISCHER LTD.

The final chapter of the Diasonograph story began in 1980 when EMI sold its medical ultrasound business to H. G. Fischer Inc., USA [69]. A new company, Fischer Ultrasound, was then formed, located in the former Nuclear Enterprises factory at Sighthill, Edinburgh.

A Fischer 4200S.

A modular ultrasound scanning system was produced, based on a console called the Fischer 4200S [74] (Figure 29a). This was similar to the console of the EMISONIC 4201 but without the long persistence monitor. The analogue scan converter was replaced by a digital scan converter, commercial examples of which were produced from 1976, although it took a few more years for their performance to match that of analogue scan converters [75]. This console could be combined with either the Diasonograph 4200 rectilinear B-scan mechanics, a more flexible articulated B-scan arm mounted on a substantial support column that was clearly from the Diasonograph stable [76] (Figure 29b), or a real-time hand-held sector-scanner probe (Figure 37c).

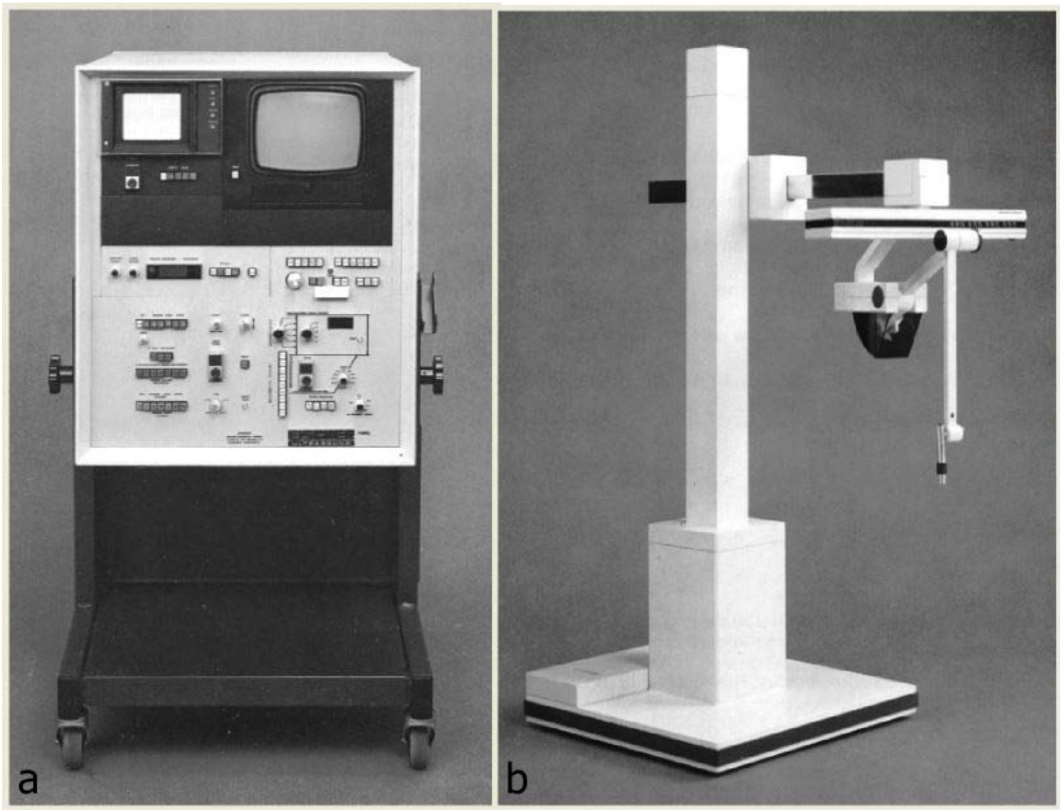

Fig. 29 a) Fischer 4200S console. From Fischer Ultrasound sales leaflet for 4200S [74]. b) Articulated arm option for the Fischer 4200S. From Fischer Ultrasound sales leaflet for the Articulated Scan Arm [76].

B. Other Fischer Ultrasound Products.

Fischer produced other diagnostic ultrasound products in the 1980s, principally real time systems such as the MARTI mechanical spinner [77], one of which was in the Queen Mother's Hospital between 1980 and 1986 [56]) and the LINUS linear array scanner [78]. Manufacturing continued in Edinburgh until 1995 [68].

VIII. CONTEMPORARY DEVELOPMENTS.

The purpose of this section is to lend some perspective to the Diasonograph story by briefly reviewing developments in medical ultrasonic imaging that were occurring elsewhere at the same time.

A. Other non-commercial B-scanning systems in the late 1950s.

In the late 1950s, before the Glasgow B-scanning work had resulted in a commercial system, researchers in other centres were also developing clinically useful ultrasound B-scanners. The water-bath approach was made more acceptable for clinical use by having the patient in acoustic contact with, but not immersed in, a water-filled bag or tank, within which the transducer was scanned. For example, in Japan, between 1954 and 1957, Surgeons Kenji Tanaka & Toshio Wagai at the Juntendo University, Tokyo, together with physicist Yoshimitsu Kikuchi and engineer Rokuro Uchida, built a scanner involving a water-filled bag that was lowered into contact with a patient lying on a couch [79][80]. In the USA, in 1957, Howry's group developed the 'Pan Scanner'. This consisted of a semi-circular water tank that half-surrounded the seated subject, allowing compound scanning of internal organs from a wide range of angles [81]. In 1960, at the Commonwealth Acoustics Laboratory (CAL) in Australia, later to become the Ultrasonic Institute, engineer David Robinson with physicist George Kossoff and obstetrician William Garret, designed and built a water-tank compound scanner, somewhat on the lines of the Pan Scanner but with a smaller angular width of arc [82]. It was specifically intended for obstetrics and had much superior signal processing and compounding. The CAL group went on to develop systems for imaging other parts of the body, including eyes and breasts, setting world-beating standards in lateral resolution and signal processing. Some of this work is described in the next section (*B*).

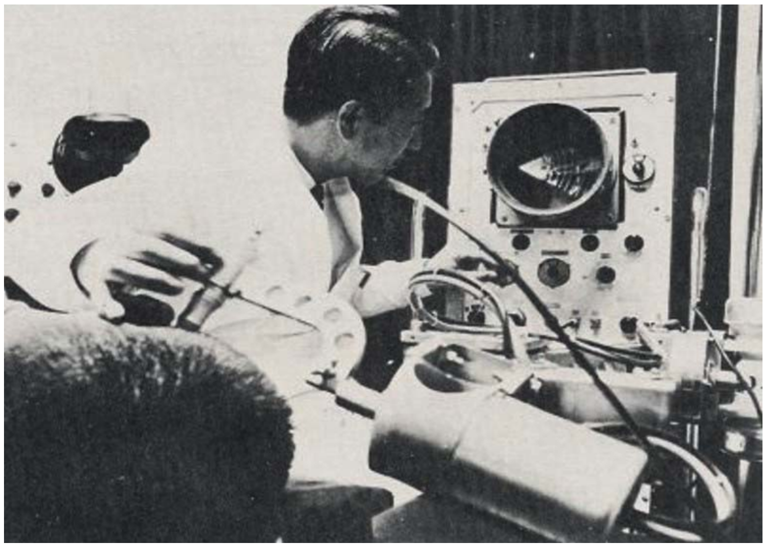

Fig. 30 The One-point Contact Sector Scanner of Kikuchi [83] being used by to scan a brain c 1957. It was also used successfully, later, in obstetrics and gynecology. Courtesy of the BMUS Historical Collection.

Unknown to Brown, as he worked on his bed-table contact scanner in 1957, a different form of contact scanner was being developed by Kikuchi and the Juntendo group. They called their technique ‘One-point contact-sector scanning tomography’ [83], since the transducer was constrained to rotate about its face, in contact with a fixed point on the patient’s skin (Figure 30). Originally, the system was designed as a means of imaging the brain, for which a fixed point of contact on the skull had the advantage that artefacts due to variations in skull thickness were reduced, but the scanner later proved popular, in Japan, for scanning obstetric, gynecological and general abdominal cases.

B. Commercial B-scanners contemporary with the Diasonograph scanners.

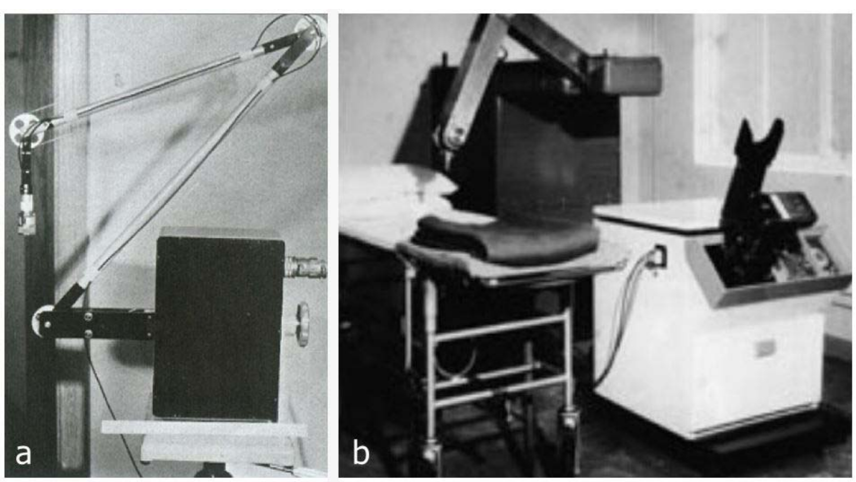

Fig. 31. a) The ‘Porta-Scan’ articulated-arm scanner designed in 1962, by engineers William Wright and Ralph Meyerdirk and commercially produced in 1963 by their own company, Physionic Engineering Inc., Colorado. b) A more sturdy articulated-arm scanner built by medical physicist Peter Wells, of Bristol General Hospital, UK around the same time as the Porta-scan. This was connected to an NE 4101 Diasonograph console, as shown. Photos courtesy of the BMUS Historical Collection.

In 1963, an articulated arm scanner, the 'Porta-Scan" (Fig. 31a) was produced by Physionic Engineering Inc., in Colorado. This company had been formed in 1962 by engineers William Wright and Ralph Meyerdirk, who had been working with Holmes and the Howry group. This type of probe support arm was much less bulky than the Diasonograph rectilinear rail-based system, and allowed easier probe movement, although it did not share its intrinsic rigidity and positional accuracy. At about the same time, medical physicist Peter Wells, at Bristol General Hospital, UK, developed a more sturdy example [84], which he interfaced to an NE 4101 Diasonograph console (Fig. 31b). Articulated arms became the norm in commercial compound contact B-scanners, other early examples being the Combison 1, from Kretztechnik in 1966, the SSD-10 from Aloka in 1967, the Picker Laminograph, a development of the Porta-Scan, in 1969.

Meanwhile, the era of water-bag scanners was far from over. In fact, the first ultrasound B-scanner to be commercially produced was the SSD-1 water-bag scanner (Figure 32), from the Japanese company, Aloka, in 1960. This company was founded by Uchida, previously with the Juntendo group, and the scanner was a development of their work.

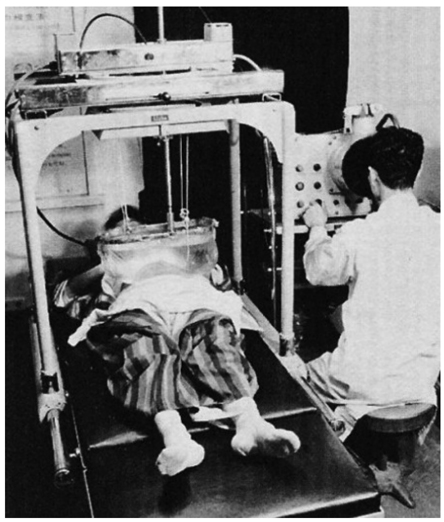

Fig. 32 The Aloka SSD-1 water-bag scanner, introduced in 1960. This was the commercial development of the system developed by the Juntendo University group (Section VIII *A*). Photo courtesy of the BMUS Historical Collection.

In 1965, a real-time water-bag-based mechanical scanner, the 'Vidoson', was commercially introduced by Siemens Medical Systems, Germany (Figure. 33). Developed in-house by engineer Richard Soldner, physicist Heinz Kresse and laboratory head Wolfgang Krause, this device involved the rotation of a wheel with three evenly spaced transducers set into its rim, rotating about the focal axis of a parabolic mirror. The beams reflected from the mirror remained parallel to the mirror's principal axis as they made repeated linear sweeps across the mirror's aperture, albeit at non-uniform speed. The Vidoson was the first commercial real-time ultrasound scanner; it achieved a frame rate of 15 images per second, each made up of 120 lines. The designers had initially planned to create a breast scanner, but the final device found its principal métier in obstetric and gynecological applications.

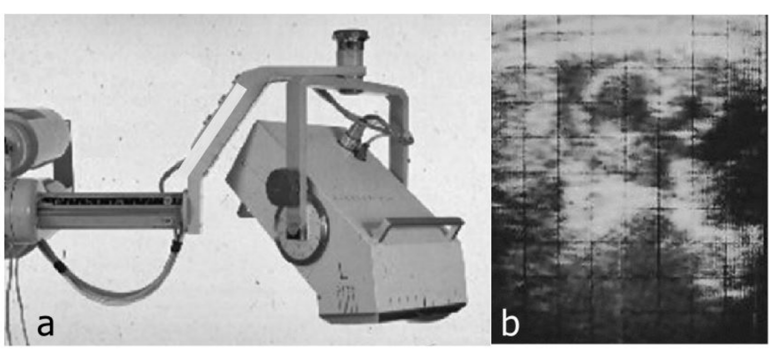

Fig. 33. a) The 'Vidoson' real-time water-bath scanner, was commercially introduced by Siemens Medical Systems, Germany, in 1965. As each of three transduces was rotated around the focal line of a parabolic mirror, its reflected beam was swept across the aperture, remaining parallel to the principal axis. b) An example of a single frame from an obstetric patient. Courtesy of the BMUS Historical Collection.

The mid-1970s witnessed the zenith of water-tank scanning. This took the form of the Australian 'Octoson', which involved the patient lying on a flexible waterproof sheet, forming the upper surface of a water-filled bath (Figure 34a). This scanner was the commercial version of a prototype annular array compound scanner developed by the team at CAL between 1973 and 1974 [85]. It was marketed from 1975 by Ausonics Pty., a company created by the laboratory (by then renamed the Ultrasonics Institute) for the purpose. Water tanks have a unique advantage in that they allow the use of large aperture annular array transducers, which can produce very narrow, dynamically focused, transmit-receive beams, and hence much better lateral resolution than is possible with a contact scanner. By using eight annular array transducers, arranged in an arc (Figure 34b), the time for each scan was kept to just 4 seconds. Each transducer was rocked through a range of angles such that eight sector-shaped scans were generated, each having 500 lines. These sector scans overlapped in the target region of the patient, producing a compound scan with precisely defined registration, as well as high line density, image uniformity and grey scale (Figure 34c). More than 200 Octosons, costing around $A100,000 each, were sold world-wide, before real-time, hand-held scanners became dominant.

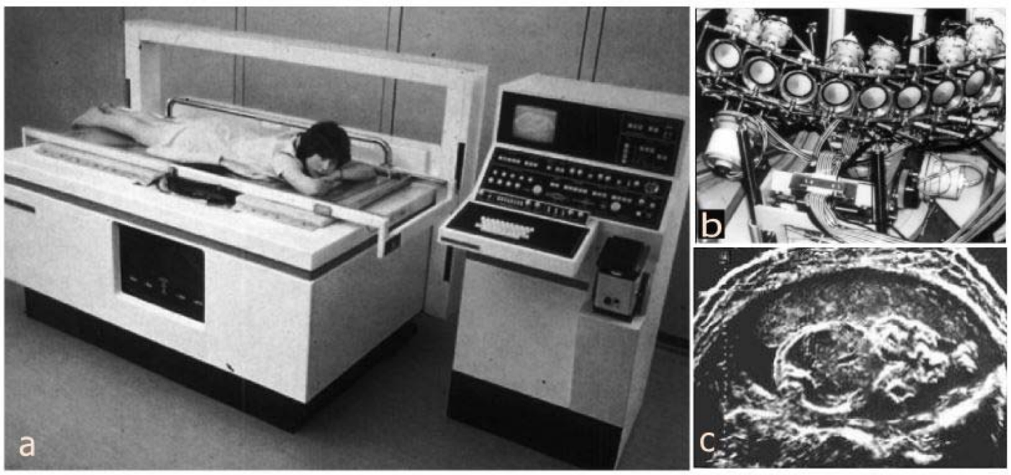

Fig.34 a) The 'Octoson' water-tank scanner, developed by the Ultrasonics Institute, Sydney and marketed, from 1975, by Ausonics Pty. b) Sector scan images from eight large aperture, dynamically focused annular array transducers, were combined to form a compound B-scan image. The image quality was unrivalled for its time, as illustrated by the obstetric example (c). Images from the Octoson sales brochure.

C. The real-time revolution.

A revolution began in the late 1960s and early 1970s that would ultimately lead to the near universal use of real-time, hand-held scanners. These can be categorized broadly as working either by: electronically stepping the beam along a linear array of transducer elements (linear array probes), electronically deflecting the beam to scan in a sector format (phased array probes), or mechanically sweeping the beam through a sector or in a linear fashion (mechanical scanners).

i. Early linear array probes.

In the west, it was long accepted that the first prototype diagnostic linear array system was one built by a group at Erasmus University, Rotterdam, led by Nicolaas Bom [86]. In fact, unknown to western researchers, at the same time as this group was building a scanner that gave an image of just 20 lines, a vastly more sophisticated prototype linear array scanner, with 181 channels (scan lines) and 200 narrow rectangular transducer elements, acting in groups of 20, was developed in Japan [87]. It was the work of Takasuke Irie and his supervisors Yoshio Hagiwara and Rokuro Uchida of the company 'Japan Radiation and Medical Electronics Inc' (later to become Aloka). Ignorance of this remarkable Japanese achievement continued through the 1970s and beyond, as western researchers and manufacturers produced their own linear array scanners. The first commercial example, in 1972, was the 20-channel Organon Teknika 'Multiscan', a direct implementation of Bom's 20-channel system. This was followed, in 1973, by the much superior and very popular 61-channel ADR scanner (Figure 35), made by the Advanced Diagnostic Research Corporation in the USA. A second ADR scanner, the 'ADR 2130', with electronic focusing, was marketed in 1975. Concurrent with, but unaware of, American developments, the author worked on ways of increasing the number and density of scan lines. The most successful method was to use adjacent groups of narrow rectangular elements [88] [89]. A commercial spin-off from this work was 'RITA', a 40-channel add-on system from GEC Medical Ltd for enhancing an existing A-mode or M-mode instrument with a real-time B-scan facility. In 1976, a newly formed, Edinburgh-based company, Diagnostic Sonar, produced 'System 85', a 48-channel linear array scanner: This had a simultaneous A-scan display and prominent electronic caliper, reflecting the background of the company founder, Hans Gassert, who had hitherto worked for Nuclear Enterprises in marketing and sales.

Fig. 35. The popular 61-channel ADR linear array scanner, produced by the Advanced Diagnostic Research Corporation in the USA, in 1973. Photo courtesy of the BMUS Historical Collection.

ii. Early phased array (electronic sector scanner) probes.

Phased array probes were first investigated as means of medical diagnostic imaging by Jan Somer at the Institute of Medical Physics-TNO, Utrecht, the Netherlands, in the mid-1960s. His array probe (Figure 36a) covered a 90° sector with only 21 elements, operating at a frequency of just 1.3 MHz, as he was primarily interested in imaging the brain through the intact skull, although some heart imaging was undertaken [90]. The

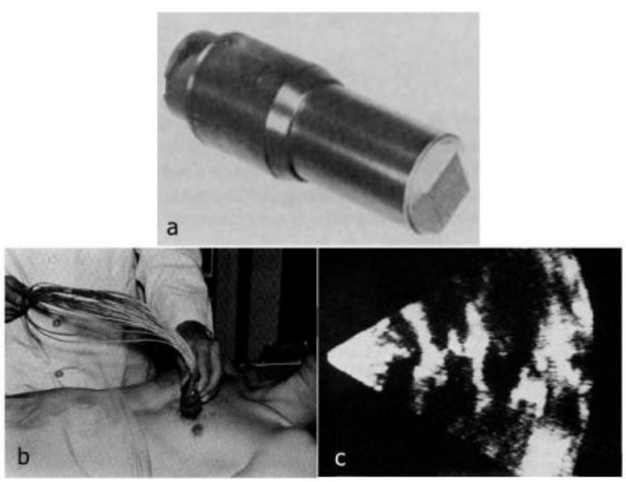

Fig. 36 a) Phased array probe made by Jan Somer of Utrecht University in 1968. Courtesy of Jan Somer. b) Prototype phased array from Frederick Thurstone's group at Duke University. c) Example of a heart scan from the Duke University. Photos b) and c) reproduced from Kisslo et al (1976) [93].

production version of this system was marketed as the ‘Echostat’ by the Diagnostic Electronic Corporation, USA in 1976, making it the first commercial diagnostic phased array scanner. However, it was too far ahead of its time and the limited technology available to Somer did not do the concept justice; consequently only a few were sold before it was overtaken by competition from commercial manufacturers [91]. The potential of the technique was further demonstrated by a group of biomedical engineers at Duke University, Durham, N Carolina, led by Frederick Thurstone, using digital technology (Figures 36b and 36c) [92][93]. By the end of the 1970s, technological advances meant that systems with much higher image quality from manufacturers such as Varian and Hewlett Packard entered the market.

iii. Early mechanical real-time probes.

Mechanical real-time probes involving reciprocating, linear scanning of transducers are subject to vibration problems when used with lower frequency, and therefore larger and heavier, transducers. Hence, for abdominal or cardiac use, sector scanners are the norm, and only this type will be mentioned here. The first mechanical real-time probe for scanning the heart was built in 1973 by James Griffith and Walter Henry at the National Institute of Health [94]. A 12mm diameter, 2.25 MHz transducer was driven by a crank attached to an electric motor such that it rocked back and forth continuously through a 30° sector at a rate of 15 Hz. The transmit pulses and echo processing were provided by a Smith Kline Ekoline-20 A-scanner, at a PRF of 2 kHz. Thirty images of clinically useful quality were produced every second, each consisting of 66 scan lines. In an effort to reduce the problem of vibration associated with rocking a transducer back and forth, in 1975, Hans Hendrik Holm and colleagues at the Gentofte Hospital, Copenhagen, Denmark built a system featuring a probe containing a 6 cm diameter wheel that spun continuously against an oil film on the patient’s skin [95]. Four evenly spaced transducers were set around the rim of the wheel, each being connected, in turn, to the transmit/receive circuitry as it passed over the skin. This produced 16 sector images per second, each consisting of 69 scan lines in a sector width of 50 °.

Commercial mechanical real-time probes, of both ‘rocker’ and ‘spinner’ types were produced from the mid-1970's. In 1974, Toshiba, in Japan produced their first prototype real-time mechanical sector scanner, the SSL-51H. It produced 30 images per second, each consisting of 120 scan lines, it had a variable sector width from zero to 65° and the choice of interchangeable focused or unfocused transducers. In 1975, engineers Reginald Eggleton and Kenneth Johnston in Indiana, USA, described an ‘add-on’ system which could be connected to an existing M-mode heart scanner to enable it to provide real-time sector B-scans [96]. It comprised a compact, hand-held, cylindrical probe with a transducer at one end, rocking through ± 15° about the principal axis of the cylinder, and a plug-in module of associated electronics. Two transducers, at 2.25 MHz for adults and 3.5 MHz for children, could be interchanged, and the frame rate (0 to 60 Hz), PRF and depth of view could be varied. This system, with its ‘rocker’ type of probe achieved commercial success as the ‘Cardioscan’.

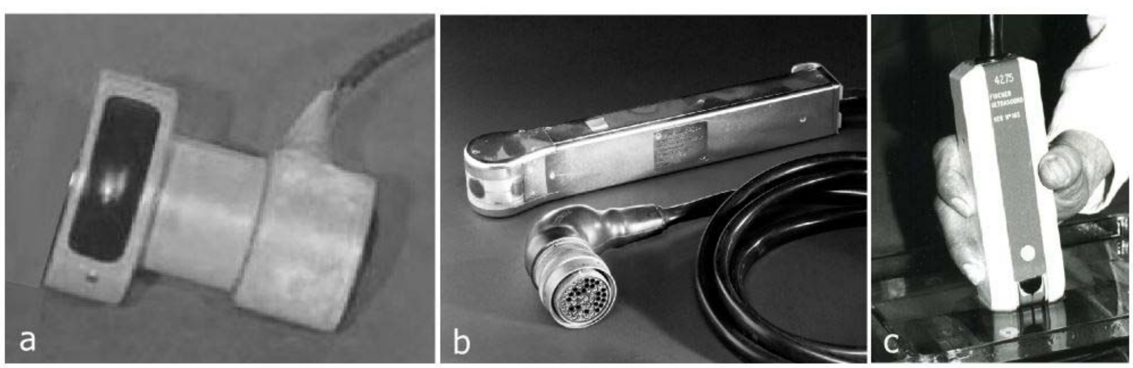

Fig. 37) a) The probe of the Combison 100 mechanical real-time scanner, produced by Kretztechnic in 1976. b) The EMISONIC 4264 ‘spinner’ mechanical real-time sector scanner, offered as an option with the EMISONIC 4200 Diasonograph. This probe was developed by Norman McDicken’s medical physics group at Edinburgh University. Photo courtesy of the Science Museum Group Collection © The Board of Trustees of the Science Museum. c) The Fischer 4275 further development of (b), available from around 1980 as an option with the Fischer 4200S. Photo courtesy of Norman McDicken.

In 1976, the Austrian company Kretztechnik produced the Combison 100. The probe of this scanner had a relatively large (approximately 10 cm) diameter continuously spinning wheel within a close-fitting oil bath, which had a roughly 5 cm long aperture, covered by soft plastic, in its rim (Figure 37a). Five 3.5 MHz transducers were evenly spaced around the rim of the spinning wheel, each of which became ‘live’ as it passed across the aperture. The large wheel and wide aperture gave the advantage of a wide field of view close to the probe. In 1979, Norman McDicken and his medical physics group at the University of Edinburgh described their system [97] in which 4 transducers, set in the rim of a continuously spinning, 3 cm diameter, wheel at one end of an approximately 20 cm long probe could generate a sector of up to 180°. This system was more compact than previous 'spinner' designs and was produced commercially as a real-time plug-in option (Figure 37b) for the EMISONIC 4200 Diasonograph and later, in an even more compact form (Figure 37c), for the Fischer 4200S, as discussed in Sections VI and VII.

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I would like to thank Jan Somer for providing me with reference [87] in English, Norman McDicken for the photograph of the spinner probe shown in Figure 37c, Kevin Martin for electronic copies of the various Nuclear Enterprise, EMI and Fischer sales brochures, referenced in the text and reproduced in the Appendix, and Francis Duck for the list of Diasonograph locations also given in the Appendix. I am also grateful to John Fleming, for sharing his detailed knowledge of the early Diasonographs and to Tom Szabo, formerly of Hewlett Packard, for information about the early commercial development of phased arrays.

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Appendix

Reproductions of the sales brochures and leaflets of the Diasonographs and related commercial equipment referred to in this article, as well as a list of the locations of archived Diasonographs, are available in the appendix at the end of this special issue (pp 660-730).

Author biography

Tony Whittingham ARCS BSc MSc PhD FInstP FIPEM graduated in Physics and Maths from Imperial College, London in 1965, before working on the dielectric properties of tissues in the Medical Physics Department at Aberdeen University. He became a Lecturer in Ultrasonics there in 1970, giving him the opportunity to become well acquainted with the NE 4101 Diasonograph.

From 1972 until retirement, he was Head of the Ultrasound Section of the NHS Regional Medical Physics Department in Newcastle upon Tyne, making pioneering contributions to linear array scanner design, developing CT and other ultrasound imaging systems, and designing instruments for measuring beam shapes, acoustic pressure, power and intensity. He has written and lectured extensively on beam-forming, ultrasound safety and modern developments in ultrasonic imaging technology. He has chaired the safety committees of BMUS and EFSUMB, co-authored Standards for the IEC and is a Past-President and an Honorary Member of the British Medical Ultrasound Society.