The early days of medical ultrasound imaging with particular reference to developments in Glasgow

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Abstract - The development of B-mode imaging, including features such as contact scanning, spatial compounding and a limited form of grey scale display, is reviewed up to the 1960s, in relation to the work of Brown and Donald in Glasgow.

Keywords - ultrasound, B-mode, A-mode, M-mode, history, pulse-echo, transducer, scanner, cross-sectional, 2D.

I. INTRODUCTION

The aim of this article is to review early developments in two-dimensional ultrasound imaging, up to the 1960s, around the time of the Glasgow work. The histories of methods for interrogating a single line, such as A-mode and M-mode, will therefore be mentioned only as they provide a background to the early 2D imaging methods. Likewise, there will be no mention here of the measurement of blood flow and tissue movement using the Doppler effect.

II. ORIGINS

The impetus for ultrasound imaging came from the sinking of the Titanic in 1912 and the breakout of the First World War in 1914. In one case the need was to detect icebergs, in the other it was to detect enemy submarines. Progress in transducer technology quickly followed, leading to the use of the piezoelectric crystal quartz transducers in naval ASDIC systems in 1917 (later to be renamed SONAR). By the 1940s, ultrasound A-mode pulse-echo detectors were being introduced for flaw detection in metals and fish finding [1]. Some medical researchers were optimistically investigating the possible therapeutic use of ultrasound, for example, to treat gastric ulcers and arthritis [2].

III. EARLY INVESTIGATIONS USING TRANSMISSION

In the late 1930s, Karl Dussik, a Viennese neurologist, began attempts to produce the ultrasonic equivalent of an X-ray image of the skull and brain by transmission imaging [3]. Unfortunately, his claim that his images revealed brain structure and pathology was later shown to be ill-founded by teams at Siemens, Erlangen, Germany [4] and, independently, at MIT, Cambridge, Massachusetts [5], on both theoretical and experimental grounds. Transmission was also used by André Dénier and colleagues at the research center in Salpêtrière in Paris in 1946. They measured transmission losses through samples of bone and soft tissue in the hope that the positions of organs could ultimately be mapped out [6]. In 1949, Wolf-Dieter Keidel, a physiologist at the University of Erlangen, Germany, reported transmission measurements through the thorax using 57.5 kHz ultrasound that demonstrated the periodic changes in heart volume accompanying the beating of the heart [7].

IV. A-MODE AND M-MODE IN THE 1940s AND 50s

The suggestion that the pulse-echo A-mode method (similar to that used in metal flaw detectors) might be able to detect soft tissue pathology was first made in 1940 by H Gohr and T Wedekind from the Medical School of Cologne, Germany, but they did not publish any experimental results [8]. In 1949, at the Argentinian laboratory of the American electronics company RCA, R P Mclaughlin and G N Guastavino demonstrated the detection of a stone embedded in an excised kidney, and speculated on the possibility of cross-sectional imaging [9]. In the same year, George Ludwig, a medical officer at the Naval Medical Research Institute in Bethseda, Maryland, reported that A-mode equipment could detect the presence of gallstones implanted in dogs [10]. Also in 1949, John Wild, an English surgeon, working at the University of Minnesota in the USA, motivated by the occurrence of bowel failure in people suffering from bomb blast, used A-mode equipment to measure changes in bowel wall thickness [11].

In the 1950s, the A-mode technique began to be established in clinical applications. In 1955, Swedish neurosurgeon Lars Leskell [12] introduced its use in encephalography and in 1956, G Mundt and W Hughes [13] used it for eye measurements. M-mode is a development of A-mode in which a brightness modulated version of the display line is swept sideways across the screen at a constant speed, each echo tracing out a graph of depth versus time, from which the target's velocity along the line can be calculated. Cardiologist Inge Edler and physicist Hellmuth Hertz, in Lund, Sweden, were the first to apply M-mode scanning to the heart, publishing their results in 1954 [14], and establishing what was to become an invaluable tool for cardiology.

V. EARLY B-MODE (CROSS-SECTIONAL) IMAGING.

The first successful ultrasonic pulse-echo cross-sectional images of tissues were obtained by Douglass Howry, a radiologist in Denver, USA, working in collaboration with his wife Dorothy and two engineers, Roderick Bliss and

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Gerald Posakony of the University of Colorado. In 1949 they started experimenting with a water bath system, which they named the "Somascope", built in the basement of Howry's home (Fig. 1).

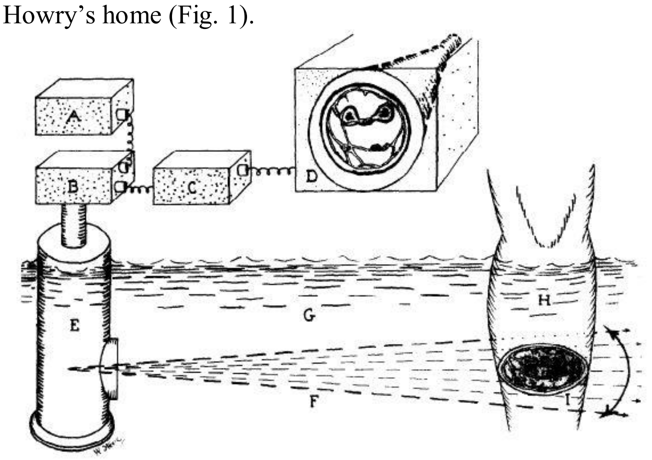

Fig. 1. Block diagram, from [15], of the early 'Somascope' used by Howry and his colleagues to obtain cross-sectional images in 1950 -51.

A description of their method and images of in-vitro specimens were published in 1952 [15].

Cross-sectional imaging systems in the 1950s usually required the subject to be either partially immersed in a water bath or to sit, stand or lie in acoustic contact with a water-filled bag containing the transducer scanning mechanism. The first such system was Howry's Mark II Somascope, developed in 1952-53 in collaboration with Posakony and another electrical engineer, Richard Cushman [16].

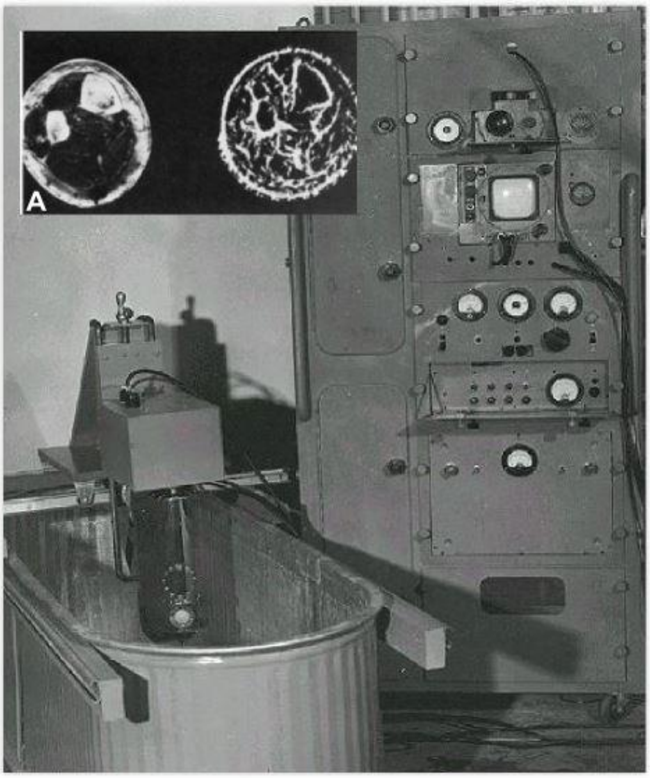

Fig. 2. The second 'Somascope' system developed by Howry's team. The subject sat in the water-filled, modified horse trough, across which the transducer (mounted on the vertical column) was driven. Images of leg cross-sections obtained with the system are inset.

Financial support was secured by his director, nephrologist Joseph Holmes. This system featured a horse trough (Fig. 2), across which was swept a lithium sulphate focused transducer mounted on a rail. The transducer could be angled in a horizontal plane to produce compound scans; this gave better delineation of specular reflecting interfaces such as the boundaries of organs [17]. Their ultimate example of compounding was in 1954 when images of the neck were formed by superimposing images from multiple linear sweeps of the beam across the neck from different directions around a tank made from the gun turret of a B29 aircraft [17].

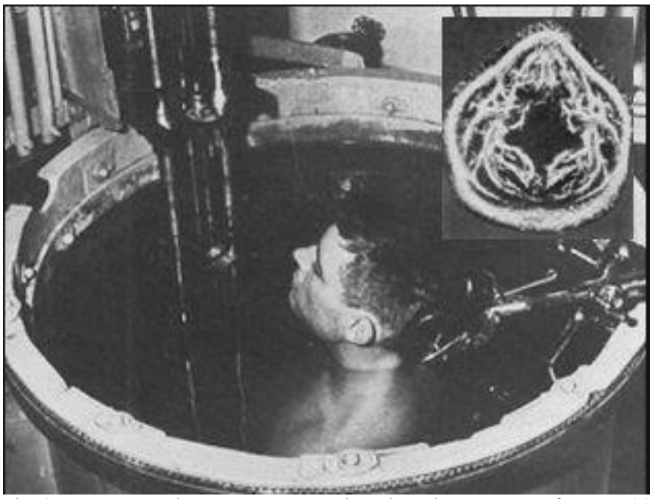

Fig. 3. Howry's "Mk. IV Somascope", based on the gun turret from a B29 bomber. The linear sweep mechanism of the transducer, shown here at the left, moved around the subject. An example of a neck cross-sectional image obtained with this equipment is inset.

This apparatus, the Mk IV Somascope, completed in the mid-50s, is shown in Fig. 3. The subject here is Cushman, immersed up to his chin, a lead brick on his lap helping to hold him down. A headrest, shown on the right, helped the subject to remain very still while all the sweeps were completed. In 1957, the Howry team made a non-immersion system, known as the 'Pan scanner' by half surrounding the seated subject with a large water bag containing the scanning mechanism [17].

Meanwhile in Japan, in the early 1950s, the potential role of ultrasound A-mode scanning of the brain was being investigated by surgeons Kenji Tanaka and Toshio Wagai at the Juntendo University Hospital, Tokyo, working in collaboration with engineers Shigeru Nakajima and Rukuro Uchida of the Japan Radio Company Ltd. (later to become Aloka Ltd) and engineer Yoshimitsu Kikuchi from the Tohoku University, Sendai. By 1954 this work had led to the production of rudimentary 1MHz cross-sectional images of the skull using a water bag offset technique [18]. In 1956 Wagai and Kikuchi attended an international conference in the USA where they met up with other researchers, including Dussik, Wild and Howry. The following year the Japanese team developed a water bag system for breast scanning [19]. This was further developed to become commercially available in 1960 as the SSD-1 (Fig. 4) from the Japan Radiation and Medical Electronics Inc. (later renamed Aloka)

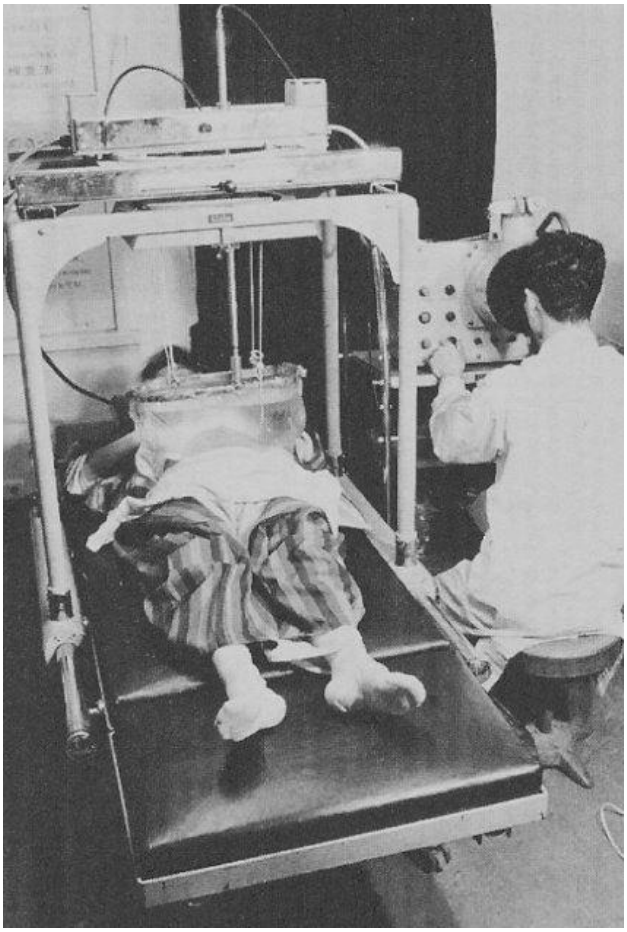

Fig. 4. The SSD-1 linear mechanical scanner, commercially available in 1960 from Japan Radiation and Medical Electronics Inc. (Later Aloka).

The outstanding exception to the use of immersion or large water bags was the work by John Wild and electronic engineer John Reid, who, in 1953, built the world's first hand-held, mechanically driven contact scanner, which they used successfully to produce real-time grey-scale images of breast tumours [20]. This "two-dimensional echoscope", as Wild called it, is shown in Fig. 5. It had a small water-filled chamber mounted beneath it, within which a 15 MHz transducer was driven back and forth over a 6.5 cm travel by an electric motor and worm screw drive. A photograph of Wild, assisted by Reid, using the device to scan a subject's breasts featured on the front cover of the March 1955 edition of Electronics magazine (Fig. 6).

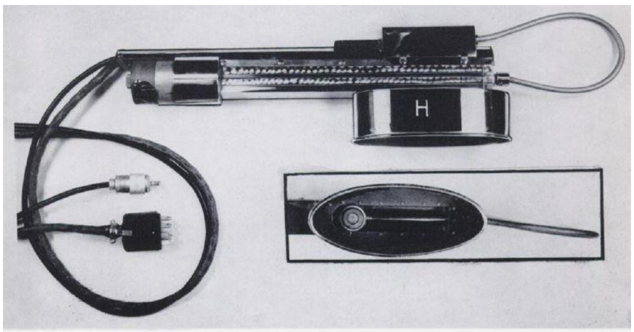

Fig. 5. The hand-held, real-time, mechanical scanner developed by Wild and Reid in 1953 for breast imaging. The view upwards into the water chamber shows the transducer at one end of its reciprocating travel.

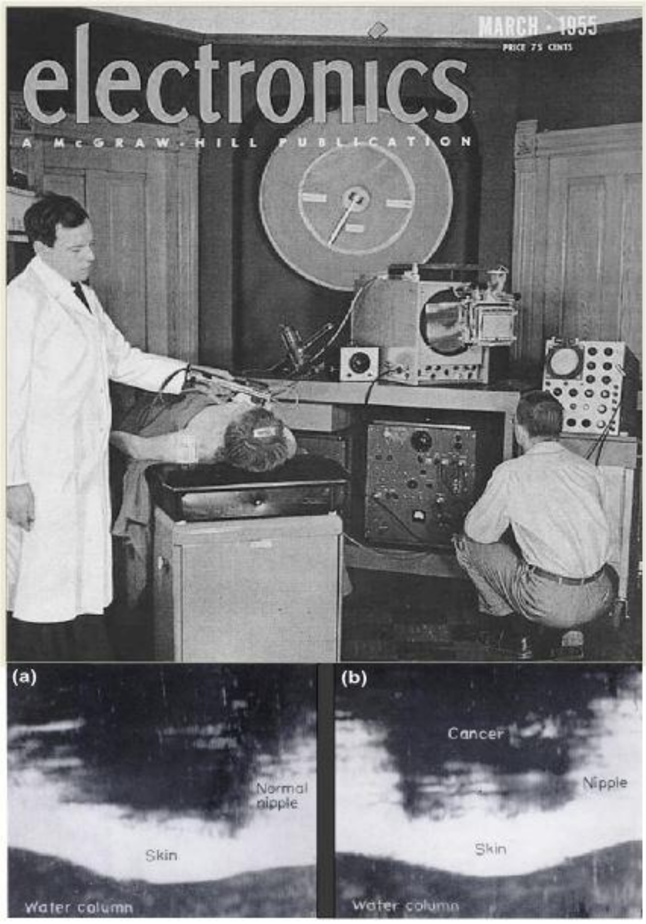

Fig. 6. Cover picture of Electronics magazine in 1955 showing John Wild and colleague John Reid using their "two-dimensional echoscope" contact scanner to image a breast. Inset (a) is their image of a normal nipple. Inset (b) shows a nipple with cancer behind it.

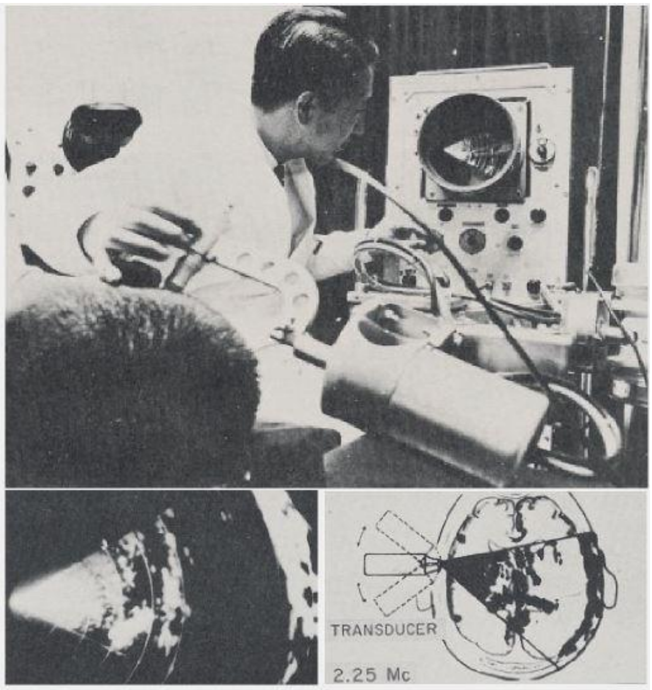

Fig. 7. Toshio Wagai using the "one-point" contact sector scanner designed by Kikuchi in 1957. It was later used in obstetrics.

This work was very much ahead of its time as it would be a further two decades before other real-time hand-held mechanical B-mode scanners were to be developed.

Even further removed from water baths or bags, in 1957 Kikuchi and colleagues published the design of a system (Fig. 7) where the transducer was in direct contact with the patient [21]. Following on from their earlier water bath approach to brain imaging, this scanner was primarily designed for trans-cranial imaging, although it was later used in abdominal and obstetric applications. The transducer was constrained to rotate about its face, producing a sector shaped image. By having a fixed point of contact the intention was to reduce artefacts due to variations in skull thickness.

VI. B-MODE DEVELOPMENTS IN GLASGOW

In 1955, Glasgow obstetrician Ian Donald began making A-mode measurements on pathological tissue samples, using a metal flaw detector. He had met John Wild and read his publications on ultrasound and was keenly interested in the possible clinical benefits of ultrasound in gynaecology. On hearing of Donald's work, Tom Brown, a young electrical engineer at Kelvin and Hughes, the company that had designed Donald's flaw detector, offered his help. His involvement was welcomed by Donald, particularly after he replaced their outdated instrument (Mk IIb) with the latest model Kelvin and Hughes flaw detector (Mk IV), thereby transforming the quality of the results that Donald and his registrar John MacVicar were getting. Brown was familiar with a form of 'B-scope' radar display in which the positions of reflecting targets are presented as a two dimensional map and he saw the potential for a similar approach to producing cross-sectional medical ultrasound images. Donald had seen the cross-sectional images already produced by both Wild and Howry but he was not convinced that this type of image would add much diagnostic information to what he was now getting using his improved A-mode equipment. In any event, he chose not to show their images to Brown [22].

This may have been fortuitous, as Brown later said that if he had seen Howry's "exquisite and quite extraordinary and beautiful pictures" he may not have been so resolute in defending the contact scanning approach against the bias towards water baths of his manager at Kelvin and Hughes [22].

Nevertheless, with Donald's initially hesitant support, Brown proceeded to design and build his "bed-table" contact scanner (Fig. 8), completing it in 1957 [23]. With this scanner the user could move the transducer by hand anywhere within a fixed vertical transverse plane, keeping the transducer face lightly pressed against the patient's skin, which was kept lubricated with oil. This plane was defined by the position of a wheeled carriage, that could be moved transversely on rails across a bed-table, which itself could be moved longitudinally above and along the patient. The transducer could be angled or rocked within the scan plane from any position, thus giving the benefit of compound scanning, mentioned above in connection with Howry's system.

This scanner was not very easy to use, and the image quality depended very much on the skill of the user. Brown, who had previously been involved with the design of an automatically scanned metal flaw detector, felt that an automatic system was more likely "to give a consistent scanning pattern" [22]. Consequently, Brown and other engineers from Kelvin and Hughes, designed and built a much more sophisticated scanner. In this machine, the transducer was kept in light contact with the patient's skin, using a pressure sensing switch, while it was scanned and rocked automatically across the patient (Fig. 9). Part of the reason for the large and somewhat intimidating gantry that supported the transducer above the patient was Brown's ambition (which remained unfulfilled) that future modifications would allow the transducer to automatically scan multiple closely spaced planes and thus gather 3D echo data. This automatic scanner was used by Donald and MacVicar to produce clinically valuable results until 1965.

Despite its ingenuity, the automatic scanner did not attract any potential buyers [22].

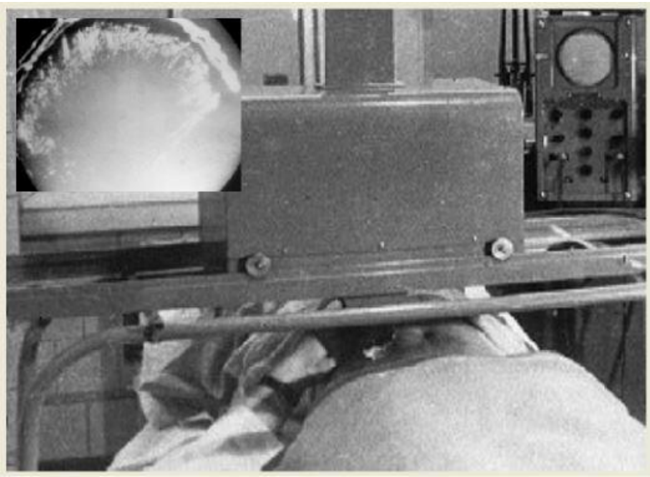

Fig. 8. Brown's bed-table contact scanner. The operator's forearm and hand can be seen, bottom left, guiding the transducer.
Inset: image of an ovarian cyst obtained with the equipment (on a different subject).

Fig. 9. The automatic contact scanner being used by Donald, with MacVicar assisting. The transducer was housed in the ball-like structure on the left.

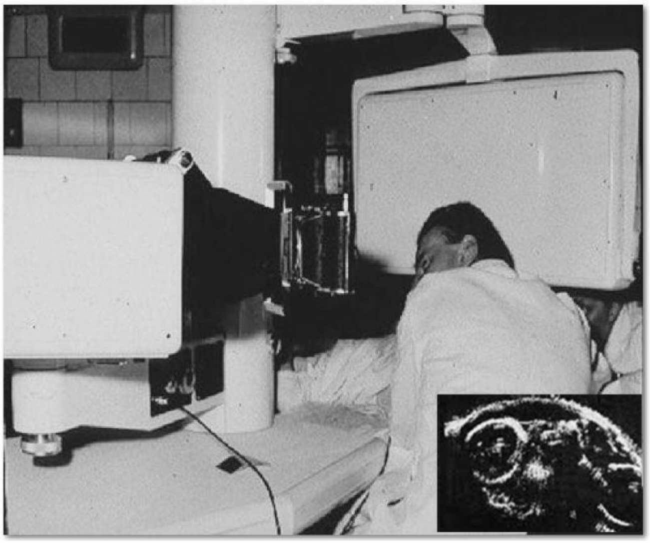

Fig. 10. The machine made for Sunden being used by Donald prior to its delivery to Lund, Sweden in 1962. An image from the machine revealing twin fetal heads is shown inset.

Moreover, when Bertil Sunden, an obstetrician in Lund, Sweden, who had worked with the bed-table scanner during a placement in Glasgow, placed an order for a machine in 1959, he specifically requested that it should have a manually guided transducer.

Brown and the Kelvin and Hughes team therefore abandoned automatic scanning in a major re-think for Sunden's machine, inviting Dugald Cameron of the Glasgow School of Art to improve the ergonomics and styling. The resulting machine (Fig. 10) was delivered to Sunden in 1962 after extensive clinical testing by Donald and MacVicar. It had a much slimmer and less intimidating rectangular enclosure for the transducer position measuring and scan-plane defining frame. This enclosure was now supported over the patient by a hinged arm from a substantial column to the side of the patient. The probe support and measurement system within the housing was rectilinear (Fig. 11), with a 'vertical' (Y) rail free to slide along a horizontal (X) rail, mounted parallel to the top side of the enclosure. The probe could be rotated about the lower end of the Y rail. Cable systems and linear potentiometers measured the X and Y coordinates, while a sine-cosine potentiometer measured the angle of the transducer relative to the Y axis. The dotted nature of some of the interfaces shown in the example scan inset into Fig. 10 is due to the low pulse repetition frequency, adopted as a precaution against possible hazards to the fetus, of which little was known at the time.

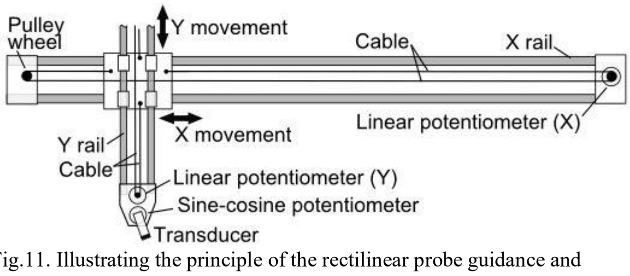

Fig.11. Illustrating the principle of the rectilinear probe guidance and coordinate measurement system in the Diasonograph. The upper part of the Y rail has been omitted for compactness.

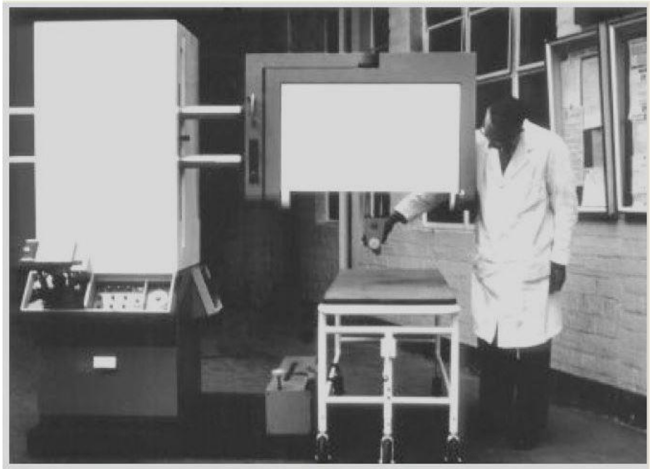

Fig.12. One of the early Diasonographs of the mid-1960s

In the late 1950s, Kevin and Hughes was re-branded under the name of its parent company, Smiths Industries Ltd. In 1962, electrical engineer, John Fleming joined the firm. He was later to co-author, with medical historian Malcolm Nicholson of Glasgow University, an authoritative book on the history of diagnostic ultrasound in Glasgow [22]. Fleming was tasked with making improvements in the electronics for a production version of the Sunden machine while Brown oversaw improvements to the mechanical design. The resulting machines were given the name 'Diasonograph', and a dozen had been sold by 1966. Fig. 12 shows an early production model, with Arthur Johnson, one of the draughtsmen, standing beside it. The use of a slightly modified wheeled hospital trolley, as seen in the photograph, provided a simple means of changing the longitudinal position of the scan plane relative to the patient.

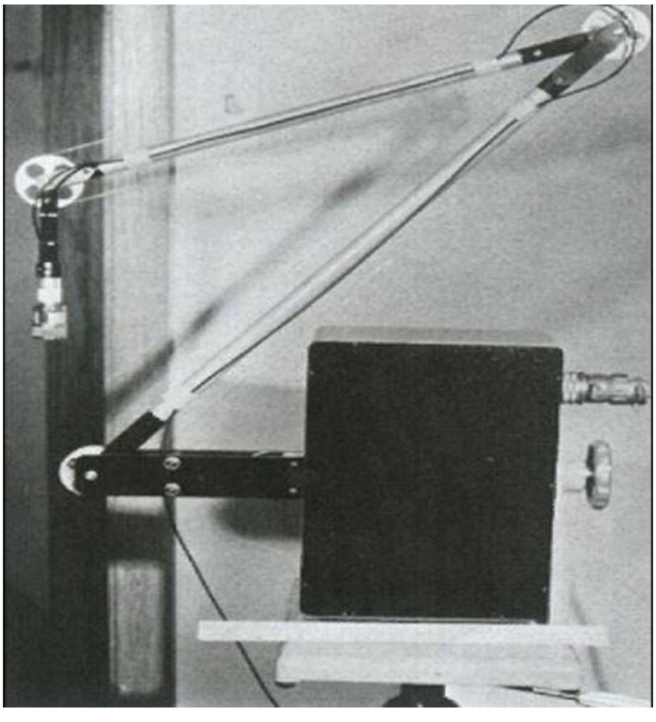

Fig.13. The articulated arm of the scanning apparatus produced by Wright and Meyerdirk in 1963 and marketed by their company Physionic Engineering Inc, Longmont, USA, later to become Picker.

In 1967 the medical ultrasound interests of Smiths Industries were taken over by Nuclear Enterprises, an Edinburgh based medical electronics company. Nuclear Enterprises went on to make further substantial improvements, achieving sales of over 100 machines, first the NE 4101 and then the NE 4102, in which thermionic valves were replaced by transistors [22].

VII. CONTEMPORARY DEVELOPMENTS.

After seeing Brown's automatic scanner at an exhibition in 1959, engineers William Wright and Ralph Meyerdirk, working with Holmes at the University of Colorado, built a contact scanner with a similar rectilinear scanning mechanism to that being developed in Glasgow for the Sunden machine [24]. In 1962, Wright and Holmes left Colorado University to form their own company, Physionic Engineering Inc., later to become Picker Inc., to produce and market the 'Porta-Scan" articulated arm scanner (Fig. 13). This articulated arm design was less bulky and allowed easier probe movement than the Glasgow rectilinear rail-based system. From the mid-60s onward, B-scanning systems were produced commercially in other countries, including Austria, where Kretztechnik launched the 'Combison 1' in 1966, and in Japan, where Aloka produced the 'SSD 10' in 1967. Both of these machines used an articulated arm to support the probe.

Some manufacturers continued to use water bath systems until the end of the 1960s. These included the German 'Vidoson' real-time machine produced by Siemens Medical Company in 1965. In this design, the transducer rotated about the focal axis of a parabolic mirror, such that the transmit beam remained parallel to the mirror's principal axis as it made repeated linear sweeps across the mirror's aperture, albeit at non-uniform speed (Fig. 14) [25]. Researchers at the Commonwealth Acoustics Laboratory in Australia (later to become the Ultrasonic Institute) also continued to use water bath compound scanners in their successful quest to set new standards in lateral resolution, signal processing and grey scale display [26], eventually culminating in the Octoson water bath scanner, of which over 200 were made and sold by Ausonics Pty Ltd. in the mid 1970s. The 1970s, however, was principally the decade of 'the real-time revolution', with the advancement of hand-held, real-time, scanners, ultimately leading to the high levels of performance evident today.

VIII. DISCUSSION

This review has outlined the development of B-mode imaging, including features such as contact scanning, spatial compounding and a limited form of grey scale display, up to the time of Brown and Donald's work in Glasgow. The importance of the Glasgow work was that it firmly established the invaluable role of ultrasound imaging in obstetrics and gynaecology and that it led to user-friendly scanning systems becoming commercially available on a large scale. The key to the Glasgow team's success was the symbiosis of a clinician with great drive and willingness to test and use new developments on his patients, and a bright and enthusiastic engineer, backed by a very supportive engineering firm. In addition, the contrast between liquid, soft tissue and bone masses encountered in obstetrics and gynaecology made image interpretation much easier than that facing earlier workers, who had largely chosen to investigate more challenging targets such as the skull and breast.

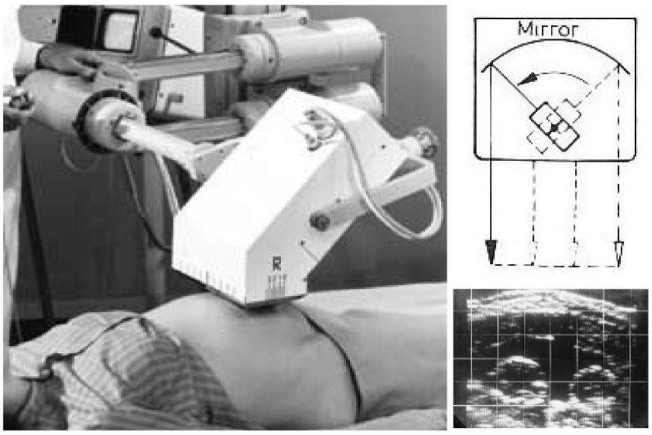

Fig. 14. The Vidoson water bath real-time scanner. The probe rotated about the focal axis of a parabolic mirror, A still image of twins obtained with it is inset.

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