AUSTRALIAN CONTRIBUTIONS TO MEDICAL DIAGNOSTIC ULTRASOUND

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The Ultrasonics Institute of the Commonwealth Dept of Health provided a focus in Australia for the development of technology and techniques for medical ultrasonic imaging. The Institute was one of the early participants in the development of the technique, and has made a number of contributions to the development of the field. These include transducer theory and technology, ultrasonic imaging system design, the study of artifacts, computer processing and Doppler signal processing. The introduction by the Institute of the grey-scale technique provided the basis for successful high-quality imaging from real-time systems, which now form the basis of ultrasonic imaging. The Institute worked closely with medical specialist collaborators in each diagnostic area.

INTRODUCTION

The commencement of research in medical ultrasound in Australia was due to the vision and entrepreneurial skills of the Director of the Commonwealth Acoustic Laboratories, Mr. Norman Murray. The Laboratories were within the Commonwealth Department of Health, and concerned with hearing conservation, industrial noise measurement, and the design, manufacture and provision of hearing aids to ex-servicemen and children. In the mid-1950s, Murray recognised that there was a gap in awareness of ultrasonics in Australia, and identified a number of areas for research [1]. One of these was the use of pulse-echo ultrasound for diagnostic imaging, particularly visualising the uterine contents in pregnancy, without the potential harmful effects of X-rays to the fetus.

In late 1959, a newly graduated engineer, George Kossoff, was appointed to the staff of the Laboratories, and, assisted by a technical officer, began a number of projects, including development of a scanner for providing cross-sectional images of the pregnant uterus and fetus. In mid-1961 the author and a second technical officer were appointed to expedite the development of the diagnostic imaging scanner. The first images of the pregnant uterus and fetus were shown at an international conference in the USA in 1962 and proved to be equal to or better than any others shown at the conference [2]. This was the start of Australia's continuing contribution to the development of ultrasonic medical diagnostic imaging.

TECHNICAL CONTRIBUTIONS

Transducers and early scanners

At the outset, knowledge of transducer theory and the ultrasonic properties of tissue was sparse, the ultrasonic appearance of tissue was unknown, and the required performance challenged the ability of current technology. This was indeed a fertile area for research! Design and construction of the scanner for examination of the pregnant uterus involved work in three main areas; transducers and their beams, signal processing of ultrasonic echoes from tissue, and design of electronic circuits using cutting edge technology.

The work on transducers involved analysis of the effect of backing and matching on transducer performance [3], and the investigation of the beams obtained from weakly focussed transducers [4]. These papers are considered landmarks, and have been referred to consistently since that time. The use of transducers with excellent properties contributed substantially to the quality of images obtained, and thus the success of our early scanners.

The design of the electronic system of the scanner presented its own challenges. Use of water path scanning permitted use of an optimal transducer beam pattern, but rendered the system liable to multiple echoes or reverberation within the water bath, requiring specific logic circuits for their removal. The scanning accuracy requirements on the electronics of 0.1% was equivalent to measurement laboratory accuracy of the time. The display system was required to store echoes from a number of lines of sight acquired over a period of up to thirty seconds. Display storage tubes were just being developed, and we were using prototypes, with no useful technical information available regarding the associated circuitry. The currently available vacuum tubes were being replaced by transistors.

Following the successful establishment of the program of imaging the pregnant uterus [5,6], scanners using the same principles, but differences in scanner geometry and operating frequency, were designed for other regions of the body; the eye [7], breast [8] and, using time-motion (M-mode) display, the heart [9].

Artifacts

The study of reverberations in the water coupling bath of the scanner led to the recognition of artifacts occurring due to reflection and refraction within tissue. Artifact is the term used when the appearance of the image is incorrect, due to variations in the propagating properties of tissue. The first paper published on the subject came from our work in Australia [10]. The study of artifacts has become a major subject in the education of clinical practitioners who interpret ultrasonic images, and must recognise them to avoid errors in diagnosis.

Grey-scale

It was soon found that the dynamic range of received echoes was extremely large, and the ability of the display device to display this range was limited. The orientation of the scan plane was carefully selected and compound scanning (with many overlapping and intersecting lines of sight) employed.

In this way, as far as possible each interface between adjacent organs was intersected at right angles somewhere in the scan.

In the late 1960s, Kossoff espoused the concept that the image would be better if, instead of concentrating on the outlines of the organs, the system was optimised to display the lower amplitude of echoes from within the tissue of each organ. This required considerable compression to match the even wider echo signal dynamic range of interest, but more importantly, a considerably better performance of all parts of the signal processing chain to avoid the large signals from tissue boundaries overloading the system and obscuring the smaller echoes of interest. Thus, the transducer, pre-amplifier, compression amplifier, display amplifier and display device all required extensive modification [11].

The weakest link in this chain at the time was the display. The best grey scale was obtained from a time-exposed film, but the scanning had to be done "blind", although Polaroid "instant" development film system was used. Careful control was required of the scanning rate, scan line density, screen brightness and contrast and camera aperture settings. Despite the operational difficulties of this system, the images showed considerable improvement, with a more complete rendition of the scanned anatomy, and less dependence on compound scanning to display the complete image. The grey-scale technique was quickly adopted for all UI scanners [12, 13, 14], and its role in ultrasonic imaging demonstrated [15].

The grey-scale technique was "exported" to the U.K. during the two-year posting of David Carpenter to the Royal Marsden Hospital in London in 1972-3 [16]. He implemented the technique in the skin-contact scanner developed there, demonstrating that the superior images were due simply to the application of improved techniques.

Developments in technology, particularly the analogue (and later digital) scan converters, made the technique more "operator friendly", and by the late 1970s, it was soon employed on the commercial scanners which were becoming available at the time. More importantly, the use of grey-scale made it possible to obtain meaningful images with simple scans, with the ultrasonic lines of sight from a single direction, rather than the previous compound scan. This in turn meant that real-time scanning with simple scans were still able to image organs and regions even without seeing echoes specifically from the boundaries of the organs. The current state of the art in medical ultrasonic imaging uses real-time simple scanning first made practical by the Australian demonstration of the grey-scale approach to signal processing.

Octoson

In the early 1970s, all commercially available ultrasonic scanners relied on manual scanning of a transducer. We began to develop an automated water-bath compound scanner, to provide each image in a precise plane, accurately registered with all the other images, and acquired with an automated repeatable scan motion. The device consisted of a large water tank with a flexible plastic window on the top to which the patient's body surface was applied. Inside the tank was an arm holding eight transducers, which all scanned in synchronism, with ultrasonic pulses being transmitted from each transducer in turn before the set of transducers advanced to the next angular position. The arm could be move it in three translation directions, and two rotations, allowing an image to be obtained at any orientation and position, and accurately registered with all other scans. A single image was acquired in about two seconds, and consecutive scans providing a series of slices could be performed rapidly, and provide the clinician with an accurate 3-D representation of the region. A further serial set in another direction, or a number of oblique scans through particular structures could be obtained to provide further information if required. The prototype was completed in 1974, and with its eight transducers and living in a pool of water, it was named the "Octoson" [17]. It was used for examining the pregnant uterus, abdomen, heart and breast.

The commercial potential for this machine was apparent, and after considerable negotiations with a number of interested parties, the rights were let to the Nucleus Group, an active Australian medical equipment company. The company Ausonics was formed as a subsidiary to Nucleus to manufacture and sell the Octoson. Other companies in the Nucleus Group were Telectronics, and later Cochlear. Approximately 200 commercial Octosons were sold for $100,000 each, or total sales of $20M. Of these 90% were exported, mostly to the USA, but others also to Japan, Italy, France, Sweden, China, and Holland. A second system was derived from the Octoson approach specifically for the breast, called the System 1, with approximately 100 units sold. It was designed in Australia, and after some time, production was moved to Japan, where it was manufactured under licence.

The Octoson provided a broad image of the anatomy scanned, allowing the position, orientation and relationship of the various body components to be easily appreciated. It was suitable for a wide variety of organs and regions, but did not cope well with overlying bone or air-containing tissue. Thus it was impeded in the thorax by lung and ribs, and in the lower abdomen by bowel gas unless this could be displaced or replaced with liquid. In the areas where imaging was possible, the image quality was superior to that available from either the current manually operated skin-contact scanners, or the emerging real-time scanners.

At the time that the Octoson became available commercially, two factors limited its widespread acceptance. The release of X-ray Computed Tomography provided an automated cross-sectional imaging modality, which offered a wide field of view but was not limited to particular areas. The Octoson was left to compete on its better information in some conditions, its greater safety in pregnancy and its lower cost. The image quality obtained from commercial real-time ultrasonic scanners had improved due to the adoption of grey-scale and improvements in transducer and beam- and image-forming technology. Although they lacked registered serial scans and had a restricted field of view, the feedback afforded by the manipulation of the real-time scan plane by the operator was an attractive way of gaining the 3-D appreciation of the scanned region. The real-time scanners also had a cost advantage over the Octoson. In the fullness of time, the last surviving Octosons in the clinical environment were used as front-ends for computer or other research systems.

Computer processing, image formation and tissue characterisation.

Our first computer for processing ultrasonic signals and images was installed in 1972. Again, it pushed the bounds of current technology and could only record the envelope of the detected ultrasonic signals, as the upper limit of sampling was 3 MHz. With this system, the first ultrasonic 3-D rendition of serial section ultrasonic image planes was achieved [18].

The Octoson provided an ideal "front-end" for acquiring ultrasonic data. The automated scan with well-identified scan line origins, positions and orientations greatly assisted in image re-construction algorithm development. Methods were developed for interpolation between scan lines to reduce the number of lines needed to obtain a real-time image, and hence increase the maximum acquisition rate, which were subsequently used in commercial real-time scanners.

The ability to record a scan and its accompanying ultrasonic signals was of great assistance in acquiring signals for ultrasonic tissue characterisation. This was a subject of great interest in the 1980's. Its promise was to provide an ultrasonic "pathology" to identify diseased from healthy tissue. Considerable effort was expended on this subject at our laboratory and in many others around the world [19]. Unfortunately, no significant method has yet passed the "acid test" of being used at an institution other than the one(s) at which it was developed.

Doppler processing for total flow

The Doppler frequency shift resulting from reflection of ultrasonic signals from moving structures (and particularly red blood cells) had been used for fetal pulse detectors, and for assessing the apparent rate (velocity) of flow in vessels and heart chambers. Our contribution was to combine imaging of the vessel with the use of a broad Doppler beam encompassing the entire vessel and appropriate signal processing to obtain quantitative measurement of blood flow within a vessel. [20]

With its well-registered and controllable scan planes, the Octoson formed an ideal platform for the total volumetric flow studies in a number of areas. Much of the work was on the measurement of blood flow in the fetus in order to identify those at high risk of birth complications. Other studies were on the vessels of the abdomen, in particular the liver and spleen. As the Octoson was not freely available, the technique was not taken up widely, although further development has been directed towards implementation in real-time scanners, where commercial development is possible.

CLINICAL APPLICATIONS

From the outset, the group of engineers and physicists at the Laboratory worked closely with medical consultants in each area of application. In the early development of each project, there was a need to interpret the information on the ultrasonic images, which were often of poor resolution, and providing images of structures not previously able to be imaged. The scanner settings and design decisions in implementing the signal processing system significantly influenced the appearance of the images. Recognition of the structures displayed, and more importantly the structures missed in the image, led to design modifications to improve this aspect of imaging performance. On the clinical side, studies were performed of the reliability of imaging various organs, and the reliability of measurements made on the images. This required close collaboration between the equipment designer and the clinician, leading to a fruitful cross-fertilisation of ideas, with the clinician suggesting equipment enhancements and the engineer suggesting clinical applications.

This close collaboration between the clinician and the design engineer in both the equipment design and image analysis led to long-lasting professional relationships, and joint publications in both technical and clinical journals. The close multi-disciplinary approach was unusual for its time, or even for the present day.

It was unusual for a single group to develop apparatus for many different areas of application. The group of medical specialists with whom we worked came from a number of specialties. They became the nucleus for the formation of the Australasian Society for Ultrasound in Medicine (A.S.U.M.) and the establishment of scientific and education meetings to spread knowledge in ultrasound to other specialists.

Separately from the Laboratory, medical specialists from throughout Australia began to investigate ultrasound using commercially available equipment [21]. The two strands of development were brought together by the formation in 1970 of A.S.U.M. The standard of clinical practice of ultrasound in Australia is very high by world standards. This is due in no small part to the activities of A.S.U.M. in education and certification activities.

ORGANISATIONAL ARRANGEMENTS

In 1975, the Ultrasonics Research Section of C.A.L. was changed to a separate Branch of the National Health and Medical Research Division within the Commonwealth Department of Health and called the Ultrasonics Institute. At its formation it had a staff of 24, and 10 medical collaborators.

During the mid 1980s, the Department of Health became aware that the Ultrasonics Institute, although achieving significant scientific and commercial results, was not directly supporting any of the Department's authorised functions. Following extensive negotiations, the Institute, along with its funding allocation and all its staff were transferred to the CSIRO Division of Radiophysics in 1989, as the Ultrasonics Laboratory within the Division. Following amalgamation of the Divisions of Radiophysics and Applied Physics into a Division of Telecommunications and Industrial Physics in CSIRO in 1998, the staff members of the Ultrasonics Laboratory have been incorporated into the Division.

With the transfer to CSIRO came a change in culture, and the required emphasis of the work. No longer was it enough to provide improvements in health care. The work needed to have measurable impact on the subject, preferably demonstrated by the uptake of the developed techniques (and associated royalties), or even better by direct funding of the research effort. This was in a climate of increasing research and development effort by the commercial manufacturers. They were reluctant to entrust the success of their new equipment to an outside body, and research funds were not sufficient to maintain the effort at its previous levels. Some research work has been performed for one of the major medical ultrasound equipment manufacturers, resulting in incorporation of Doppler signal processing techniques developed at our laboratory in their current equipment. It is anticipated that this relationship will continue.

There has been an expansion in the scope of research by staff previously from the Laboratory. Our medical and computer technology was applied to projects to assess beef quality on the hoof, funded by the Meat & Livestock Research Authority. The Dept of Defence funded development of technology to image the surface of underwater objects in turbid water in the range one to six metres using Megahertz ultrasound. Other projects involve image processing in other medical imaging areas, using skills and background knowledge in medical imaging developed in ultrasound.

CONCLUSION

When our work commenced on diagnostic ultrasonic equipment, there were only a handful of groups working in the area. Following our success (measured by image quality) at the initial meeting, the publications from our group were closely watched by our international colleagues. Because of our geographical remoteness, interaction was limited to the written word, with occasional visits in association with scientific conferences. The early interactions led to a series of longer visits by laboratory staff, during which the work of the Laboratory became more widely known. From that time on, the Australian work was well represented at overseas conferences. The group has contributed 580 publications to the archival scientific literature. In later discussions with contemporary researchers, it was learnt that they felt that our early papers provided the "existence theorem" for the capabilities of ultrasonic imaging.

The Ultrasonics Institute formed a nucleus of expertise which attracted considerable medical interest and led to the formation of the Australasian Society for Ultrasound in Medicine. The activities of the Institute and of the Society have resulted in the standard of practice of ultrasound in Australasia being very high by world standards.

Medical ultrasound imaging is now the most commonly used medical imaging modality after plain X-ray, and is the largest market within medical imaging. It is a source of considerable personal pride for all members of our staff of that we had the opportunity and ability to make a contribution to a subject which has so dramatically changed the face of medicine within our professional life-times.

The significant impact of the Australian contributions on the development of medical ultrasonic imaging are credit to all of the staff of the Laboratory in all its guises who made it happen, and a tribute to the vision and entrepreneurial skill of its instigator, Norman Murray, without whom it would never have begun.

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