The Ultrasonix 500RP: A Commercial Ultrasound Research Interface

Thaddeus Wilson, *Member, IEEE*, James Zagzebski, *Associate Member, IEEE*, Tomy Varghese, *Senior Member, IEEE*, Quan Chen, *Student Member, IEEE*, and Min Rao

***Abstract*—Unlike researchers in magnetic resonance imaging who have considerable access to high level tools and to data at a very basic level on their scanners, those involved with ultrasound have found little in the way of meaningful and widespread access to even the most basic echo signals in their clinical systems. Interest has emerged, however, in ultrasound research interfaces on commercial scanners to provide access to raw ultrasound data and control of basic research functions. This paper describes initial experience gained on one such ultrasound system. The Ultrasonix 500RP system provides research access to the data at multiple points in the signal processing chain and allows control over most imaging parameters. The Ultrasonix system allows for three methods of research control. One is implemented along with the standard clinical imaging software using "mouseover" screens on the periphery of the application window. These screens are configured by the user to display various signal processing variables, which can be modified in real time. Second, the system can be controlled via a user-written remote control client application interacting through the clinical exam software. Lastly, the user can write a complete application which initializes the basic ultrasound module but need not use the Ultrasonix clinical exam software. All of the modes can be done locally on the scanner itself or via a network, and are based on software developed in C++ with libraries supplied with the scanner.**

Two examples are presented in this paper from the evaluation of the system in "real world" applications. Measurements of absolute backscatter coefficients and attenuation coefficients versus frequency are shown and elastograms utilizing spatial compounding are described.

I. Introduction

Ultrasound is a popular medical imaging modality because it offers the ability to visualize soft-tissue contrast and blood flow patterns in real time with a low-cost, portable, and safe system. Ultrasound imaging has reached a considerable level of technical maturity, with the advent of computer- and software-based scanners, new transducer technology including relatively broad bandwidth and fully populated two-dimensional (2-D) arrays, novel pulse sequencing, stable contrast agents, unique image and signal post processing, and increasing use of 3-D acquisition and display. Thus, the modality is used effectively in a wide range of clinical specialty areas. Even with recent advances in ultrasound, however, current B-mode images are still evaluated in a qualitative manner. Any quantitative frequency information carried by the echo signals in ultrasound is lost because signals are subjected to envelope detection, scan conversion, and log compression. Clinical and research users of these systems who may wish to explore alternative processing techniques cannot readily acquire raw radio frequency (RF) data utilized in image production because those data are discarded once the envelope signals are derived.

A need exists for an ultrasound system with an open architecture for direct digital access to the various ultrasound data streams. It would also be desirable if such systems enabled researchers to reprogram and reconfigure the ultrasound system to implement new imaging techniques. The digital architecture and the software control of modern ultrasound systems introduce the possibility of both providing extensive user control of transmission and reception parameters during pulse-echo experiments and providing users with echo signal data at various stages of echo-signal processing. At the moment, however, such features are available to system engineers, but are not available to researchers.

This lack of readily available tools for researchers in ultrasound was the emphasis of a workshop held on March 26th, 1999, which was co-sponsored by the National Cancer Institute (NCI) and the Office on Women's Health (OWH). The meeting participants generated a report outlining the requirements to address this problem [1]. The mandate of the workshop was to examine the current state of ultrasonic imaging with regard to availability of research interfaces on commercial clinical scanners and to suggest improvements in the infrastructure. It was stated in their report that although ultrasound has a significant clinical impact and in some cases can account for a third of the imaging procedures in a hospital, there is still inadequate access to the operation of commercial scanners for scientists which would aid them in their research. In many cases, as the report noted, experimenters continue to "reinvent the wheel" by trying to duplicate features that ought to be provided in a good ultrasound research interface (URI). It was also noted that the number of ultrasound scientists with significant research access to their clinical scanners was a small fraction of their counterparts involved in magnetic resonance imaging [1].

Many manufacturers and laboratories have found ways to provide at least minimal access to data from commer-

Manuscript received May 31, 2005; accepted November 5, 2005. This work is supported in part by NIH grants R21-CA100989, R21-EB002722, and R21 EB003853.

T. Wilson is with the Department of Radiology, University of Tennessee, Memphis, TN 38163 (e-mail: tawilson@utmem.edu).

J. Zagzebski, T. Varghese, Q. Chen, and M. Rao are with the Department of Medical Physics, The University of Wisconsin-Madison, Madison, WI 53706.

Digital Object Identifier 10.1109/TUFFC.2006.110

cial ultrasound machines. Siemens (Siemens Ultrasound, Issaquah, WA) provided a custom modification on an early Sonoline machine, providing RF analog signals along with line and frame synchronization for external digitization purposes [2]–[4]. Hall *et al.* [5] applied echo signals from a Siemens Quantum 2000 to measure glomerular diameters in human kidneys after the manufacturer provided analog RF data along with timing pulses for transmit and frame synchronization. Later, Hall *et al.* [6] demonstrated access to the DSP subsystem of a Siemens Elegra scanner for algorithm implementation in the real-time imaging chain. In response to the need described by the workshop mentioned above, NCI solicited proposals from industry to develop a URI, and subsequently Siemens was the recipient of the only contract awarded. This interface was demonstrated at the meeting of the Radiological Society of North America (RSNA) in 2003. The Axius Direct URI available on the Siemens SONOLINE Antares™ scanner enables users to acquire raw RF data from regions of interest throughout the image plane. Echo data are available in B-mode and M-mode, as well as pulsed Doppler and color flow imaging modes. Also, user-defined scripts can be used to record and reproduce RF acquisitions for combinations of front panel control settings such as transmit level, center frequency, beam angle, and focal depth. This interface is complemented by a set of Matlab tools developed at the University of California, Davis, which reads echo and image data files and performs basic image processing operations.

General Electric's Logiq 700 machine (General Electric Medical Systems, Waukesha, WI) provided in-phase and quadrature (IQ) data via a custom board added to the system backplane. McAllister *et al.* [7] also had success in controlling the aperture of the Logiq 700 machine. GE's more recent Logiq 9 provides IQ data for Doppler mode only, whereas the GE Vingmed System V and Vivid series system provide IQ B-mode data, as demonstrated by Pislaru *et al.* [8]. The Kretz Combison system (Kretztechnik, Zipf, Austria) has been used by researchers to get full RF via external digitization in early models, as demonstrated by Lorenz *et al.* [9].

Several older analog scanners could be modified to provide both timing and RF data. For example, the Acuson 128XP/10 (Acuson, Mountain View, CA) could be customized to provide analog timing and intermediate frequency (IF) summed signals [10], and the Siemens Sequoia can provide IQ beamformed data. Philips/ATL (Phillips, Seattle, WA) has also provided RF analog and digital data on a number of their HDI scanners, including the Ultramark 9 [11]. Boston Scientific Clearview IVUS provides a separate device from the manufacturer to output a trigger and RF signal. Varghese *et al.* [12] are using a modified Aloka SSD 2000 scanner (Aloka Inc., Tokyo, Japan) by exploiting test points provided on various printed circuit boards (PCBs) of the scanner to digitize the RF signal as well as provide the necessary timing signals. More recently, the laptop-based portable ultrasound scanner from Terason (Burlington, MA) stores the raw RF data with each acquisition, which can then be acquired using a proprietary program from the manufacturer. Researchers at University of Virginia who have experience with many of the aforementioned systems have been funded by the NSF on proposal number 0079639 to provide real-time acquisition of 128 channels of data over a period of 1.6 seconds on an HP/Agilent SONOS 5500 scanner [13]. Finally, although it is not a clinical scanner, Jensen *et al.* [14] recently built a custom ultrasound research scanner for real-time synthetic aperture data acquisition.

The purpose of this paper is to describe an ultrasound research platform that allows easy access to raw RF data as well as user software control over many system functions. The ES500 machine from Ultrasonix Corporation (Ultrasonix Medical Corporation, Vancouver, BC, Canada) is based on an open personal computer (PC) platform, where the conventional exam software can run either as a single application or as one of multiple applications on the host PC. The PC also runs connectivity, interface, and control software in parallel. The computer can control imaging parameters and apply various post-processing and display methods in real time on RF, IQ, and envelope data to output and store the ultrasound information. When the machine is in research mode, users can build, develop, and run client software applications that perform customized signal processing, carry out special echo acquisition sequences, and synchronize with external devices, such as stepper motors.

II. System Description

The Ultrasonix 500 Research Package (RP) is a recently developed ultrasound system with an open architecture that is based on a personal computer and re-programmable integrated circuits [15]. The use of a PC allows engineering access to the image data and straightforward incorporation of new advances in hardware and software. Moreover, in its current revision the RP offers not only access to the echo data streams at multiple points in the imaging chain but also control of many beamforming and image processing parameters from software. The end user can interact or interface with the RP in three functional aspects as depicted in the flowcharts referred to below.

Fig. 1 is a flowchart illustrating the simplest of all of the operational schemes available with the RP. In this mode of operation the user interacts with the scanner on the local PC and affects changes on the system within the exam software supplied by the manufacturer. The Ultrasonix 500 exam software is the primary ultrasound operation/display software. When running on a clinical Ultrasonix 500 system, the exam software runs in full screen mode, and its user interface is similar to most clinical ultrasound imaging systems. On the RP system, however, the exam software runs in a stand-alone window on the display, and thus appears as any other application running on a Microsoft Windows XP interface.

As illustrated in Fig. 1, the exam software runs on top of the ultrasound module. The exam software is used to ad-

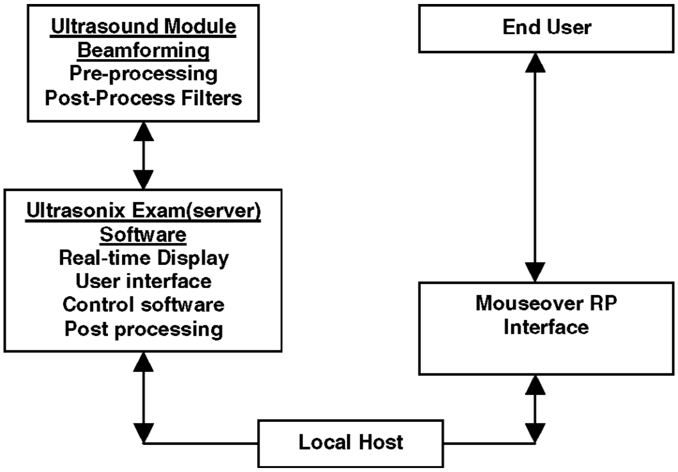


Fig. 1. Overview of control of the Ultrasonix system via the exam software and the graphical mouseover windows.

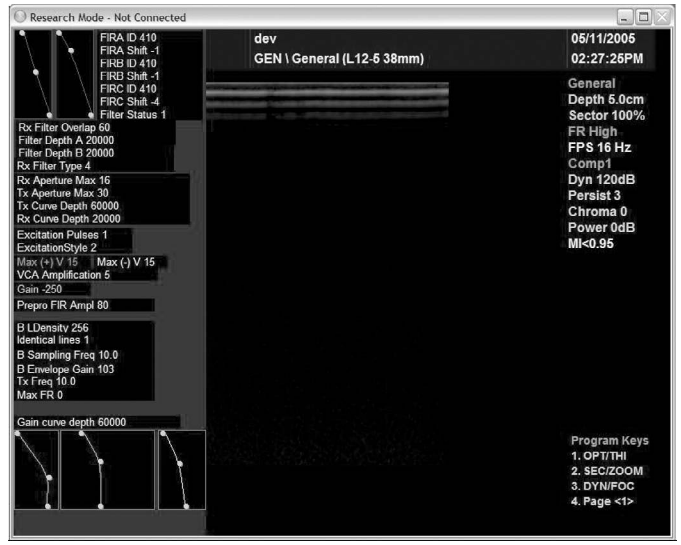


Fig. 2. Ultrasonix B-mode window depicting one of the mouseover control screens (in blue to the left of the screen) used to adjust parameters on the scanner in real time.

just and vary parameters in the ultrasound module. These changes applied to the basic hardware via the scanner console through the ultrasound module are transparent to the user/sonographer from the normal operation of any other scanner. The ultrasound module consists of bit files which are loaded into field programmable arrays upon initialization of the hardware; its function constitutes the most basic operation of the machine. The module communicates with various array transducers and performs pre-amplification, beamforming, and signal preprocessing. This module is preconfigured with appropriate instructions for the various imaging modes supported on the scanner, and at present the user can only affect changes in the ultrasound module via predefined variables accessible either by way of the exam software interface or custom programming discussed below. The preprocessed ultrasound signal is sent from the ultrasound module in real time via direct memory access (DMA) to the PC, where it is then operated upon by the exam software, which has shared access to the PC memory.

In the mode of interaction depicted in Fig. 1, the user interacts with the RP system via a set of windows which appear when the mouse cursor is moved over the sides of the exam software window frame. These are referred to as "mouseover windows." The mouseover windows contain parameters which are related to numerous imaging variables such as transmit frequency, depth, line density, imaging mode, number of focal zones, excitation pulse shape and power, and RF filter frequencies.

An example of the default left mouseover window of the RP is shown in Fig. 2. Similar windows appear on the right and bottom of the window as the mouse cursor is moved to those sides of the exam window. The default parameters are shown, but with some simple modifications other parameters of interest can be added or deleted from the windows according to the user's preference. Virtually all software parameters can be adjusted via the RP.

Inherently, the PC is capable of multiple processes, and this is the basis of the second method of interfacing with

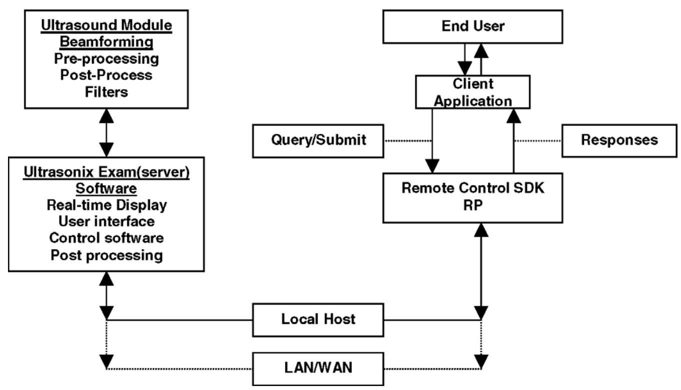


Fig. 3. Remote client mode of utilizing the Ultrasonix system via the exam software.

the Ultrasonix RP, which is depicted in Fig. 3. The system provides a software development kit (SDK) to enable user access to many system functions. Users who are familiar with the C++ programming language can immediately develop client applications. Examples of client software capabilities include communicating with the exam software via messaging and the RP application program interface (RP API) as well as accessing memory to retrieve pre-scan converted or post-scan converted data in real time. Depending on the imaging modes, the client software can access envelope-detected, I/Q, and/or RF beamformed data. Users also can set up the exam software using the API to send software interrupts synchronized with echo signal frames. They then can retrieve and control parameters of the exam software through messaging using the API.

The client can access other peripheral devices either locally or over a network, allowing for synchronization of operation of the scanner with other instruments. Included with the RP from Ultrasonix are a number of sample applications as well as help/documentation on the RP API.

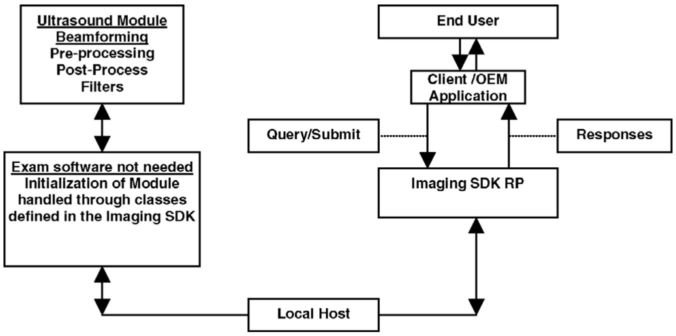


Fig. 4. Overview of control of the Ultrasonix System wholly by an SDK which includes classes designed to initialize the firmware of the ultrasound module currently with the default settings used in the exam software.

For example, the sample application named "remote control" demonstrates how data are accessed, processed, and displayed, and how variables affecting imaging are queried, messages received, and new values submitted through the client application, either locally or via a network. A researcher can modify this code to gain familiarity with working with the system, and he/she can immediately begin to use the system for experimental purposes.

The networked control of the scanner was found to be useful in the sharing of a single scanner between facilities until a system could be installed at both participating sites. To run the remote control application, the exam software must be operating on the local host. The exam software handles the initialization of the ultrasound module discussed previously. Exploitation of the existing exam software to communicate with the ultrasound module distinguishes the first two methods of utilizing the RP from the last method.

Fig. 4 depicts the final method of interacting with the RP. The imaging SDK referred to in the right side of the figure, unlike the remote control SDK in Fig. 3, includes a set of C++ classes used to initialize the ultrasound module. A separate set of documentation is available describing these classes. This mode of operation would be advantageous if the user wished to control the scanner using an existing application, as is the case for many original equipment manufacturers (OEMs). It also would be useful in those cases where the exam software had too much overhead or too many extraneous functions running on the PC. Typically, the exam software requires about 40% of one of the two on-board processors for operation, leaving roughly 1.5 processors (Athlon 1.8 GHz at the writing of this paper) for the client software. This method of operation is the most basic and requires the user to write a complete application. A sample imaging project written in Microsoft Visual Studio is included with this SDK. In order to gain a preliminary understanding of the functions available in the SDK and the way in which data are passed to them, the class list and members of those classes have been included in Appendix A.

Table I is a summary of the research mode capabilities on the Ultrasonix RP. Acquiring RF echo data is one of the key features provided and is discussed in more detail here. This can be done on the Ultrasonix system either by setting a toggle parameter on a mouseover window to enable RF mode or by writing specific applications based on the SDK to acquire data directly from PC memory. When interacting in the method shown in Fig. 1, a user would first enable the RF mode. The freeze button can then be used to save the most recent cine loop of RF data to the limit of available memory on the machine.

TABLE I
FEATURES FOR VERSION 1.0 ULTRASONIX RP.

RF acquisition
RF acquisitions at 1/3rd real frame rate, up to 8 cm in size
Transmit
Adjustable transmit frequencies and beamshapes at 25 ns resolution
Adjustable polarity of transmit pulses and transmit power + and −
Per-element control of time delay
Adjustable aperture, focal point, line density
Adjustable FOV, PRF, frame rate, angle
Receive
Preprocessing Filter selection and control
Variable speed of sound adjustment
Reproducible digital TGC curves
Tools
External and internal triggering capabilities
Visual C++ sample code/sample code
Controllable over a network

When the system is in RF mode, frame rates decrease because of data line speed limitations since each line is delayed to allow data from the previous line to reach the PC memory. RF echo signal data at a bit depth of 14 bits are available at digitization rates of 40 samples/microsecond for all beam lines in a frame over an 8-cm range. Users can also acquire pre-beamformed data by adjusting the receive aperture to a single element of interest. Currently this would require repeating the acquisitions a number of times, where the number equals the number of beam lines in a frame times the maximum number of receive elements per line, in order to collect a full frame to 8 cm. This limitation is currently due to a data storage issue that depends on the field-programmable gate array (FPGA) and its external static random access memory (SRAM) memory, which is about 2 MB at the writing of this paper. There is interest in improving this limitation, but Ultrasonix does not have immediate plans to do so. However, the modular architecture of the new revision of their scanner would make this fairly simple to add on to the main board business-card-size memory cards to capture pre-beamformer data and then transfer to PC memory. It may also entail the use of the imaging SDK method described in Fig. 4 to free needed resources on the programmable arrays rather than initializing them with extraneous filtering, etc., which are not needed by the researcher but are loaded with the standard exam software.

There are additional research functions on the research interface that can be controlled by one of the methods outlined in Figs. 1, 3, and 4. These functions include control over the transmit pulse (which has three states of +/−/0 to create square waves with a time resolution of 12.5 ns per character; transmit pulse + and − voltages controlled independently), control of the angle of the beam axis for any transmit-receive sequence, adjustment of filters in the receiver, variation of the speed of sound assumed in the beamformer process, introduction of reproducible TGC curves, and availability of external and internal triggering capabilities.

III. Examples of the Use of the Ultrasonix RP

Presented here are "real world" examples of the use of the URI. These and similar examples could also serve in a suite of tests of signal fidelity, synchronization, and linearity of the system.

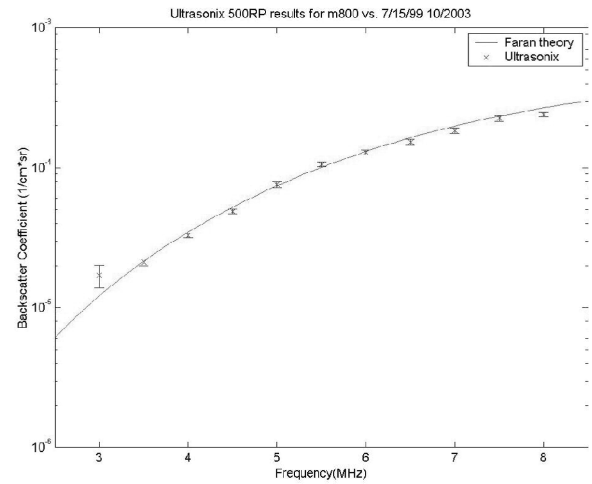
Given the inconsistencies between measurements on backscatter and attenuation coefficients versus frequency in two recent American Institute of Ultrasound in Medicine (AIUM) round robin studies among laboratories specializing in such measurements [10], [16], it was felt that one of the examples of the use of this scanner should be for the measurement of these values. This would test the signal fidelity on the Ultrasonix scanner using a relevant ultrasound tissue characterization research problem. The second example presented for elastographic imaging is a test of the system's bandwidth, signal-to-noise ratio, control of external devices such as stepper motors, and control of steering of the transmitted beam [17].

A. Measurement of Backscatter and Attenuation Coefficients

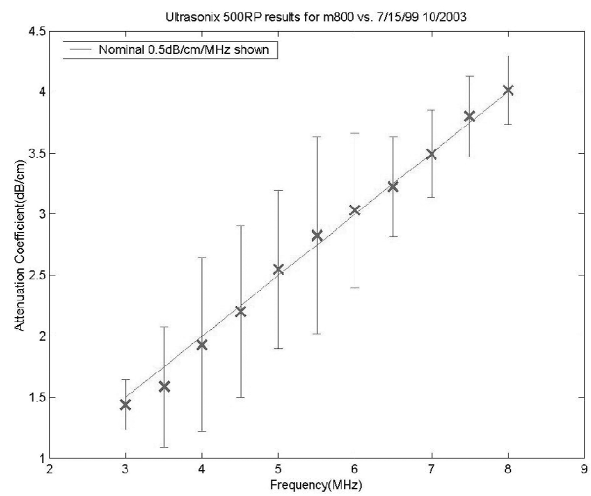
Ultrasound researchers have long used the backscatter coefficient (BSC) to quantify the acoustical scattering properties of tissue [2], [3], [18]–[21]. This parameter is defined as the differential scattering cross section per unit volume in a 180° direction to the incident wave. Measurements of the BSC are challenging, as illustrated in two round robin studies sponsored by the AIUM [10], [16].

The Ultrasonix machine was used for measuring backscatter coefficients, utilizing a reference phantom method described previously [22]. A well characterized sample consisting of glass beads (mean diameter of 49 μm and 800/cc) as a source of scattering in a milk and agarose background material was used. The sample has a nominal attenuation of 0.5 dB/cm/MHz. The scattering and attenuation properties of the phantom have been verified using test cylinders created at the same time the larger phantom was poured and also using the phantom itself on other clinical scanners adapted to provide either analog RF or digital IQ data.

Image and RF echo data were acquired from the sample using an L12-5 broadband, linear array transducer running at 8 MHz. Echo signals were bandlimited to 10 MHz due to a hardware low pass filter. The cine loop size was set for single images, and data were acquired for 50 image scanning planes, with the transducer repositioned between acquisitions to obtain independent, uncorrelated echo signals. System gains had been adjusted manually so that the B-mode image appeared uniform with no obvious regions of image saturation as judged visually. After acquiring echo data from the sample, signals also were obtained from a reference phantom using the same frequency, output, and gain settings.



(a)



(b)

Fig. 5. (a) Backscatter coefficients (x symbols) measured from a phantom using a reference phantom and the Ultrasonix 500RP. Theoretical values using Faran's calculation and the properties of the constituent materials are plotted as well (solid line). (b) Attenuation coefficients measured from a phantom using the Ultrasonix 500RP. The phantom has been measured previously and designed to have a nominal attenuation of 0.5 dB/cm/MHz.

Data reduction consisted of first applying a 4 μs narrowband filter to the signals, and then calculating the average analytic signal amplitude squared versus depth for these filtered signals. The sample attenuation coefficient at the filter center frequency was then determined by fitting a line to the ratio of the natural logarithm of the average amplitude squared data from the sample versus the reference. The slope of this fitted line has been shown previously to be related to the difference between the attenuation coefficient of the reference and that of the sample [22]. The BSC at the same frequency was then obtained by correcting for attenuation affects to derive a single ratio value. This value was then multiplied by the known BSC of the reference to determine the BSC for the sample. The procedure was repeated for frequencies throughout the bandwidth of the echo signal data.

Fig. 5 presents results obtained using the 500RP to collect the data from this sample and a reference [22]. The absolute backscatter (left) and attenuation (right) coefficients versus frequency are presented. Results of a theoretical calculation based on Faran's work [23] is presented as well. The Faran calculation for scattering assumes the following parameters for the scatterers and background material respectively; sound speed 5570 m/s and 1540 m/s, density 2.54 g/cc and 1.04 g/cc, and Poisson's ratio of 0.21. The experimental results and theoretical calculations for backscatter are in excellent agreement, and the attenuation data are also in very good agreement with the nominal value for the sample.

B. Spatial Angular Compounding using Beam Steering in Elastography

Elastic properties of tissues are yet another parameter derived using ultrasound echo data. For example, strain imaging has recently evolved as an important area of research for diagnosing masses in the breast, prostate, and other organs [24]–[26]. One method that is utilized to generate strain images is to apply a small ($< 1\%$ of the height of the sample) quasistatic compression to the area being imaged using a compression paddle or the transducer surface itself. Pre-compression and post-compression RF echo data are closely compared using, for example, a one-dimensional normalized cross-correlation applied to the RF signals. This yields local tissue displacements along the ultrasound beam direction in response to the applied compression. Tissue strain is obtained by computing the gradient of the displacement estimates [27].

The Ultrasonix 500RP's research interface readily allows an expert programmer to enter the research environment and alter the operating conditions and introduce new echo signal processing techniques. In this example, the Ultrasonix 500RP system has been programmed to obtain frames of beam-steered RF echo data, each frame acquired at a different insonification angle [28]. Multiple frames of beam-steered data may be utilized both for improving the noise properties of the subsequent elastogram using spatial angular compounding [28]–[30] and for obtaining normal and shear strain tensors in elastography [31], [32].

An automated beam-steering and data acquisition algorithm for elastography was implemented on the Ultrasonix 500RP system at the University of Wisconsin-Madison [28]. In this application, the Ultrasonix system controls a stepper motor apparatus that applies a precisely controlled compression to the sample under investigation. This in turn enables synchronized acquisition of both the pre- and post-compression RF data sets during a compression sequence. The algorithm first acquires frames of pre-compression RF data. The initial frame is obtained using beams emerging normal to the array, as in conventional data acquisition with a linear transducer. Subsequent frames are acquired using parallel beams steered in directions ranging from $-15°$ to $15°$ with respect to the normal to the array, varying in $1°$ increments. This is done after an initial pre-compression of the phantom to ensure proper contact [28]. The stepper motor is then activated to compress the phantom at a specified compression increment (achieving a 0.5% or a 1% strain), following which the post-compression RF data are acquired. The compression direction is vertical, that is, perpendicular to the array surface. Frames of post-compression RF data are acquired at each of the steered beam angles used for acquiring pre-compression signals.

Data are then transferred to a separate workstation for analysis. Alternatively, the computer on the Ultrasonix 500RP can be used for real-time analysis of the data acquired. In either case, the analysis routines compute local displacements in the sample for each beam direction by correlating the pre- and post-compression echo data along individual beam lines. In the examples shown below, a 3-mm finite duration window with a 75% overlap of the data segments was used in the cross-correlation analysis. A 5-point, one-dimensional median filter was then used to reduce outliers in the displacement estimates, following which a 3-point, least-squares strain estimator [33] was used to generate local strain estimates. The resultant "angular strain images" were filtered using a 5×5 median filter to suppress strain outliers.

Spatial angular compounding using beam-steered data acquisition frames from a linear array transducer are described by Rao *et al.* [28]. These are formed by averaging strain data from the angular strain images. The angular strains contain both axial and lateral strain components, however. Thus, appropriate scaling of the angular strain must first be done to obtain only the axial strain estimates [29]. The scaled values, scan converted to a common Cartesian grid [28], are then averaged, or compounded.

Examples of angular elastograms obtained on a tissue-mimicking elastography phantom [34] along with the spatial angular compounded results are shown in Fig. 6. The phantom imaged has a 2-cm cylindrical inclusion encased within a uniform background. The inclusion is three times stiffer than the background. For the vertically directed compression of the phantom, Fig. 6 illustrates angular elastograms measured along the $0°$ (vertical), $10°$, $12°$ beam-steered directions.

Figs. 6(d) and (e) present elastograms after applying spatial compounding. Note the significant improvement in the visual quality of the compounded elastograms. The dotted lines on the elastograms indicate the regions over which scaled strain estimates over the entire angu-

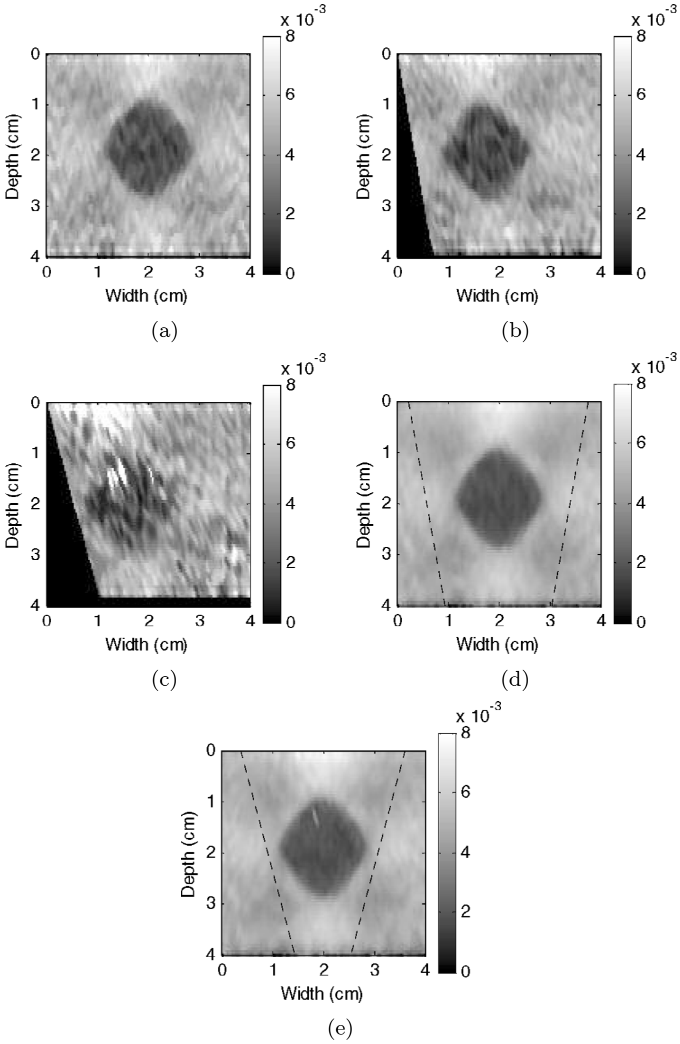


Fig. 6. Axial strain elastograms obtained using a beam-steering angle of (a) 0°, (b) 10°, and (c) 12°. The angular compounded elastograms are shown in (d) over −10° to 10° and (e) over −15° to 15°. Data were collected using a 0.5% compression at 1° angular increments on the Ultrasonix 500RP.

lar insonification range were averaged to obtain the compounded elastogram [28]. Overall image quality improvements of the compounded results are clearly seen in that these images are much smoother than their uncompounded counterparts in Figs. 6(a), (b), and (c).

IV. Discussion

The field of ultrasonic imaging could significantly benefit by greater access for researchers to the underlying operation of current scanner technology. While basic "ultrasound engines" are available, the complexity and limited nature of these devices tends to limit the scope of investigations to only a few laboratories. The widespread availability of ultrasound instrumentation in the clinical arena makes an ultrasound research interface on a commercial scanner attractive. However, at the present time, few URIs on commercial systems exist, and those that do are generally limited in their availability and functionality. Researchers face a problem similar to that faced by OEMs in their quest to bring a product to market in a timely and cost-efficient manner. In the case of research, it is a concept or new technology that is being realized. By providing control of a scanner including such items as transmit power, pulse shape, aperture, DSP resources, and other parameters, the need to "reinvent the wheel" when exploring new concepts and imaging paradigms might be eliminated. Thus, both scanner manufacturers and ultrasound researchers would benefit.

A URI would have to meet two criteria to be an effective tool for research, education, and product development. First, the URI should not be excessively limited in its functionality, implying that the user should be able to control and interface to the system in virtually all aspects of operation. For example, if a researcher needs to go out of normal acoustical output limits, this should not be an impediment. Second, as important as making the tool without significant limits on its use is, its accessibility should be to as many traditional and nontraditional researchers as possible. The latter might include engineers, inventors, and scientists in small colleges and developers in small businesses.

A URI on an affordable machine may increase the number of people working in the field, which should have a positive affect on advances in medical ultrasound. Therefore, the total cost of ownership of any URI and scanner must be within the means of this untapped pool of researchers. This would still imply that researchers will have to "buy into" a specific platform to conduct their work. It is hoped that this exclusivity will be mitigated as more manufacturers ascribe to a common set of features, in part defined by the research community, to be offered in their respective URIs. As the market becomes more standardized it should become more competitive as well. The Ultrasonix and Siemens interfaces constitute the most robust commercially available URIs on the market today. Each URI goes beyond the simple offerings of RF signal access to allow the user to configure the system for custom operation in some form or another. The 500RP currently would cost between \$65k and \$100k USD depending on the configuration and support.

At the present time, the Ultrasonix 500RP system may not meet the needs of all ultrasound researchers. For example, the system evaluated in this work is limited to just under 8 cm of raw data collection for each beam line within a frame, which restricts its use to areas such as superficial anatomical structures or to partial views of larger organs. This would not affect all researchers in the same way, but it is still a feature that needs further refinement. In RF mode, the Ultrasonix 500RP system tested takes a 2/3 reduction in frame rate from that achieved during conventional imaging. At the writing of this manuscript, Ultrasonix has reported that their new "Sonix RP" system provides full-frame RF with no loss in frame rate. This was reportedly done by removing a first-in, first-out (FIFO) register and streaming the data in real time via the peripheral component interconnect (PCI) bus into the PC's memory. As this new system has not been tested, this information can only be reported, but this would make the system much more attractive, particularly if it provides the same overall research functionality of the 500RP system reported here. Also, according to the company, this modification will likely not be made to their older ES500RP platform. Finally, the sample remote control application, hardware test program, and mouseover interface in the exam software allow for control over all of the parameters, but the system is best utilized at the programmer's level. The real-time control of the system could benefit greatly by a more developed graphical user interface or a higher level scripting language.

At present the RP500 system only has 32 receive channels, but the newer Sonix RP has 64 independent receive A/Ds which can be multiplexed to make the system equivalent to 1024 independent processing channels. With their modular architecture, future Sonix platforms may be able to host many more independent receive A/Ds which might be used for 2-D array applications. The Ultrasonix RP500 described in this paper would also benefit significantly by an increased acoustic bandwidth for the system, with 15–20 MHz as a minimum upper limit. The company's most recent scanner reportedly meets this bandwidth requirement. The current RP needs a multi-channel simultaneous pre-beamformer RF acquisition feature rather than the user having to adjust the RX aperture as discussed earlier. Some researchers might also want the flexibility of using the on-board FPGA or digital signal processing (DSP) devices in their research to increase pre-processing speed. One such example of using this faster processing might be the realization of a real-time quantitative imaging mode such as elastography. In order to facilitate this, the API from Ultrasonix will need to be expanded to allow open access to these devices. The interface to the hardware level could also be expanded by providing an easy means for prototyping new transducers. Finally, in the present revision of the RP, the user can adjust variables of virtually all software parameters used by the exam software. However, the documentation is not sufficient to do this without interacting with the support engineers at Ultrasonix, which could become a hindrance for both the researcher and the company.

Caution should be exercised as there are no limits placed upon the variable selection, which could lead to harm of the system and/or a patient if used in an inappropriate manner. However, this concern should be adequately addressed by appropriate institutional oversight and prudent judgment of qualified users. As stated earlier, in some circumstances this flexibility in variable selection in a URI is essential to certain research. As one can see, this URI is not complete but still it is a very useful tool for ultrasound research.

While a small company such as Ultrasonix will likely not dominate the clinical ultrasound market, such an organization would be well positioned to become a leader in the niche research arena and OEM venue by offering at this point an unparalleled ultrasound research tool in terms of its level of access for development, education, and experimentation. In the long run, the ultrasound imaging field should benefit from discoveries by clinical, academic, and independent investigators, as well as through the current practice of advancements within manufacturing facilities. While the system is lacking some desirable features in its current revision, it is hoped that Ultrasonix will continue to devote resources to refining this tool. Given enough interest, other manufacturers will also see the value to the entire community as well as their own business to develop their own URI. It is important for the research community to define the standards needed to be met by these URIs, and this will occur most effectively through dialogue among manufacturers and users of ultrasound research interfaces.

Appendix A

In order to gain some familiarity with the level of control over the system and how data are passed, this appendix presents a brief summary of the classes included with the remote control SDK and their member functions [35].

Class List:

CIRPCapture	This interface encapsulates the server's response to the CIRPRemoteControl::getScreenCapture method. The server returns one or more images that have been captured. This interface provides access to these images. One or more images are contained within the object, depending on the parameters passed to CIRPRemoteControl::getScreenCapture. This class is usually used in response to the WM_RP_RECV_CAPTURE_RESP message.
CIRPCineBlock	This interface encapsulates the server's response to the CIRPRemoteControl::getCineLoop method. The server returns one or more images that have been captured. This interface provides access to these images. One or more images are contained within the object, depending on the parameters passed to CIRPRemoteControl::getCineLoop. This class is usually used in response to the WM_RP_RECV_CINEBLOCK_RESP message.
CIRPRemoteControl	This interface issues requests to the server. It also handles connecting and disconnecting from the server.
CIRPVarList	This interface encapsulates the server's response to the CIRPRemoteControl::getVariableList method. This class is usually used in response to the WM_RP_RECV_VARLIST_RESP message.
CIRPVarValue	This interface encapsulates the server's response to the CIRPRemoteControl::getVariableValue method. This class is usually used in response to the WM_RP_RECV_VARVALUE_RESP message.
CIRPZoneAction	This interface encapsulates the server's response to the CIRPRemoteControl::getZoneActions method. This class is usually used in response to the WM_RP_RECV_ZONEACTION_RESP message.

CIRPZoneList	This interface encapsulates the server's response to the CIRPRemoteControl::getZoneList method. This class is usually used in response to the WM_RP_RECV_ZONELIST_RESP message.
vCURVE	Curve Variable type
vDATE	Date Variable type
vGAINCURVE	Gain Curve Variable type
vRECT	Rectangle Variable type
vTIME	Time Variable type

CIRPCapture members:
CIRPCapture(LPCVOID lpvoid)
getImageCount(void) const
getImageData(DWORD dwIndex) const
getImageLength(DWORD dwIndex) const

CIRPCineblock members:
CIRPCineBlock(LPCVOID lpvoid)
getBlock(void) const
getBlockLength(void) const
getFrameCount(void) const
getFrameLineCount() const
getFrameLineSize(void) const

CIRPRemoteControl members:
acquireFrames(DWORD dwFrames) const
Connect(LPCWSTR lpszHostname)
Connect(LPCSTR lpszHostname)
Disconnect(void)
displayText(LPCWSTR lpszText) const
displayText(LPCSTR lpszText) const
doZoneAction(DWORD dwZoneID, DWORD dwActionID) const
getCineLoop(DWORD dwDataBlockID) const
getCineLoopFrame(DWORD dwDataBlockID, DWORD dwFrameID, LPBYTE *pBuffer) const
getCineLoopFrame(DWORD dwDataBlockID, DWORD dwFrameID, DWORD dwLength, LPBYTE *pBuffer) const
getDataBlockCount(void) const
getFrameInterrupts(HWND hWnd) const
getFrameLineCount(DWORD dwIndex) const
getFrameLineLength(DWORD dwIndex) const
getPostProcessBitDepth(DWORD dwIndex) const
getPostProcessBufferCount(void) const
getPostProcessBufferLength(DWORD dwIndex) const
getPostProcessFrame(DWORD dwDisplayID, DWORD dwLength, LPBYTE *pBuffer) const
getPostProcessHeight(DWORD dwIndex) const
getPostProcessWidth(DWORD dwIndex) const
getScreenCapture(DWORD dwOptions, Compression eCompression=jpeg_e) const
getVariableList(void) const
getVariableValue(DWORD dwVariableID) const
getZoneActions(DWORD dwZoneID) const
getZoneList(void) const
Initialize(HWND hWnd)
modifyVariable(WORD wID, int i) const
modifyVariable(WORD wID, LPCTSTR s) const
modifyVariable(WORD wID, vRECT &r) const
modifyVariable(WORD wID, COLORREF c) const
modifyVariable(WORD wID, vDATE &d) const
modifyVariable(WORD wID, vTIME &t) const
modifyVariable(WORD wID, vCURVE &cv) const
modifyVariable(WORD wID, vINTARRAY ia) const
modifyVariable(WORD wID, vGAINCURVE &gc) const

CIRPVarList members:
CIRPVarList(LPCVOID lpvoid)
getVariable(DWORD dwIndex, DWORD &dwID, DWORD &dwType, DWORD dwBufferLength, LPTSTR lpszVarName) const
getVariableCount(void) const

CIRPVarValue members:
CIRPVarValue(LPCVOID lpvoid)
getVariableID(void) const
getVariableLength(void) const
getVariableValue(DWORD dwBufferLength, LPVOID lpValue) const

CIRPZoneAction members:
CIRPZoneAction(LPCVOID lpvoid)
getAction(DWORD dwIndex, DWORD dwBufferLength, LPTSTR lpszActionName) const
getActionCount(void) const
getZoneID(void) const
getZoneType(void) const

CIRPZoneList members:
CIRPZoneList(LPCVOID lpvoid)
getZone(DWORD dwIndex, DWORD &dwID, DWORD &dwType, DWORD dwBufferLength, LPTSTR lpszZoneName) const
getZoneCount(void) const

Following is a code excerpt from the Ultrasonix RP SDK user manual demonstrating the use of the SDK to acquire a post-processed bitmap from the system.

```
Bitmap *GetPostProcessBitmap(const CIRPRemoteControl *rc)
{
   LPBYTE pBuffer = NULL;
   DWORD dwLength = 0;
   DWORD dwIndex = 0;
   BITMAPV5HEADER bmh;

   ZeroMemory(&bmh, sizeof(BITMAPV5HEADER));

   // get the index of the post-process frame we want to retrieve,
   // in this case it is the last one
   dwIndex = rc->getPostProcessBufferCount() − 1;
   // get the length (in BYTEs) of the selected frame
   dwLength = rc->getPostProcessBufferLength(dwIndex);

   bmh.bV5Size = sizeof(BITMAPV5HEADER);
   // get the frame's width
   bmh.bV5Width = rc->getPostProcessWidth(dwIndex);
   // get the frame's height
   bmh.bV5Height = −1 * me->m_rc->getPostProcessHeight(dwIndex);
   bmh.bV5Planes = 1;
   // get the frame's bit depth
   bmh.bV5BitCount =
     static_cast<USHORT>(rc->getPostProcessBitDepth(dwIndex));
   // the compression is always RGB (i.e. uncompressed)
   bmh.bV5Compression = BI_RGB;

   pBuffer = new BYTE[dwLength];
   rc->getPostProcessFrame(dwIndex, dwLength, &pBuffer);

   return Bitmap::FromBITMAPINFO((BITMAPINFO *)&bmh, pBuffer);
}
```

References

[1] G. E. Trahey, K. Ferrara, J. B. Fowlkes, B. B. Goldberg, C. Merrit, M. Insana, R. Mattrey, J. Ophir, P. L. Von Behren, J. Allison, K. Thomenius, H. Routh, and P. Pesque, "Ultrasonic imaging: Infrastructure for improved imaging methods," *Report of the OWH/NCI Sponsored Workshop*, Mar. 1999, National Cancer Institute, http://imaging.cancer.gov/reportsandpublications/ReportsandPresentations/UltrasoundImagingInfrastructureon-ImprovedImagingMethods.

[2] Z. F. Lu, J. A. Zagzebski, R. T. O'Brien, and H. Steinberg, "Ultrasound attenuation and backscatter in the liver during prednisone administration," *Ultrasound Med. Biol.*, vol. 23, no. 1, pp. 1–8, 1997.

[3] J. A. Zagzebski, Z. F. Lu, and L. X. Yao, "Quantitative ultrasound imaging: In vivo results in normal liver," *Ultrason. Imag.*, vol. 15, no. 4, pp. 335–351, 1993.

[4] J. J. Mai and M. Insana, "Strain imaging of internal deformation," *Ultrasound Med. Biol.*, vol. 28, pp. 1475–1484, 2002.

[5] T. J. Hall, M. F. Insana, L. A. Harrison, and G. G. Cox, "Ultrasonic measurement of glomerular diameters in normal adult humans," *Ultrasound Med. Biol.*, vol. 22, no. 8, pp. 987–997, 1996.

[6] T. J. Hall, Y. Zhu, and C. S. Spalding, "In vivo real-time freehand palpation imaging," *Ultrasound Med. Biol.*, vol. 29, no. 3, pp. 427–435, 2003.

[7] M. J. McAllister, K. W. Rigby, and W. F. Walker, "Evaluation of translating apertures based angular scatter imaging on a clinical imaging system," in *Proc. IEEE Ultrason. Symp.*, 2001, pp. 1555–1558.

[8] C. Pislaru, J. D'hooge, S. V. Pislaru, E. Brandt, R. Cipic, C. E. Angermann, F. J. Van de Werf, B. Bijnens, M. Herregods, and G. R. Sutherland, "Is there a change in myocardial nonlinearity during the cardiac cycle," *Ultrasound Med. Biol.*, vol. 27, no. 3, pp. 389–398, 2001.

[9] A. Lorenz, H.-J. Sommerfeld, M. Garcia-Schürmann, S. Philippou, T. Senge, and H. Ermert, "Diagnosis of prostate carcinoma using multicompression strain imaging: Data acquisition and first in vivo results," in *Proc. IEEE Ultrason. Symp.*, 1998, pp. 1761–1764.

[10] E.-L. Madsen, F. Dong, G. R. Frank, B. S. Garra, K. A. Wear, T. Wilson, J. A. Zagzebski, H. L. Miller, K. K. Shung, S. H. Wang, E. J. Feleppa, T. Liu, W. D. O'Brien, Jr., K. A. Topp, N. T. Sanghvi, A. V. Zaitsev, T. J. Hall, J. B. Fowlkes, O. D. Kripfgans, and J. G. Miller, "Interlaboratory comparison of ultrasonic backscatter, attenuation, and speed measurements," *J. Ultrasound Med.*, vol. 18, no. 9, pp. 615–631, 1999.

[11] S. Y. Emelianov, M. A. Lubinski, A. R. Skovoroda, R. Q. Erkamp, S. F. Leavey, R. C. Wiggins, and M. O'Donnell, "Reconstructive ultrasound elasticity imaging for renal pathology detection," in *Proc. IEEE Ultrason. Symp.*, 1997, pp. 1123–1126.

[12] T. Varghese, J. A. Zagzebski, G. Frank, and E. L. Madsen, "Elastographic imaging using a handheld compressor," *Ultrason. Imag.*, vol. 24, pp. 25–35, 2002.

[13] C. M. Fabian, K. N. Ballu, J. A. Hossack, T. N. Blalock, and W. F. Walker, "Development of a parallel acquisition system for ultrasound research," presented at Proc. SPIE Med. Imag., San Diego, CA, 2001.

[14] J. A. Jensen, O. Holm, L. J. Jensen, H. Bendsen, S. I. Nikolov, B. G. Tomov, P. Munk, M. Hansen, K. Salomonsen, J. Hansen, K. Gormsen, H. M. Pedersen, and K. L. Gammelmark, "Ultrasound research scanner for real-time synthetic aperture data acquisition," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 52, no. 5, pp. 881–891, 2005.

[15] R. Rohling, W. Fung, and P. Lajevardi, "PUPIL: Programmable ultrasound platform and interface library," in *Medical Image Computing and Computer Aided Interventions (MICCAI 2003)*, Montreal, PQ, Canada, Nov. 2003, pp. 424–431.

[16] K. A. Wear, T. A. Stiles, G. R. Frank, E. L. Madsen, F. Cheng, E. J. Feleppa, C. S. Hall, B. S. Kim, P. Lee, W. D. O'Brien, Jr., M. L. Oelze, B. I. Raju, K. K. Shung, T. A. Wilson, and J. R. Yuan, "Interlaboratory comparison of ultrasonic backscatter coefficient measurements from 2 to 9 MHz," *J. Ultrasound Med.*, vol. 24, pp. 1235–1250, 2005.

[17] T. Varghese, J. Ophir, E. E. Konofagou, F. Kallel, and R. Righetti, "Tradeoffs in elastographic imaging," *Ultrason. Imag.*, vol. 23, no. 4, pp. 216–248, 2001.

[18] K. K. Shung and G. A. Thieme, Eds. *Ultrasonic Scattering in Biological Tissues.* Boca Raton, FL: CRC Press, Inc., 1993.

[19] S. A. Goss, R. L. Johnston, and F. Dunn, "Comprehensive compilation of empirical ultrasonic properties of mammalian tissues," *J. Acoust. Soc. Amer.*, vol. 64, no. 2, pp. 423–457, 1978.

[20] G. Sommer, E. W. Olcott, and L. Tai, "Liver tumors: Utility of characterization at dual-frequency US," *Radiology*, vol. 211, no. 3, pp. 629–636, 1999.

[21] M. L. Oelze, W. D. O'Brien, Jr., J. P. Blue, and J. F. Zachary, "Differentiation and characterization of rat mammary fibroadenomas and 4T1 mouse carcinomas using quantitative ultrasound imaging," *IEEE Trans. Med. Imag.*, vol. 23, no. 6, pp. 764–771, 2004.

[22] L. X. Yao, J. A. Zagzebski, and E. L. Madsen, "Backscatter coefficient measurements using a reference phantom to extract depth-dependent instrumentation factors," *Ultrason. Imag.*, vol. 12, no. 1, pp. 58–70, 1990.

[23] J. J. Faran, *Sound Scattering by Solid Cylinders and Spheres.* Cambridge, MA: Harvard University, 1951.

[24] B. S. Garra, E. I. Cespedes, J. Ophir, S. R. Spratt, R. A. Zuurbier, C. M. Magnant, and M. F. Pennanen, "Elastography of breast lesions: Initial clinical results," *Radiology*, vol. 202, no. 1, pp. 79–86, 1997.

[25] J. Ophir, I. Cespedes, H. Ponnekanti, Y. Yazdi, and X. Li, "Elastography: A quantitative method for imaging the elasticity of biological tissues," *Ultrason. Imag.*, vol. 13, no. 2, pp. 111–134, 1991.

[26] K. M. Hiltawsky, M. Kruger, C. Starke, L. Heuser, H. Ermert, and A. Jensen, "Freehand ultrasound elastography of breast lesions: Clinical results," *Ultrasound Med. Biol.*, vol. 27, no. 11, pp. 1461–1469, 2001.

[27] T. Varghese, E. E. Konofagou, J. Ophir, S. K. Alam, and M. Bilgen, "Direct strain estimation in elastography using spectral cross-correlation," *Ultrasound Med. Biol.*, vol. 26, no. 9, pp. 1525–1537, 2000.

[28] M. Rao, Q. Chen, H. Shi, and T. Varghese, "Spatial-angular compounding for elastography using beam-steering on linear array transducers," *Med. Phys.*, vol. 33, no. 3, pp. 618–626, 2005.

[29] U. Techavipoo, Q. Chen, T. Varghese, J. A. Zagzebski, and E. L. Madsen, "Noise reduction using spatial-angular compounding for elastography," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 51, no. 5, pp. 510–520, 2004.
30

[30] U. Techavipoo and T. Varghese, "Improvements in elastographic contrast to noise ratio using spatial-angular compounding," *Ultrasound Med. Biol.*, vol. 31, no. 4, pp. 529–536, 2005.

[31] U. Techavipoo, Q. Chen, T. Varghese, and J. A. Zagzebski, "Estimation of displacement vectors and strain tensors in elastography using angular insonifications," *IEEE Trans. Med. Imag.*, vol. 23, no. 12, pp. 1479–1489, 2004.

[32] M. Rao, Q. Chen, H. Shi, T. Varghese, E. Madsen, J. Zagzebski, and T. A. Wilson, "Normal and shear strain estimation using beam steering on linear-array transducers," *Ultrasound Med. Biol.*, 2006, submitted for publication.

[33] F. Kallel and J. Ophir, "A least-squares strain estimator for elastography," *Ultrason. Imag.*, vol. 19, no. 3, pp. 195–208, 1997.

[34] E. L. Madsen, G. R. Frank, T. A. Krouskop, T. Varghese, F. Kallel, and J. Ophir, "Tissue-mimicking oil-in-gelatin dispersions for use in heterogeneous elastography phantoms," *Ultrason. Imag.*, vol. 25, no. 1, pp. 17–38, 2003.

[35] Ultrasonix, *Ultrasonix Research Package v1.10 Software Development Kit (SDK) Documentation.*. Vancouver, BC, Canada, Ultrasonix Medical Corp.:

Thaddeus A. Wilson (S'87–M'00) received his B.S. degree in electrical engineering from Christian Brothers University in Memphis, TN in 1991, and went on to receive his Ph.D. degree in 2000 from the University of Wisconsin-Madison in Medical Physics. He is an assistant professor in the Department of Radiology at the University of Tennessee in Memphis and is certified by the American Board of Radiology in Diagnostic Radiological Physics.

His current research interests include the realization of real-time ultrasound tissue characterization imaging for use in a clinical setting and the evaluation of new ultrasound technology as teaching aids. Dr. Wilson's professional and scientific affiliations include the IEEE, the American Institute of Ultrasound in Medicine, and the American Association of Physicists in Medicine.

James Zagzebski (A'89) was born in Stevens Point, WI in 1944. He received the B.S. degree in physics from St. Mary's College, Winona, MN, and the M.S. degree in physics and the Ph.D. degree in radiological sciences from the University of Wisconsin, Madison. He is a professor of medical physics and of radiology and human oncology at the University of Wisconsin, Madison, WI.

His research interests include ultrasound imaging and tissue characterization, flow detection and visualization using ultrasound, and technological assessment of imaging devices. Dr. Zagzebski's professional affiliations include the IEEE, the American Institute of Ultrasound in Medicine, and the American Association of Physicists in Medicine.

Tomy Varghese (S'92–M'95–SM'00) received the B.E. degree in Instrumentation Technology from the University of Mysore, India in 1988, and the M.S. and Ph.D. degrees in electrical engineering from the University of Kentucky, Lexington, KY, in 1992 and 1995, respectively. From 1988 to 1990 he was employed as an Engineer in Wipro Information Technology Ltd. India. From 1995 to 2000, he was a post-doctoral research associate at the Ultrasonics laboratory, Department of Radiology, University of Texas Medical School, Houston, TX. He is currently an Associate Professor in the Department of Medical Physics at the University of Wisconsin-Madison, Madison, WI. His current research interests include elastography, ultrasound imaging, ultrasonic tissue characterization, detection and estimation theory, statistical pattern recognition, and signal and image processing applications in medical imaging. Dr. Varghese is a senior member of the IEEE and the American Institute of Ultrasound in Medicine (AIUM), and a member of the American Association of Physicists in Medicine (AAPM) and Eta Kappa Nu.

Quan Chen (S'03) was born in Xinhua, China, in 1975. He received his B.S. degree in physics from Nanjing University, Nanjing, China, in 1996. He spent two years in the Master's program in physics, Southeast University, Nanjing, China, before coming to the United States in 1998. He earned the M.S. and Ph.D. degrees in medical physics in 2000 and 2004, respectively, both from the University of Wisconsin-Madison, Madison, WI. He is currently employed by Tomotherapy Inc., Madison, WI, to develop image processing techniques for image-guided radiation therapy (IGRT).

His research interests include computer modeling in ultrasound, parametric imaging (elastography, scatterer size, and attenuation), and computer vision in medical imaging (including segmentation and deformable registration in ultrasound and CT images).

Min Rao was born in Anqing, China, in 1977. She received the B.E. degree and the Ph.D. degree in electrical engineering from Southeast University in Nanjing, China, in 1999 and 2004, respectively. She is currently pursuing the Ph.D. degree in medical physics at the University of Wisconsin-Madison.

Her research interests include elastography, ultrasound imaging, and signal and image processing applications in medical imaging.