HEWLETT PACKARD - INNOVATIONS THAT TRANSFORMED DIAGNOSTIC ULTRASOUND IMAGING

Thomas L. Szabo, PhD

Biomedical Engineering, Boston University, Boston USA

I. SETTING THE STAGE

This is the chronicle of how Hewlett Packard Medical Products in Andover, Massachusetts, USA (HP) became the world's leading echocardiography company starting as a concept at Hewlett Packard Research Laboratories in 1973 until its transfer to Agilent Technologies in November 1999. The author worked at HP in Andover from early 1981, just before the first system shipped, until the transfer of the medical products group in 1999. Before we start, what was the company's interest in medical ultrasound and what was the state of the art in ultrasound imaging?

Hewlett Packard, an instrument company, acquired the Sanborn Company in 1961 with the anticipation of entering the medical instrumentation market. At that time, Sanborn had a number of premier products including electrocardiographs and other medical test and measurement instruments. In that same year, HP's common stock first appeared on the New York Stock Exchange. The original Sanborn had about 950 employees and was located in Waltham, Massachusetts just outside Boston.

After the acquisition of Sanborn, HP explored new diagnostic markets that would add to and complement the recording systems and monitoring equipment that it currently sold. New diagnostic products were aimed at both clinical researchers in academic medical centers. The 7214A Ultrasound Diagnostic Sounder, a general-purpose instrument useful for cardiac, ophthalmological, neurological brain, fetal and kidney examinations was introduced in 1967. It could be used with 1.0, 2.5,5.0 and 10.0 MHz transducers. Interest in neurological ultrasound brain studies led HP to introduce products specifically for neurologists, the 7215A and later the 7215B Ultrasound Echoencephalograph. Their primary purpose was to characterize midline shifts and brain tumors. While the 7215A and 7215B enjoyed interest not only from neurologists but a number of other disciplines as well, the market was judged not to be large enough for more instruments at that time.

John Hart worked on both the 7214A Diagnostic Sounder and the 7215A/B Echoencephaloscope which was used to view the midline of the brain using ultrasound in either a pulse-echo or a through transmission mode. This A-mode (amplitude mode indicating echo amplitudes versus time) device was constructed as a plug-in to an existing HP 140T storage oscilloscope. It had a time gain compensation control, later to become a standard feature in ultrasound.

Just as this product derived from existing HP technology, future HP imaging systems would utilize features of the 78500 series Patient Information Center which centralized the monitoring of patients' vital signs at a nurses' station including ECG) [1] and was designed by the HP Waltham group in 1980. Once again, HP's strengths in waveform display and measurement were evident in the monitoring system as well a new multi-microprocessor architecture which included a newly developed MC5 microprocessor chip. The HP MC5, made with Hewlett Packard's CMOS exclusive silicon-on-sapphire (SOS) process, was one of the fastest 16 bit microprocessors available at 5MHz, and featured a high level instruction set to simplify the routing of data and later played a key role in HP's first ultrasound imaging system.

Meanwhile, in the 1970's, ultrasound imaging was diverging from single transducers on mechanical scanning arms and storage displays into arrays of transducers electronically scanned. The array development was split into linear and phased arrays. Whereas the A (amplitude)-line was one dimensional, the addition of an electronic geometric scanning method introduced the second dimension. In Figure 1, a simple linear array, introduced and popularized by N. Bom [2], in the early 1970's, is shown. Here a row of individual transducers are sequentially addressed by transmitting a pulse and receiving echoes along a line (like an A-line) and displaying each of these lines in their proper sequential geometry on a storage scope. Unbeknown to them, K. Irie at Aloka Japan, had demonstrated [3,4] linear arrays in which overlapping groups of elements were combined and sequenced to provide lines of much higher sensitivity. Whittingham independently had a similar idea of shifting elements in groups along the array and showed abdominal, obstetric and cardiac images using his scheme in 1975 [5]. Even earlier, by the early 1950's, J.J. Wild and J. Reid had taken advantage of World War II surplus radar units to demonstrate ultrasound imaging with handheld linear arrays [6].

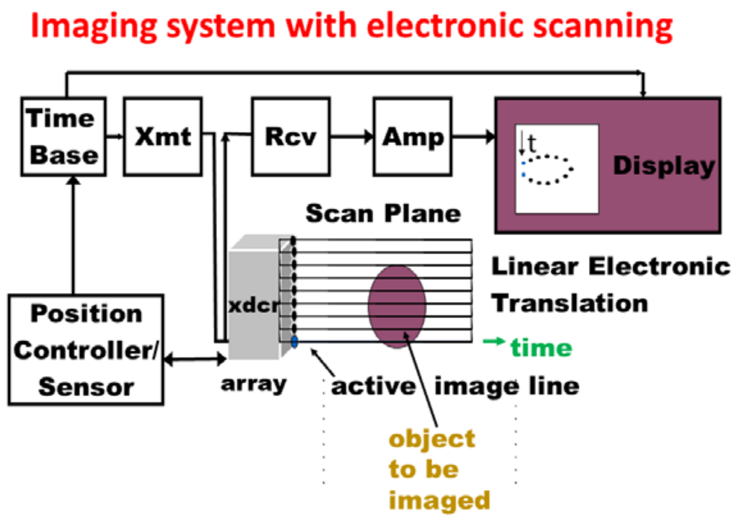


Fig. 1 Basic setup for B (Brightness)-mode imaging in which elements in an array are sequentially switched to produce image lines. (From [8])

Phased arrays, while superficially similar in physical appearance to a linear array, in that array elements are most often arranged in a row, differ in their scanning mechanism. Phased arrays in ultrasound were derived from sonar and radar arrays which swept a radial beam in a full circle or a sector of a circle for a plan position indicator (PPI) display that represented the radar antenna in the center of the display, with the range distance being the radial arm. The distinction between the scanning mechanisms is illustrated in Figure 2 [7]. Linear arrays incrementally scan laterally as Δx, whereas sector scanners change in angle line by line, as Δθ.

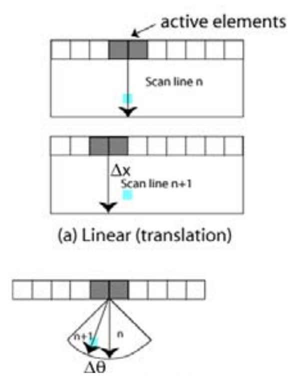


Fig. 2 Scanning mechanisms:A. Linear translation (rectangular image) B. Angular translation (sector image) (From [8]).

Historically, the term "phased array" came from radar where alterations in phase (within one cyclic period) were used to manipulate the beam. Somer [3,9] realized that for ultrasound, time delays were more appropriate for steering. He reached this conclusion from the need to send short pulses to achieve high axial resolution along the direction of propagation which, in turn, required wider bandwidths. His Electroscan 1 and 2 systems demonstrated [3,10] electronic steering of an ultrasound beam for imaging of the brain. To include wider bandwidths, he employed 30-32 meters of cables for finely tuning the delays needed for steering and three racks of equipment. At a Paris conference in May 1971 [3], Professor Frederick Thurstone asked to borrow a film made by Somer's system as an aid to obtain funding for his imaging work at Duke University.

Working with his student Olaf van Ramm, Thurstone designed a sector scan ultrasound imaging system with a major improvement: focusing. They used a PDP-11 computer to create rapidly the necessary time delays from wideband lumped constant analog delay lines to both steer and focus an ultrasound beam. Their initial system employed a 1.8 MHz sixteen element array with a footprint (active area) of 14 mm x 24 mm. By compressing the echo signal envelopes logarithmically as brightness modulation on an HP 1311 scope display, they demonstrated a greater range of echo amplitudes in cardiac images than previously possible. They were able to enhance image resolution by introducing dynamic focusing on reception of the echoes. Their work, presented as demonstrations and video tapes at conferences and in two seminal papers [11,12] showed that real-time cardiac imaging was possible and attracted international interest. The present author was amazed to see their images at the IEEE Ultrasonics Symposium in 1976 [13].

II. HEWLETT PACKARD LABORATORIES: PROTOTYPE ULTRASOUND IMAGING SYSTEM

Dave Wilson and John Larson, who worked together in Hewlett Packard's Research Laboratories in Palo Alto were inspired by Thurstone and van Ramm's talk on their new ultrasound imaging system employing two-dimensional electronic beam steering, given at an Acoustical Holography conference at a nearby hotel in 1973 [14]. Dave Wilson, a physicist who had been interested in medical imaging, was excited by the talk and became a champion for initiating an ultrasound imaging project at the labs. John Larson, who had just completed his PhD in Electrical Engineering at Stanford in 1971, specializing in piezoelectric ultrasound devices, was also on board. "Let's build one!" exclaimed Dave Wilson. With a four element array and crude imaging system, they helped convince Ed Karrer, who in turn obtained support from higher management for the project.

For Ed Karrer, it was the right idea at the right time. Hewlett Packard was uniquely poised for ultrasound imaging; it had scientists with the relevant expertise, experience in crystallographic quartz resonator standards, analog radar beamformers and chip design, state of the art fabrication facilities, many measurement and instrument products including the HP 2100 real-time minicomputer controller and HPIB interface bus for interconnecting instruments as well as a good relationship with the Stanford Medical School. The team was put together in late 1973 with Ed leading the group including John Larson, Dave Wilson and Rick Pering, a EE design engineer; they put together a prototype imaging system with the HP 2100. Within a few weeks, they had a working system with a 16 element array and the HP controller; however, they found that their array had grating lobe artifacts [15] and insufficient dynamic range. Still, they were able to see valves of the heart. They sought the advice of Dr. Richard Popp, a Stanford physician, who gave valuable feedback for improvements. He explained that they were seeing a heart valve but also other ghost valves which turned out to be artifacts of the imaging system (due to grating lobes). Scaling up the delay line approach to more channels that were needed to improve resolution and eliminate grating lobes would be prohibitively expensive. In 1975, Sam Maslak, a freshly graduated MIT PhD in EE joined the team to work on system architecture. A picture of the system in 1976 is shown in Figure 3. Amin Hanafy, who had some experience in designing phased arrays joined them in 1976 from the HP medical group in Massachusetts. Later Fleming Dias aided with transducer construction.

The overall goal was to develop a working proof-of-principle prototype system and transfer the technology to the HP Andover division for a design of a real-time cardiac ultrasound system. Several major challenges lay ahead for the team. The major ones were to improve image quality and real-time frame rate and to provide an economical solution to the time delay problem.

The key to improved resolution lay with the improving the array design. The team selected a 2.5 MHz array of 64 individually addressable elements. The number of active elements determined the lateral or azimuthal resolution and their spacing on half-wavelength centers eliminated grating lobe artifacts [15] seen in earlier designs. Packaging the array into a compact handheld unit suited for intercostal imaging proved challenging and necessitated the elimination of several artifacts [16,17]. A Mount Fuji artifact, so called because the top of the sector image was obscured by snow like reverberations that extended into the first several centimeters at the top of the image (as seen on a logarithmic image scale), proved especially challenging. Other issues such as inter-element coupling, element connections, directivity, new materials resulted in an impressive number of journal articles [18-27], significant design improvements, inventions [28-38] and frequent consultations with engineers Jim Fearnside, Jerry Leach, Dave Miller, and Gary Seavey from HP Andover. Their efforts [16] resulted in a short axial pulse with a resolution of about three wavelengths. To further improve out of plane resolution, Dave Wilson designed a rubber elevation lens to focus the beam in the elevation plane (perpendicular to the imaging or azimuth plane).

To be successful, phased arrays required precise time delay adjustment so that the waveforms arriving at N different element locations would arrive in synchronism, ideally resulting in a gain of N. Delay lines available at the time provided only approximate coherence because they came in standard available delay lengths.

Fig. 3 Rick Pering images a water balloon with HP labs system in 1976 (Courtesy of Ed Karrer)

In 1975 Hewlett Packard Labs team (Pering, Maslak and Wilson acting as system architects) [16] came up with a cost-effective solution for the beam former that would provide precise control and greatly reduce the number of delay lines needed; Rick Pering [39-41] invented a tapped summing delay line [39] which replaced many individual delay lines. As described in the patent Sam Maslak assigned to Hewlett Packard [42], it was disclosed that these switchable delays of the tapped delay line were combined with finely tuned delays provided by adjusting mixer phases in a heterodyne intermediate frequency scheme. The imaging system consisted of racks of equipment connected together as shown by Fig. 3. Also Dave Wilson developed a pulsed beam-former simulation program to predict the beam quality. By December 1978, Sam Maslak left the labs to pursue other ultrasound imaging interests at a more urgent pace [43]. In 1981, Amin Hanafy joined Maslak to found the startup ultrasound company, Acuson [44].

For their final design thirty-two central elements were used for transmit and all sixty-four could be receive elements. The lateral round trip (pulse echo) resolution for an equal number of transmitters and receivers is estimated by the equation for the best possible full width half maximum (FWHM) (-6 dB) beamwidth,

$$\mathrm{FWHM}=0.886\lambda F/L = 1.36F/(Lf) \tag{1}$$

in which F is focal length (mm), λ is wavelength (λ =1.54(mm/μs)/f (MHz)) and L is the active aperture, L=np, n being the number of active elements and f the transducer center frequency in MHz. . For a well sampled array, L=np=nλ/2, the period p is a half wavelength and

$$\mathrm{FWHM}=1.77*F/n\ . \tag{2}$$

For the well sampled array, resolution improves inversely by the number of elements. For the prototype system, the resolution at 12 cm can be estimated as midway between a 32 channel and a 64 channel system or 2.91mm. At 2.5 MHz, the prototype system experimentally achieved a -6 dB resolution at 7 cm in water of 2.5 mm in azimuth, 1 mm in range, and 3.5 mm in elevation [17].

John Larson also developed an idea for adding a linear array by a method he called “tractor treading,” an idea he invented from working on a farm. The scheme involved moving a group of active elements along a linear array by dropping and gaining an element on each end using a switching mechanism and shifting the focusing coefficients along the active elements; see Fig. 2a.

The prototype system block diagram [16,17] shown in Fig. 4 was described in papers co-authored by Karrer, Dias, Larson, Pering, Maslak and Wilson in 1980. A computer (the central processor was an HP 2100 minicomputer) orchestrated the different functions of the system. First, a command initiated a series of transmit pulses, delayed according to a selected focusing depth and steered for each image line, which were sent to the center transmit elements of the array. Second, pulse echoes arriving at array elements along the transmitted line direction were passed through a series of time gain compensation (TGC) amplifiers where they were sent to mixers. Third, depending on the transducer center frequency f_c, a local oscillator frequency f_0 was selected to produce the signals at an intermediate frequency (I.F.). Mixer local oscillators have a common frequency, but each channel had unique mixer phases which changed to support beam steering (line direction) and focusing by the phased array. Fourth, the delay lines needed to achieve the coarse delays were selected as needed to achieve focusing. Fifth, dynamic focusing was achieved by periodically updating the mixer local oscillator phases with depth. Sixth, the outputs of the delayed signals were summed together. Seventh, each beamformed line was then converted to a rectangular brightness modulated image on a cathode ray tube. The transfer of prototype 64 channel system to the HP group in Andover for conversion into a cart-based ultrasound imaging system began in 1977.

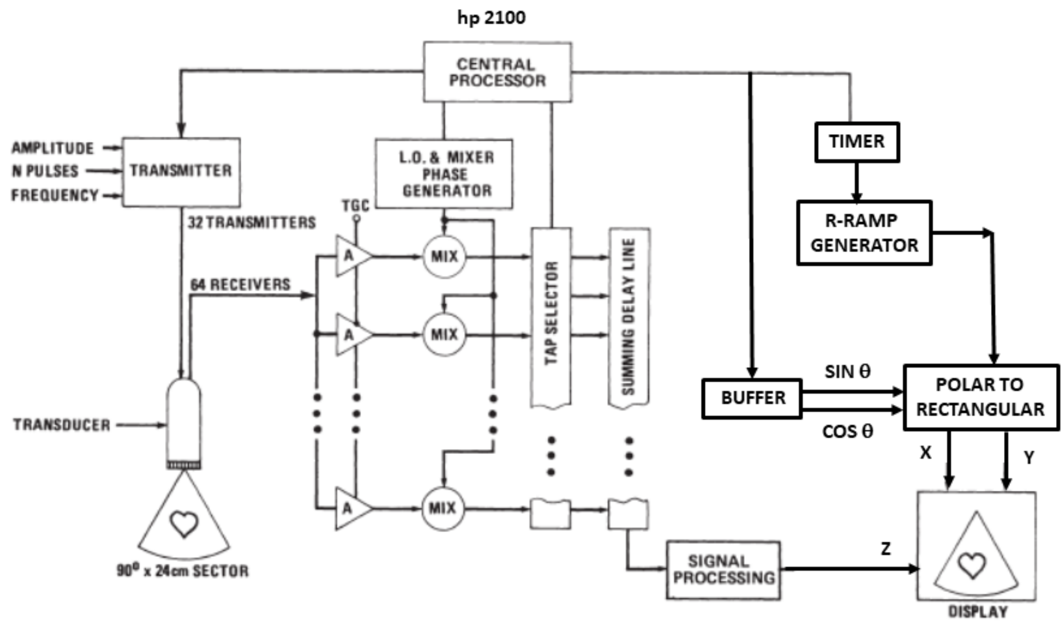


Fig. 4 HP Labs prototype ultrasound imaging system block diagram circa January,1977([16_17] and modified courtesy of Ed Karrer).

III. HEWLETT PACKARD ANDOVER: DESIGNING AND SHIPPING THE FIRST MODERN CART-BASED ULTRASOUND SYSTEM

A small core group led by John Hart, Director of Engineering, and Dave Perozek, the Division Manager, began working on a new ultrasound imaging system in 1976. In the late summer of 1977, Larry Banks, Arthur Dickey, Ray O'Connell, Ron Gatzke, and John Hart spent several weeks at HP Labs learning about the prototype ultrasound imaging system. On their return, they rattled around the new facility at Andover, Massachusetts, largely empty at the time, which was built on farmland on the shore of the Merrimac River. Their goal was not to replicate the prototype system with its racks of equipment, as shown in Fig. 3, but to design a cart-based, mobile, user friendly, real-time cardiac ultrasound imaging system with high image quality. By early 1978, with the first system block diagram, Ron Gatzke worked on analog and mechanical design, Ray O'Connell on scan conversion, Arthur Dickey on digital design, Larry Banks on the system controller, and Jim Fearnside on software. The transducer was supplied by HP labs. Fifteen boards were designed by three people to put together the first working system. The minicomputer was replaced by three fast MC5's, the same microprocessors that were used in the HP Patient Monitoring Center. The complicated routing of instructions was divided into three subsections: the front end (scanner), back end (display) and user interface(controller).

Fig. 5 Hewlett Packard 77020A phased array ultrasound cardiac imaging system with transducer shown on left side (Illustration by courtesy of Koninklijke Philips N.V).

The first imaging session in the late summer of 1978 was a disaster. The system did function as designed but revealed that some of the assumptions made in the original design fell short of what was necessary for a high quality image. “It was like searching for a polar bear in a snowstorm,” recalled John Hart. The image was blocky, full of noise and lacked contrast. A deeper understanding of the significance of small quantization errors and better characterization of the transducer response were needed. The team set to work resolving issues and expanded with new hires. An innovation was that the beamformed data was signal processed, envelope detected, digitized and passed to the digital scan converter for eventual display in real time in an interlaced sixty Hz format. One of the major areas for improvement was the digital scan converter. A group consisting of Hugh Larsen, Steve Leavitt and Barry Hunt designed a new scan conversion algorithm, the r-theta converter, which translated the radial geometry of the sector scan (Figure 2B) into the rectangular world of pixels on the display and eliminated the blockiness (quantization) and Moire patterns prevalent on previous ultrasound systems [45]. Ron Gatzke and six others achieved the highest part density in the Medical Products Group on their scanner boards each of which had twelve channels [46]. Jim Fearnside led a group on transducers which initiated investigations on transducer properties and their measurement and others examined ways of improving beamforming and system performance.

It is not the purpose of this study to document the design of the first Hewlett Packard diagnostic ultrasound imaging system, the HP 77020A, because it has been already described in incredible detail in a series of articles appearing in three issues of the Hewlett Packard Journal [47-49]. Instead, some of the revolutionary features of the system will be emphasized since the HP 77020A became the forerunner of the modern ultrasound imaging systems that were to follow.

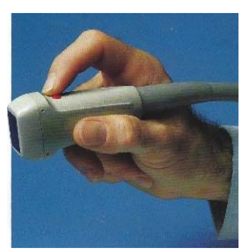


Fig. 6 21200C 2.5 MHz 64 element array (Illustration by courtesy of Koninklijke Philips N.V).

As seen in Figure 5, the HP 77020A was mobile, on a cart with wheels unlike its predecessors which had racks of equipment, and were fixed or sometimes, on wheels. While not the first commercially available phased array system (a 32 channel Varian system was selling at that time); the HP imaging system struck a death knell to most previous ultrasound imaging systems based on mechanical and rotating single transducers. The future for ultrasound imaging became electronically scanned phased and linear arrays. In Figure 6 is a picture of the first HP phased array, the 21200C with sixty-four 2.5 MHz elements which came with the HP 7702A system. Because of its unique heterodyne beamformer architecture, sixty-four channels were able to fit in a cart-based system for the first time. A lightweight, easily maneuverable, handheld 64 element phased array transducer designed for intercostal spacing provided a small footprint (acoustic window) yet a large interior field of view with a sector scan format. The display offered a large smoothly interpolated, highly detailed, high resolution real-time image unlike previous ultrasound imagers, which often offered repurposed oscilloscope monitors or small displays. For transmitting, the 77020A had thirty two newly designed fast transmitters and for receiving, sixty four receive elements with dynamic focusing. Eight time gain compensation controls helped offset absorption and beam losses.

A single central MC5 microprocessor orchestrated the entire system consisting of three subsystems, two of which had their own microprocessor as illustrated by Figure 7, and juggled peripheral devices and the user interface as well. The user interface provided not only acoustic control of transmit focus and scan depth but also the capabilities to annotate and enter patient data by a keyboard, make measurements on the image via a provided joystick, and control video recording of the display in a centralized location. Another innovation was to include M-mode with B-mode in the first multimode display. A key design strategy for Hewlett Packard to grow their customer base was to provide an upgrade path: HP customers were assured that they could always upgrade their system to the latest version.

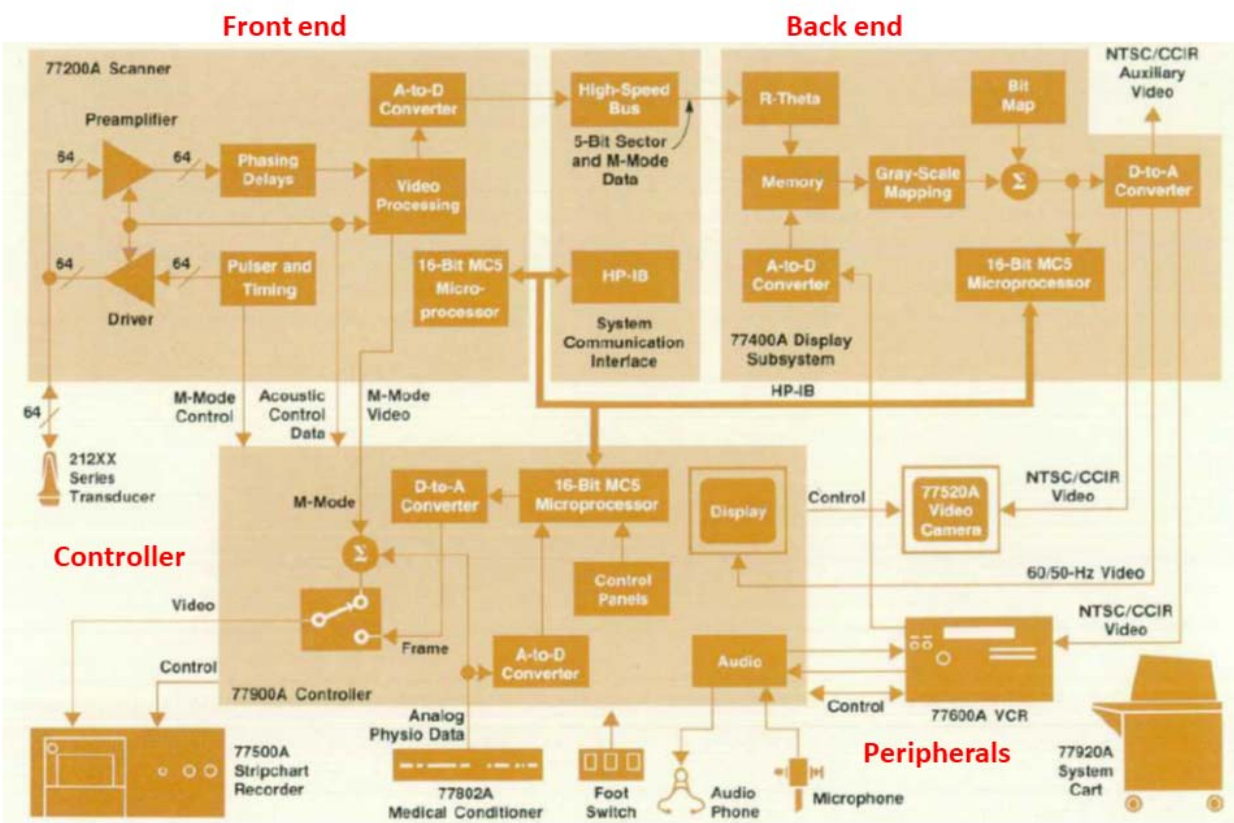


Fig. 7 HP 77020A block diagram showing the front end, back end and controller subsystems (Illustration by courtesy of Koninklijke Philips N.V).

Fig. 7 also illustrates some of the other details of the system architecture. The subsystems were linked by the HP-IB interface bus and software which allowed communication and control throughout the HP 77020A system. The stripchart recorder, a holdover from the Sanborn era, was in a separate cart and eventually deleted.

IV. TRANSDUCERS

Each element in an array can be considered to be an individual transducer. Figure 8 shows the construction of an array. Transducers are piezoelectric devices which send pressure waves into the body on the application of voltage impulses and reciprocally convert returning ultrasound pulse echoes back into electrical signals which eventually are assembled into an image. Ideally, each element should be identical to control beam properties which directly affect image quality. Higher frequency arrays required the fabrication of increasingly small elements repeatably to achieve a period, p, of half a wavelength (recall λ=c/f). Fig. 8 shows array construction.

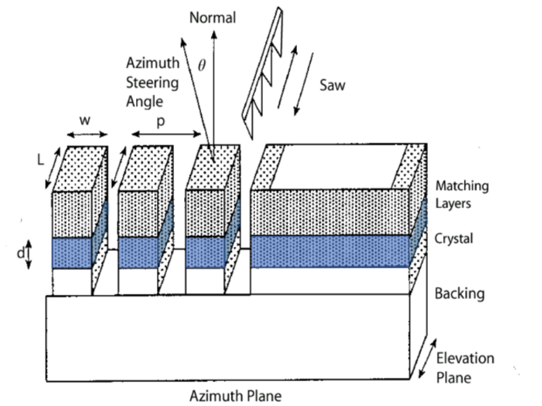


Fig. 8 Array construction showing elements of period p and width w.

Early recognition of the importance of transducers resulted in investments in advancing design through simulation, new materials and extensive measurement and fabrication capabilities. Nearly all arrays were fabricated in house and underwent rigorous measurements and quality checks. Improvements in measurement capabilities both in the engineering and manufacturing laboratories took advantage of the latest Hewlett Packard instrumentation in oscilloscopes, spectrum analyzers, network analyzers, computer and digital memories. Realistic internally developed one dimensional transducer design programs considerably sped up the transducer product cycle [50-52]. Later, commercially available programs were used. Finite element programs such as PZFlex modeled more complicated array effects due to unwanted array construction interactions [53] and were validated by an advanced laser probe measurement system [54]. Improvements in array construction reduced these second order effects and unwanted image artifacts. The key to accurate modeling lay in the development and careful characterization of new materials [55] and piezoelectrics [53] used in arrays. Higher performance design depended on finding materials with specific acoustic and mechanical properties. Experts at the forefront of transducer science were added to an already experienced transducer team: T.R. "Raj" Gururaja, inventor of piezoelectric composites, Jie Chen, an expert on piezoelectric materials and Martha Grewe, an expert on designing matching layers.

The steady cutting edge progression in transducer performance tracked the expansion of the bandwidth and sensitivity of arrays as shown in Figure 9. High sensitivity is related to the transducer's ability to receive weak pulse echoes from deep within the body (penetration depth). Bandwidth is highly valued because the greater the fractional bandwidth (usually expressed as -6dB value)FBW =100*($f_{-6dBhigh}$- $f_{-6dBlow}$)/f_{center}), the more frequencies of operation can be fit into it. The first generation of transducers had a bandwith appropriate for a single imaging frequency (Figure 9A) 30%. The next improvement, wideband arrays expanded the frequency range to include a Doppler frequency and an imaging frequency (Figure 9B), FBW >40%. In the next "dual" generation of transducers, bandwidth accommodated two imaging frequencies FBW>60%. The following transducer family, the "ultraband" group was wide enough to hold an imaging frequency, f_c, as well as its second harmonic, 2 f_c (Figure 9C), FBW>85%. A single crystal transducer (described later) could replace several narrower band transducers (Figure 9D), FBW>100%.

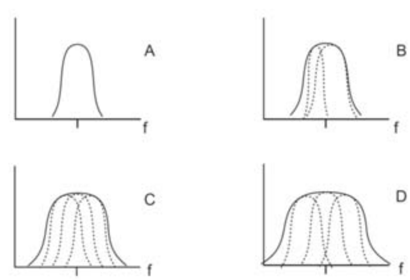


Fig. 9 Progression of increasing bandwidth for HP transducers from 1981 to 1999 (from [8]).

Until June 1990, most of the HP transducer arrays were of the sector type (Figure 2b). At that time, HP introduced the world's first steerable focusing linear array. With a center frequency of 7.5 MHz, the array was guided by a tractor-treading principle in which the 128 channels of the system were connected to the 288 elements of the array through electronic switches. Unlike previous arrays, the image could be steered in the shape of a parallelogram, resulting in high resolution images of detailed vessel structures and blood flow in unparalleled clarity. In addition, the formats of Figures 2a and 2b could be combined in a new trapezoidal image format: a rectangular format plus two half sectors on each end. As an added bonus, the 21258B operated at 5.5 and 7.5 MHz, and its sister array, the 21255B, at 3.7 and 4.5 MHz. These new arrays were championed by Rick Snyder and a group led by Ray O'Connell, with Matt Mooney and Martha Grewe Wilson designing the transducer [56].

HP expanded its transducer family by designing arrays specialized for different clinical applications. An assortment of different types available in 1999 is illustrated by Fig. 10.

One specialized type of array is the transesophageal probe, a small high frequency phased array which when placed in the esophagus, provides an unobstructed acoustic window in close proximity to the heart, thus bypassing intervening layers of fat and muscle which could degrade transthoracic cardiac ultrasound imaging. Jim Fearnside was an early advocate for transesophageal probes; Linda Carlson took on the challenge of facilitating clinical evaluation of and training for them. The first Hewlett Packard Transesophageal probe (TEE), introduced in 1986, a 5 MHz 64 element array mounted on the end of a gastroscope, allowed high definition views of the heart and blood flow. The gastroscope was necessary to manipulate the probe into a desired position to see selected features of the heart. An improvement, in terms of viewing capability was the TEE biplane which consisted of two orthogonal switchable 5 MHz 48 element arrays became available in 1990.

Fig. 10 A sampling of HP transducers circa 1999 (Illustration by courtesy of Koninklijke Philips N.V).

Even though others had thought of the concept of a rotatable TEE [57], it wasn't until Jim Fearnside's team, including Mike Peszynski, designed a multiplane or Omniplane transducer as a practical reality [58-60] at HP. The Omniplane TEE, a 5 MHz 64 element array mounted on the distal end of a gastroscope released in 1992, could be rotated precisely through a motorized drive and new gastroscope. This control capability overcame many of the previous positioning difficulties, provided repeatability and produced spectacular images. Because of the clarity of images, cardiac surgeons and anesthesiologists as well as cardiologists wanted the Omni; it was in great demand [61]. The next version, the Omni 2, which could acquire a sequence of images placed at precise angles, made possible the first three dimensional images of a live beating heart. See Fig. 10. A transthoracic version of the Omni for 3D and small pediatric transesophageal probes followed. Mike Peszynski, inventor on four TEE patents assigned to Hewlett Packard continues to innovate these probes for Philips and holds several dozen patents at last count (see matrix arrays).

What was the ultimate performance possible in a transducer? Had the end of the road been reached? Piezoelectric materials used for ultrasound arrays were polycrystalline ceramics whose initially randomly oriented domains could be mainly but imperfectly aligned in the same direction by a process called "poling," the application of a high voltage. Another type of piezoelectrics, initially investigated by Toshiba [62] for medical ultrasound, are single crystalline materials which offer the potential of nearly perfect domain alignment, resulting in extremely high electromechanical coupling and high applied strains.

In the spirit of finding an ultimate transducer material, T.R. Raj Gururaja and Jie Chen began exploring options. Through Jie Chen's connections with the Shanghai Institute of Ceramics, Chinese Academy of Sciences (SICCA), which had the capability to grow these types of crystals under extremely exacting conditions, the first sample, the size of a mustard seed, was obtained in 1996. Realizing that there was no program in the United States to systematically investigate single crystalline materials which would be best suited for transducer arrays, Raj led workshops and helped organize a team suitable for a project of this scope. In January, 1998, we submitted, along with Michael Greenstein and Paul Lum, of HP Research Labs, a single crystal research proposal to Wallace Smith, Office of Naval Research [63] which was ultimately funded. A two year program to develop domestic sources to grow large enough samples suitable for arrays and to characterize the basic anisotropic piezoelectric and dielectric properties of the materials was underway. Meanwhile, Jie Chen received a sample from SICCA from which they were able to make the first array. Even though only twenty elements survived, a fractional bandwidth greater than 100% was achieved in 1998. The transducer group opened a commanding competitive lead in finding sources for larger single crystals and the crystal orientations optimal for arrays. Even though this group [64,65] persisted through a reorganization (Hewlett Packard split into Agilent Technologies and Hewlett Packard in 1999) and an acquisition by Philips, their work led to a new generation of transducer arrays with properties that far surpassed all previously made transducer arrays. After seven years more of development by Philips, this new technology became the highly successful generation of transducers branded "PureWave,"[66] and has led to even greater innovations (see matrix arrays).

V Color flow/doppler

It is impossible to capture the many innovations over the twenty year period at HP Andover in a short article, so you will find highlights here rather than a comprehensive history. Eventually, the engineering team grew from 50 in 1983 to 200 in 1999. Leaders of the HP Imaging Systems following John Hart included Paul Magnin, Al Kyle and Cynthia Danhier. Each ultrasound imaging system came out as an upgrade usually identified by a letter. This meant that whatever system a customer had, it was "upgradeable" to the latest version, which required technical and software forethought. Shown in Figure 11 are the upgraded HP imaging systems for the first few years.

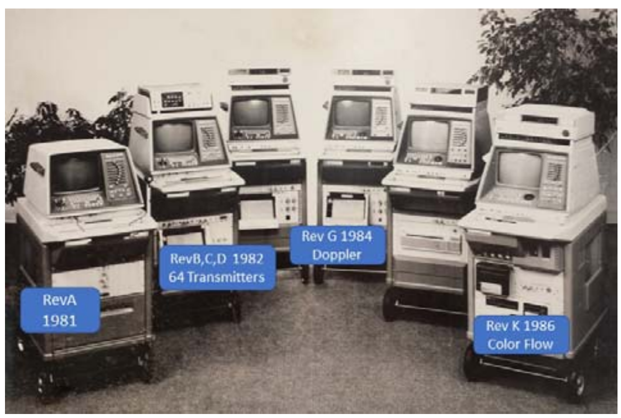


Fig. 11 HP imaging system upgrade path from 1981 to 1986 (Illustration by courtesy of Koninklijke Philips N.V and annotated by Karl Thiele).

One of the most popular upgrades was Rev K, color flow imaging. Barry Hunt related the back stories behind the addition of Doppler and Doppler color flow imaging to the system. In the early nineteen-eighties, the engineering team working on Doppler was falling behind and an outside word class expert was called in to assess the situation. He identified six major problems with their present approach. For a large consulting fee, he offered his services to fix the problems in a short amount of time. John Hart met with the team behind closed doors. He asked them "Should we hire this expert or solve the problems ourselves? You decide." The team unanimously chose to solve the Doppler issues themselves. The learning process was painful, but they redesigned, added synchronization and routed pulsed wave Doppler through the array and separately isolated continuous wave Doppler. The resulting Doppler upgrades, Rev G in 1984 and H and I in 1985 were successful. Once again, detailed descriptions of the Doppler systems appeared in the HP Journal [49].

One aspect of the HP culture (discussed later) was that engineers were encouraged to innovate. While the scanner engineering group was busy with the next step in the evolution of the system (system 2), a new idea emerged. Paul Magnin did a study of color flow algorithms. Based in part on their experience of the Doppler improvements, Barry

Hunt and Dave Hempstead realized that it may be possible to add a color flow capability to the present system architecture. They submitted a proof of principle proposal, System 1 Flow Mapping Proposal, in April 1984. With Ray O'Connell's help , these ideas were posed to management. Steve Leavitt was tasked to manage a small group including Barry Hunt, Dave Lipshutz and Dave Hempstead to do a paper study on implementing Color Flow Mapping. Dave Lipshutz came up with an innovative scheme. Instead, by the summer, the group decided to build a prototype system using separate scan converters synchronized together to represent the red, blue and green colors and they took advantage of the new pulsed Doppler architecture and used an HP 150 controller. By November 1984, they succeeded in making the first color flow image. This skunkworks approach is shown in Figure 12. Afterwards, serious incorporation of color flow mapping into the existing imaging system began. Management gave a green light to the color flow mapping project and postponed work on system 2.Taking advantage of the inherent flexibility of the system architecture and the Doppler improvements, a larger team including Paul Magnin, Ron Gatzke, Karl Thiele, Tomo Hasegawa and Les Halberg among others, was able to fit color flow into the existing cart. A clinical trial with Dr. J. Kisslo at Duke went well. The introduction of the first color flow mapping in North America as the Rev K upgrade in the fall of 1986 was one of the most successful HP ultrasound innovations. These efforts were described in articles and a series of patents [67-70]

Fig. 12 First HP prototype color flow mapping system, Nov. 1984, Insert: color flow image. (Courtesy, Barry Hunt).

VI. Matrix array

The race to obtain better image quality and resolution, was often played out by increasing the number of channels in the system as predicted by Eq. 2. Another fundamental limitation was that this improvement only applied to the azimuth plane which was controlled by electronic control of the focusing and steering of the beam through array elements. The other dimension, orthogonal to the imaging plane, or elevation plane (Figure 8) was typically focused at only one depth by a mechanical lens. The unfortunate consequence of this approach was that strong scatterers lying outside the imaging plane were mapped into the imaging plane. The method needed for perfect three dimensional electronic focusing in both dimensions was well known: a two-dimensional array. The barrier to this approach was that even more elements and system channels were needed: on the order of n-squared. For example, a typical 1D array would have 64 to 128 elements; scaled to a 2D array, this may involve 4000 or 16000 elements!

For many years, the problem of the 2D array seemed insurmountable and compromise solutions, such as sparse arrays and cross arrays, had very high clutter levels and therefore poor image quality [71]. Marty Mason, transducer manager, challenged Bernie Savord to implement 3D imaging electronically. Bernie Savord begrudgingly complied, not thinking it was possible. To his amazement, he found a solution and that it could have been done with technology fifteen years earlier. The breakthrough was to organize the 2D elements in groups, each of which had a set of "microbeamformers" or subarrays for fine delay adjustments and the outputs of which were routed to a summing node [72]. Each summing node corresponded to the usual number of beamformer channels in the system which performed the coarse delay functions. Then, the imaging planes could be stepped across the array. He found the grouping concept in John Larson's earlier patent useful [73]. In 1996, Bernie Savord started on implementations for miniaturizing the microbeamformers to fit within the probe handle [74,75]. One of the challenges of the integration of the large number of microbeamformers was to minimize heat consumption in the handle.

Another major challenge was how to construct the array and connect to thousands of elements, each of which was spaced at about half a wavelength apart. Fortunately, this was a problem that had been worked on for years both at

HP Andover by Rod Solomon [76] and at HP research labs by Michael Greenstein [77-79], so a fitting and practical solution was developed.

In parallel, another effort was needed to transform the acquired array data into three-dimensional visualizations. Arthur Dickey's forethought of this challenge put Karl Thiele in search of a solution. Working together, Karl Thiele and Bernie Savord put together the first working prototype shown in Figure 13. One of the two connectors in Figure 13A was for the analog signals that plugged into the imaging system, and the other was used for the signals needed to program the probe. By 2001, at the American Society of Echocardiography annual meeting, they put on a private demonstration of the matrix array prototype shown in Figure 13.B and real-time 3D imaging to enthusiastic responses. After considerable work by a Philips team, the 2.5 MHz X4 matrix array was shipped as a product in 2002, along with a new system to run it, the SONOS 7500. Not only did this transducer have 2880 elements, but all the microbeamformer electronics also fit in a handle not much bigger than the first 64 element HP phased array (Figure 6) and they served the function of hundreds of front end boards. Later the single crystal transducer design (Pure Wave) was incorporated into a matrix array in the X7-2 with 2500 elements. Similarly, matrix array transesophageal probes with thousands of elements became reality [80]. At the latest count as of this writing, the X-6 matrix array has over 9000 elements [81].

Fig. 13 Matrix arrays with microbeamformers in the handle: A.(left) first working prototype B. (right) close to final product (Courtesy of Karl Thiele).

VII. OPTIGO

In 1998, a small group began working on the SPUD (Small Portable Ultrasound Device) imaging system based on novel concepts. The team included Jim Fearnside, Rachel Kinicki, Joe Fallon, Mike Anthony, Charles Dowdell, Ted Fazioli, Matt Mooney and Steve Leavitt. The goal was to cram an entire imaging system in a size smaller than a laptop and it would be battery-operated, low cost and light weight. The design centered around application specific integrated circuits(ASIC's). Steve Leavitt developed one which included both scan conversion and color flow mapping. The team also created beamformer ASIC's in which there was a processing channel for each element in a phased array transducer . Each beamformer ASIC replaced several scanner boards of earlier full sized imaging systems. Also, other formats such as linear, curved linear and combination formats could be accommodated. The TGC controls were automated and the user-interface consisted of intuitive simple controls. The result was a reconfigurable and scalable ultrasonic imaging system which could adapt to different types of transducers. Output could be stored on a memory card and the display was a 6.5" LCD screen. In addition, different operating modes, processing algorithms and display options were under software control [82]. Even greater miniaturization was achieved by using the microbeamformer principles used for the matrix arrays. Here, for these one dimensional arrays, sub-beamformers, as shown in Figure14, could be put right in the probe handle, aiding the further miniaturization of the overall device. The device appeared as a Philips product, the OptiGo in 2002 aimed initially at the cardiac screening system. [83], (see Figure15). The challenge of how to mass-market a low cost ultrasound product. (about ten thousand dollars) delayed the release of the OptiGo. The sales problem was that incentive was always greater for selling a regular sized system with a larger profit margin than that for an OptiGo . A second problem was the lack of a hard copy output needed for medical billing. The beamformer in the handle foreshadowed the Philips' Lumify in which, after considerably more development and miniaturization, the front end and entire beamformer and processing were fit into the transducer handle by November 2015 and connected to a smartphone for display and communication to the web.[84].

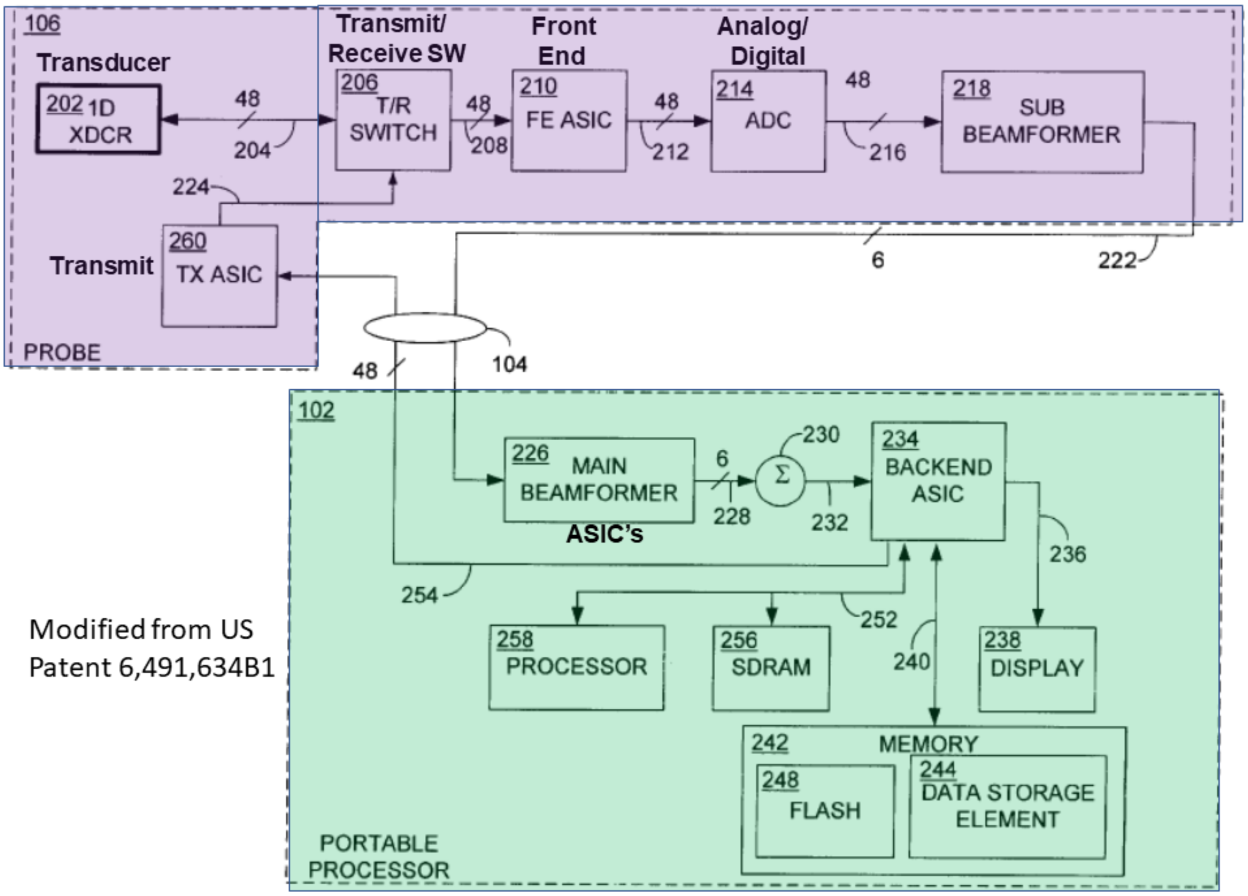


Fig. 14 Block diagram for portable ultrasound imaging system with sub-beamformers in probe handle (From US Patent 6,491,634B1).

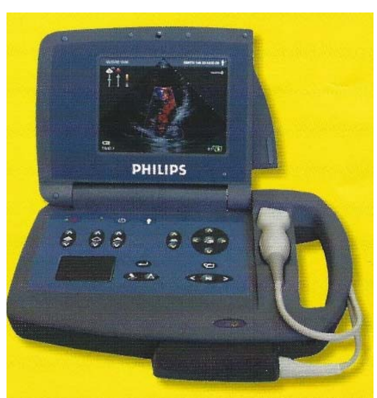


Fig. 15 OptiGo portable low cost ultrasound imaging system released by Philips in 2002 (Illustration by courtesy of Koninklijke Philips N.V).

VIII. Research system (PAWS)

In 1992, Steve Leavitt floated the idea of a research ultrasound imaging system to management. His concept was to digitize the radiofrequency inputs of each of the transducer elements and store them in a digital memory for prototyping future systems, new beamforming and signal processing schemes. Management agreed and Steve Leavitt led a group including Dave Lipshutz, Ron Gatzke, Ban Dinh and Bernie Savord to design the system. As shown in Figure 16, the main processor of the Phased Array Work Station (PAWS) was an expensive Convex-240 (240Megaflops) supercomputer which required massive electrical cabling which Ban Dinh installed. A software acquisition controller managed the setting of a SONOS1500 front end the analog output of which was routed into the PAWS cart which included 10 bit 20 MHz analog to digital conversion boards for digitizing the signals from each of the 128 transducer elements. The output of these boards was fed in parallel simultaneously into a bank of random access memory units which in turn streamed their output into the Convex supercomputer which then organized the data into long term digital storage. The Convex then ran algorithms which processed the data and formed images.

The PAWS system was instrumental for trying out different approaches for the future digital system design, nicknamed "Titan," which eventually became the SONOS 5500, released in 1997. PAWS was modified to try out new arrays such as electrostrictors. Steve Leavitt led the Advanced Projects Group for 1992 to 1995 after which it was led by Jim Fearnside. Don Orfino wrote software in MATLAB which emulated the standard delay and sum beamformer, filtering, back end and display processing and controls. He later left and joined Mathworks which produces MATLAB. The present author explored 1.5D electrostrictive arrays (intermediate between 1D and 2D arrays [85]) on the system and the effects of aberration, based on a joint project with Prof. R. Waag at the University of Rochester for obtaining acoustic chest wall data [86]. He also investigated applying seismic algorithms with Dan Burns, a consultant. The seismic processing eliminated much of the clutter in cardiac images but, took too long to run, even on a supercomputer [87].

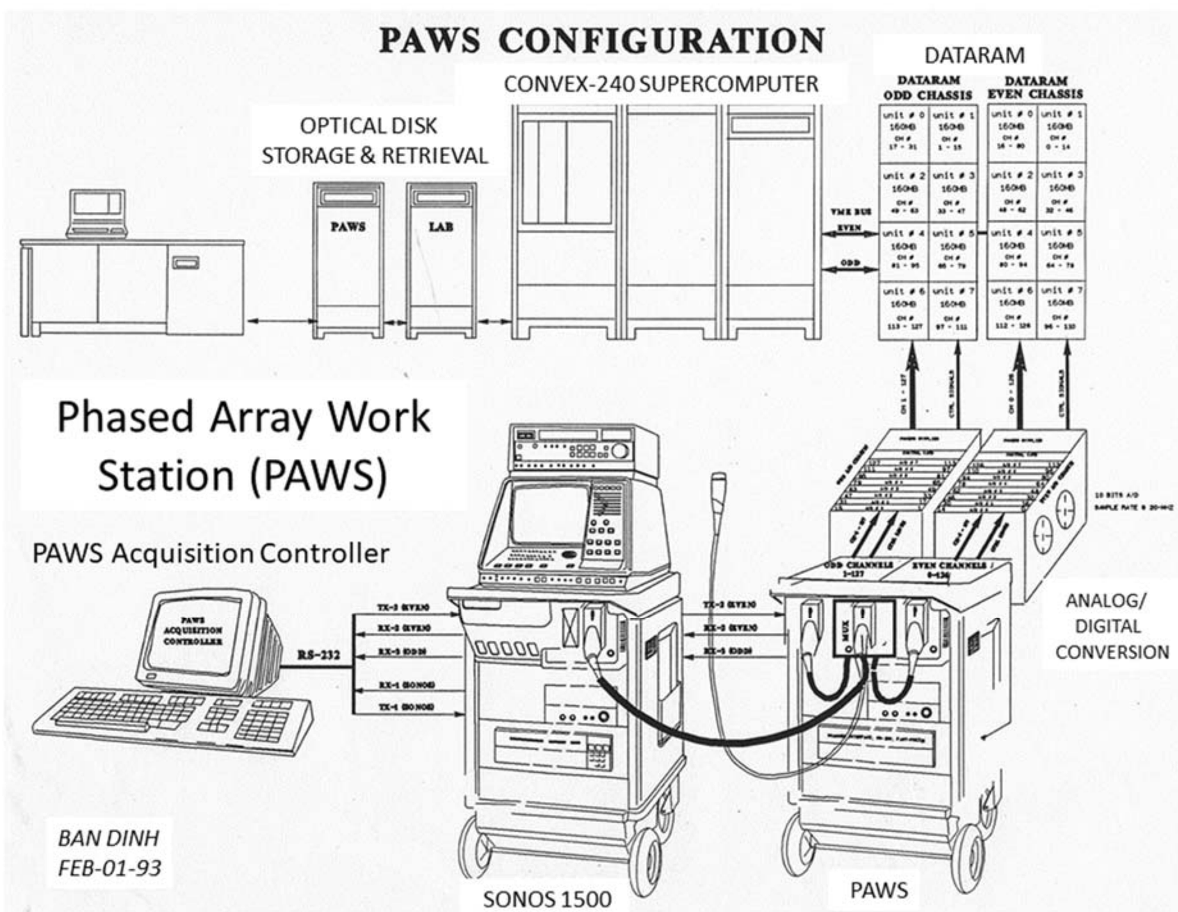


Fig. 16 PAWS system (Courtesy of Ban Dinh).

After about five years, Moore's law caught up with the Convex supercomputer. Hewlett Packard's state of the art workstations had evolved to be as powerful as a 1992 Convex-240. By then, too, the SONOS 5500 digital imaging system had become both a product and an experimental base for testing new imaging ideas. In an ironic twist, the next generation of Convex computers were based on HP RISC (Reduced Instruction Set Computer) microprocessors (used in workstations) running in parallel. In 1995, Hewlett Packard acquired Convex. PAWS was dismantled and donated to charity. The concept of PAWS, then protected by HP proprietary restrictions, reemerged in present day ultrasound research systems which consist of a software controlled front end, high speed digitization and storage and imaging system simulation in software.

IX. HP vs. ACUSON

Sam Maslak left HP labs in November, 1978 after assigning the mixer imaging system architecture patent [42] to HP. By 1981, Maslak and Robert Younge, a colleague at Hewlett-Packard, joined with Amin Hanafy, a key transducer expert at HP medical products and HP labs, to form Acuson in 1981. They were able to raise sufficient venture capital based on their business plan [88,89] by January 1982. Based on the assumption that the plan was executed, a primary emphasis was the radiology market, including obstetrics. The obstetrics segment, which propelled ultrasound imaging into existence [90], continues to be one of the largest ultrasound imaging market segments. Acuson's strategy was to provide a premium image, called the "gold standard" at a premium price. In ten months, a prototype system capable of producing either sector or linear format images passed its first water tank trial [91]. In 1983, Hugh Larsen left HP Medical Products to join the Acuson team. By the end of 1983, Acuson shipped its first thirty systems [92]. How was it possible for Acuson to produce a quality system so quickly? Sam Maslak offered advice for startups: address (and eliminate) technical risk [92] first. From the outset, he was keenly aware of beating the competition [93]. To compare major HP and Acuson events, a timeline is provided by Figure 17.

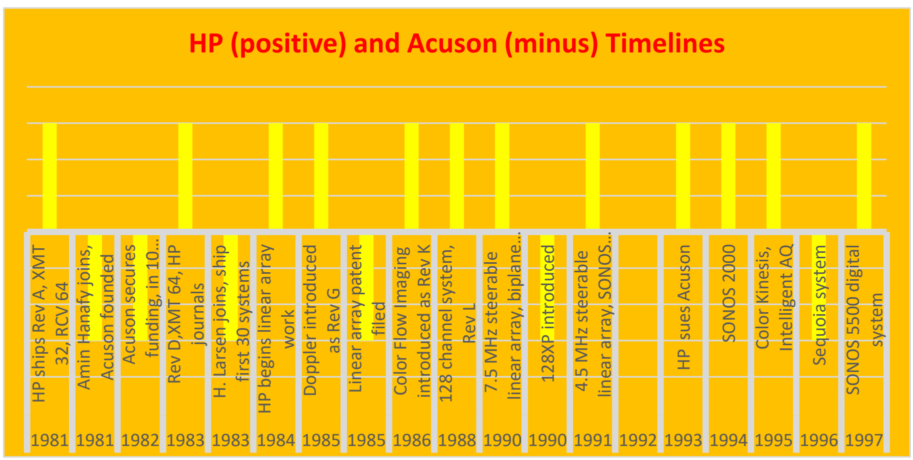


Fig. 17 Timelines for HP (positive bars) and Acuson (negative bars) product and other events.

Sam Maslak explained how Acuson was able to produce high quality imaging: "Computed Sonography [94]." He emphasized that a hybrid analog/digital computer in the Acuson system managed the imaging parameters. By comparison, HP had a scanner microcomputer for controlling beam characteristics as well as an overall system controller microcomputer (Figure 7). Resolution is mainly controlled by the number of elements, according to Eq. 2. Acuson had 128 elements at its first launch compared to HP's 64. HP did not catch up to 128 elements until 1988 with Rev L. Contrast was another factor Maslak identified which meant low sidelobes obtained through apodizing or weighting the output of the elements [95]. HP was aware of this as well; see Figure 2 in [16], a 1980 paper describing the HP system to which Maslak was a coauthor. The last factor identified in [94] is image uniformity obtained by using a "tracking lens," in the Acuson system as well as by keeping the F number (=F/L) constant (see Eq. 1) in the "tracking lens" with depth. In the HP systems as well as the HP labs prototype an equivalent process was used called "dynamic focusing."Acuson advertised "upgradeability" as a key feature of their systems. By the time Acuson introduced its first system, HP was on its third upgrade, Rev. D.

Relations between HP and Acuson remained cordial until Acuson, which had spectacular growth and success in the radiology and obstetrics markets, decided to enter the echocardiology market, in which HP was the dominant leader. Once this entry happened, Acuson and HP were on a collision course. To recap some of the highlights of HP development on the timeline, previously described, 1986 saw the introduction of color flow, and in 1990 and 1991, the entry of the first steerable linear arrays. Meanwhile, Hugh Larsen and Sam Maslak filed a strategic patent on behalf of Acuson in November 1985 on linear arrays which was granted in October 1987 [96]. The curious aspect of this patent was that it was entirely dependent on Maslak's mixer patent assigned to HP during his HP labs days; .ie. it could not be implemented unless the company had a license to use the earlier patent [42]. In 1993, HP had strong evidence that Acuson was infringing on their mixer patent [42] and filed a law suit against Acuson [97]. Acuson countersued, claiming that HP had infringed on their linear array patent [96]. By then, HP had two linear array products on the market; it had been using the tractor treading concept that traced back to John Larson, who did not file a patent based on HP interests at the time. Even though the results of negotiations between the two parties were not made public, the fact that HP continued selling linear arrays and Acuson still had their systems indicated a truce was reached.

By 1993, both companies were more interested in their futures. Acuson invested heavily in their new Sequoia platform [88], so much so, that their profits flattened and they began to lose their market share. When Sequoia debuted in 1996, it followed a previous Acuson trajectory of super premium systems that outperformed others and was also, by far, the world's most expensive ultrasound system. Acuson's premise that premium systems create their own market no longer held in changing economic times [88]. Competitors had also produced systems with excellent images and cost consciousness had set in. Meanwhile HP launched their premium digital system, the SONOS 5500 in 1997. In the echocardiology market segment, by 1983, HP quickly rose to the top and stayed there as Figure 18 shows.

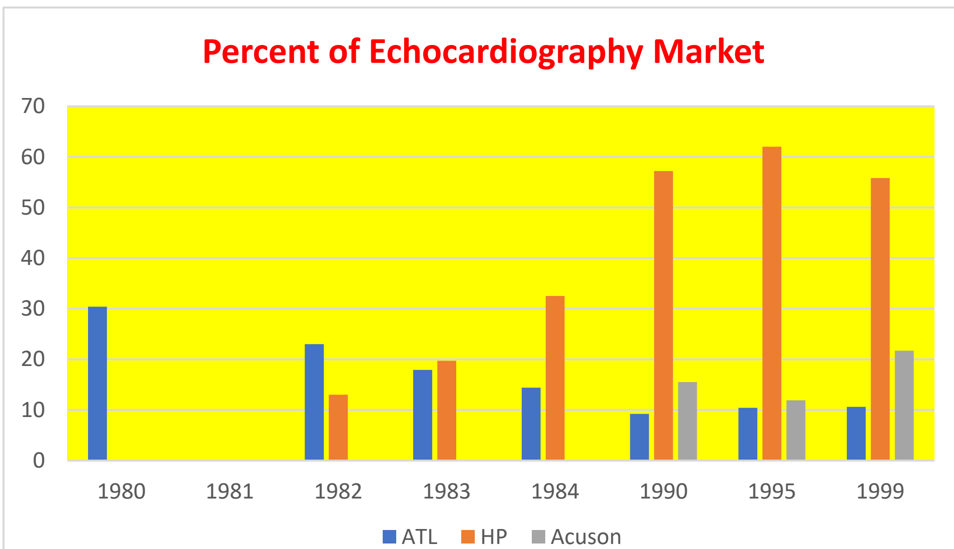


Fig. 18 Percentage of total echocardiography market for ATL , HP and Acuson by year (Courtesy of Harvey Klein).

Even greater changes were in store for diagnostic ultrasound. In 1980, before HP's entry, twelve companies shared most of a total ultrasound imaging market of two hundred and seven million dollars [98]. By 1998, three companies held 48% of the overall diagnostic ultrasound two and a half billion dollar market: ATL 18%, HP 16% and Acuson14% [98]. In a surprise move, Philips acquired ATL in late 1998. Due to internal squabbles, Hewlett Packard split into Hewlett Packard (computers, printers, etc.) and Agilent Technologies (instrumentation, electronics) in November 1999. At the time of the split, Hewlett Packard had grown to a forty-two billion dollar company employing eighty-four thousand people worldwide. Recall that Hewlett Packard entered the medical business by acquiring Sanborn and it joined the New York stock exchange in 1961. Siemens acquired Acuson in September 2000 for seven hundred million dollars and Sam Maslak stepped down as CEO. In November 2000, Philips, which had a previous relation with HP, acquired the health care group (including ultrasound) from Agilent Technologies. The CEO of Agilent remarked "We concluded we had higher priorities to invest in and health care came in the bottom of the list."[99]. Today through acquisition of the top ultrasound companies, Philips Health care dominates the health care market and ultrasound imaging and benefitted from Hewlett Packard's legacy of innovation. Now only three large companies lead the medical imaging market: Philips, General Electric and Siemens.

X. HP WAY

The work environment at HP Andover inspired innovation and teamwork. The HP Way evolved from the combined experiences of Bill Hewlett and Dave Packard from decades of company growth [100]. An open, collegiate atmosphere encouraged individual motivation, initiative, creativity, freedom and trust. Consider that this whole ultrasound imaging enterprise began because of an enthusiastic engineer and a physicist at Hewlett Packard Laboratories, not from a top-down directive.

An informal, decentralized management style prevailed based on "management by objective" which allowed some flexibility in how team players could best achieve common purposes. "Management By Walking Around," encouraged open communication between managers and their team. Because Hewlett and Packard realized that company growth depended on a continual influx of new product ideas, engineers were encouraged to innovate and supply stocks remained open so they could try out new ideas. In the beginning, there were two coffee breaks with free doughnuts which led to learning about other projects and forging new collaborations. There were also beer busts, picnics, and community contribution activities. HP tended to hire well qualified people and keep them which led to company loyalty. During downturns in the economy, everyone took a 10% cut (working 9 days out of 10) until the economy recovered. Employees were eligible to participate in profit sharing in the form of buying Hewlett Packard stock at subsidized rates. Also there was a commitment to produce quality high performance products which resulted in greater customer satisfaction.

At its best, the HP Way worked well. In this article are examples of trusting in individuals to make decisions and to recover from failure, ideas arising from within, teamwork required for large complex projects, managers challenging others to do the seemingly impossible, and an overall commitment to excellence.

ACKNOWLEDGEMENTS

In an article of this length, regrettably, I was not able to include many of the people and achievements that occurred at HP Andover. Even though technology was highlighted, other parts of the team such as marketing and manufacturing also played important roles. In particular, marketing's enthusiastic engagement propelled the success of the ultrasound imaging enterprise. Manufacturing's partnership with engineering assured that high quality, reliable and easily reproduceable products found their way to customers worldwide. I am grateful to my former colleagues at Andover and at the former research labs who spent many hours explaining and recalling events for this article. In particular, I would like to thank Linda Bogdanoff, Linda Carlson, Jie Chen, Ron Gatzke, Martha Grewe Wilson, Kurt Guggenberger, Raj Gururaja, Ed Karrer, Barry Hunt, John Larson, Al Kyle, Steve Leavitt, Paul Magnin, Jim Mniece, Mike Peszynski, Bernie Savord, Rick Snyder, and Karl Thiele. Special thanks to Harvey Klein for digging up archival market data. The author takes responsibility for any errors and omissions.

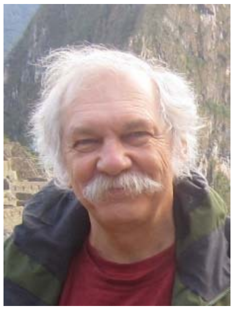
REFERENCES

1. J. M. Rueter, Multi-Processor Architecture and Communications for Patient Monitoring Hewlett Packard Journal, 31(11), November 1980 pp15-18.
2. N. Bom, C.T. Lancee, J. Roelandt, F.C. van Egmond, Two Multi-Element Systems For Real Time Cross-Sectional Analysis Of The Heart, Proc. of 1973 Ultrasonics Symp.,1-3.
3. J. C. Somer , "The history of real time ultrasound," International Congress Series,12/ (2004), pp 3-13
4. Takasuke Irie and R. Uchida, Aloka, 200 element Linear array Imaging System, Japanese Society of Ultrasonics in Medicine, 1971.
5. T.A. Whittingham, "A Multiple Transducer System for Heart, Abdominal and Obstetric Scanning, Excerpta Medica International Congress Series, Proceedings of the Second European Congress on Ultrasonics in Medicine, Munich, 12-16 May, 1975,pp59-60.
6. J.J.Wild and J. Reid, "Cancer Detector," Electronics, March 1955
7. T. L. Szabo and P. A. Lewin, "Ultrasound Transducer Selection in Clinical Imaging Practice," J Ultrasound Med. 2013; 32:573–582.
8. T. L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, p10 and a generic reference to this book.
9. J.C. Somer, "Electronic Sector Scanning for Ultrasonic Diagnosis," Ultrasonics, July 1968, pp. 153–159
10. T. L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, p15.
11. O. T. Van Ramm and F. L. Thurstone, Cardiac Imaging Using a Phased Array Ultrasound System:I. System Design, Circulation, 53 (2), February 1976, pp258-262.
12. J. Kisslo, O. T. Van Ramm and F. L. Thurstone, Cardiac Imaging Using a Phased Array Ultrasound System: I. System Design, Circulation, 53 (2), February 1976, pp262-267.
13. F. L. Thurstone and O. T. Van Ramm, Acoustical Imaging With A Linear Phased Array, Proc. of 1975 Ultrasonics Symp.,73-74.
14. F. L. Thurstone and O. T. Van Ramm, "A New Ultrasound Imaging Technique Employing Two-Dimensional Electronic Beam Steering," ultrasonics Acoustic Holography Conference, Springer, Boston,1973, pp249-259.
15. T. L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, pp 221-224.

16. H. Edward Karrer, J. Fleming Dias, John D. Larson, Richard D. Pering, Samuel H. Maslak, David A. Wilson, A Phased Array Acoustic Imaging System For Medical Use, 1980 Ultrasonics Symposium – 757-762.
17. Karrer .E., Dias J.F., Larson J.D., Pering R.D., Maslak S.H., Wilson D.A. (1982) A Phased Array Acoustic Imaging System for Medical Use. In: Alais P., Metherell A.F. (eds) Acoustical Imaging. Acoustical Imaging, vol 10. Springer, Boston, MA. https://doi.org/10.1007/978-1-4684-3944-1_5
18. J.D. Larson, J.G. Leach, "Tungsten-Polyvinyl Chloride Composite Materials - Fabrication and Performance," 1979 Ultrasonics Symposium Proceedings, pp. 342–345, IEEE 79CH1482–9
19. John. D. Larson, "A New Vibration Mode in Tall, Narrow Piezoelectric Elements," 1979 Ultrasonics Symposium Proceedings, pp. 108–113, IEEE 79CH1482–9
20. John D. Larson, III, An Acoustic Transducer Array for Medical Imaging- Part I, Hewlett Packard Journal 1983,34:10, 17-22
21. David G. Miller, An Acoustic Transducer Array for Medical Imaging- Part I, Hewlett Packard Journal 1983,34:10, 22-26
22. Amin Hanafy, Characterization of Multielement Acoustic Arrays by Acousto-Optic Diffraction Methods, Ultrasonic Imaging 1980 2:2, 122-134
23. Amin Hanafy, Dead Zone Elimination in Acoustic Arrays, Ultrasonic Imaging 1980 2:4, 302-312
24. Amin Hanafy and Mauro Zambuto, Real Time Acoustic Imaging by Holographic Interferometry, Ultrasonic Imaging 1980 2:4, 313-323
25. Amin Hanafy, Vibration Analysis of Single Element Transducer in Acoustic Arrays, Ultrasonic Imaging 1981 3:2, 173-182
26. J. Fleming Dias, Construction and Performance of an Experimental Phased Array Acoustic Imaging Transducer
27. Ultrasonic Imaging 1981 3:4, 352-368.
28. John D. Larson, III, "Apparatus and method for suppressing mass/spring mode in acoustic imaging transducers," U.S. Patent #4240003AHewlett-Packard Company, 1980-12-16.
29. Amin M. Hanafy, "Acoustic electric transducer with shield of controlled thickness," U.S. Patent #4277711A, Hewlett-Packard Company, 1981-07-07.
30. Amin M. Hanafy, "Acoustic electric transducer with slotted base," U.S. Patent #4277712A Hewlett-Packard Company, 1981-07-07
31. John D. Larson, III David G. Miller, "Acoustic transducer with flexible circuit board terminals," U.S. Patent #4404489A, Hewlett-Packard Company, 1983-09-13.
32. J. Fleming Dias, H. Edward Karrer, John D. Larson, III, David A. Wilson, Amin M. Hanafy, "Acoustic imaging transducer," U.S. Patent #4482834A Hewlett-Packard Company, 1984-11-13.
33. John D. Larson, III, "Acoustic image signal receiver providing for selectively activatable amounts of electrical signal delay," U.S. Patent #5187403A Hewlett-Packard Company,1993-02-16.
34. John D. Larson, III, "2-d phased array ultrasound imaging system with distributed phasing," U.S. Patent #US5229933A, Hewlett-Packard Company, 1993-07-20.
35. John D. Larson, III, "Acoustic image acquisition using an acoustic receiving array with variable time delay," U.S. Patent # 5263004A, Hewlett-Packard Company, 1993-11-16.
36. David G. Miller, J.D. Larson, III, "Backing for acoustic transducer array," U.S. Patent #5267221A, Hewlett-Packard Company, 1993-11-30.
37. J.Fleming Dias, "Ultrasonic sensor with starved dilatational modes," European patent 0397958B1, Hewlett-Packard Company, 1995-04-19.
38. J. Fleming Dias, "Method for making integrated matching layer for ultrasonic transducers," U.S. Patent #5511296A Hewlett Packard Company, 1996-04-30.
39. Richard D. Pering, "Acoustic imaging apparatus," U.S. Patent #4116229A, Hewlett-Packard Company, 1978-09-26.
40. Richard D. Pering, "Delay circuit," European Patent #0167157A2 Hewlett-Packard Company,1986-01-08.
41. Richard D. Pering,"Amplitude insensitive delay lines in an acoustic imaging system," U.S. Patent # 4633308A, Hewlett-Packard Company, 1986-12-30.
42. S.H. Maslak, "Acoustic Imaging Apparatus," U.S. Patent #4,140,022, Hewlett-Packard Company,1979-02-20.
43. Maslak, Smithsonian Institution's Videohistory Program (1997) The History of Acuson Ultrasound Machines. Video transcript, p.86.
44. Hanafy, Smithsonian Institution's Videohistory Program (1997) The History of Acuson Ultrasound Machines. Video transcript, p.136-137.
45. S.C. Leavitt, B. F. Hunt, and H.L. Larsen, A Scan Conversion Algorithm for Displaying Ultrasound Images, Hewlett Packard Journal 1983,34:10, 30-34.
46. R. D. Gatzke, J. T. Fearnside and S. M. Karp, "Electronic Scanner for Phased -Array Ultrasound Transducer," Hewlett Packard Journal December 1983,13:20.
47. Hewlett Packard Journal October 1983,34:10.
48. Hewlett Packard Journal December 1983,34:12.
49. Hewlett Packard Journal June 1986,37:20:48.
50. T. L. Szabo, "Miniature Phased-Array Transducer Modeling and Design," Proc. of 1982 Ultrasonics Symp., IEEE Cat #82CH1823-4 SU, pp 810-814z.
51. T.L.Szabo, "Principles of Nonresonant Transducer Design," Proc. of 1984 Ultrasonics Symp., IEEE Cat #84CH2112-1 SU, pp 804-808.
52. T. L. Szabo, "Transducer Arrays for Medical Ultrasound Imaging," Ultrasound in Medicine , eds. F. A. Duck, A. C. Baker, and H. C. Starritt, (Institute of Physics Publishing, Bristol, UK, 1998), pp 91-111.
53. K.E. Guggenberger, "A fiber -optic interferometer for characterizing surface motion of acoustic array," MIT thesis, MIT library.
54. D.J. Powell, G.L. Wojcik, C.S. Desilets, T.R. Gururaja, K. Guggenberger, S. Sherrit, and B.K. Mukherjee, "Incremental "Model-Build-Test" Validation Exercise for a 1-D Biomedical Ultrasonic Imaging Array," Proc. of 1997 Ultrasonics Symp., pp 1669-1674.
55. T. L. Szabo and J. Wu, "A model for longitudinal and shear wave propagation in viscoelastic media," J. Acoust. Soc. Am., 107(5), May 2000, pp2437-2446.
56. M. G. Mooney and M. G. Wilson, "Linear Array Transducers with Improved Image Quality for Vascular Ultrasonic Imaging," Hewlett Packard Journal 1994,45:4, 43-51.
57. M. Schluter, B.A. Langenstein,, J. Polster , et al.,M., "Transesophageal Cross-Sectional Echocardiography with a Phased Array System", Apr. 1982, British Heart Journal, vol. 48: 67–72.
58. R. J. Solomon, M.K. Mason, G. Gruner and J.T. Fearnside, "Transducer Positioning System," Hewlett-Packard Company, US Patent 5181514, 1993-01-26.
59. M.Peszynski, "Rotatable Ultrasound Transducer Finger Probe," US Patent 5598846, Hewlett-Packard Company, 1997-02-04.
60. J. T. Fearnside, "Design Considerationsfor a Transesophageal Probe," Cardiovascular Imaging by Ultrasoundund in Medicine, eds. P. Hanrath, R. Uebis and W. Krebs, (Kluwer Acadmic Publishers, Dorddrecht, the Netherlands, UK, 1993), pp 279-286.

61. F.A. Flaschskampf, R. Hoffman, M. Verlande, W. Schneider, W. Ameling and P. Hanrath, “Initial Experience with Multiplane Transesophageal Echo-Transducer: Assessment of Diagnostic Potential,” European Heart Journal (1992) 13:1201-1206.
62. Y. Yamashita, “Large Electromechanical Coupling Factors in Perovskite Binary Material System,” Japanese Journal of Applied Physics, 33(1(9B)),1994,pp 5328-5331.
63. T.R. Gururaja, Jie Chen, T.L. Szabo, M. Greenstein and P. Lum, “Medical Ultrasound Imaging Using PMN-PT and PZN-PT Single Crystals with Extremely High Electromechanical Coupling Constant,” Proposal submitted to Wallace. A. Smith, Office of Naval Research, January 27, 1998.
64. T.R. Gururaja, R.K . Panda, J. Chen and H. Beck, “Single Crystal Transducers for Medical Imaging Applications,”
65. J. Chen, R. Panda, P.G. Rafter and T.R. Gururaja, “Wideband Piezoelectric Transducer for Harmonic Imaging,” US Patent 6,532,819 B1, 2003-18-03, originally assigned to Agilent Technologies, now held by Philips.
66. J. Chen, R. Panda, and B. Savord, “Realizing dramatic improvements in the efficiency, sensitivity and bandwidth of ultrasound transducers,” Philips white paper, 2006.
67. P.A. Magnin, A Review of Doppler Flow Mapping Techniques, Proc. of 1987 Ultrasonics Symp., pp 669-677.
68. S. C Leavitt "Method and apparatus for ultrasonic color flow imaging," US Patent 6,370,264, 2002-04-09, assigned to Hewlett Packard.
69. S. C Leavitt, “Method and apparatus for signal dependent gain control,” US Patent 5,063,931,1991-11-12, assigned to Hewlett Packard
70. S. C Leavitt, D. Lipschutz; S.E. Lincoln; K.Thiele; and P.A. Magnin;“Flow imaging detector,” US Patent 4,790,323, 1988-12-13, assigned to Hewlett Packard.
71. T. L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, pp 243-247.
72. B. Savord and R. Solomon, “Fully Sampled Matrix Transducer for Real Time 3D Ultrasonic Imaging,” Proc. of 2003 Ultrasonics Symp., pp 945-953.
73. John D. Larson, III , “2-d phased array ultrasound imaging system with distributed phasing”, US Patent 5229933A, 1993-07-20, originally assigned to Hewlett Packard later to Agilent Technologies Inc , expired.
74. B.J. Savord, “Beamforming methods and apparatus for three-dimensional ultrasound imaging using two-dimensional transducer array,” US Patent 6013032A, 2000-01-11 originally assigned to Hewlett Packard, now held by Philips.
75. B. J Savord, and K. E Thiele, “Phased array acoustic systems with intra-group processors,” US Patent, 5997479A, 1999-12-07, originally assigned to Hewlett Packard, now held by Philips.
76. R. J Solomon, “Two-dimensional ultrasound phased array transducer” US Patent6894425B1, 2005-05-17, Koninklijke Philips Electronics N.V.
77. Daane, L; Greenstein, M A demountable interconnect system for a 50 x 50 ultrasonic imaging transducer array,” IEEE TRANS. UFFC 44(5),1997, pp978-982
78. Michael Greenstein, EP JPH0779498A “Z-axis conductive laminar backing layer for acoustic transducer”, 1995-03-20, Hewlett Packard Co
79. M. Greenstein, “Electrical interconnecting method for multilayer transducer element in two-dimensional transducer array”, US Patent JPH07170600A, 1995-07-04, Hewlett Packard Co
80. T.L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, pp409-411.
81. http://www.aapm.org/meetings/amos2/pdf/59-17272-97172-944.pdf ,accessed 3/23/2021.
82. C Leavitt, J. R Fallon, M. P Anthony, T. P Fazioli, and C. R Dowdell,, "Portable, configurable and scalable ultrasound imaging system," US Patent 6,540,682B1, 2003-04-01, now held by Philips.
83. S.C. Leavitt, B. J Savord, B. M Herrick, J. R Fallon and M. Mooney, "Sub-beamforming apparatus and method for a portable ultrasound imaging system," US Patent 6,491,634B1, 2002-12-10, originally assigned to Agilent Technologies, now held by Philips.
84. https://www.usa.philips.com/healthcare/sites/lumify, accessed 3/23/2021.
85. T.L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, pp234,246-247.
86. L. M. Hinkelman, T. L. Szabo, and R. C. Waag, "Measurements of ultrasonic pulse distortion produced by human chest wall," J. Acoust. Soc. Am. 101(4), April 1997, pp 2365-2373.
87. T. L. Szabo and D. R. Burns, "Seismic Signal Processing of Ultrasound Imaging Data," Acoustical Imaging Volume 23. , eds. S. Lees L.A. Ferrari, (Plenum Press, New York, 1997), pp131-136 .
88. http://www.fundinguniverse.com/company-histories/acuson-corporation-history/ ,accessed 3/23/2021.
89. https://www.ob-ultrasound.net/acuson_a.html ,accessed 3/23/2021.
90. T.L. Szabo, Diagnostic Ultrasound Imaging: Inside Out , Elsevier, Oxford, 2014, pp12-13 and Figure 1.12.
91. Maslak, Smithsonian Institution’s Videohistory Program (1997) The History of Acuson Ultrasound Machines. Video transcript, p110.
92. Jedrzejewicz, Smithsonian Institution’s Videohistory Program (1997) The History of Acuson Ultrasound Machines. Video transcript, p.224
93. S.H. Maslak ,”Perspectives on Starting and Running a Medical Ultrasound Company,” Proc. of 2002 Ultrasonics Symp., pp 1534-1539.
94. S.H. Maslak, “Computed Sonography”, Ultrasound Annual 1985, R.C.. Sanders and M.C. Hill, eds., Raven Press, New York, 1985.
95. J. N. Wright,” Resolution issues in medical ultrasound,’ Proc. of 1985 Ultrasonics Symp., pp 793-799.
96. S.H. Maslak and H. G. Larsen, “Dynamically focused linear phased array acoustic imaging system, US patent 4699009A,,1985-12-17, assigned to Acuson, now held by Siemens.
97. Hewlett-Packard Co. v. Acuson Corp., No. C-93-0808 MHP, 1993 WL 149994 at *2 (N.D. Cal. May 5, 1993)
98. Amar Bhidé, Srikant Datar Katherine Stebbins, Case Histories of Significant Medical Advances: Ultrasound, Working Paper 20-003, Harvard Business School, 2019 and 2020.
99. https://money.cnn.com/2000/11/17/deals/agilent/index.htmmoneyweb, accessed 3/23/2021.
100. D. Packard, “The HP Way: How Bill Hewlett and I built our company,” Harper Collins , New York, 1995.

AUTHOR BIOGRAPHY



Thomas L. Szabo, BS, MS, PhD, has been a Professor of Biomedical and Mechanical Engineering at Boston University since 2001. He started his career doing research on surface acoustic wave devices at AF Cambridge Research Laboratories. While investigating the imaging of coal seams in the UK at Oxford University for a year, he decided to pursue medical imaging. He joined Hewlett Packard in Andover, MA in 1981 to conduct research and development on diagnostic ultrasound. His book, "Diagnostic Ultrasound Imaging: Inside Out", second edition, is a widely used text on the science and technology of medical ultrasound. He is a fellow of the ASA and AIUM and a senior life member of the IEEE.

Email: tlszabo@bu.edu"