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Synthetic Transmit Aperture in Ultrasound Imaging

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The paper describes the use of synthetic transmit aperture (STA) imaging in medical ultrasound. The synthetic aperture (SA) imaging is a novel approach to today's commercial systems. In these systems the image is acquired sequentially one image line at a time that puts a strict limit on the frame rate and the possibility of acquiring a sufficient amount of data for high image quality. This limitation can be lifted by employing SA imaging where the data are acquired simultaneously from all directions over a number of emissions, and the full image can be reconstructed from those data. Due to the complete data set, it is possible to have full transmitting and receiving focusing at the entire image region to improve the contrast dynamic and spatial resolution.

The paper describes the STA imaging with a single element transmitting and all elements receiving apertures. In experiments, 32-element linear transducer array with 0.48 mm inter-element spacing and a burst pulse of 100 ns duration were used. The single element transmission aperture was used to generate a spherical wave covering the full image region. The 2D ultrasound images of wire phantom are presented to demonstrate the benefits of SA imaging.

Keywords: ultrasound imaging, synthetic aperture, beamforming.

1. Introduction

Medical ultrasound imaging is a technique that has become much more prevalent than other medical imaging techniques since this technique is more accessible, less expensive, safe, simpler to use and produces images in the real time. However, images produced by an ultrasound imaging system, must be of sufficient quality to provide accurate clinical interpretation. The most commonly used image quality measures are spatial resolution and image contrast which can be determined in terms of beam characteristics of an imaging system: beam width and side-lobe level. In the design of an imaging system, the optimal set of system parameters is usually found as a trade-off between the lowest side-lobe peak and the narrowest beam of an imaging system.

In conventional ultrasound imaging systems, when one transducer (in mechanical wobble) or linear array are used, the quality of images directly depends on the transducer acoustic field. Also in conventional ultrasound imaging, the image is acquired sequentially one image line at a time that puts a strict limit on the frame rate that is important in the real-time imaging system. Low frame rate means that moving structures (e.g. heart valves) are not easily imaged and diagnosis may be impaired. This limitation can be lifted by employing SA imaging. The basic idea with synthetic aperture (SA) is to combine information from emissions close to each other. The synthetic aperture method has not been previously used in medical imaging. This method is a contrast to the conventional beamforming, where only imaging along one line in receiving is used. The SA method aspects are discussed in [1].

In the synthetic aperture method, as well as in the conventional method, the peak acoustic power limits the signal-to-noise ratio (SNR) in the ultrasound images. This limitation can be overcome by using long wide band transmitting sequences and compression techniques on the receiver side. Longer signals allow to obtain results similar to that obtained using single short pulses but with a much higher amplitude [2, 6]. There are several papers in literature concerning the similar boundary-condition problem of signal compression in medical diagnostic imaging [3, 4]. In comparison with other coded excitation schemes, such as chirp, pseudo-random sequences and Barker codes, the complementary Golay sequences allowed virtually side-lobe free operation.

There are some different beamforming methods. In the classical Synthetic Aperture Focusing Technique (SAFT), only a single array element transmits and receives at each time. All the elements are excited sequentially one after the other, and the echoes received are recorded and stored in the computer memory. It reduces the system complexity and the frame rate, but requires data memory for all data recordings. The main disadvantage of SAFT is the low signal-to-noise ratio (SNR) and as a result, the poor contrast resolution. In the Multielement Synthetic Aperture Focusing (MSAF) method, at each time a group of elements transmit and receive signals simultaneously. The transmit beam is defocused to emulate a spherical wave. The SNR is increased compared to SAFT, in which only a single element is used in transmit and receive.

In this paper a synthetic transmit aperture (STA) method for medical ultrasound imaging system is described. Compared to other beamforming methods, the advantage of this approach is that a full dynamic focusing can be applied to the transmit and the receive producing the highest quality of images while maintaining or even drastically decreasing the time of image acquisition which allows to increase the frame rate.

2. Synthetic transmit aperture beamforming

The problems with medical ultrasound include low imaging depth and that high resolution is achieved only where the transducer is focused. Another problem is the decreasing of SNR with depth. The basic idea with synthetic aperture is to combine information from emissions close to each other. The idea, first described in [5], was to transmit an unfocused wave from one element and only use dynamic focusing when receiving for all points the wave passed. This is a contrast to the conventional beamforming, were only imaging along one line in receiving is used. This means that every image line is imaged as many times as the number of elements used. This will create an equal amount of low resolution images which are summed up to create one high resolution image.

One of the important processes in ultrasound imaging systems is the beamforming. There are many different beamforming methods. In this paper the STA method is discussed, where at each time one array element transmits a pulse and all elements receive the echo signals. Here data are acquired simultaneously from all directions over a number of emissions, and the full image can be reconstructed from this data (see Fig. 1). The advantage of this approach is that a full dynamic focusing can be applied to the transmission and the receiving giving the highest quality of image.

In the STA method focusing is performed by finding the geometric distance from the transmitting element to the imaging point and back to the receiving element. The structure of the synthetic aperture and geometric relation between the transmit and receive element combination is shown in Fig. 2.

When a short pulse is transmitted by the element m and the echo signal is received by the element n, as shown in Fig. 2, the round-trip delay is

$$\tau_{m,n} = \tau_m + \tau_n, \tag{1}$$

where (m, n) is a transmit and receive element combination, $0 \le m, n \le N-1$.

The delays for the m-th element and n-th element are

$$\tau_m = \frac{1}{c}\sqrt{x_m^2 + r^2 - 2x_m r\sin\theta}, \qquad \tau_n = \frac{1}{c}\sqrt{x_n^2 + r^2 - 2x_n r\sin\theta}, \tag{2}$$

where x_m, x_n are the positions of the m-th and n-th elements, respectively, and r is the distance between the synthetic aperture centre and the point (r, θ).

For an N-element array for each point in the image, the A-scan signal can be expressed as

$$A\left(t\right) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} y_{m,n}\left(t - \tau_{m,n}\right), \tag{3}$$

where $y_{m,n}(t)$ is the echo signal and $\tau_{m,n}$ is the beamforming delay for the (m, n) receive and transmit element combination given in (1). The first and second summations correspond to transmit and receive beamforming.

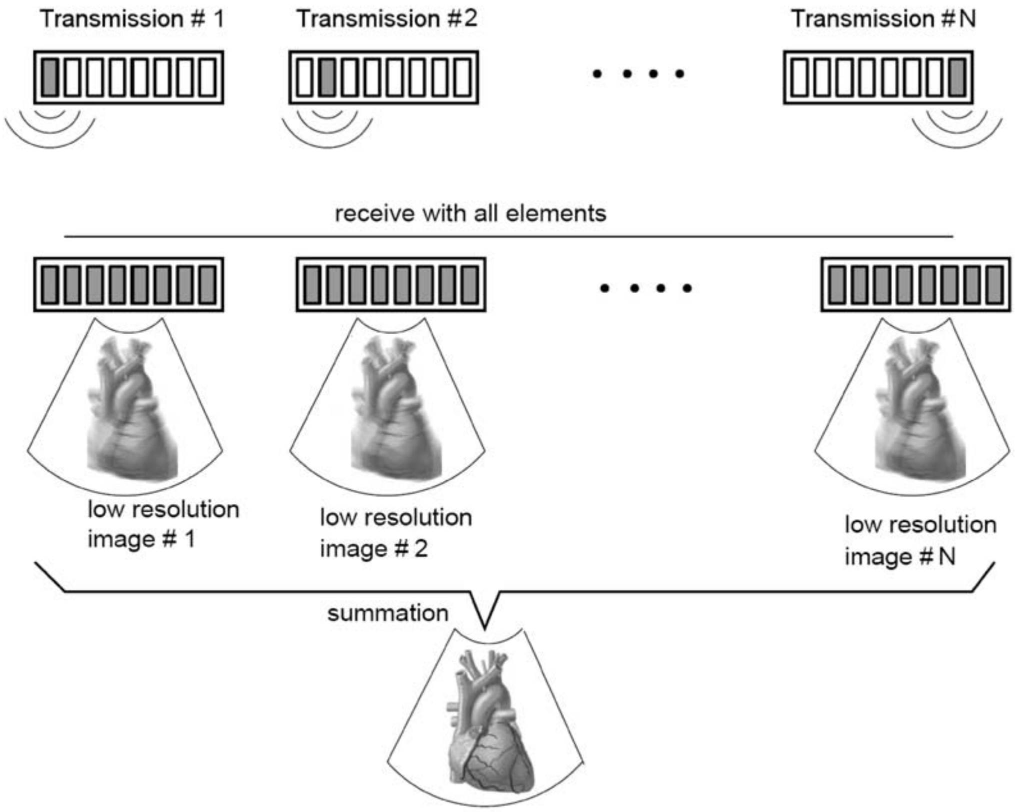

Fig. 1. Low resolution images combined to produce a high resolution image. One element transmits at the time, while all are used to receive. The images is then added into one high resolution image.

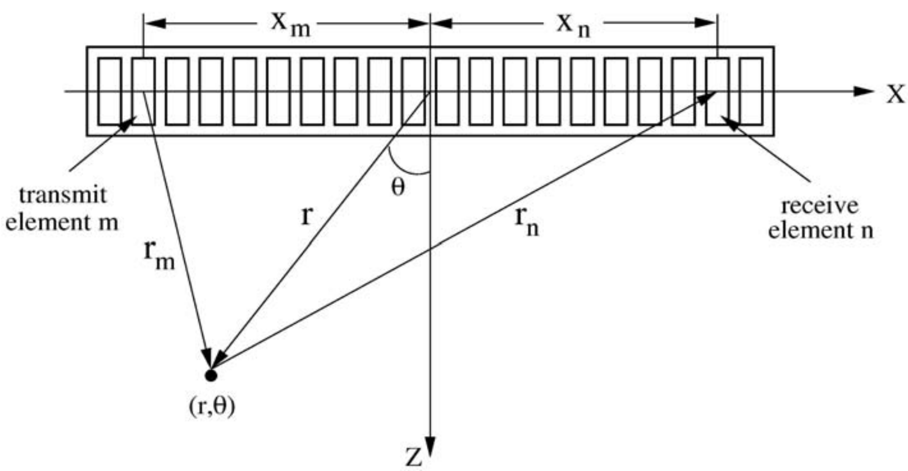

Fig. 2. Geometric relation between the transmit and receive element combination and the focal point.

3. Ultrasound imaging system

A simplified block diagram of an ultrasound imaging system is shown in Fig. 3.

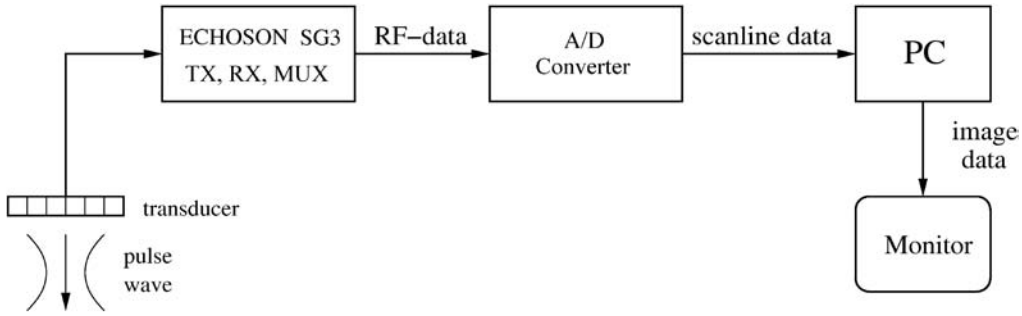

Fig. 3. Block diagram of an ultrasound imaging system.

Echoson SG3 is a programmable analog beamformer frontend. It consists of 32 channel pulser, the input amplifier and analog sum circuitry. The beamformer enables full control of the selected 32 consecutive channels/transducers of a linear array transducer. The parameters of transmission and reception are programmable from a PC using a serial port (RS-232). Using the SG3 one can switch on arbitrary transmit and receive channels in the selected 32 channels aperture. The second block, A/D converter extracts the RF data, acquires it and sends to the PC. Next, the collected digital data were processed offline and displayed on the monitor. All the post processing and display is done on the computer using Matlab. The processing creates 2D ultrasound imaging focused in every point of the image.

The system enabled to perform simulated multichannel acquisition for the synthetic aperture imaging. Using a single channel digitizer and switching receiving transducers able it is possible to gather RF data for up to 32 lines. Repeating this procedure for each of the 32 TX transducers 32 full RF images that are the input to the synthetic aperture algorithm is obtaied.

Synthetic aperture image reconstruction requires a huge amount of data storage and processing power. In the synthetic aperture processing, all the scan lines (full image) are created in each and every firing, where in the standard beamforming only a single line is created. The amount of raw RF data needed in STA imaging for the reconstruction of a single image is proportional to $D_{\mathrm{RF}} \cdot N^2$ and the number of delay-and-sum operations is $D_{\mathrm{RF}} \cdot N^3$, where D_{RF} is the number of samples in a single RF line. For a typical 128 elements linear array with 15 cm penetration ($D_{\mathrm{RF}} = 8000$ at 40 MHz sampling frequency) storage requirements are $\approx 131 \cdot 10^6$ samples, and the number of delay-and-sum operations is $\approx 16.8 \cdot 10^9$.

Examples of delays calculated for different pairs of transmit and receive elements of 32-elements linear transducers with 0.48 mm inter-element spacing, the nominal frequency 5 MHz and sound speed $c = k1540$ m/s are presented in Table 1.

Table 1. Time delay for selected pairs of transmitted and received elements.

Transmit-Receive elements	$R = 10$ mm, $\theta = 30°$			$R = 100$ mm, $\theta = 10°$		
	τ_m [μs]	τ_n [μs]	τ_{mn} [μs]	τ_m [μs]	τ_n [μs]	τ_{mn} [μs]
1-1	5.84	5.84	11.68	64.27	64.27	128.54
1-2	5.84	5.76	11.6	64.27	64.30	128.57
...						
1-31	5.84	9.58	15.42	64.27	65.87	130.14
1-32	5.84	9.84	15.68	64.27	65.94	130.21
32-31	9.84	9.58	19.42	65.94	65.87	131.81
32-32	9.84	9.84	19.68	65.94	65.94	131.88

4. Computer simulation

Simulation is a fundamental way of testing methods. This is done to confirm or reject a hypothesis in a controlled environment. Since it is possible to control all parameters in a simulation, one can set up a simple model and then gradually transform it into something more similar to reality. Once this is done, one can continue the measurements and confirm or reject the simulations for a real setup in vivo or on a phantom. All simulations in this work are carried out in the powerful software, *Field II*(1). The program is developed especially for investigating ultrasound fields and gives the possibility to simulate and calculate ultrasound fields and defining one's own transducer. The accuracy is very high since *Field II* is based on a numerical analysis and is therefore not restricted by any approximations when calculating fields. *Field II* runs under Matlab which makes it even more versatile and useful. This is the reason why *Field II* is used worldwide.

To simulate measurement numerous parameters have to be set. The transducers used in the measurements later described are the linear transducer LA510 from Echoson. The parameters used in the simulations are set to be similar to those of the transducer. The medium in the simulations is homogenous and its only variable parameter is the speed of sound. In the simulations no attenuation is considered. Even so, echoes far from the transducer become weaker and have a lower amplitude because the energy is spread out. These simplifications do not affect in principle the method and in the measurements these simplifications have been taken into consideration.

The parameters in the computer simulation are the same as those used later in the experiments. It means a 32-element linear transducer array with 0.48 mm inter-element spacing and one-cycle burst pulse at the nominal frequency of

(1) Field II is a powerful simulation program, developed by Jørgen Arendt Jensen.

5 MHz. The simulation 2D ultrasound image of phantom obtained by the computer is shown in Fig. 4. The phantom medium is without any attenuation and consists of a collection of point targets.

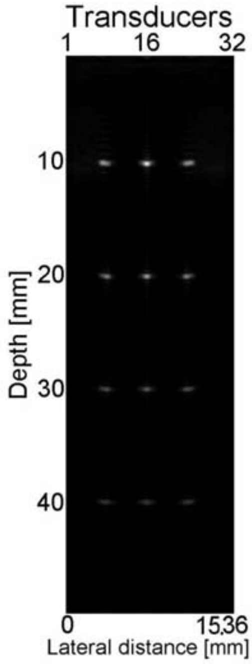

Fig. 4. 2D ultrasound phantom with point targets.

5. Experimental results and discussion

The 32-element linear transducer array with 0.48 mm inter-element spacing and a burst pulse with time duration 100 ns (a half-cycle at nominal frequency 5 MHz) were used. The inter-element space is about 1.5λ. All the elements are used for both transmitting and receiving. One single element in the transducer transmitting aperture was used to generate a spherical wave covering the full image region. Each time, only one element transmits the probing signal and all elements receive the echoes. The transmit and receive elements combination gives a total of 32×32 possible RF A-lines. All these possible A-lines echo signals were sampled independently at 50 MHz and stored.

The wire phantom used in the experiments consisted of 24 wires 0.1 mm in diameter positioned every 2 mm axially and at an angle of 75 degrees. This phantom allows to examine the axial and lateral resolution at various depths in the ultrasound image as well as the focal and dead zone registration. This multi wire phantom surrounded by water allows to obtain high amplitude echo signals from the wires because there was almost no attenuation.

Three of 1024 (32 × 32) received RF echo signals which were digitized and stored in the PC are shown in Fig. 5.

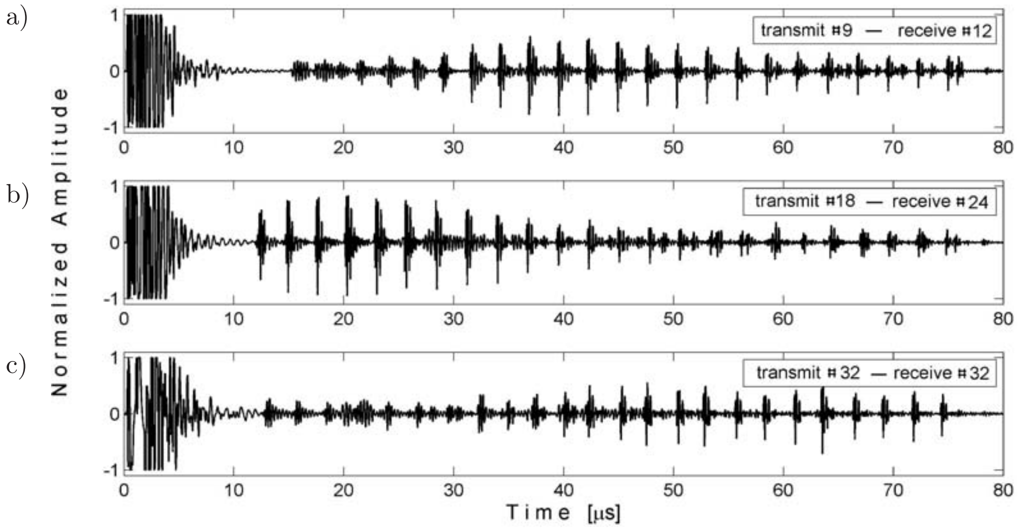

Fig. 5. The recorded by PC RF echo signals: a) element #9 is transmitting – element #12 is receiving, b) #18 transmitting – #24 receiving, c) #32 transmitting – #32 receiving.

All these RF echo signals are different and the echo time position and signal amplitude in every case depend on the sound field and the geometrical position of the transmitting and receiving transducers. After all emissions, the full set of the RF A-lines echo signals needed to reconstruct one 2D B-mode ultrasound image are obtained. For this aim the RF lines are input to the synthetic aperture algorithm which calculates the time delay for every imaging point.

Mentioned above, a single element in the transducer aperture is used for transmitting a spherical wave covering the full image region. The received signals for all or a part of the elements in the aperture are sampled for each transmission. This data can be used for making a low resolution images (Fig. 6a–6c), which is only focused in receive due to the unfocused transmission. The focusing is performed by compensating the geometric distance from the transmitting element to the imaging point and back to the receiving element and can be obtained from Eq. (3). These low resolution images need to be added coherently to form the final high resolution image (Fig. 6d).

The comparison of the reconstructed wire phantom images obtained using STA method and standard the linear array scanning with the commercial ultrasound scanner Antares (Siemens, Mountain View, CA, USA) are shown in Fig. 7. The 128-element linear transducer array with 0.3 mm pitch (VF13-5) and a burst cycle pulse at the nominal frequency of 10 MHz were used in the scanner.

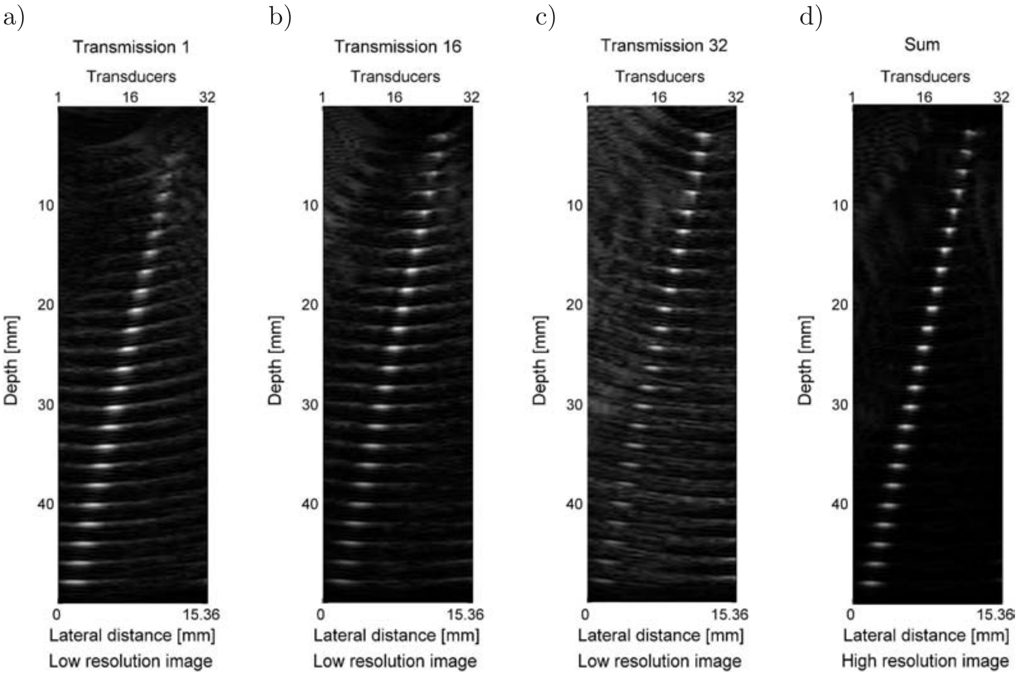

Fig. 6. Low resolution images combined to produce a high resolution image. One element transmit at the time, while all are used to receive. The images are then added into one high resolution image.

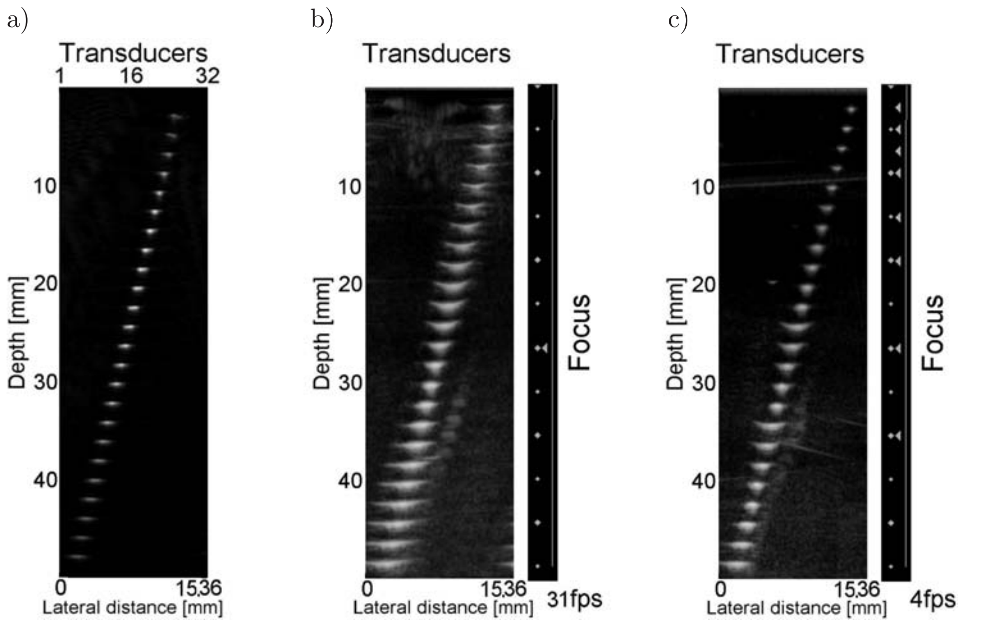

Fig. 7. 2D ultrasound images of the wire phantom: a) using STA method; b) ANTARES ultrasound scanner with one focal point; c) ANTARES ultrasound scanner with 8 focal points.

The maximum quantity of focal points, which were equal to 1 and 8, were chosen in the ultrasound scanner; they are marked by triangles in the bar. It should be noted, that the frame rate in case 8 focal points dramatically decreases down to 4 fps (in the case of one focal point it is equal to 31 fps). Such frame rate is definitely insufficient to normal examine the dynamically moved organs, such as the heart, where a high frame rate even up to 50 fps is required.

In Fig. 7 it can be easily seen, that the axial and lateral resolutions at the top and at the bottom parts of the image are different and depend on the focal point quantity in these regions.

For the STA method (Fig. 7a), the axial image resolution is clearly better than that obtained with the standard beamforming (ANTARES) focused at one single depth (Fig. 7b). When the 8 focuses are chosen, the axial resolution improves but the frame rate decreases drastically down to 4 fps (Fig. 7c).

Also the results show the effectiveness of the STA method and its resistance to the refraction, attenuation, and reflection of ultrasound waves. Using the STA method the final image is obtained by summing up the images obtained in transmitions of different elements of the aperture, as result the possible interference on the 2D image is eliminated.

6. Conclusion

The work concerns the investigation of the STA method that allows to increase the system frame rate and thus to improve the image quality. The paper has given an example of how a medical SA ultrasound imaging can be acquired and processed. The STA method was investigated both by simulation and experimentally. The phantoms, which contain wires, were used to test the image quality in general.

The images reconstructed from the STA system give a better image resolution than those of the conventional ultrasound system maintaining the frame rate high. The disadvantage of the STA system is that the storage and processing requirements are higher than in the conventional beamforming, because the RF data must be stored for every combination of transmit and receive elements, and later recombined.

The synthetic aperture method can be applied in a standard ultrasound scanner. Introduction of the STA method in medical ultrasound increases the effectiveness and quality of the ultrasound diagnostic.

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