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Implementation of a Versatile Research Data Acquisition System Using a Commercially Available Medical Ultrasound Scanner

Martin Christian Hemmsen, Svetoslav Ivanov Nikolov, Mads Møller Pedersen, Michael Johannes Pihl, Marie Sand Enevoldsen, Jens Munk Hansen, and Jørgen Arendt Jensen

Abstract—This paper describes the design and implementation of a versatile, open-architecture research data acquisition system using a commercially available medical ultrasound scanner. The open architecture will allow researchers and clinicians to rapidly develop applications and move them relatively easy to the clinic. The system consists of a standard PC equipped with a camera link and an ultrasound scanner equipped with a research interface. The ultrasound scanner is an easy-to-use imaging device that is capable of generating high-quality images. In addition to supporting the acquisition of multiple data types, such as B-mode, M-mode, pulsed Doppler, and color flow imaging, the machine provides users with full control over imaging parameters such as transmit level, excitation waveform, beam angle, and focal depth. Beamformed RF data can be acquired from regions of interest throughout the image plane and stored to a file with a simple button press. For clinical trials and investigational purposes, when an identical image plane is desired for both an experimental and a reference data set, interleaved data can be captured. This form of data acquisition allows switching between multiple setups while maintaining identical transducer, scanner, region of interest, and recording time. Data acquisition is controlled through a graphical user interface running on the PC. This program implements an interface for third-party software to interact with the application. A software development toolkit is developed to give researchers and clinicians the ability to utilize third-party software for data analysis and flexible manipulation of control parameters. Because of the advantages of speed of acquisition and clinical benefit, research projects have successfully used the system to test and implement their customized solutions for different applications. Three examples of system use are presented in this paper: evaluation of synthetic aperture sequential beamformation, transverse oscillation for blood velocity estimation, and acquisition of spectral velocity data for evaluating aortic aneurysms.

I. Introduction

D IFFICULTIES accessing ultrasound data in the laboratory and clinic have not only limited the basic research, but have also hindered the clinical testing of new ultrasound applications. To access raw ultrasound data,

researchers have worked with ultrasound manufacturers to build custom ultrasound systems such as RASMUS [1], [2] and SARUS [3], but because of their size, these scanners are inaccessible in the clinic. There also exist some commercial or partially commercial ultrasound systems that target the research or original equipment manufacturing (OEM) market, i.e., OPEN [4], Verasonics [5], Samplify, FEMMINA [6], and DiPhAS [7]. Recently, several research interface platforms for clinical ultrasound scanners have been developed for systems such as Hitachi HiVision 5500 [8], Siemens Antares [9], Ultrasonix 500 [10], and Toshiba Aplio. With the introduction of research interface platforms on clinically available scanners, it is now possible to acquire and store data. However, for a system to be suitable for acquisition of data for clinical evaluations, the system must keep factors such as identical transducer, region of interest, and recording time constant on both the reference and the experimental image. Another system requirement is the ability to acquire and store data fast enough for multiple acquisitions during a normal ultrasound examination, and under normal operating conditions. The objective of this work is to develop and implement a versatile research data acquisition system using a commercially available medical ultrasound scanner. This will allow researchers and clinicians to rapidly develop applications and ease the transition to the clinic for evaluation.

The ProFocus research package was developed by BK Medical ApS (Herlev, Denmark) to ease experimental ultrasound data acquisition and control of scanner operation. The research package is an independent development product that complements their ProFocus scanner and is, as such, not a released product. The package includes a UA2227 research interface for real-time data acquisition and remote control of basic scanner operation and a software toolbox for easy access of the complete control parameter set. The research package offers access to beamformed RF data and provides flexible manipulation of control parameters including filtering, compression, transmit level, excitation waveform, beam angle, and focal depth.

The developed research data acquisition system consists of a standard PC and a ProFocus ultrasound scanner. The system uses an open architecture that allows acquisition of data for experimental research, such as developing new image processing algorithms. With the system, users can tailor the data acquisition to fit their working envi-

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ronment, while still maintaining the clinical integrity of using a robust medical device. This will allow researchers and clinicians to rapidly develop applications and move them relatively easy to the clinic for evaluation. A central part of developing new applications and methods is determination of both technical and diagnostic efficacy. With the system, users can acquire interleaved data sequences switching between multiple user defined imaging configurations. This, in combination with the ability to acquire and store multiple data sets during the same examination, makes the system adequate for clinical trials.

This paper describes the capabilities of the research data acquisition system, and demonstrates how it is used to test and implement customized solutions for different research applications. Three examples of system use are presented: evaluation of synthetic aperture sequential beamformation (SASB), transverse oscillation (TO) for blood velocity estimation, and acquisition of spectral velocity data for evaluating aortic aneurysms.

The remainder of this manuscript is organized as follows. Section II and III describes the system and developed Matlab tools, and Section IV presents three examples of system use, followed by conclusions in Section V.

II. System Description

The developed ultrasound research system consists of a commercially available ultrasound scanner (2202 ProFocus equipped with a UA2227 Research Interface, BK-Medical AsP, Herlev, Denmark) and a standard PC. The research interface implements a camera link protocol and allows the acquisition of digital beamformed RF echo data. The acquired data can be received by any video grabber card that supports a camera link. In our configuration, an X64-CL Express camera link (Teledyne Dalsa, Waterloo, Ontario, Canada) is used. The developed software running on the PC is based on libraries by Sapera, now a part of Dalsa. The PC is also connected to the scanner through an Ethernet link which provides access to system parameters. The research and OEM interfaces on the 2202 ProFocus architecture allow external devices to control and access data on the scanner. The OEM interface makes it possible to set and read system parameters and can be used to stream processed images. It is basically a substitute for the normal interface: keyboard, track ball, and screen, and enables embedding in third-party products as a self-sufficient component. The research interface, on the other hand, streams data before envelope detection. Unlike some other research interfaces, all data are sent out of the scanner. It is, however, possible to filter out undesired modes and, e.g., only receive color flow map (CFM) or B-mode data.

Fig. 1 illustrates the data flow and the structure of the software and hardware in the system. Raw channel data from the individual transducer elements are sampled and sent to the beamformer. The beamformed data are minimally processed because, aside from an optional time-
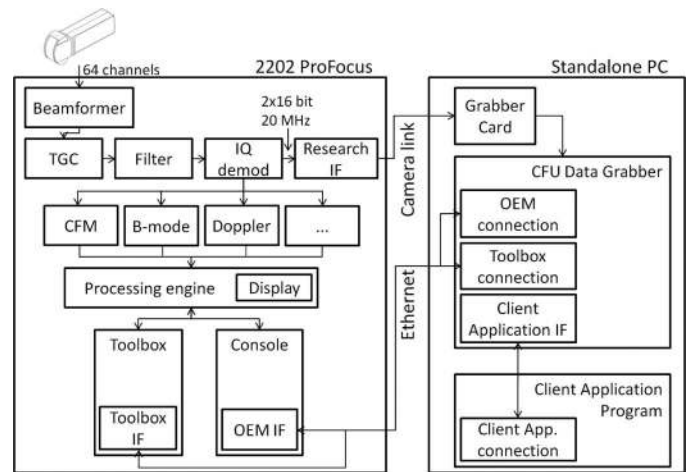

Fig. 1. Data flow and structure of the software and hardware of the system. Arrows indicate the direction of the data flow.

variant band-pass filter, the only other processing is application of the time-gain compensation (TGC) and transformation to baseband in-phase and quadrature (I/Q) data and downsampling by a factor of 2. The beamformed data stream is processed and sent to the research interface.

The I/Q data are further processed to generate B-mode, CFM, Doppler, and M-mode images. The results of this processing are transferred to the processing engine for subsequent post-processing and display. The user interface and the calculation of control parameters are handled by the main application, called Console. The system architecture of the 2202 ProFocus makes it possible for several standalone applications to coexist and to interact with the control parameters. One such application is the Toolbox, and it is used for debugging of the system, for prototyping of new algorithms, and for image optimization. Examples of image optimization are the design of pulses, definition of receive F-number, and specification of center frequency and bandwidth for the sliding filter. One can view the Toolbox as a form of parameter control unit. Furthermore, it implements an interface that allows remote reading and writing of a complete control parameter set. The OEM interface is implemented by a module in the Console. As such, it has access to the control parameters, and has knowledge of the user input. Using the OEM interface, one can, for example, query which transducer is used, get information about image geometry and imaging mode, set focus depth, manipulate settings, and start or stop the scanner. One can view the OEM interface as a form of remote control. Furthermore, it can stream processed images as they were displayed on the scanner screen. The research interface is implemented as a separate hardware module. One can stream raw beamformed data to external devices using the research interface. Each scan line in the data stream is tagged with a header containing information as to what kind of acquisition the line belongs: B-mode, CFM, or Doppler. It also contains information about the length of a line, if the line is last-in-frame, and if the line is last-in-block, where block refers to the block

of data needed to estimate flow. The remote control of acquisition and parameters is handled by the application called CFU Data Grabber. The application implements a communication module to the OEM interface and the Toolbox interface. Furthermore, it implements an interface that makes it possible for third-party programs, such as Matlab (The MathWorks Inc., Natick, MA), to interact with the application.

A. Data Acquisition

The acquisition of data is controlled through the CFU Data Grabber software and can be performed with a single button click. Alternatively, the acquisition can be issued from a third-party program using messaging. In both cases, data are acquired and temporarily stored in memory for review or download to a hard drive for storage. The maximum length of acquisition stored in memory varies depending on the depth of acquisition, the number of scan lines or ultrasound beams used to create a single frame, and the frame rate. A typical setup recording two interleaved B-mode frames, each with 384 emissions, 15 cm penetration depth, and a frame rate of 7 Hz, allows acquisition of a 22-s sequence. Fig. 2 shows the CFU Data Grabber GUI, which allows upload of a control parameter set, called a usecase, to the scanner, and acquisition, review, and download of data to hard drive. The user can use the review function to display the acquired B-mode image of the first frame; once the user is satisfied with their scan, the data can be saved to the hard drive. The stored data files can later be opened on any computer for analysis and processing. The data storage time is approximately 15.1 s for a 3-s interleaved B-mode sequence including complete scanner settings and patient information.

The scan sequence of the ProFocus is defined as a set of one or multiple basic modes. The basic modes available on the ProFocus are B-mode, M-mode, CFM-mode, and spectral Doppler mode. The scan sequence can be split into

Fig. 2. CFU Data Grabber GUI that is available on the PC for uploading a usecase to the scanner, acquisition of data, review, and download of data to the hard drive.

two independent views; view A and view B. Each view can be a composition of one or more basic modes, and view A and view B can be updated simultaneously. This feature allows interleaved data to be acquired, switching between multiple basic modes, maintaining identical transducer, scanner, region of interest, and recording time on both views. This allows for acquisition of an experimental and standardized data set for evaluation of new processing methods.

The data available for acquisition in all basic modes are beamformed complex baseband I/Q data. To complement the I/Q data, acquisition of the complete control parameter set, including the individual basic mode setups and the scanner user interface setup is available. The scanner user interface setup is called the OEM parameters.

B. Parameter Control

The system allows manipulation of the control parameters in two ways, either through the Console or using standalone applications such as the Toolbox. The Console is the standard user interface and the main application. Modifications made through the Console are limited to standard clinical use and a set of precalculated and safety-validated control parameter setups. The Toolbox allows manipulation of the full control parameter set, and any changes made through the toolbox require a safety verification to ensure that the U.S. Food and Drug Administration (FDA) regulations are not violated [11]. A subset of the available parameters is given in Table I. These parameters are not available on the normal clinical interface or other typical scanners. The manipulation of the control parameters allows a wide degree of experimentation with receive and transmit aperture control, color flow control, and Doppler control. We describe these control parameters subsequently, and the examples included in Section IV demonstrate their use. Modifications made through the Toolbox can result in non-validated setups and measurements must be performed to ensure FDA regulations are not violated.

1) Receive and Transmit Aperture Controls: The receive and transmit aperture controls give the user the ability to control the fundamental parameters related to the formation of an echo line. The available parameters range from adjusting the size and growth of the aperture to controlling the weighting of the individual elements. Some of the parameters are described in the following:

- Aperture growth and dynamic focusing. By default, the system dynamically moves the receive focal point outward and grows the aperture to optimize echoes received from increasing depths. With the Toolbox, the user is given the control to override this dynamic updating and define a static size and focal position of the receive aperture. Hereafter, the default state is referred to as a dynamic aperture, and the opposite state is a static aperture. Of course, the user must choose the focal position and size for a static aperture.
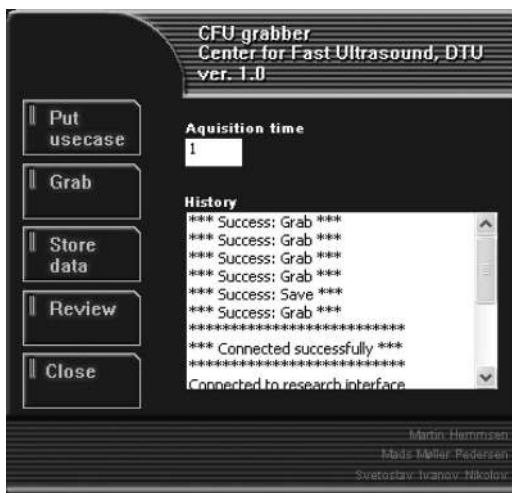
TABLE I. Description of a Subset of the Parameter Controls.

Parameter	Description
Dynamic focusing and dynamic apodization	Receive aperture dynamic focusing and aperture growth can be disabled individually. When disabled, receive aperture size and focal position are fixed.
f-Number	Receive and transmit aperture size can be adjusted individually.
Receive apodization	Receive apodization can be chosen from a fixed list of standard curves such as Hamming, Gaussian, or rectangular apodization, or optionally a custom-made apodization matrix can be uploaded. If defined as a matrix, the apodization can vary between individual beam lines.
Receive time delay profile	Receive time delay profile can be specified individually for each image line when dynamic focusing is disabled.
Line density	The image line density can be chosen from a range of half an element pitch to two element pitch.
Speed of sound	Speed of sound can be specified to match the imaging application.
Excitation waveform	A bipolar excitation waveform can be specified with a time resolution of 8.3 ns.
Region of interest	The region of interest can be adjusted in all imaging modes.
Ensemble size and pulse repetition frequency	The ensemble size and pulse repetition frequency can be adjusted in both CFM imaging and Doppler imaging. A change in the ensemble size or pulse repetition frequency will trigger an automatic recalculation of the shot macro.

- Aperture focal position. When the receive aperture is static, the user can adjust the focal depth and angular spacing between the scan lines. The transmit focal position is adjusted independently.
- Aperture size. The user can adjust the aperture size in dimensionless units of f-number.
- Aperture apodization. The user is given the ability to select between a set of predefined receive aperture weight functions, such as Hamming, Gaussian, or rectangular apodization, or optionally to upload a custom-made apodization matrix. If defined as a matrix, the apodization can vary between individual beam lines.

2) Color Flow Control: The color flow control gives the user the ability to control the fundamental parameters related to the formation of the echo lines for CFM. The available parameters range from adjusting the size of the color box to adjusting the time between individual beam lines. Some of the parameters are described in the following:

- Region of interest. By default, the region of interest is selected as a square in the center of the imaging plane. The user is given the control to move and change the region of interest, either through the Console or the Toolbox.
- Ensemble size. The ensemble size is the number of color firings that are used in the velocity estimate along each beam line. The user is given the ability to experiment with the number of acquisitions to fit a specific application.
- Pulse repetition frequency. The pulse repetition frequency determines the time between two successive echo lines. The user is given the ability to change this frequency to fit a specific application. A change in the pulse repetition frequency, region of interest, or ensemble size will trigger an automatic recalculation of the basic mode acquisition sequence.

3) Doppler Control: The Doppler controls give the user the ability to control the fundamental parameters related to the formation of the echo lines for Doppler imaging.

The available parameters span from adjusting the length of the echo lines to adjusting the time between each acquisition. Some of the parameters are described in the following:

- Range gate. The parameters related to the range gate determine the angle of the beam line relative to the center of the aperture and the length of the echo line. The user is given the control to move and expand the range gate, either through the Console or the Toolbox.
- Pulse repetition frequency. As with the color flow control, the pulse repetition frequency can be specified.

C. Data Management

Data management of the OEM parameters, usecase, and I/Q data are split into three different file types and formats. The file format used for handling I/Q data is a custom-made file format. The file handling is developed in C++ and enables the user to load specified frames from a long data sequence, without loading the entire data set first. Data are stored as 16-bit signed integers.

For handling the OEM interface data characteristic, a C++ class called oemArray is implemented. The design of oemArray resembles to a great extent the design of mexArray by Matlab. One of the design ideas was that oemArray should be able to create its own queries to the OEM interface, and parse the data contained in a data string received by the OEM interface. The full parameter set describing the characteristics of the user interface on the scanner is saved in XML format. The resulting OEM parameter file is a complete description of the scanner user interface setup and includes information such as zoom, overall gain, persistence, and various other visualization settings. The scanner parameters aid the user in replicating experiments by setting up the Console in the exact same mode as it was when the parameters were saved. A library is provided to read and write the parameters in Matlab.

The usecase is a complete description of the control parameters used by the scanner. It includes information such as excitation waveform, receive F-number, center frequency, and bandwidth for the sliding filter. The control

TABLE II. DESCRIPTION OF A SUBSET OF THE FUNCTIONS AVAILABLE IN THE SOFTWARE DEVELOPMENT KIT.

Function name	Description*	Matlab call
Connect	Opens a connection to the CFU Data Grabber application. Optionally, an IP address can be specified as a char array.	.Connect
Disconnect	Disconnects any open connections to the CFU Data Grabber application.	.Disconnect
Grab	Grabs *N* seconds or *N* frames of data to application memory.	.Grab('Nsec') or .Grab(N)
Review	Displays the first B-mode data frame envelope detected and log-compressed to 60 dB dynamic range.	.Review
Save	The function allows storing of the usecase, OEM parameters and acquired I/Q data, to a specified filename. The procedure for saving the usecase and OEM parameters includes fetching the active parameters on the scanner and transferring to local hard drive. I/Q data must have been acquired to application memory before the function call.	.Save('C:test','usecase') .Save('C:test','oem') .Save('C:test','frame') .Save('C:test','all')
Load	The function allows uploading of a specified usecase or OEM parameter file to the scanner.	.Load('C:test','usecase') .Load('C:test','oem')
Send_msg	Transfers a message to the OEM interface (oem) or to the research interface (ri) on the scanner.	.Send_msg('oem','msg') .Send_msg('ri','msg')
Read_Usecase	Reads the specified file, parses the data and returns a Matlab structure.	Read_Usecase('c:test.dat')
cff_file_open	Opens a user specified cfu file type and returns a file identifier.	cff_file_open('c:test.cfu')
cff_file_close	Closes the file specified.	cff_file_close(fid)
cff_file_plane_read	Returns the data from the specified file and plane number.	cff_file_plane_read(fid,plane_nr)

*OEM = original equipment manufacturing; I/Q = in-phase and quadrature.

parameters aid the user in replicating experiments, and creating simulations using tools such as Field II [12], [13] with a setup identical to that used in measurements. The parameter set is saved in ASCII format. This allows the user to open the file with a normal text editor to read or write application-specific initialization of control parameters.

III. MATLAB TOOLS

The CFU Data Grabber application implements an interface that makes it possible for third-party products, such as Matlab, to interact with the application via messaging. The interface provides the user to access the service interface layer in the application, giving access to system functions. Because many researchers utilize Matlab for data analysis, a software development toolkit (SDK) for Matlab is developed. The SDK implements a CFU_Data_Grabber class that allows a flexible manipulation of the control parameters and data acquisition. Further, the SDK implements a set of functions for basic file handling of the files collected with the system. A description of CFU_Data_Grabber member functions and functions available for file handling are listed in Table II.

IV. RESULTS

The developed ultrasound data acquisition system has been extensively used to acquire *in vivo* data from volunteers in the clinic as well as phantom measurements in the lab. Three research studies that have benefited from the system are presented here.

A. Preliminary Evaluation of Synthetic Aperture Sequential Beamformation

1) Background: In multi-element synthetic aperture (SA) imaging, the basic idea is to create a pressure wave from multiple elements with a focused transmission. The concept of using the transmit focal point as a virtual source was introduced by Passmann and Ermert [14]. Virtual sources in synthetic aperture focusing (SAF) were further investigated by Frazier and O'Brien [15], Nikolov and Jensen [16], [17], and Bae and Jeong [18]. It was shown that the virtual source coincides with the focal point of the transducer and that a depth-independent resolution can be achieved. Kortbek *et al.* introduced in [19] the concept of sequential beamforming to SA imaging to reduce system requirements for real-time implementation. It was shown that for a multi-element linear-array transducer, the lateral resolution could be made more range independent and improved significantly compared with conventional dynamic receive focusing (DRF). In [20], Hemmsen *et al.* applied SASB to medical ultrasound imaging using convex array transducers. It was shown that the method is applicable for medical imaging and improves the lateral resolution compared with DRF.

The basic idea in synthetic aperture sequential beamforming (SASB) is to create a dual-stage procedure using two separate beamformers. In the initial stage, a beamformer using a single focal point in both transmit and receive creates a set of focused image lines. A second-stage beamformer creates a set of high-resolution image points by combining information from multiple first-stage focused image lines. The effect is a dynamically expanding array as the image depth increases and a more range-independent lateral resolution is obtained.

In the following example, the developed system is used to acquire I/Q signals to create B-mode images using DRF and SASB. In this experiment, the lateral resolution and SNR of SASB will be calculated and compared with DRF. Furthermore, *in vivo* data are acquired, and B-mode images are generated for a visual comparison and evaluation of the image quality of the two image modalities.

2) Method: In the following experiment, an abdominal 3.5-MHz probe with a room-temperature vulcanization (RTV) lens (3ML35CLA192, Sound Technology Inc., State College, PA) was used. In the first part of the experiment, the transducer was clamped to immobilize the transducer over a speckle phantom (Model 571, Danish Phantom Service, Frederikssund, Denmark). A water bath at the top of the phantom provided a coupling medium between the transducer and the phantom. The transmit frequency of the transducer was set to 5 MHz, and the transducer was fixed such that the transducer surface was parallel to the phantom. Using the Console application, both view A and view B were set to simultaneous B-mode imaging with a field of view of 14.6 cm and neutral TGC. Using the Toolbox, dynamic receive focusing and dynamic apodization were disabled on view A. Subsequently the f-number were fixed to 2 in both transmit and receive, and the transmit and receive foci were set to 70 mm. The transmit focus point for view B was set to 105.5 mm with a transmit f-number of 5 and receive f-number of 0.8. Using the Matlab SDK, 20 frames of beamformed I/Q data from view A and view B were acquired interleaved with identical excitation waveforms, TGC, and overall gain in both setups. The scan sequence was specified to a line density of 2 lines per element, resulting in 384 lines for each image. The acquired I/Q data from view A were subsequently processed using the Beamformation Toolbox III [21] to generate SASB second-stage RF data. The method used to compute the SNR of the second-stage data and the acquired data from view B is described as

$$\text{SNR}(z) = \frac{1}{L} \sum_{l=1}^{L} \frac{S(z,l)^2}{N(z,l)}, \quad (1)$$

where L is the number of acquired beam lines and $S(z,l)$ and $N(z,l)$ are the mean power of the signal and noise at depth z for the lth beam line; they are expressed as

$$S(z,l) = \frac{1}{N} \sum_{n=1}^{N} x(z,l,n),$$

$$N(z,l) = \frac{1}{N} \sum_{n=1}^{N} (x(z,l,n) - S(z,l))^2,$$

where $x(z,n)$ is the sample at depth z for the nth frame and N is the total number of acquired frames.

In the second part of the experiment, the transducer was clamped to immobilize the transducer over a wire and contrast phantom (Model 525, Danish Phantom Service, Frederikssund, Denmark). A water bath at the top of the phantom provided a conducting medium between the transducer and the phantom. The transmit frequency was set to 5 MHz, and the transducer was fixed such that the vertical wires were placed along the vertical center of the field of view. The usecase from the first experiment was uploaded to the scanner and 20 frames were acquired. The acquired I/Q data from view A were subsequently processed to generate SASB second-stage data. The second-stage data and the acquired data from view B were envelope detected, log-compressed, and scan converted to create B-mode images. Using the B-mode images, the lateral resolutions at full-width at half-maximum (FWHM) and −20 dB were extracted.

In the final part of the experiment, an *in vivo* scan of the Morison's pouch from a 30-year-old male volunteer was scanned. The scanner setup, control parameters, and scan sequence were identical to those used in the first and second parts of the experiment.

3) Results: Fig. 3(a) presents the SNR calculated as the ratio between the mean power of the signal divided by the power of the noise. The gray line represents the SNR using DRF and the black line using SASB. The SNR using SASB is on average 6.2% or 1.18 dB better than the SNR using DRF.

Fig. 3(b) presents the lateral resolution calculated from the B-mode images of the measurement on the wire and contrast phantom. The lateral resolutions are calculated at FWHM (solid line) and −20 dB (dashed line) using DRF (gray line) and SASB (black line) in the range 10 to 140 mm. At FWHM and −20 dB, the lateral resolutions
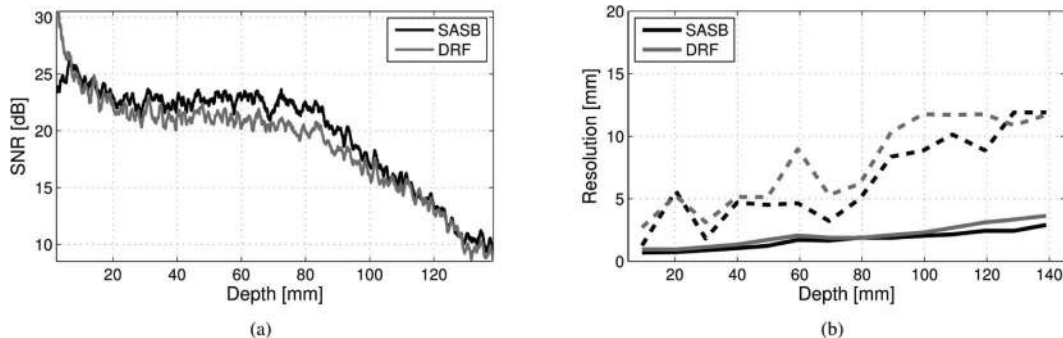

Fig. 3. (a) Visualization of the SNR using synthetic aperture sequential beamformation (SASB; solid black line) and dynamic receive focusing (DRF; solid gray line). (b) Visualization of the lateral resolutions at FWHM (solid line) and −20 dB (dashed line) using DRF (gray) and SASB (black).
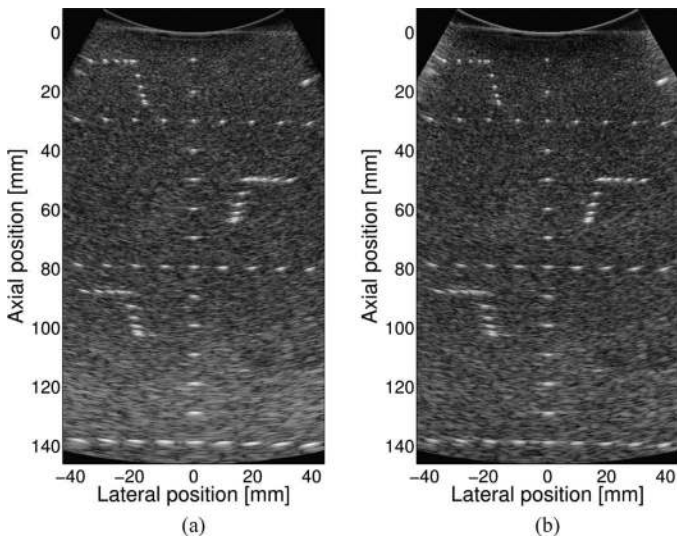
Fig. 4. Visualization of wire and contrast phantom measurement, using (a) dynamic receive focusing beamforming and (b) synthetic aperture sequential beamformation.

are on average improved by 18.4% at FWHM and 17.4% at −20 dB using SASB. The standard deviation of the lateral resolution at FWHM was improved from 0.9 mm using DRF to 0.7 mm using SASB. At −20 dB, the standard deviations were 3.5 for both modalities.

For visual inspection, Fig. 4 displays the B-mode images created from the measurement on the wire and contrast phantom, using (a) DRF and (b) SASB. Note how SASB is able to maintain a more isotropic point spread function through depth and has a better lateral resolution. Fig. 5 displays the B-mode images from the *in vivo* measurement of the Morison's pouch, the right kidney, and the adjacent part of the liver from a 30-year-old male, using (a) DRF and (b) SASB.

4) Summary: Three experiments were performed. The first two experiments were performed to measure the performance of SASB compared with DRF. The SNR and the lateral resolution were used as quantitative measures. The third experiment was performed as a preliminary *in vivo* evaluation of the method. The evaluation using the quantitative measures showed the ability of SASB to decrease the standard deviation of the lateral resolutions at FWHM, the ability to obtain a more isotropic point spread function compared with DRF, and to improve the SNR. The performance gain using SASB compared with DRF was further supported by *in vivo* scan of the right kidney and the adjacent liver. The presented results prove the viability of SASB for 2-D ultrasound imaging using commercially available equipment.

B. Transverse Oscillation for Blood Velocity Estimation

1) Background: Medical ultrasound is widely used to study blood flow dynamics in the human circulatory system. For example, the estimation of blood flow velocities plays a key role in diagnosing major diseases in the carotid arteries [22]. However, blood velocity estimates using conventional color flow imaging or Doppler techniques are angle-dependent. That is a major limitation, and poses a huge challenge for quantitatively estimating the magnitude of the blood velocity.

Several techniques [23]–[27] have been proposed to compensate for the inherent angle dependency problem. In this case, the transverse oscillation (TO) method suggested by Jensen and Munk [28] is used. Anderson [29] suggested a similar approach. The TO method has demonstrated promising *in vivo* results [30], [31]; however, the previously reported results have been obtained using the experimental scanner RASMUS [1], [2].
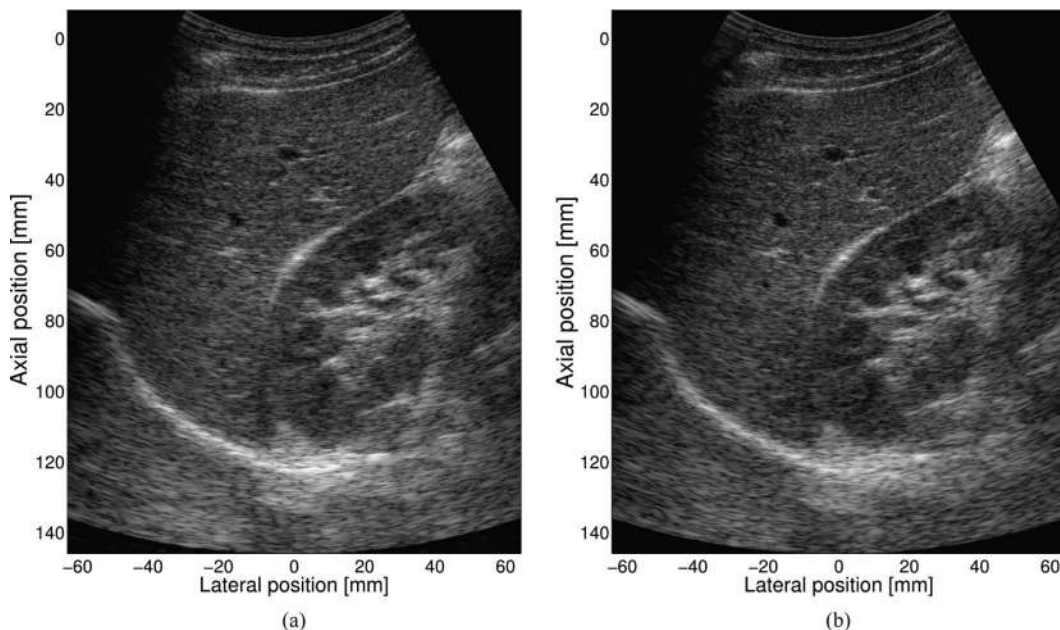

Fig. 5. Visualization of *in vivo* measurement of the liver (left side of the image) and right kidney (right side of the image) and Morison's pouch, not containing fluid, using (a) dynamic receive focusing and (b) synthetic aperture sequential beamformation.
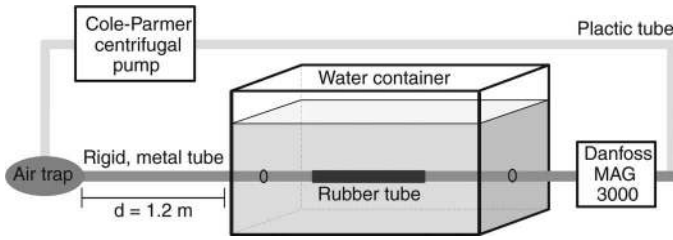
Fig. 6. The flow rig setup with a Cole-Parmer centrifugal pump, an air entrapment device, a water container with a rubber tube, and a Danfoss MAG 3000 magnetic flow meter. Note that this figure is not to scale, and that the entrance length of the tube is more than 1.2 m, enough to ensure fully developed laminar flow. A fixture can be placed in the water container to keep the transducer fixed at a known beam-to-flow angle.

TABLE III. PARAMETERS FOR THE EXPERIMENTAL
FLOW RIG MEASUREMENTS.

Scanner parameters	Value
Pulse repetition frequency	1.3 kHz
Speed of sound	1480 m/s
Number of transmit cycles	6
Ensemble size	16
Transmit focus depth	15 mm
Center frequency of the CFM pulse	5 MHz
Transmit f-number	4
Line density	1 per element
Multibeam (parallel beamforming)	3

The basic idea in the TO method is to create a double oscillating field by using special apodization profiles in receive. Two lines with a lateral displacement of one-quarter spatial wavelength, corresponding to a 90° phase shift, are beamformed simultaneously in receive. A center line is also beamformed for traditional axial velocity estimation. For a description and derivation of the estimator, the reader is referred to Jensen [32]. The lateral wavelength, λ_x, can be found by

$$\lambda_x = 2\lambda_z \frac{z}{D}, \qquad (2)$$

where λ_z is the axial wavelength, z is the depth, and D is the distance between the two peaks in the receive apodization.

In the following example, the initial work on investigating the feasibility of a commercial implementation of the TO method for clinical use is presented. The developed research data acquisition system is used to acquire RF data from a flow rig for a statistical evaluation of the TO implementation.

2) Method: In the following experiment, a linear-array transducer (BK8812, BK-Medical, Herlev, Denmark) was used. Velocity measurements were performed using a custom-made circulating flow rig to evaluate the TO method. The setup consists of a long rigid metal tube replaced by a rubber tube (radius 5.7 mm) inside a water-filled container as illustrated in Fig. 6. The tube is filled with a blood mimicking fluid [30]. A centrifugal pump (75211–60, Cole-Parmer, Vernon Hills, IL) controls the fluid flow, and a magnetic volume flow meter (MAG 3000, Danfoss A/S, Sønderborg, Denmark) is used to measure the actual volume flow. The centrifugal pump is only able to keep the flow constant at sufficiently low flow rates ($Q < 60$ L/h); therefore, the peak velocity of the flow, v_0, was set to 0.215 m/s. The entrance length of the tube is more than 1.2 m, and, under the given settings, is sufficient in length to ensure fully developed flow. The transducer was fixed at a distance of 16 mm to the center of the rubber tube and the beam-to-flow angle was set to 90°.

Using the Console application, view A was set to B-mode and CFM imaging. Several parameters were set

manually in either the Console or the Toolbox. They are listed in Table III. Setting the multibeam parameter to 3 means that three lines are beamformed simultaneously in receive: Two are TO lines, one is a center line for conventional axial velocity estimation.

Subsequently, the CFM receive delays and apodizations were downloaded from the scanner, modified according to the principles of the TO method, and then uploaded to the scanner again. With a focal point at 15 mm, a line density of 1 line per element, and beamforming the two TO lines next to each other (i.e., $\lambda_x/4$ is equal to the pitch), the spacing between the two aperture peaks must be 6.6 mm. The transmit and receive aperture functions are illustrated in Fig. 7.

Using the Matlab SDK, beamformed RF data from view A were acquired. Although data for whole CFM frames were acquired, only the central CFM line was extracted from each frame for further offline processing using Matlab. Seventy-five flow profiles were generated for the purpose of investigating the performance of the TO estimator.

The performance of the method is investigated by comparing the true profile with the measured velocity profiles. The measured velocity is estimated from several emissions. The average, $\bar{v}(z_k)$, of N estimates and the estimated standard deviation, $\sigma(z_k)$, are calculated at each discrete depth as

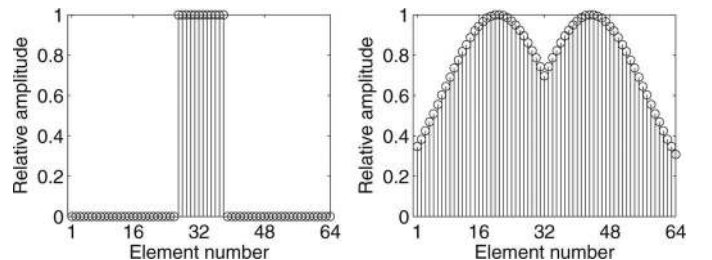$$\bar{v}(z_k) = \frac{1}{N} \sum_{i=1}^{N} v_i(z_k) \qquad (3)$$

Fig. 7. The transmit and receive aperture for the transverse oscillation (TO) estimator with a transmit focal depth at 15 mm. The transmit aperture is rectangular, and the f-number is 4. The receive aperture is the TO apodization.

$$\sigma(z_k) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(v_i(z_k) - \overline{v}(z_k))^2}, \qquad (4)$$

where $v_i(z_k)$ is the ith velocity estimate at the discrete depth z_k.

3) Results: Fig. 8 shows the estimated lateral velocity component of the flow profiles for 75 measurements at a beam-to-flow angle of 90°. It also indicates the mean estimate $\pm$ 1 standard deviation and the expected true velocity. The TO method is clearly able to estimate the lateral velocity component, which is not possible with conventional estimators. As expected, the estimated lateral velocity profile has a parabolic shape.

There is a mismatch between the theoretical λ_x from (2) and the simulated mean $\overline{\lambda}_x$ in the generated TO field because the assumptions for the Fraunhofer approximation are not fully met. The consequence of this is underestimated velocities. Using Field II, the mean lateral wavelength can be estimated based on the 2-D spatio-temporal frequency domain of the combined pulse-echo TO field. At 15 mm, the theoretical λ_x is 1.35 mm and the simulated mean $\overline{\lambda}_x$ is 2.66 mm. Calculating the relative bias between the simulated mean value and the theoretical value, one obtains $(2.66 - 1.35)/2.66 = 0.494$. The bias correction factor is therefore 1.494, and this value is multiplied to the estimated velocity. The mean $\overline{\lambda}_x$ is simulated for each 1/2 mm from 10 to 22 mm and interpolated before bias compensation is applied to the 75 velocity profiles. With this bias compensation, the mean of the estimated velocities closely follows the theoretical profile.

4) Summary: By using the research data acquisition system, beamformed data for the TO method were obtained. Based on these data, the transverse (lateral) ve-

Fig. 8. (top) Transverse oscillation estimated lateral velocities for 75 flow profiles with a beam-to-flow angle of 90°. (bottom) Mean estimate $\pm$ 1 standard deviation and expected theoretical velocity profile.

locity component perpendicular to the ultrasound beam could be measured. The results demonstrate that the TO method is suitable for a commercial implementation.

C. Acquisition of Spectral Velocity Data for Evaluating Aortic Aneurysms

1) Background: Medical ultrasound is commonly used to study and diagnose cardiovascular disease because it provides a non-invasive, real time imaging technique to visualize pathology in both the solid arterial wall and abnormal flow patterns in the blood. One of the first attempts to quantify blood velocities was performed by Satomura [33] using a continuous wave Doppler system and estimating the flow pattern from the Doppler spectrum. This system was then further developed into a pulsed-wave system able to probe at a certain depth and thereby possibly to investigate individual blood vessels, mapping the velocity and time evolution of the velocity [34]. Blood consists of many scatterers, and it is the reflective scattering from these that constitutes the flow signal from the blood. The basic principle in spectral recordings using the pulsed wave system is that several pulses are emitted into the tissue from the same position. The received backscattered signal is then sampled at the time relative to the emission, yielding a frequency that is proportional to the blood velocity [35].

In the following application, the developed system is used to acquire RF signals to obtain patient-specific spectral measurements to calculate velocity profiles in the human abdominal aorta. These velocity profiles are intended to be applied as inlet condition for the pulsating blood in a patient-specific fluid-structure interaction model which can be used as part of the diagnostic process of cardiovascular disease.

The finite element (FE) analysis of the combination of solid arteries (structure) and flowing blood (fluid) has developed over the years with different purposes and spectral measurements have been used as a tool to construct realistic numerical models of the fluid-structure interaction [36], for example, in the clinical quantification of coronary plaque progression, ultrasound simulation of velocity fields based on computational fluid dynamics [37], and rupture risk assessment of abdominal aortic aneurysms [38]. The spectral measurements are rarely used for purposes other than determination of inlet conditions in these simulation models. With the versatile data acquisition system, the large amount of data can be used for further analysis of modeling results; for example, the wall displacement during the heart cycle can be measured and compared with simulated results, providing a method to evaluate the performance of different structural material models.

2) Method: Data for the presented application of the research interface origins from a study on the biomechanical properties of the human abdominal aorta. The total data set was collected from a group of 11 healthy volunteers and consists of a magnetic resonance angiography and an
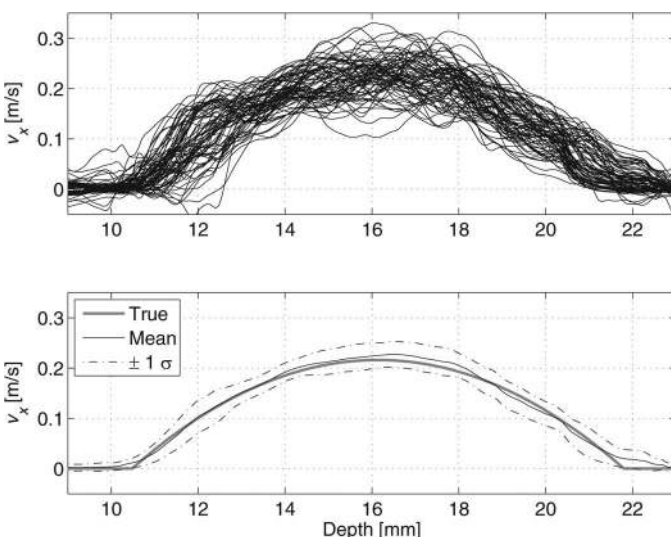
ultrasound scan using the spectral Doppler method to obtain measurements of the blood flow in the abdominal aorta. To demonstrate the use of the research data acquisition system, the collection and processing of spectral Doppler measurements from a 53-year-old healthy male is presented.

The data acquisition was performed using a convex array transducer (BK8803, BK-Medical, Herlev, Denmark) with a center frequency of 5 MHz. Using the Console, a scan sequence containing B-mode and Doppler mode was specified. The pulse repetition frequency of the spectral Doppler mode was set to 2 kHz, interleaving the acquisition of the individual scan lines from the two basic modes.

The same clinician performed all ultrasound scans to avoid differences in scanning technique from subject to subject. During the scans, the clinician was asked only to adjust the size of the range gate, angling of the flow direction relative to the beam direction without allowing beam steering, and the overall gain using the only the Console. The reason for this was to standardize the scanning sequence, and only allow changes in the scanner setup that would not affect the data acquisition method. This limitation of manipulation with control parameters was decided with the intention of providing clinicians with a simple method to collect flow data for investigation of pathological flow patterns. Fig. 9 illustrates the Console interface, and the different control parameters available for the clinician to adjust are listed to right of the duplex image display. Four data sequences of spectral Doppler spectrum data and B-mode image data were obtained from the volunteer, and RF data for each sequence was acquired and stored subsequently using the Matlab SDK.

The acquisition time for each blood flow measurement was set to five seconds in the CFU Data Grabber, corresponding to approximately five cardiac cycles. The volunteer was asked to stop breathing during each of the acquisitions to ensure as few artifacts from movement of the surrounding abdominal structures as possible. Each of the collected RF data sets for velocity estimation of the blood flow is a matrix with 10 240 lines and 1062 samples in each line. Subsequently, data was processed offline to inspect the quality of the RF data and to calculate the spectral density spectrogram of the received flow signals. Each spectral density spectrum was calculated from 16 emissions, each having an overlap of 50%. Each spectral density spectrum had a length of 128 samples and the time between spectra was 5 ms, resulting in 1011 spectra.

3) Results: Fig. 10 shows the computed spectral density spectrum from the acquired RF data sequence corresponding to the setup displayed in Fig. 9. Comparing the two spectral density spectra, a high similarity is seen. In both spectra, the peak velocity is approximately 68 m/s in the forward flow direction (from proximal to distal relative to the heart) and a peak velocity in the backward flow direction of approximately 29 m/s. In general, the peak forward velocity in the abdominal aorta is around 0.5 to 0.6 m/s with a mean velocity of 0.08 to 0.2 m/s [39].

Fig. 9. Duplex interface on the Profocus scanner during data acquisition. All parameters listed to the left are also registered in the usecase produced in each data acquisition sequence.

Thus, this volunteer showed a slightly increased velocity in the abdominal aorta compared with the general case.

The velocity change can be used to establish a patient-specific inlet condition for each patient-specific abdominal aortic geometry, constructing a realistic simulation model for diagnostic purposes. This is done by assuming that the inlet cross-section is rotationally symmetric, the flow is fully-developed, and that the blood is a Newtonian fluid, in which case Womersley's theorem can be used to determine the flow pattern during the cardiac cycle.

4) Summary: The research data acquisition system facilitates access to raw flow data from spectral Doppler spectral measurements which can be directly applied in a finite element model for simulation of patient-specific flow and biomechanical properties of the arterial wall. This is an important step toward a realistic patient-specific simulation model to support diagnosis of various cardiovascu-
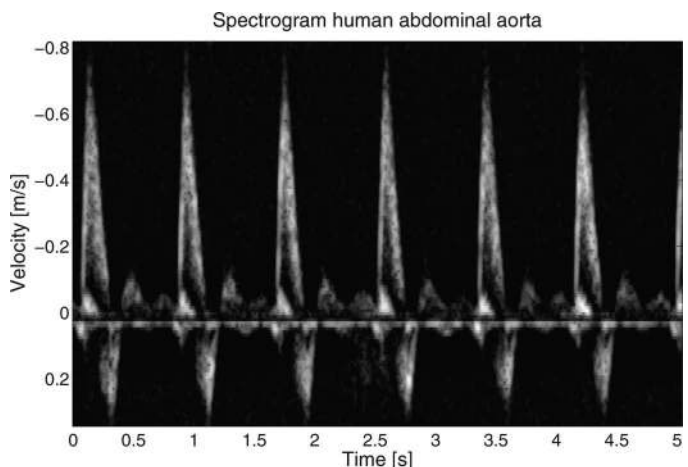

Fig. 10. Spectral density spectrum of the blood velocity in the abdominal aorta using the extracted research data set from the scanning sequence corresponding to the interface shown in Fig. 9.

lar diseases which can be introduced to and used directly in the clinic.

V. Conclusions

A versatile and open architecture research data acquisition system using a commercially available medical ultrasound scanner has been implemented. The system consists of standard PC and a BK Medical ProFocus ultrasound scanner. The system uses an open architecture that allows acquisition of data for experimental research, such as developing new imaging processing algorithms. With the system, users can tailor the data acquisition to fit their working environment while still maintaining the clinical integrity of using a robust medical device. This will allow researchers and clinicians to rapidly develop applications and move them relatively easy to the clinic.

The clinical usability of the scanner, including the frame rate, is unaffected by data acquisition. Furthermore, the system allows remote control of basic scanner operation, and provides software for easy access to the complete control parameter set. The system allows access to beamformed RF data and provides flexible manipulation of control parameters such as filtering, compression, transmit level, excitation waveform, beam angle, focal depth, etc. The system offers high-speed data acquisition, beneficial for clinical scanning and system evaluation.

Data acquisition can be controlled through a GUI running on the PC or by using third-party products such as Matlab. The developed SDK gives researchers and clinicians the ability to utilize Matlab for data analysis and flexible manipulation of control parameters. Because of these advantages, research projects have successfully used the system to test and implement their customized solutions for different applications. We believe that the system can contribute to accelerated advancements in ultrasound imaging by allowing more ultrasound researchers to test and clinically evaluate promising new applications.

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