Ultrasonic medical imaging: past, current and future

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ABSTRACT

Ultrasonic imaging began, like life, in the sea, with the development of sonar for detecting submarines after World-War 1. However, to begin to image soft tissues the ranging time of ocean sonars needed to be reduced, and the electronics speeded up, by a factor of about the ratio between nautical miles and centimeters. This was only possible after the electronic developments made for radar in World-War 2. The rest of our technical history closely follows the developments in semiconductors and fabrication methods that led to modern electronics.

This is a largely personal story of a recently graduated engineer with radar experience, who began with fabricating equipment to be used in the hospital to diagnose breast cancer, and continued with involvement the development of echocardiography and Doppler devices. Along the way many others have contributed to the field, including work in other countries that is not covered here.

In future, ultrasonic imaging may hold the key to understanding some fundamental questions in human health if adopted for screening studies. It alone offers a relatively inexpensive imaging method that is free of known hazards.

Keywords: Ultrasound, Ultrasonic imaging, Echocardiography, Doppler, flow imaging, scattering.

1. INTRODUCTION

Although Langevin introduced the use of sound waves for detecting submarines and other ships in the years following WW1, the practical use of higher frequency sound waves was largely a laboratory curiosity for many years. In the 30's in Europe, Sokoloff and Pohlmann used transmission methods for imaging industrial subjects. In 1945 Firestone patented the use of pulse-echo ultrasound for finding flaws in "solid bodies of the order of eight feet in size". This application succeeded and continues today for examining castings, forgings and railroad rails and axles. Pulse-echo techniques were further extended to high frequencies for measuring elastic constants in small specimens; setting the stage for the application to medicine.

It was not surprising that the first application to medical diagnosis was to use the simpler transmission method, as in conventional x-ray. The Dussik brothers attempted to image the ventricles in the brain about 1947 by transmitting ultrasound through the skull. But the possibilities of the pulse-echo method were appreciated by others, too. About 1949 Dr. George Ludwig obtained such equipment from General Precision Laboratories to perform studies on detecting gallstones. He later went with the group at M.I.T. that was working to verify the Dussik methods (which were later abandoned). These years also marked the start of work by Drs. Howry in Colorado and Wild in Minnesota on the clinical use of pulse-echo ultrasound in diagnosis. An idea of the state of knowledge of ultrasound at the time can be found in a book by Bergmann.[1]

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2. THE EARLY YEARS OF PULSE-ECHO IMAGING

Dr. John J. Wild started by using a radar trainer that had been installed at the Naval Training Station in Minneapolis.[2] A sketch of the trainer is shown in Fig. 1. The device was developed during WW 2 to train bombardiers and radar operators to be able to navigate over the islands of Japan. It was an adapter for an aircraft radar. The radar pulses were converted to ultrasound pulses that illuminated a relief model of an island in the bottom of a water tank. Since the speed of sound in water was much less than the speed of radar pulses in air the models were only a few feet long, and could be scanned by the sound beam from the rotating transducer. The transducers were x-cut quartz thickness resonant at 15 MHz.[3] These were mounted in a cartridge that we later incorporated into the clinical equipment.

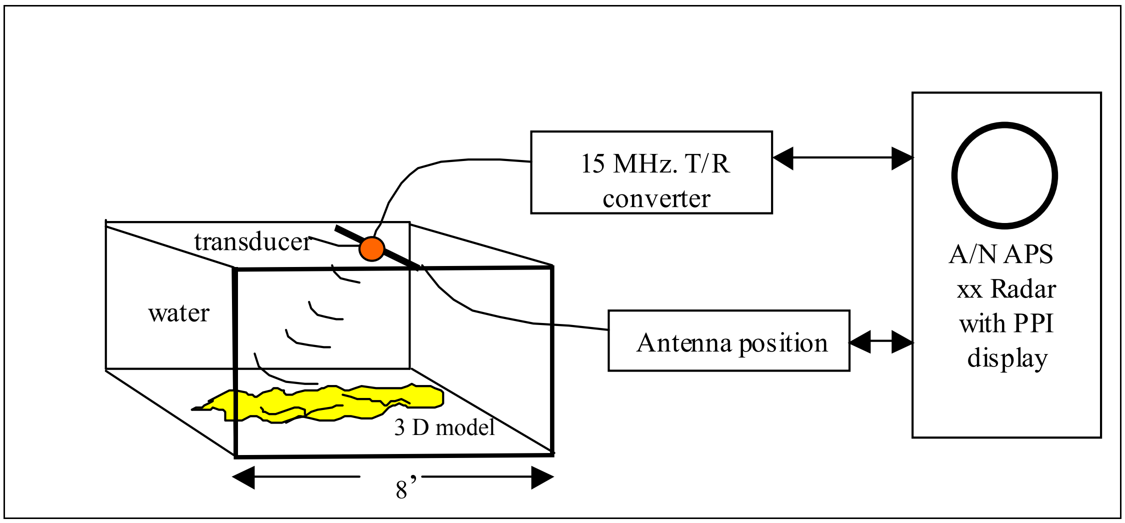

Fig. 1 Sketch of the Bell and Howell 15MHz ultrasonic radar trainer.

John soon tired of hanging over the edge of the water tank to hold specimens in the sound beam. He was helped by Donald Neal, who was in charge of the trainer, to mount a transducer in a hand-held tube that contained a water column. This hand-held transducer was used to examine the thickness of stomach and bowel specimens. Wild was looking for a method to measure bowel thickness *in-vivo*. One of the specimens contained a cancer and he was able to detect the lesion outside of the visible ulcer. This result and others were used to obtain an N.I.H. grant to move his studies to the University of Minnesota Medical School. He needed someone to build equipment that could be used in his laboratory and I was offered the position. The work was helped by the fact that Don was a friend of mine from high school.

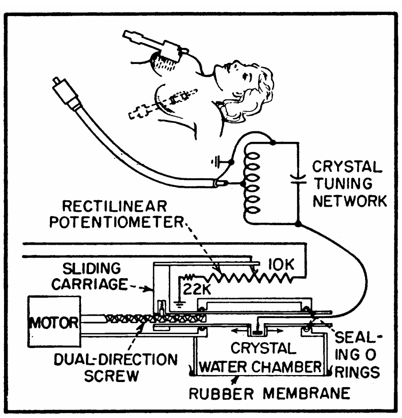

Fig. 2 Schematic of the breast scanner

I had graduated from the Electrical Engineering department in 1950 just when engineering jobs were scarce. Previously I had been in the Navy in WW2, graduating from the electronic technician program and spending a few months maintaining radars on a light cruiser, so had some practical experience. The first job at the medical school was to build a basic pulse-echo instrument with a standard oscilloscope display of echo amplitude vs. time (A mode), which we did in Wild's unheated basement during a Minnesota winter.

To examine patients the instrument was mounted on a cart and moved to the hospital. The area under the A mode trace on the oscilloscope was found to be an indicator of cancer, when compared to the numbers from normal tissues in the opposite breast.[4] The reports of these studies were greeted with some skepticism in medical meetings, and there was considerable resistance to funding the work by N.I.H. Medical research at the time was largely conducted on animals and removed tissues, and the idea of using patients was not appreciated. The diagnosis of soft tissues through the skin was new, and the use of such an unlikely means as sound waves did seem rather a stretch to many. The difficulties he encountered have been analyzed elsewhere.[5] Work on the speed of sound in tissues by George Ludwig suggested the possibility of using a scanned sound beam to make images of tissue structures.[6] Distortion would be minimal since the speeds in different soft tissues did not differ by more than a few percent. Besides, we were not interested in geometrical accuracy, but in observing amplitude differences. With two weeks' work we had an intensity-modulated display and a sector scan instrument. Our first images were reported in *Science* magazine.[7]

The results using the scanned images were somewhat better, and we saw such interesting images as those from liquid-filled cysts in the breast that clearly differentiated them from solid tumors. This is a determination that is still important today. We were encouraged to construct a scanner with a wider field of view, and came up with that shown in Fig. 2.

This instrument moved the transducer crystal along a straight line using two spiral gears from level-wind fishing reels. This was coupled to the horizontal centering control to produce a scan format that is similar to that of today's linear arrays. We termed it the "B" scan because it was similar to the "B" azimuth vs. range display used in expanded radar displays.

2.2 Howry-Holmes scanner

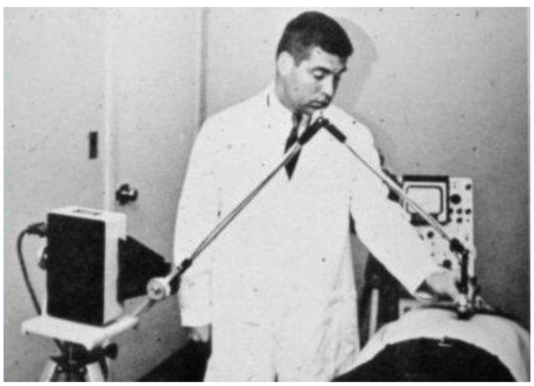

Fig. 3 The jointed arm mechanical scanner in use.

While we were beginning our clinical series we received an anonymous note directing us to an interesting paper in a journal we would not have seen otherwise. This was the first publication by the Colorado group, showing their compound-scan images. Their pictures were better than ours, but needed the subject to be immersed in a water tank while being scanned. This drawback was removed when the jointed-arm mechanical scanner was introduced later, see Fig. 3. This instrument was used to pioneer ultrasonic scanning in obstetrics, which was needed then since the hazards of ionizing radiation were just being appreciated. The instrument went commercial and dominated the clinical field for many years.

One drawback to these early clinical machines was the use of manual scanning. As the technician repeatedly scanned over an area the screen filled in with echoes. This may have started the perception among some clinicians that much training was required.

A second drawback was the use of storage tubes for the display. The screen had only two brightness levels and did not display gray scale images for many years. The breakthrough came with Castro's domination of Cuba, when aircraft were being hijacked to Havana. The Hughes Aircraft Corp. developed a scan converter with gray scale display for use in baggage screening x-ray machines that were adopted as a component of ultrasonic scanners. The gray scale instruments were very successful in clinical uses that justified the investment required, and obstetrics was a natural.

2.3 Endoscopes in 1955

More instruments were built that could approach common sites of cancer. Because of the limited range at 15 MHz these were endoscopes. A rotating head instrument was used with the plan-position-indicator (PPI) display that is familiar to observers of weather radar on the evening news. Another was the oscillating sector scanner for examining the head of the cervix. These instruments required careful construction to accommodate the crystal cartridge and its' feed, provide space for the electrical impedance matching network and keep these separate from a channel for the water needed to fill the coupling bag used to provide acoustic contact with the tissues.

Following this effort a thesis was done using a Schlieren optical system to image sound fields and to verify O'Neills' theory of focusing lenses. We also verified that electronic delays could accomplish focusing, paving the way for modern dynamic focusing. It was time to move beyond 15 MHz.

3. ECHOCARDIOGRAPHY

After Drs. Hertz and Edler published their pioneering work on ultrasound for examination of the heart in *Acustica* it came to the attention of Herman Schwan's group and of the clinicians at the University of Pennsylvania. Open-heart surgery was just coming into use and a method to select patients for the safer closed-chest procedure was needed, just as I was looking for advanced degree work. Obtaining transducers was always a problem for the early workers, which we solved by making our own using stock disks of barium titanate, see Fig. 4. These used a laboratory centrifuge to pack a mixture of tungsten powders against the ceramic disk, which gave the required bandwidth. The electronic

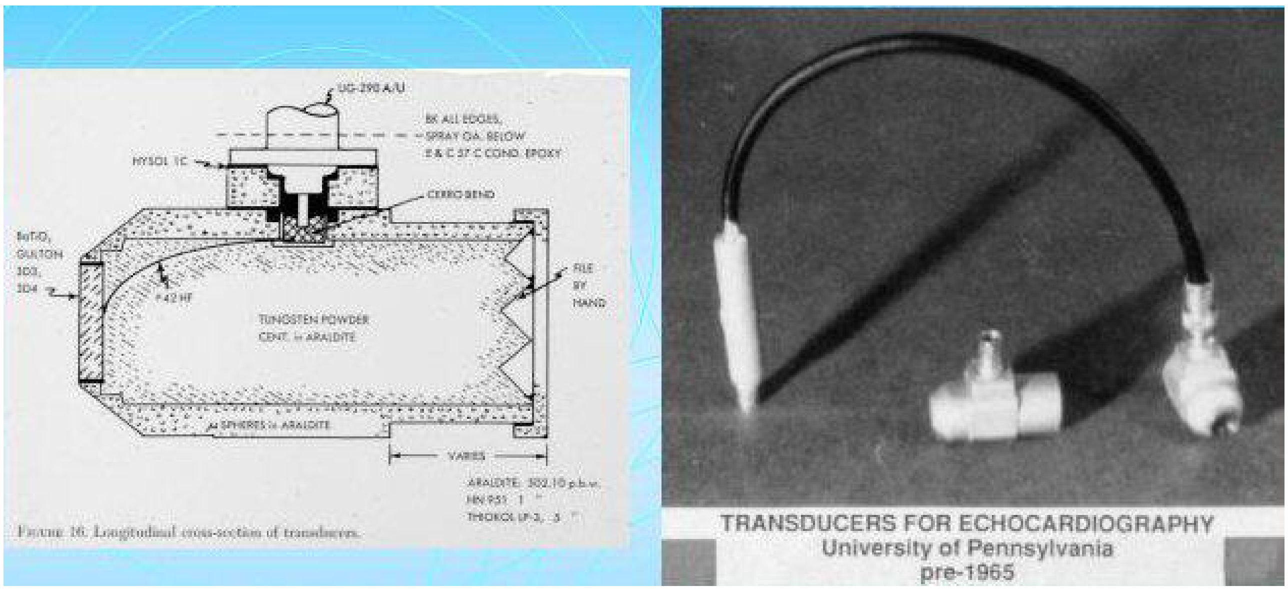

Fig. 4 Transducers for Echocardiography.

equipment was built using vacuum tubes, bypassing the early transistors, which presented problems with handling high voltages as well as requiring too much re-education on my part. I did not have the time!

There was some delay as we tried to find out which structure was responsible for the rapidly moving echo from the heart that had been shown to be diagnostic for mitral stenosis. Work on small, rapidly beating, dog hearts was dropped immediately when Dr. Edler's thesis was received, proving that we were actually seeing echoes from the moving mitral valve itself. This application arrived just as interest in clinical ultrasound was flagging and revived clinical interest in time for the introduction of the commercial joined-arm scanners.

One problem with cardiac diagnosis by ultrasound remained. The condition of leakage called mitral insufficiency (MI) could not be identified by the motions of heart structures that were revealed by standard echocardiography. To diagnose MI we needed to image flow. The recently described ultrasonic Doppler effect described by workers at the University of Washington offered a way to do this. So a position there was accepted. As I was leaving the patient selection procedure was approved for Blue Cross reimbursement, which was very gratifying.

A more detailed history of echocardiography has recently appeared.[8]

4. WORK IN SEATTLE

The group headed by Dr. Robert Rushmer at the University of Washington had developed continuous-wave (cw) Doppler devices and methods for diagnosing the peripheral circulation. When I arrived Donald Baker pulled a block diagram for a proposed pulsed Doppler out of his files to show to me. This was intended to be able to separate targets in range, something that a cw Doppler could not; and was what we needed for the heart. It seemed a reasonable idea and work was started under an N.I.H. grant for instrument development. All of this without extensive mathematical analysis.

We spent much time trying to figure out how it did work. So we developed the idea of “fast time” along the range axis and “slow time” along the real time axis that is shown in Fig. 5. The amplitude of an echo from a moving structure will fluctuate from firing to firing. A sample-and-hold circuit would yield samples of an audio frequency (and eliminate the prf) without any reference to the Doppler effect!

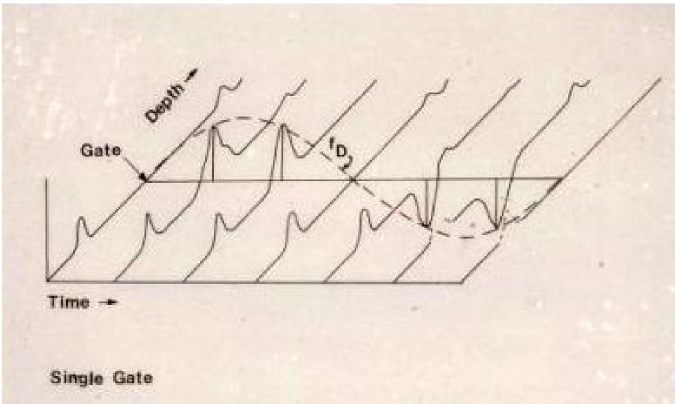

Fig. 5 Operation of pulsed Doppler in the time domain.

Additional work developed a fast rotational compound scanner that was transferred in the 1980s to the Advanced Technology Laboratories as the basis for their fast mechanical scanner. When it was fitted with an annular transducer array and dynamic focusing it produced some of the most detailed images possible. The resolution of images from the early linear and phased arrays did not come close for some years.

When the saws used for fabricating integrated circuits were used to slice ceramic materials for transducers it was finally possible to make the very narrow array elements (with low crosstalk) that were needed to make superior images. The annular arrays still offer a better slice thickness, which is needed for really good 3-D images, if 2-D slices from such data are to have resolution that is comparable to 2-D phased arrays.

Further work in Seattle helped to pioneer the application of vascular ultrasound to the diagnosis of stroke. Merrill Spencer and I founded the Institute of Applied Physiology in Medicine to do this, and also worked on many topics in applied Doppler such as the quantification of stenosis and the detection of air emboli. Along the way a number of pioneering vascular laboratories were established.

5. THE PRESENT AND FUTURE

The offer of a chair professorship at Drexel University (with a salary not dependent on grants) attracted me back to Philadelphia as the study of Biomedical Engineering was becoming popular. This center and many others now conduct interesting work with new ideas still in the research pipeline. The field of diagnostic ultrasound has reinvented itself every few years with new ideas proving that the pioneers had only scratched the surface of the field. The work at Drexel and at Thomas Jefferson still goes on with a continuation of the first effort on identifying cancer in ultrasonic scans of the breast. The newer methods of signal processing have yielded very promising results that only need a blinded study with more participants to influence medicine.[9]

Currently the field has widespread application in clinical medicine, but in the US largely as an adjunct to other imaging modalities that have far more freedom. The other modalities allow operator adjustment of patient exposure to ionizing radiation and to electromagnetic heating. They allow injection of various materials (contrast) into the blood stream, some of which have known deleterious effects. In ultrasound we are not allowed to do any of these actions, even with exposures and agents that are safe in moderation. Perhaps the current fear of untoward effects has gone too far, in view of the widespread use of ultrasound all over the world. In some areas it is the only affordable imaging method.

The future possibilities of contrast that can be targeted to stick to tumors or organs are exciting. They open the way to delivering therapies, and in the past therapy has driven the development of diagnostic methods. As the whole world adopts the unhealthy lifestyles of the “advanced” cultures we may be in dire need of better therapies and diagnostic methods. This behooves us to get on with the job of adapting ultrasound to be a more useful screening tool. Perhaps we could prevent more illness if we could follow developments throughout life in large populations.

ACKNOWLEDGMENTS

My thanks to all of my close collaborators, students and friends over the years. You have made our field into what is is today. Figure 2 is reprinted by permission of VNU Business Publications.

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