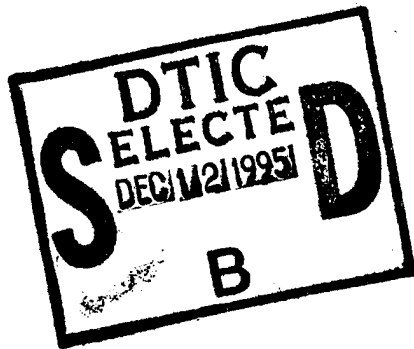


# ARPA/ONR Medical Ultrasonic Imaging Technology Workshop

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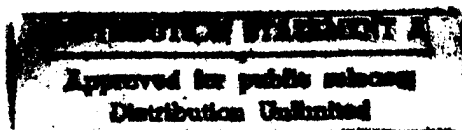


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# *Agenda*



ARPA/ONR Medical Ultrasonic Imaging Technology Workshop  
24-26 January 1995

Tuesday 24 January 1995

- 0800-0820 Perspectives on Planned Defense Programs in Medical Ultrasonics  
F. W. Patten, I. Skurnick, and W. A. Smith,\* ARPA and \*ONR
- 0825-0845 Basic Problems in Aberration Correction  
B. D. Steinberg, University of Pennsylvania
- 0850-0910 Two-Step Aberration Correction  
M. O'Donnell, S. Krishnan, and K. W. Rigby,\* University of Michigan and \*General Electric CRD
- 0915-0935 DISCUSSION
- 0935-0955 COFFEE BREAK
- 0955-1015 Phase Aberrations in Quantitative Ultrasonic Imaging  
J. H. Rose, M. R. Holland,\* M. Bilgen, K. W. Hollman,\* S. A. Wickline,\* and J. G. Miller,\*  
Iowa State University, and \*Washington University
- 1020-1040 Quantitative Three Dimensional Imaging in Ultrasound  
A. J. Devaney, Northeastern University
- 1045-1105 Waveform Aberrations in an Animal Model  
B. S. Robinson, A. Shmulewitz, T. M. Burke, and J. E. Powers, ATL
- 1110-1130 DISCUSSION
- 1130-1230 LUNCH
- 1230-1250 Topics in Ultrasonic Imaging  
D. E. Robinson, Y. Li, D. A. Carpenter, and G. Kossoff, CSIRO
- 1255-1315 Three Dimensional Cardiac Ultrasound — The Next Generation  
R. W. Martin, and F. H. Sheehan, University of Washington
- 1320-1340 Real-Time Ultrasonic Tomography  
M. S. Good, G. J. Posakony, S. R. Doctor, R. J. Littlefield, and M. A. Lind, Pacific Northwest Lab
- 1345-1405 Time for a New Paradigm for Ultrasonic Medical Imaging  
D. Vilkomerson, EchoCath
- 1410-1435 DISCUSSION
- 1435-1455 COFFEE BREAK
- 1455-1515 Volumetric Ultrasonic Assays of Tissue Microstructure and Blood Flow  
F. L. Lizzi, E. J. Feleppa, and K. W. Ferrara, Riverside Research Institute
- 1520-1540 Multiorgan Diagnostic Screening and Minimally Invasive Therapy with Portable Ultrasound  
C. Oakley, L. J. Busse, and D. R. Dietz, Tetrad

*letter  
enclosed*

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A-1

- 1545-1605 Hand-Held Ultrasound  
M. O'Donnell and M. Karaman, University of Michigan
- 1610-1630 High Definition Ultrasonic Imaging  
I. G. Stiglitz, S. R. Broadstone, and G. R. Benitz, MIT Lincoln Laboratory
- 1635-1700 DISCUSSION

**Wednesday 25 January 1995**

- 0800-0820 Factors Affecting the Accuracy and Stability of Adaptive Imaging Using Two-Dimensional Arrays  
G. E. Trahey, Duke University
- 0825-0845 Two-Dimensional Arrays for Medical Ultrasound Imaging  
S. W. Smith, Duke University
- 0850-0910 A Novel Ultrasound Three-Dimensional Approach  
A. Nicoli, N. Butler, T. White, and M. Lasser, Loral Infrared Imaging Systems
- 0915-0935 DISCUSSION
- 0935-0955 COFFEE BREAK
- 0955-1015 "Non-Invasive Surgery" Applied to the Control of Hemorrhage from Blunt Trauma  
Edward C. Driscoll, Jr., FOCUS Surgery
- 1020-1040 Development of Very High Frequency Ultrasonic Imaging Systems  
J. P. Jones, University of California Irvine
- 1045-1105 High-Frequency Acoustic Imaging for Early Detection of Skin Breakdown  
J. E. Sanders, R. A. Roy, and B. S. Goldstein, University of Washington
- 1110-1130 DISCUSSION
- 1130-1230 LUNCH
- 1230-1250 Assessment of Advanced Laser Ultrasonic Technology  
R. M. Grills and A. J. Patrick,\* Ultra Image International and \*Textron Defense Systems
- 1255-1315 Functional Ultrasound  
R. W. Gill, L. S. Wilson, T. Loupas, and G. Kossoff, CSIRO
- 1320-1340 The Use of Diagnostic Ultrasound for Radiolucent Shrapnel Detection and Wound Assessment  
L. A. Crum and R. W. Martin, University of Washington
- 1345-1405 Elastography: Imaging of Tissue Elastic Properties In Vivo  
J. Ophir, I. Cepedes, N. Maklad, B. Garra,\* and H. Ponnekanti  
University of Texas and \*Georgetown University
- 1410-1435 DISCUSSION
- 1435-1455 COFFEE BREAK

- 1455-1515 The New Theory of Sonoelasticity  
K. J. Parker, L. Gao, S. K. Alam, D. J. Rubens and R. Lerner, University of Rochester
- 1520-1540 Clinical Uses of Sonoelasticity  
D. J. Rubens, K. J. Parker, L. Gao, S. K. Alam, and R. Lerner, University of Rochester
- 1545-1605 A New Approach to Remote Ultrasonic Evaluation of Viscoelastic Properties of Tissues  
for Diagnostics and Healing Monitoring  
A. P. Sarvazyan, Rutgers University
- 1610-1630 Medical Ultrasound Image Improvement Opportunities: (1) Improved Battlefield Imaging through  
Correction of Tissue Induced Aberrations; (2) Improved Breast Cancer Detection through Inverse  
Scattering  
S. Johnson, TechniScan
- 1635-1700 DISCUSSION

**Thursday 26 January 1995**

- 0800-0820 Sattelite Telemedicine  
B. K. Stewart and S. J. Carter, University of Washington
- 0825-0845 Net-Shape Piezocomposite Transducers for Ultrasonic Imaging Arrays  
L. J. Bowen and R. L. Gentilman, Materials Systems
- 0850-0910 Ultrasonic Transducer/Array Research at Penn State  
K. K. Shung, W. Cao, W. J. Hughes, J. Meilstrup, T. Shrouf, W. J. Thompson, Jr., and R. Tutweiler  
Pennsylvania State University
- 0915-0935 Science and Technology Based Developments at NRL Related to Medical Ultrasonic Imaging  
H. H. Chaskelis, Naval Research Laboratory
- 0940-1005 DISCUSSION
- 1005-1025 COFFEE BREAK
- 1025-1045 Full Bandwidth Utilization with Digital Beam Forming  
J. E. Powers, R. R. Entekin, and J. Souquet, ATL
- 1050-1110 High-Speed, Low-Power Signal Processors for Portable Medical Ultrasound  
A. M. Chiang, TeraTech Corporation
- 1115-1135 Digital Technology for Medical Ultrasound Imaging  
M. N. Witlin and M. E. Haran, Loral Federal Systems
- 1140-1200 DISCUSSION
- 1200-1300 LUNCH

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# *Abstracts*



## BASIC PROBLEMS IN ABERRATION CORRECTION\*

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Aberrated ultrasonic wavefronts produce aberrated images. Aberration arises from two processes, incoherent scattering and coherent interference. Local speed perturbations about the average propagation speed in tissue are responsible for scattering. Discreet jumps at or across tissue boundaries cause the latter.

For totally unrelated physical reasons the spatial extent of these phenomena are much the same. Both scattered fields and multipath arrivals from, say, refraction cluster about the direct path with radii of a few degrees. Consequently, it is easy to confuse the two. Worse still, the total distortion field appears highly complicated structurally because it is the coherent sum of fields caused by at least two different types of independent phenomena. The scattered field produces a clutter-type halo about the direct return from a target, much like atmospheric humidity causes a ring around the moon. Coherent interference produces distinct multipath arrivals.

Because both fields cluster close to the path of the direct target echo, broad beams from small transducers tend to resolve neither. The high resolution echoscanners of the next generation (large, 2-D array systems), however, will be plagued with loss of contrast due to scattering and to false targets due to multipath. Adaptive phase deaberration corrects the former to a large extent (15-20 dB). It does nothing for the latter.

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\* Presented at ARPA/ONR Medical Ultrasonic Imaging Technology workshop, Lansdowne VA, 24-26 January 1995.

## TWO-STEP ABERRATION CORRECTION

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The phase sensitive signal recorded by a transducer array can be used to compute the cross-correlation function between all nearest neighbor element pairs. From these measures, the phase error function across the array can be estimated. Corrected images can then be formed by offsetting beam forming delays on both transmit and receive according to the measured error function. A phased array imaging system capable of real-time phase aberration correction has been constructed to test the method. Results, including real-time corrected images, will be presented demonstrating the potential for aberration correction with this system.

If aberrations can be accurately modeled simply as time delay, or phase, errors, then correlation processing, as implemented in the real-time scanner described above, can provide nearly ideal corrections. Recent work from several laboratories, however, has questioned whether a simple phase screen model is adequate to describe aberrations in medical ultrasound. These studies show that both the amplitude and phase vary across the aperture. A more complete phase aberration correction system, therefore, must correct for both phase and amplitude errors to minimize the effect of index of refraction variations on large array image quality.

To overcome the limitations of the correlation based method, we have examined additional aberration correction schemes minimizing the effects of both amplitude and phase errors. The most successful is a two-step procedure. First, major phase aberrations are removed with the correlation based system. Then, an adaptive compensation routine is applied to remove beam forming artifacts due to amplitude aberrations and any residual phase errors. The adaptive routine, called PARCA (Parallel Adaptive Receive Compensation Algorithm), minimizes image artifacts due to imperfections not corrected by the correlation-based method.

Experimental results on 128 and 64 channel systems will be presented for two different tissue equivalent phantoms to highlight some of the benefits and limitations of aberration correction using PARCA. Overall, the compensation algorithm is able to fully recover image quality for moderate phase and amplitude aberrations. These results strongly suggest that the two-step procedure should produce a robust system for full aberration correction in medical ultrasound.

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## PHASE ABERRATIONS IN QUANTITATIVE ULTRASONIC IMAGING

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The premise that underlies this presentation is that cross-fertilization between the medical and materials communities may contribute to successful approaches for overcoming limitations to ultrasonic imaging imposed by phase aberrations in inhomogeneous, anisotropic media such as soft tissue. ARPA initiated a program in the early 1970's aimed at developing the scientific fundamentals for quantitative nondestructive evaluation (QNDE) that provided significant insights into the effects of phase aberration on ultrasonic imaging. Two-dimensional imaging arrays were developed by two different subgroups (G. Kino at Stanford and K. Lakin, at USC and ISU) in the mid to late seventies. However, the work was abandoned in the early 1980's in part because of significant phase aberrations even in apparently uniform plates of metal. Substantial efforts were devoted to finding alternative methods for flaw characterization based on broadband inverse scattering theory, which led to the development of the inverse Born approximation. However, phase aberrations were also found to be the limiting problem in the successful implementation of these inverse scattering methods. A knowledge of the origin of phase aberrations in metal plates may provide insight into the corresponding medical imaging problem. The most important source of phase variations in structural solids are small (several percent) unknown anisotropies in the sound velocity that arise due to the forging or rolling of the plate. We have reported anisotropies of similar magnitudes in the velocity of myocardial tissue. Rough and irregular surfaces (loosely analogous to subcutaneous fat layers) are a second source of phase variations in metal parts. Irregularities in the shape of the scatterer (such as roughness) can also severely degrade the ability to size the flaw. Several methods have been proposed for the correction of aberrations. One uses a broadband signal and knowledge of the low- and high-frequency asymptotics of the flaw's scattering amplitude, with the low-frequencies determining the centroid of the flaw and the high frequencies determining sharp boundaries of the crack or void. Another method of correction involves inversion of the scattering data using a priori assumptions about the nature of the flaw. Still another approach to reducing phase aberration involves finding a point scatterer that is near the region of interest, and then focusing the array on that known point scatterer. Similar approaches have been discussed in the medical imaging literature and an important variant of the last approach is the time-reversal mirror of Fink et al. We will discuss some of the fundamental physical processes that give rise to phase aberrations and compare the results of several proposed solutions in an effort to make available to the biomedical community some of the results investigated by the QNDE community.

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# Quantitative Three-dimensional Ultrasound Imaging

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January 20, 1995

## ABSTRACT

The general theory of quantitative imaging of three-dimensional, semi transparent (soft tissue) objects using acoustic waves is presented. The theory is developed for the case of transmission type experiments appropriate to ultrasound diffraction tomography but is applicable with minor modifications to reflection geometries appropriate to pulse echo imaging. The imaging problem is formulated from first principles in terms of the three-dimensional acoustic wave equation and is shown to reduce ultimately to an inverse scattering problem. By use of certain linearizing approximations the inverse problem is shown to reduce to a conventional (coherent) imaging problem having a well defined point spread function (PSF) that can be computed in terms of the experimental parameters and imaging geometry. It is shown that this formulation allows quantitative acoustical imaging to be treated completely analogously to coherent optical imaging and, in particular, leads to a characterization of image quality in terms of the PSF and its spatial Fourier transform, the coherent transfer function (CTF). Inherent limitations of three-dimensional imaging are discussed based on the computed PSF for certain canonical geometries. These limitations are shown to be partially overcome by using suites of scattering experiments and/or beam scanning techniques such as focus-on-transmit and focus-on-receive. The talk includes a discussion of the validity of the weak scattering approximations that underlie the imaging model as well as discussion of the use of the wave aberration function for characterizing image quality. The talk is illustrated with simulated experimental results.

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## WAVEFORM ABERRATIONS IN AN ANIMAL MODEL

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A major obstacle facing medical ultrasound is the suboptimal image quality seen in a large percentage of patients due to wavefront distortions imposed by inhomogeneous tissue. More universal application of ultrasound requires that this patient dependency be reduced or eliminated. This is especially important in emergency, battlefield, and other remote applications where size and portability requirements rule out other more costly technologies such as CT or MRI.

Most correction techniques proposed to date assume a simple lensing distortion that can be largely removed by delay corrections. However, none of these techniques have demonstrated significant improvements of *in vivo* images. This can be attributed to three factors:

- the aberrations are not due to simple delay distortions but are the result of spectral, multipath and other distortions,
- the effects are 3D in nature and cannot be compensated using conventional 1D arrays, and
- the implementations tried to date do not have sufficient complexity (delay precision, number of channels, array dimensionality, real-time, etc) to accomplish the goal.

Animal experiments have been performed which verifies the first two of these claims, i.e. that the aberrations are more complicated than pure delays, and that they are 3D in nature and will require 2D arrays to compensate.

Using a live pig model, data was acquired from individual elements of a 48 channel, 2.5 MHz phased array in both transmission and backscatter modes. Analysis of "first arrival" segments revealed arrival time variations of 21 ns RMS, peak correlations below 0.6 (implying spectral distortions), and amplitude variations of 7 dB when the full (13 mm) elevational aperture of the receiving array was applied at the skin surface. Arrival time variations increased to between 41 and 70 nSec RMS (depending on array orientation) when the elevational aperture was stopped down to 1 mm showing the 3D nature of the effect and the averaging due to the larger aperture. In addition, significant "multi-path" energy was observed in the period following the first main arrivals. Delay aberrations were reduced to below 6 ns RMS following removal of the abdominal wall when the full elevational aperture was applied at the liver capsule. Progressive dissection of the abdominal wall layers produced little qualitative improvement in image quality after removal of the subcutaneous fat layer (in the first 1 cm) but noticeable improvements were observed when the entire abdominal wall (4 cm total) was removed.

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## TOPICS IN ULTRASONIC IMAGING.

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Substantial improvements in the quality of ultrasonic images of tissue are likely to come from developments in two areas. The use of true three-dimensional data obtained from a 2-D aperture will reduce the scanning required for the examination of a volume of tissue, and provide the basis for a more complete data set from ultrasonic scanning for more sophisticated display and automated or remote image interpretation. The development of algorithms to correct the aberrations caused by tissue inhomogeneities will provide clearer images, and allow ultrasound to be used with greater diagnostic accuracy on many more people and in a wider variety of conditions. Access to 3-D data will also enhance the performance of aberration correction algorithms. The Ultrasonics Lab. (UL) is currently active in both areas.

In collaboration with GEC-Marconi Systems in Australia we are developing a 3-D ultrasonic imaging system for use in sea-water. It uses a sparse array with an aperture of tens of centimeters and a frequency in the low Megahertz range. The data size dictates that novel, compact image-forming techniques be used, and these are a suitable area for collaborative generic research for medical applications.

Two approaches are being pursued for aberration correction. The STARS system is based on a forward modelling technique, and is directed at removing aberrations caused by superficial tissue overlying the examined area. It operates by imaging the superficial layers, and using *a priori* information to interpret the identity of the anatomical structures imaged to derive a set of corrections to the focussing algorithm. A method based on data redundancy has also been developed which overcomes shortcomings in the existing techniques and allows corrections to be made for aberrations deep in the image. Both techniques have been demonstrated using live human data. Further research is necessary on the properties of tissue which cause aberration and robust algorithms to reduce them.

The CSIRO Ultrasonics Laboratory (previously the Ultrasonics Institute, Australian Federal Dept. of Health) has been involved in Medical Ultrasonics research since 1959. It transferred to the CSIRO (Commonwealth Scientific and Industrial Research Organisation) in 1989, which encourages commercial collaborations.

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## THREE DIMENSIONAL CARDIAC ULTRASOUND - THE NEXT GENERATION

Roy W. Martin, Ph.D. and Florence H. Sheehan, M.D.\*  
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The heart is an elegant but complex three dimensional (3D) organ. Two dimensional (2D) ultrasound allows non invasive assessment but requires complicated mental assemblage of these 2D images to diagnosis abnormality in the 3D heart. The full disease involvement or interrelationship of regionally separated impairment may be overlooked, easily underestimated, or misunderstood. Three dimensional ultrasound offers the potential to provide a more complete analysis of the size, shape, and function of the left ventricle, mitral valve, and other structures. It also provides a powerful form for studying the interrelationship of the individual regions of the heart and how disease effects these. Moreover, it provides a format in which less training is required to quickly learn and understand cardiac function and perhaps perform diagnoses. In the mid 1970's investigators at the University of Washington began exploring the use of 3D imaging for this application. Later, in the mid 1980's, the current team began investigating transesophageal 3D cardiac imaging (3D TEE) by developing a 3D scanning probe that could be placed in the esophagus. Since that time we have made advances in 3D probes, 3D data acquisition and in 3D image analysis and display. We summarize these areas:

1. A dual axis multiplane transesophageal echo probe has been recently designed and built for more complete 3D image acquisition and which includes means for external body reference location.
2. A miniaturized 3D spatial and 3D angular (6D) location device which uses magnetic techniques has been developed to allow complete visualization of any cardiac structure from multiple windows and subsequent assembly of all imaging planes in 3D space.
3. A multimedia workstation has been assembled for automating the acquisition of respiratory and electrocardiographically gated ultrasound images in digital format, and for facilitating their coordinated analysis.
4. Semiautomatic procedures have been coded for image segmentation.
5. Methods have been developed for 3D reconstruction of the left ventricle and mitral valve apparatus (including stereographic projection) and for analysis of parameters such as regional wall motion in 3D and mitral valve annular dimensions.
6. Finally, procedures have been worked out for experimental clinical validation of equipment function and the accuracy of calculated parameters. We have dedicated laboratories for probe development and in vivo animal experimentation, as well as access to patients in three major medical centers.

Our investigative team consists of participants from cardiology, anesthesiology, surgery, bioengineering, electrical engineering and statistics/morphometrics. The University of Washington team's approach to 3D imaging and analysis is at the forefront in developing the methodology for complete structural and functional characterization of the heart. This methodology has a long range potential in clinical diagnosis and treatment assessment, for example in the evaluation of patients undergoing cardiac surgery and in developing and evaluating new surgical procedures.

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## REAL-TIME ULTRASONIC TOMOGRAPHY

by

MS Good, GJ Posakony, SR Doctor, RK Littlefield and MA Lind

Inexpensive, portable diagnostic imaging systems can play a key role in decreasing battlefield fatalities and reducing the cost of military and civilian health care. Fast inexpensive computing technology will facilitate major breakthroughs in health care based on advanced diagnostic imaging. The evolution of 2-D acoustic transducer array technology with its associated beamforming electronics and reconstruction procedures will offer major improvements in both image resolution and quality by use of combined reflection and transmission modes to correct for aberrations in ultrasound propagation. One can envision an imaging "bed" containing an array of high resolution ultrasonic transducers which will allow the physician to visualize much of the patient's physiology. This bed might be integrated with other modalities (e.g., EKG, EEG, MRI, CAT) to augment and complement diagnostic processes.

In non-medical imaging applications, the use of traditional ultrasound beamformers such as ultra wideband holography and synthetic aperture focusing techniques (SAFT) have demonstrated substantial improvements in signal-to-noise ratios and resolution for 3-D volumetric imaging. A wide variety of signal processing algorithms have been developed to overcome unique problems involving acoustic anisotropy of the media being insonified. But, because most insonifications are aperture limited, the biggest improvements result when the effective aperture is increased.

The standard ultrasonic tomographic imaging approach uses a ring containing many ultrasound transducer elements to eliminate the aperture limitations. This ring forms a 2-D cylindrical array which is coupled to the patient using an expandable water bladder. The advantage of this approach is the regular geometry which permits faster and more accurate reconstruction. A variation in this approach is a flexible 2-D array placed in contact with the patient. The advantage of the flexible array is that it can be quickly applied to any location on the patient. The major difficulties of this approach are determining the accurate location of each transducer and the use of more complex and slower reconstruction processes.

The tomographic approach creates an image by transmitting with a single small element of the array to achieve a divergent ultrasonic field. All transducers receive signals and each transducer is systematically also used as a transmitter. An inversion process is performed on the resulting data to reconstruct a high resolution 3-D volumetric image. The wideband, high aperture insonification coupled with frequency dependent inversion processes including cut and split spectrum algorithms can compensate for the acoustic impedance variations to form high quality images.

The major technology gaps hindering the implementation of real-time 3-D ultrasound tomographic imaging are the fabrication of large (10,000 cm<sup>2</sup>) high density acoustic transducer arrays and availability of faster (100X) inexpensive computers. With inexpensive computation power increasing by 10X every five years, array fabrication is target of opportunity over the next five to ten years.

## TIME FOR A NEW PARADIGM FOR ULTRASONIC MEDICAL IMAGING

David Vilkomerson  
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Present medical ultrasound instruments have evolved into highly effective instruments following a particular paradigm: cross-sectional images are produced at "real-time" frame rates as a skilled operator, the sonographer; manually sweeps a scanhead over the patient's body. The sonographer selects a series of these images to be interpreted by an ultrasound-trained physician, usually a radiologist.

This paradigm was evolved when the only way to integrate the scanned information into a meaningful model of three-dimensional anatomy was in the mind of a well-trained, highly-experienced observer. Perpendicular cross-sections, known as the transverse and longitudinal views, of the region of interest are interpreted in the observer's mind as normal or pathological structures.

There are now other ways of decoding the scanned information. Modern digital processors can produce three-dimensional volumetric images from backscattered ultrasound. With the proper segmentation of the ultrasound information, i.e. recognition of the differing tissue types encountered by the ultrasound, this information can be presented in a form understandable by inexperienced observers.

We propose that ultrasound imaging systems based on three-dimensional reconstruction of ultrasound data automatically acquired and segmented should be developed. Such systems would require neither sonographers nor ultrasonically trained physicians. These systems would significantly expand the utility of ultrasound, not only in permitting defense applications in a near front-line environment, but in civilian emergency rooms as well. Ultrasound imaging systems like this would expand the usefulness of ultrasound imaging for surgeons and general practice physicians, improving health care and reducing costs.

In this presentation, we will discuss the three major elements of such a new ultrasound system: automatic volumetric scanning, tissue identification, and three-dimensional representation of anatomy. Analysis of the system characteristics, e.g. time, needed for automatic scanning, system computing requirements for tissue identification, and system display needs for anatomical representation will be presented. The particular applicability of two-dimensional arrays for such systems will be noted. New uses for such ultrasound imaging will be hypothesized.

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## **VOLUMETRIC ULTRASONIC ASSAYS OF TISSUE MICROSTRUCTURE AND BLOOD FLOW**

**F.L. Lizzi, E.J. Feleppa, K.W. Ferrara**  
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Conventional ultrasonic visualization methods map complex tissue structures into video images whose gray-scale values are not easily related to underlying tissue properties, even in high-resolution images. Several laboratories, including our own, have found that non-conventional processing of radio-frequency (rf) echo signals can extract additional, clinically important information about tissue microstructure. Similarly, non-Doppler flow-measuring techniques are providing additional quantitative information regarding blood flow within tumors and in the surround.

This presentation reviews our recent results to indicate the status of these techniques and to identify research topics warranting further investigation. Our tissue-parameter assays use temporal- and frequency-domain analyses to estimate the effective sizes, concentrations and acoustic impedances of sub-resolution tissue constituents; our blood flow assays employ a mixed-domain method to improve the spatial resolution, accuracy and dynamic range of velocity estimates. Our results in the eye, prostate, and breast indicate that comprehensive assays should include several complementary features. Volumetric 3-D assays are required for reliable differential diagnosis and for sub-classifying individual tumors in terms of potential lethality and likely responsiveness to particular therapeutic approaches. The statistical dispersion of constituent scatterer properties and the presence of sub-regions with different mean properties are of particular importance in these assays. Volumetric multi-parameter assays are also proving crucial in delineating tissue sub-volumes that are successfully modified by treatment modalities including radiotherapy, hyperthermia, and ablation.

Further exploitation of these promising non-conventional methods requires research into: fundamental scattering and propagation topics; advanced signal processing and 3-D analysis procedures; and transducer configurations and insonification patterns tailored to optimize these concepts.

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## MULTIORGAN DIAGNOSTIC SCREENING AND MINIMALLY INVASIVE THERAPY WITH PORTABLE ULTRASOUND

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The greatest potential for impacting combat casualty care is with a hand carried instrument that can be used for organ assessment, to guide therapy, and to reduce blood loss. Of all of the imaging modalities, ultrasound is the best suited for this task. External probes can be used for multiorgan assessment. Laparoscopic probes that guide minimally invasive therapy tools can be used to treat injuries. Communication of video images and 2-D and 3-D ultrasound images of internal organs can enable a surgeon at a remote site to direct the therapy.

There are several important technologies required to implement this type of instrumentation that are under development by Tetrad and that are being used in minimally invasive therapy. Laparoscopic probes of 10mm and 5mm diameter have been developed with accessories for guided therapy. Further developments in transducer technology are needed to reduce cost, to reduce size, and to increase the robustness of these devices for field use. Encoding of laparoscopic probes and surgical ports provides a convenient method for collecting 3-D data sets. Imaging systems with automated controls for use in surgery have been developed. Through customization, hand carried versions become practical. Speckle reduction shows promise in making ultrasound images easier to interpret and to enable 3-D display of internal organs as part of trauma and therapy planning.

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## HAND-HELD ULTRASOUND

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Highly mobile and low-cost ultrasound systems have been manufactured for a long time. They are not routinely used in the clinic, however, because of dramatically reduced image quality compared to the current state of the art in real-time scanners. A high quality, real-time imager must be agile yet maintain good imaging performance, determined primarily by penetration (i.e., electronic SNR), and both spatial and contrast resolution. Agility includes selectable scan formats, Doppler and color flow processing, and advanced signal and image processing. If highly portable systems are to be used routinely, even replacing stationary systems for applications such as combat casualty care, then the overall quality must approach that of current high-end imagers. The primary objective of the work presented here is to develop high quality, real-time ultrasound scanners with dramatically improved portability leading ultimately to hand-held systems (i.e., "Scanman").

Because of the severe power and size constraints of a hand-held device, we have explored synthetic aperture imaging methods. Using both simulations and experiments, a multi-element approach has been tested. This technique uses an active multi-element receive subaperture, and a multi-element transmit subaperture defocused to emulate a single element spatial response with high acoustic power. Echo signals are recorded independently on each element of the receive subaperture. Following acquisition, an image is reconstructed using the complete data set with full dynamic focus on both transmit and receive. Various factors affecting image quality have been compared to conventional imagers through measurements on different phantoms with a 3.5 MHz, 128 element array. Results will be presented showing that multi-element synthetic apertures achieve higher electronic SNR and better contrast resolution than conventional synthetic apertures. Moreover, image quality approaches full phased array performance but with an order of magnitude less electronic channels.

Although providing good image quality with reasonable electronic SNR, synthetic imaging methods are subject to motion artifacts. To minimize this, we have examined an overlapping subaperture technique to estimate motion during data acquisition. Results of initial experiments using this method will also be presented.

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# HIGH DEFINITION ULTRASONIC IMAGING

*Irvin G. Stiglitz, Steven R. Broadstone, Gerald R. Benitz  
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High Definition Imaging (HDI) techniques have been developed at M.I.T. Lincoln Laboratory for processing radar data, that provide an order of magnitude improvement in spatial resolution, suppression of artifacts due to scattering sources and clutter and the elimination of the sidelobes of the array response. Initial applications of these techniques for ultrasonic image processing has produced encouraging results. With HDI, quantitative estimates of the scattering characteristics of objects are obtained by confining the ultrasonic reflections to a one-dimensional, "ice-pick", view into the medium. The improvement is made without the loss in resolution that accompanies conventional techniques obtained using array apodization or shading. Early exploitation of these techniques have shown that HDI gives improved performance in the detection and identification of point-like objects in controlled environments (water and gelatin-filled medical phantoms) using a 32-element ultrasonic array at a frequency of 3.5 MHz. For these cases, ultrasonic data processed with the conventional methods obtained a lateral scattering resolution of several centimeters; HDI processing of the data improved the lateral resolution to 750  $\mu\text{m}$ . This improvement allows the detection of low-level scatterers that are near other features, thereby providing more accurate measurements of anatomical features.

## **FACTORS AFFECTING THE ACCURACY AND STABILITY OF ADAPTIVE IMAGING USING TWO-DIMENSIONAL ARRAYS**

*G. E. Trahey, Ph.D.*

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Most adaptive imaging schemes proposed for clinical ultrasound involve two steps: 1) measurement of arrival time profiles across the two dimensional receiver array and 2) correction of the timing of transmitted and received ultrasonic signals based on the measurements in (1). Achieving coherence across the entire two dimensional array surface over hundreds of element locations is made difficult by a number of factors including 1) echo signal decorrelation across the receive array resulting from the diffuse nature of tissue scatterers, 2) the limited depth of field of transmitted ultrasonic pulses, 3) the accumulation of timing errors across the array surface, 4) nonuniformities in elements' transfer functions, and 5) acoustic and electronic noise.

We present analytic, simulation, and experimental results which illuminate the significance of each of these factors in adaptive imaging with 2-D arrays. The impact of array geometry, algorithm selection for arrival time profile estimation, aberrating layer position, and tissue characteristics are also discussed. Schemes to improve image resolution and stability are presented.

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## TWO-DIMENSIONAL ARRAYS FOR MEDICAL ULTRASOUND IMAGING

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Two-dimensional arrays are critical to the future of medical ultrasound for focusing and phase aberration correction in two dimensions as well as high speed volumetric imaging. Two major problems in the development of 2-D arrays include fabrication difficulties and low sensitivity. The element size ( $< .35 \text{ mm} \times .35 \text{ mm}$ ) results in small clamped capacitance and high electrical impedance. Fabrication problems can be solved using multi-layer flexible circuit connectors consisting of polyimide layers  $< 25 \text{ } \mu\text{m}$  thick. Sensitivity can be dramatically improved by reducing the array element impedance using an N layer structure of PZT connected electrically in parallel and acoustically in series. The clamped capacitance is multiplied by  $N^2$  and the impedance by  $1/N^2$  compared to a single layer control element. KLM and finite element computer simulations as well as laboratory experiments show reduction of element source impedance to  $10 \text{ } \Omega$  and SNR increases of up to 40 dB for 2-D array transducers. In vivo scans using multi-layer PZT also show significant improvements.

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## **A NOVEL ULTRASOUND THREE-DIMENSIONAL APPROACH**

**January 1995**

**A. Nicoli, N. Butler, T. White, M. Lasser  
Loral Infrared & Imaging Systems  
Lexington, Massachusetts 02173**

### **ABSTRACT**

Loral has demonstrated a 42 x 64 element ultrasonic receiving array. By overcoming the problem of interfacing the transducer elements with the sensor a major constraint is lifted from the system designer. By employing manufacturing and microelectronic multiplexing techniques originally developed for infrared imaging focal planes, Loral can make densely packed ultrasound arrays and capture (sample) the return signal from all elements at precisely the same time or at predetermined delay intervals. This paper will present the implications of this capability as seen by newcomers to the ultrasound community, as well as suggesting and seeking further improvements.

Silicon multiplexers and detector arrays of other materials have been fabricated for the military for many years. The techniques required are similar to those needed for large area ultrasound transducer arrays. With these techniques the limitations cease being detector wiring and related interface issues such as A/D conversion. A fully populated 128 x 128 transducer array with 4 to 6 mil elements is reasonable with existing technology. The primary constraints now are integrated circuit size (as determined by circuit yield and cost) and signal processing rate.

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**"NON-INVASIVE SURGERY "APPLIED TO THE CONTROL OF  
HEMORRHAGE FROM BLUNT TRAUMA**

Edward C. Driscoll, Jr., PhD.

FOCUS Surgery, Inc.

225 Hammond Ave., Fremont, California 94539

FOCUS Surgery has been developing technology for "Non-Invasive Surgery" based on High Intensity Focused Ultrasound (HIFU). Initial commercial applications are being pursued in the destruction of diseased tissue in benign and malignant disorders. The lethal tissue effect is principally the result of dramatic, rapid heating leading to coagulative necrosis in as little as fractions of a second, and with the precision of a few cell diameters. Moreover, this technology can non-invasively deliver useful, controlled and localized energy to soft tissue in the body for other beneficial applications. One potential example is to stimulate or promote localized coagulation non-invasively. This could be useful to control cases of internal hemorrhage. In battlefield conditions, it has been reported that a significant source of mortality is uncontrolled hemorrhage from blunt trauma in the first hours after injury. Furthermore, conventional surgical repair of diagnosed hemorrhage can often be difficult. Similar circumstances apply to civilian trauma cases. We believe our technology can be used to non-invasively target and coagulate tissue volumes that are experiencing hemorrhage, allowing for the stabilization of the patient and later surgical repair. This may be accomplished by optimized application of HIFU alone or in conjunction with pharmacologic agents.

Our presentation will cover the basic technology, capabilities and clinical trial status of our initial markets, and an overview of our research interests directed to this new application.

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## DEVELOPMENT OF VERY HIGH FREQUENCY ULTRASONIC IMAGING SYSTEMS

JOIE PIERCE JONES

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Irvine, CA 92717

Conventional medical ultrasound imaging systems operate between 1 and 10 MHz, frequencies chosen as trade-offs between resolution and depth penetration. Recently a number of new application areas have been developed at higher frequencies. For example, systems for intravascular and dermatological imaging operate at 20 to 50 MHz. In addition, acoustical microscopy (100 MHz-1 GHz) is proving to be a useful technology for both fundamental as well as diagnostic studies. Here we make the case that the development of very high frequency (50-500 MHz) ultrasonic imaging technology utilizing recent developments in thin film transducer design could lead to a variety of new application areas and systems ranging from new research tools to new and more cost effective diagnostic instruments to simple devices that could be used in the field. Application areas include evaluation of burns and wounds; imaging of the skin; intravascular and laparoscopic imaging; and *in situ* and *in vitro* acoustical microscopy.

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## HIGH-FREQUENCY ACOUSTIC IMAGING FOR EARLY DETECTION OF SKIN BREAKDOWN

J.E. Sanders, R.A. Roy, and B.S. Goldstein  
University of Washington, Seattle, WA 98195

In persons with spinal cord injury (SCI), pressure sores are a source of tremendous physical and emotional distress. They often result in increased disability and they can lead to an early death. Pressure sores occur in 35% to 40% of SCI patients at an estimated treatment cost of \$25,000 to \$50,000 per pressure sore.

Although the exact pathophysiology and development of pressure sores is unknown, a general understanding of the basic biologic events has slowly accumulated over the last 30 years. From prolonged sitting with minimal weight-shifting, excessive pressure and shear are induced, especially at bone/soft tissue interfaces, which cause blood and lymph vessel occlusion. Prolonged loading leads to tissue ischemia and necrosis and ultimately atrophy of superficial muscle, fat, and skin. Tissue reorganization, clinically evident as a macroscopic change in shape and distribution, can displace tissue away from bony sites. A sterile abscess or cyst deep in the muscle may form. Observed pathological changes in animal models include a loss of cross-striations in muscle and a reduction in the number of myofibrils; hemorrhage into loose connective tissue; cellular infiltrate within muscle; and a reduction in collagen fiber structures. Finally, skin begins to discolor and ultimately a pressure sore becomes visually apparent. There is a critical clinically-observed characteristic about this process: Once a pressure sore is recognized by clinical examination, extensive tissue damage and necrosis have already occurred. Frequently, the extent of ischemia and injury is already into deep and adjacent muscle tissue and extensive surgical repair is required.

We propose that high-frequency acoustic imaging could be used to image the early part of the degeneration process, thereby providing a way to identify non-invasively any sites at risk for pressure sore formation. Early detection would allow early treatment which would substantially reduce the suffering and expense associated with pressure sores. There is compelling evidence that high frequency ultrasound is a most appropriate imaging modality. Though measurements to date lack sufficient resolution for the purposes of early pressure sore detection, skin and muscle thickness and shape measurements have been made at 7.5 MHz. Similarly, substantial loss of muscle fiber striation patterns and presence of cellular infiltration have also been shown detectable, as have midsize-to-large sterile abscesses and hematomas. What is needed to facilitate the application of ultrasound technology to pressure sore detection is a unit with increased resolution. Penetration depths beyond 1 cm are not necessary since the pressure sores occur near the skin surface. With these specifications, it is clear that high-frequency ultrasound (>25 MHz) is potentially applicable. This should allow detection of small sterile abscesses and hematomas, while a frequency of >50 MHz should pick up collagen architectural changes and muscle striation alterations. Both narrow-band and broad-band modalities should be considered, as well as the role of changing frequency, angle of incidence, and scattering angle. Such a device, which could be manufactured inexpensively, would ideally be very portable (hand held) and designed specifically for the early detection and characterization of evolving pressure sores.

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## ASSESSMENT OF ADVANCED LASER ULTRASONIC TECHNOLOGY

Robert H. Grills  
Ultra Image International  
Science Applications International Corporation

Alexander J. Patrick, Jr.  
Textron Defense Systems

The use of lasers to generate ultrasonic signals is a well demonstrated technology. This technology has many unique features including non-contact, small focus point, ability to handle small radius of curvatures, and the potential of rapid scanning. However, the acceptance of this technology in the market place has been limited because of the complexity of the resulting hardware, signal processing problems, and the sensitivity of the laser ultrasonic system which limits its acceptance for use in a industrial setting.

Starting in 1988, Textron Defense Systems (TDS) began the development of a low cost, light weight, compact laser ultrasonic unit for industrial applications. The LaserWave™ unit has passed through a series of development activities starting with bench top experiments, prototype units, preproduction units and finally into product status. In 1993, TDS and Ultra Image International (UII) began a joint efforts to combine the LaserWave™ with UII's advanced imaging technology. This presentation will discuss the LaserWave™ ultrasonic accomplishments, UII's advanced imaging technology, and the plans and initial results from the joint development effort.

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## FUNCTIONAL ULTRASOUND

*Robert W Gill, Lawrence S Wilson, Thanasis Loupas, George Kossoff  
Ultrasonics Laboratory, CSIRO Division of Radiophysics  
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Ultrasound, with its dynamic imaging and its capacity to display and characterise blood flow, inherently provides functional information about the patient. With present equipment, however, considerable skill is needed to acquire and interpret this information. In battlefield casualty medicine and civilian emergency care (eg ambulances and hospital emergency rooms) there is a requirement to help relatively unskilled operators to effectively acquire and interpret such functional information.

We propose the development of one or more packages which would integrate within a highly compact ultrasound machine the ability to assess a number of functional parameters, for example on the cardiovascular status of the patient, leading the user through a series of simple steps and assisting with the interpretation of the resulting data. This will require: (a) refinement of existing functional measurement capabilities of ultrasound equipment; (b) the development of new measurement techniques, and their tailoring for specific applications; (c) the development of "smart" ultrasound equipment requiring little or no operator control to optimise the data acquired; (d) standardised measurement protocols to lead the user through a specific series of measurements; (e) computer-aided diagnostic tools to assist in the interpretation of the results of the examination.

As a specific example, consider a system to assess the cardiovascular status of a patient, for example a battlefield casualty, who might be suffering from internal bleeding. A procedure such as the following could be applied: (a) ultrasound imaging is used to search for free fluid (blood) within the peritoneum and pleural spaces and around the kidneys; (b) the status of the heart is assessed, for example by estimating heart rate and cardiac output and obtaining a measure of heart wall contractility; (c) the circulatory system is assessed to identify signs of reduced blood volume and shock, eg by using a combination of colour flow imaging and pulsed Doppler to determine the perfusion of critical organs, such as the kidneys and liver, and blood flow to the limbs; (d) ultrasonic tissue characterisation is used to identify organs or tissue regions suffering from lack of oxygen. Additional measurement facilities could be built into the machine, such as a clip-on oximeter to determine peripheral blood oxygenation.

A second example could be the use of ultrasonic imaging to search for foreign objects such as shrapnel. In addition to the use of smart controls to automate the acquisition of optimum images, the machine could contain a library of normal appearances to assist the user to identify abnormalities, or computer-aided image interpretation could be used to automate this process. The development of computer image interpretation is already well advanced in areas of radiology such as mammography and chest X-ray diagnosis.

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THE USE OF DIAGNOSTIC ULTRASOUND FOR RADIOLUCENT SHRAPNEL  
DETECTION AND WOUND ASSESSMENT.

LAWRENCE A. CRUM  
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and

ROY W. MARTIN  
*Departments of Bioengineering and Anesthesiology  
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In recent military conflicts involving US military personnel, 48% of the wounds were due to fragmentation devices, vs 10% from gunshots. A large percentage of these fragmentation devices are land mines, which are increasingly constructed of non-metallic, radiolucent materials. Consequently, the major efforts of mid-echelon combat casualty care units are to assess the degree of wound injury, to determine if there are destabilizing conditions for the patient (such as uncontrolled bleeding), and to locate entrained foreign objects that may result in subsequent massive infection. Conventional systems such as x-radiography can not detect the presence of radiolucent foreign objects, or physiological conditions such as hematomas, edema, and inflammation. More sophisticated techniques such as CAT and MRI are expensive and not portable. With sufficient modification and development, existing diagnostic ultrasound imaging systems can provide an extraordinary new level of diagnosis in combat casualty care; furthermore, these systems can be made portable, are relatively inexpensive, and would have immediate and broad application to civilian use in emergency rooms and trauma centers. The problem of unexploded ordinance and land mines is also a major third-world problem, with estimates of over 100 million undetected land mines existing and over 50,000 casualties/year occurring. We propose to utilize two new techniques in ultrasound technology--correlation enhancement and sonoelasticity, that would permit the adaptation or modification of the existing technology of diagnostic ultrasound for use in wound assessment and foreign object detection.

The DoD in-force requirements that address these needs are described in NAPDD 297-093, "Advanced techniques and products for combat wound management", promulgated 3/24/92 and NAPDD 295-093, "Fleet health care technology", promulgated 12/3/91.

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## **ELASTOGRAPHY: IMAGING OF TISSUE ELASTIC PROPERTIES IN *VIVO***

*J. OPHIR, I. CESPEDES, N. MAKLAD, B. GARRA+, and H. PONNEKANTI*

*Ultrasonics Laboratory, Department of Radiology*

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*+Department of Radiology, Georgetown University Medical Center,*

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It is well known that tissue elasticity is correlated with pathology. This fact forms the basis for palpation, which is routinely used in the clinic. The drawbacks of manual palpation are low sensitivity, specificity and limited size and depth of the palpable pathology. Some time ago we reported a new ultrasonic method for imaging the elastic properties of tissues in vivo. This method is known as Elastography, and the strain image produced is known as an Elastogram. Briefly, pairs of echo RF signals are acquired immediately before and after the application of a slight axial compression to the tissue. Segments of the echo signals are analyzed pairwise and local axial tissue displacements are estimated. The axial gradient of the displacement is computed. An image (elastogram) of this displacement gradient (strain) is then produced. This method allows imaging of small, deep hard or soft tumors and other pathologies.

As long as the stress field in the tissue remains uniform, the elastogram is proportional to the distribution of tissue elastic moduli. Such uniformity can be assured by correcting for boundary conditions, and so long as the elastic contrast in the tissue remains relatively low. Departure from these conditions produces recognizable image artifacts and less quantitative images.

We have constructed an apparatus for practicing elastography in the breast. It allows a direct comparison between sonograms and elastograms of a given anatomical site. We will demonstrate that (1) elastograms convey new information, and thus the elastographic appearance of breast tumors is different than their sonographic appearance, and (2) that it is possible to elastographically visualize known breast cancers which are poorly visualized or not visualized in sonograms. Other potential applications will also be discussed, as well as the factors affecting elastographic image quality.

Supported in part by NIH grants RO1-CA38515, RO1-CA 60520, and PO1-CA64597, and by a grant from Diasonics Ultrasound, Inc.

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## **THE NEW THEORY OF SONOELASTICITY**

***K. J. PARKER, L. GAO, S. K. ALAM, D. J. RUBENS, R. LERNER***

**Rochester Center for Biomedical Ultrasound — University of Rochester  
Hopeman Building, Room 203  
Rochester, NY 14627**

Sonoelasticity is a rapidly evolving medical imaging technique for visualizing hard tumors and other abnormalities in tissues. In this novel diagnostic technique, a low frequency vibration is externally applied to excite internal vibrations within the organs under inspection. A small stiff inhomogeneity in a surrounding tissue appears as a disturbance in the normal vibration pattern. By employing a properly designed Doppler detection algorithms, a real-time vibration image can be made. A theory for vibrations or shear wave propagation in inhomogeneous tissue has been developed. A tumor or foreign inclusion is modeled as an elastic inhomogeneity inside a lossy homogeneous elastic medium. A vibration source is applied at a boundary. The solutions for the shear wave equation have been found both for the cases with and without an inclusion. The solutions take into account varying parameters such as: inclusion size and stiffness, shape of vibration source, lossy factor of the material and vibration frequency. The problem of the lowest detectable change in stiffness is addressed using the theory, answering one of the most critical questions in this diagnostic technique. Some experiments were conducted to check the validity of the theory, and the results showed a good correspondence to the theoretical predictions. These studies provide basic understanding of the phenomena observed in the growing field of clinical sonoelasticity imaging.

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## CLINICAL USES OF SONOELASTICITY

D. J. RUBENS, K. J. PARKER, L. GAO, S. K. ALAM, R. LERNER

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Two hospitals in Rochester, New York, are currently evaluating sonoelasticity for real-time clinical uses. Evidence is mounting that sonoelasticity is applicable to a variety of organs and complements the information available with conventional B-scan information. The detection of tumors in the prostate, liver, and breast is a primary focus of sonoelasticity. *In-vivo* and *ex-vivo* images compared with pathology results demonstrate that sonoelasticity improves sensitivity and provides a useful demarcation of the tumor-tissue boundary. This work is also extended to the detection of isoechoic foreign particles, for both civilian and military applications. Furthermore, quantitative applications of sonoelasticity are under development, utilizing the resonance behavior of the eye, the liver, and other organs. These are useful for characterizing the time-dependent bulk mechanical properties of tissues, with applications to a broad class of diseases and injuries. Real-time images from clinical studies will be presented to illustrate the state of the art of sonoelasticity.

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**A NEW APPROACH TO REMOTE ULTRASONIC EVALUATION OF VISCOELASTIC PROPERTIES OF TISSUES FOR DIAGNOSTICS AND HEALING MONITORING**

**A. P. SARVAZYAN**

*Department of Chemistry, Rutgers University, New Brunswick, NJ 08903.*

The objective of this research is to develop a new approach to elasticity imaging that could overcome some of the problems hindering development and clinical application of the existing approaches and could provide a shorter and easier way to realize devices for remote evaluation of elasticity and viscosity of tissues for medical applications. A further long term objective is to develop a simple, inexpensive and, possibly, hand-held ultrasonic device which in addition to the civilian health care applications of sonoelasticity, such as detection of hard lumps in breast, will facilitate specialized defense applications, e.g., diagnosis of brain trauma and edema, shrapnel detection, evaluating tissue blood supply, monitoring the healing of neuromuscular system, etc.

The main characteristic feature of the present approach is that mechanical stress needed to obtain measurable strain and evaluate elasticity is produced in a form of highly localized shear waves remotely induced by the radiation force of a focused ultrasound pulse. The frequency of shear waves (typically in the low kHz range) is adjusted such that the volume of tissue involved in this mechanical excitation is of the order of  $1 \text{ cm}^3$ .

We have theoretically estimated that the optimal choice of the parameters of an ultrasonic irradiation system enables one to induce detectable shear oscillations in soft tissues at ultrasonic exposure levels routinely used in commercial pulse Doppler or real-time B-mode and M-mode imaging devices. Model experiments made on tissue phantoms using an ultrasonic system designed for hyperthermia applications were in a qualitative agreement with the theoretical estimates. Currently, a complete theory is being developed that enables one to calculate temporal and spatial parameters of shear waves induced in a tissue with given elasticity by a known ultrasonic field. A laboratory model of the device is being designed and built.

This project is being conducted in collaboration with the Physics Department of Moscow State University, the Institute of Mathematical Problems of Biology of the Russian Academy of Sciences and the Bioengineering Program of the University of Michigan in Ann Arbor.

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I prefer an oral presentation

MEDICAL ULTRASOUND IMAGE IMPROVEMENT OPPORTUNITIES: (1) IMPROVED  
BATTLEFIELD IMAGING THROUGH CORRECTION OF TISSUE INDUCED  
ABERRATIONS; (2) IMPROVED BREAST CANCER DETECTION THROUGH INVERSE  
SCATTERING.

Steven Johnson  
TechniScan, Inc., 958 W LeVoy Dr.  
Salt Lake City, Utah 84123

TechniScan, Inc. has developed methods for removing defocusing, blurring and excess speckle generation and other adverse effects on clinical ultrasound image quality caused by the inhomogeneous variation of tissue acoustic index of refraction. One such method is based on the inverse scattering (I.S.) approach, wherein the wave equation is solved to produce quantitative images of the inhomogeneous speed of sound, absorption and density in terms of the incident field and the measured scattered field. I.S. is particularly useful when measurement of transmitted energy through tissues is possible, such as can be the case for breast imaging. In this case, the imaging and detection of breast cancer is greatly enhanced by use of wide aperture, circumscribing transducers that contribute to an I.S. improvement of 4 to 16 times (depending on lesion depth) in spatial resolving power over present clinical methods at the same frequency.

A second method, synthetic focusing, reflectivity imaging provides 3 to 12 times improved spatial resolving power. These methods have been implemented and validated with laboratory data using test objects and tissues.

A third method, based on global cross correlation functions, has undergone limited tests using computer simulated data and gave improved performance over present "phase aberration correction methods". This method was designed to correct for 2-D refraction everywhere in the reflectivity image, and not just in a "phase shift compensation layer" next to the transducer. It also has given an independent, accurate, but low band passed filtered, 2-D image of refractive index to complement the reflective image.

Laboratory mechanical and electronic scanners have been constructed to explore 3-D and real time data acquisition for future clinical applications of these methods. The Technology is also being applied in Sonar/Mine detection.

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Oral Presentation preferred. Poster Presentation acceptable  
Overhead Projector needed.

*Sattelite Telemedicine*

*B.K. Stewart and S.J. Carter, University of Washington*

*Unavailable at time of printing*

## NET-SHAPE PIEZOCOMPOSITE TRANSDUCERS FOR ULTRASONIC IMAGING ARRAYS

L. J. BOWEN and R. L. GENTILMAN,  
Materials Systems Inc.  
521 Great Road, Littleton, MA 01460.

Piezoelectric ceramic/polymer composites, originally developed under ONR funding for Navy applications, have found commercial application in medical ultrasound as imaging transducers operating at megahertz frequencies. The medical transducer industry uses dice-and-fill methods for producing the very fine piezoelectric ceramic elements required in a typical imaging array. Although this manufacturing method has served the industry well for over ten years, future requirements for higher operating frequency and 2D layout will require extremely fine elements, improved control of interelement coupling and crosstalk, and advanced array designs that challenge the capabilities of dicing technology.

Under ONR and ARPA funding, Materials Systems Inc. has developed net-shape ceramic injection molding processes for cost-effectively manufacturing complex arrays of the fine PZT ceramic elements required for advanced composite transducers. Net-shape formed piezocomposites are now becoming available in commercial quantities for the first time, allowing new transducer configurations to be developed for medical ultrasound and nondestructive testing, as well as undersea imaging, surveying, sensing, and actuation.

In this presentation, Materials Systems Inc. briefly introduces its PZT injection molding manufacturing process, and then reviews the capabilities of the process for fabricating various composite transducer designs relevant to high frequency medical ultrasound. Recent information on directly producing complex composite element layouts is presented. Additional capabilities, anticipated to become commercially available within the next one to two years, include extremely fine PZT element dimensions ( $<25\mu\text{m}$ ), high PZT volume fraction, new polymer matrix materials, improved dimensional control, large area devices, and greatly reduced cost.

The challenges involved with integrating this composite manufacturing approach into medical ultrasound systems are reviewed, and opportunities considered for applying injection molding to enhance the performance of future medical ultrasound transducer arrays.

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## Ultrasonic Transducer/Array Research at Penn State

*K. Kirk Shung, Wenwu Cao, W. Jack Hughes, Jon Meilstrup,  
Tom Shrout, William Thompson, Jr. and Richard L. Tutwiler  
Whitaker Center for Medical Ultrasonic Transducer Engineering  
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A Center for Medical Ultrasonic Transducer Engineering has been established at the Pennsylvania State University, University Park, PA, supported by a "Biomedical Engineering Special Opportunity Award" from the Whitaker Foundation, Washington, DC and contributions from ultrasonic imaging equipment manufacturers. The missions of the Center are (1) to pursue state-of-the-art research in ultrasonic transducers and arrays for medical applications by building upon the existing strengths in ultrasonic imaging, piezoelectric materials, and sonar array technology at the University, (2) to be a center of education for training ultrasonic transducer design engineers, and (3) to serve as a technology resource for ultrasonic imaging equipment and transducer manufacturers.

There are a variety of research projects currently underway at the Center which is equipped with all necessary transducer fabrication, modeling, and testing facilities including an Optison<sup>®</sup> real-time Schlieren system, a wafer dicing saw, a Paryline coating system, and the FLEX finite element analysis software. The major research efforts include the development of linear arrays of frequencies higher than 20 MHz based on fine grain PZT and single crystal relaxor materials, finite element analysis and experimental validation of interactions among elements in arrays and piezoelectric posts in composite materials, and developments in multidimensional arrays and associated beam forming electronics. Commercial PZT which has grain size approaching element size of high frequency arrays or post size of high frequency composites is deficient in these applications whereas interactions among elements or posts severely degrade the performance of an array and should be better understood. Other multidimensional array approaches such as hexagonal array that have been used in microwave and underwater acoustics and more flexible beam forming architecture should be explored. To facilitate these endeavors, a multifunctional electronic testbed will have to be developed. Recent progress that has been made in these efforts will be reviewed and future work discussed.

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# SCIENCE AND TECHNOLOGY BASED DEVELOPMENTS AT NRL RELATED TO MEDICAL ULTRASONIC IMAGING

H. H. Chaskelis

Mechanics of Materials Branch

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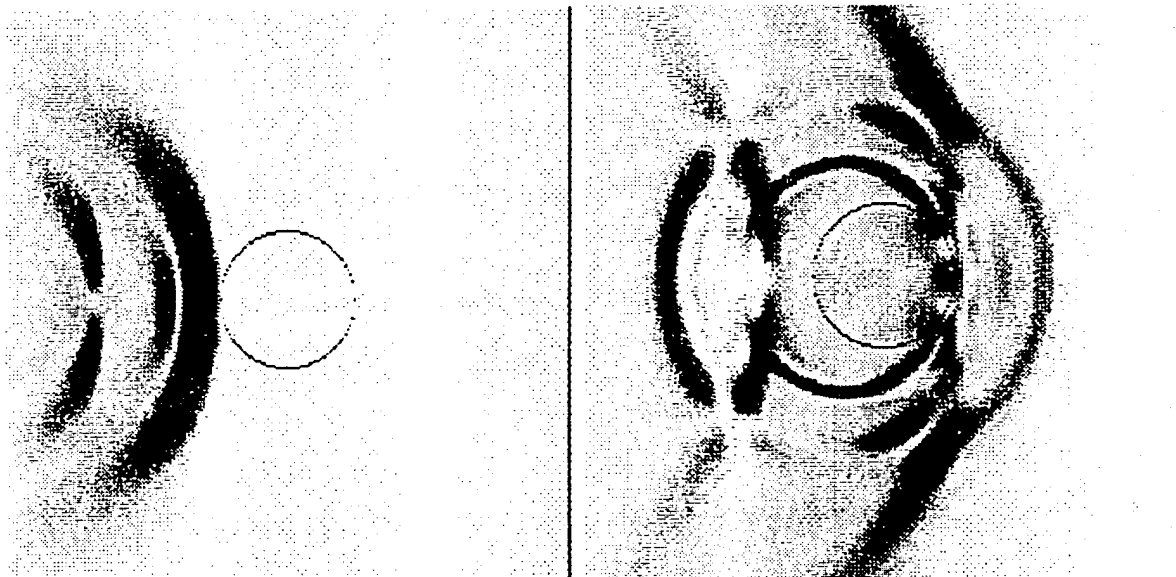
This presentation will highlight technological advances at NRL which may significantly impact the development of improved medical ultrasonic imaging capabilities. Included will be the following:

2-Dimensional acoustic wave simulator using parallel processing techniques.

Tomographic reconstruction approaches.

Transducer evaluation methods

Propagation in highly attenuative media



Simulations of acoustic waves in solid medium

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I prefer an oral presentation and will require VCR/monitor

## FULL BANDWIDTH UTILIZATION WITH DIGITAL BEAMFORMING

J. E. POWERS, R. R. ENTREKIN, J. SOUQUET

*Advanced Technology Laboratories*

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Recent advances in transducer technology have greatly increased the bandwidth that can be achieved with medical imaging ultrasound transducers. Using state of the art digital ASIC technology this bandwidth, and hence information content, can be maintained through the beamformation process. These advances in technology, combined with greatly increased digital signal processing power allow novel imaging techniques not possible with previous narrow band designs. We will discuss two techniques which have only recently become feasible within commercially produced ultrasound systems.

Speckle noise is a well known artifact of medical ultrasound images which results from the coherent beamformation process. It reduces contrast resolution, makes the image more difficult to interpret, reduces the effectiveness of compression techniques, and complicates image segmentation for 3D and automated target recognition. Image processing techniques used to smooth speckle typically blur the image decreasing detail resolution. Reducing the speckle noise without reducing spatial resolution requires averaging independent estimates of tissue backscatter at every location. This can be accomplished by acquiring the image using multiple independent frequency bands to provide uncorrelated backscatter estimates, and averaging the results.

Conversely, ultrasound bandwidth can also be used to eliminate the signal from tissue which complicates blood flow detection in moving organs. Recently developed ultrasound contrast agents consist of tiny stabilized air bubbles which resonate at typical medical imaging frequencies. At resonance, these bubbles become nonlinear, producing harmonics and subharmonics of the interrogating frequency. This gives the agent a signature allowing it to be distinguished from the surrounding tissue by a characteristic other than velocity, the signature used by Doppler and color flow techniques. By transmitting at one frequency and receiving at twice that frequency, signal to clutter increases of 15-20 dB have been demonstrated.

These new developments in medical ultrasound point the way to a new generation of products with capabilities not possible with previous, narrowband processing. These might include adaptive beamforming, automated measurements, and tissue characterization.

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## HIGH-SPEED, LOW-POWER SIGNAL PROCESSORS FOR PORTABLE MEDICAL ULTRASOUND

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Medical ultrasound, or ultrasonography, is a safe, effective and widely used diagnostic imaging modality. However, even state-of-the-art high-end phased-array ultrasound systems are based on a twenty-year old design to which only incremental improvements have been made. Systems are expensive, heavy, necessitating transport on a cart, and more importantly, image quality is well below what is theoretically possible. The opportunity exists for making significant advances in ultrasound technology, both in terms of improving image quality, providing flow imaging with better Doppler resolution and in reducing size, power consumption and cost of hardware. Furthermore, a portable, low-power, high-resolution ultrasound can be used to improve care to trauma cases such as a wounded soldier on battlefield or an injury at remote location. Future enhancements to the portable system can be videocompression of the images, so the diagnostic information obtained by the emergence medical professionals can be linked through wireless digital communication to the control center for decision support.

The need for high-throughput signal processors in an ultrasound is ubiquitous. For example, a large number of delay-and-sum circuits are needed for dynamic beamforming, a pulsed-Doppler processor is needed for providing range-and-Doppler information in a flow imaging, a bank of finite-impulse-response filters are needed to provide spatial interpolation for better range resolution, a 2-D transformation device is needed for spatial domain compression and a motion-estimation processor for time-domain compression. Each of these emerging applications needs a processor capable of more than 10,000 million operations/s (MOPs). A major hardware challenge for these applications is the development of processors capable of massive computations while being of sufficiently low-power consumption and small size to be embedded in a portable system. It is well known that conventional digital implementation offers flexibility and unlimited accuracy. However the state-of-the-art DSPs only offer several hundred MOPs/chip and each chip requires a few watts of electric power. Thus an ultrasound with conventional digital signal processors would still require hundreds of chips and hundreds of watts. This talk will describe a charge-domain processing, CDP, technology that combines high-speed, low-power analog charge-domain units with conventional CMOS digital control and memory circuits to create a new type of electronics -- chips capable of tremendous computation power while being of low power consumption and small chip area.

The shift-and-delay attributes offered by the charge-domain device are inherently matched to the time-delay function needed for dynamic focusing in a lensless ultrasound. To demonstrate further the computation power offered by this CDP technology, a single-chip Pulsed-Doppler Processor with a frequency interpolation capability, an adaptive filter implementing both an FIR filter and an LMS adaptive algorithm and an videocompression coder will also be described. A 25,000 MOPs/W performance has been demonstrated by this technology. Only when this type low-cost, low-power, high-throughput processors is utilized, a portable, high-resolution ultrasound image system will then be feasible.

DIGITAL TECHNOLOGY FOR MEDICAL ULTRASOUND IMAGING

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We have been developing and delivering U.S. Navy digital sonar systems since the early 1970's. Recently, we delivered a digital system based on Commercial-Off-The-Shelf (COTS) technology and a custom 0.5 micron VLSI product. We believe that this VLSI technology coupled with other COTS products can be used to significantly enhance medical ultrasound imaging. A single multi-chip package of these VLSI chip sets operating at 50 MHz provides 600 million operations per second. This technology provides beamformation with range dependent focusing and apodization of sensor data from arrays at a performance level not yet employed in existing medical systems. The processing capacities provided by a single 19 inch rack of electronics of our latest COTS based system will be used as an illustration. A requirement for the digital beamforming capacity for a future medical ultrasound system will be derived based on a two dimensional sparse sensor array. It will be used to illustrate a sizing procedure to determine the number of multi-chip packages required to process the sensor information in real time and the resulting resolution and field of view generated.

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