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Multielement synthetic transmit aperture in medical ultrasound imaging

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Abstract

Synthetic aperture (SA) technique is a novel approach to today's commercial systems and has previously not been used in medical ultrasound imaging. The basic idea of SA is to combine information acquired simultaneously from all directions over a number of emissions and to reconstruct the full image from these data.

The paper describes the multielement STA method in medical ultrasound imaging with a small number of elements transmitting and all elements receiving apertures. Compared to other methods the multielement STA allows to increase the system frame rate and provides the best compromise between penetration depth and lateral resolution. In the experiments a 32-element linear transducer array with 0.48 mm inter-element spacing and a burst pulse of 100 ns duration were used. Two elements wide transmission aperture was used to generate an ultrasound wave covering the full image region. The comparison of 2D ultrasound images of tissue mimicking phantom obtained using STA and multielement STA methods are presented to demonstrate the benefits of the second method.

1. INTRODUCTION

The ultrasound imaging has become much more prevalent than other medical imaging techniques since it is more accessible, less expensive, safe, simpler to use and produces images in 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, image contrast and frame rate. The spatial resolution of the ultrasound image can be improved by using several transmit beams during the interrogation of each sector, each of which is focused at a different depth. It is done in modern ultrasound imaging systems at the cost of a decrease of the frame rate, proportionally to the number of transmit foci [2]. An alternative way to obtain an appropriate spatial resolution, without the decrease of the frame rate, is to use the synthetic aperture technique.

Synthetic aperture has previously not been used in medical imaging. The basic idea of the synthetic aperture method is to combine information from emissions close to each other. The idea is to transmit an unfocused wave from one element and only use dynamic focusing when receiving for all points the wave passed, in contrast to the conventional beamforming, were only imaging along one line in receiving is used. In SA method every image line is imaged as many times as the number of transmissions used. This results in the same number of low resolution images which are summed up to create one high resolution image.

There are several methods to form a synthetic aperture for ultrasonic imaging. Synthetic aperture focusing technique (SAFT) is a classical synthetic aperture method. At each time only a single array element transmits a pulse and receives the echo signal. It reduces the system complexity, because only a single set of circuits for transmitting and receiving is needed. Multi-element synthetic aperture focusing (MSAF) is an alternative to SAFT. A group of elements transmit and receive signals simultaneously, and transmit beam is unfocused to emulate a single element response. The acoustic power and the signal-to-noise ratio (SNR) are increased compared to SAFT where a single element is used. Synthetic transmit aperture (STA), is alternate to conventional phased array. At each time one array element transmits an ultrasound pulse and all elements receive the echo signals [4]. The advantage of this approach is that a full dynamic focusing can be applied to the transmitting and the receiving, giving the highest quality of image. Synthetic receive aperture (SRA) method of imaging was proposed to improve lateral resolution. At the same time, this method uses a large transmit aperture and enables an imaging system to address a large number of transducer receive elements without the same number of parallel receive channels.

The aim of this work is to implement the multielement STA imaging method algorithm where only a small number of elements are used to transmit a pulse but all array elements receive the echo signals. The main objective is to increase system frame rate and the penetration depth maintaining the resolution of images so that smaller objects can be distinguished. The larger penetration depth can be achieved by increasing transmitted energy that allows to increase the SNR and in its turn to make ultrasound image more contrast.

Ultrasound imaging systems usually use from 64 to 128 transmit/receive channels. In order to reduce the cost of the system, the number of channels should be reduced.

2. MULTIELEMENT STA

The multielement STA imaging method represents the best solution in improving lateral resolution and penetration depth. It is known that the lateral resolution can be improved by increasing array length. Only a small number of elements are used to transmit a pulse but all array elements receive the echo signals. In practice, it is not very expensive to build a large transmit aperture, but it is very complex to form a large receive aperture. For a transmit pulse (from all transmit subapertures elements), the RF echoes for all receive elements are stored in memory. After the all RF echo signals have been acquired, the total RF sum is formed by coherently adding them together.

The multielement STA method is proposed to increase system frame rate and the speed of the image acquisition is determined by the number of transmissions M (Fig. 1). For an N-element aperture, M×N data recordings are needed for image reconstruction, where M<<N.

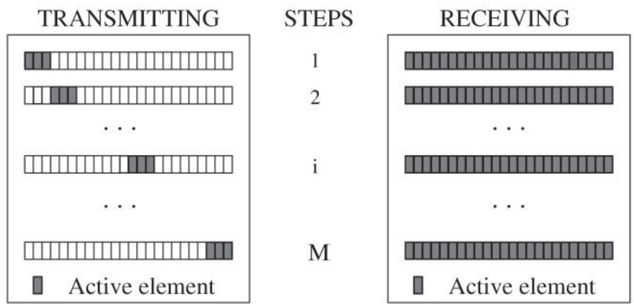

Fig. 1. Transmitting and receiving in multielement STA method

The geometrical locations of the transmit elements in a multielement array system impacts the radiation pattern of that system which in its turn impacts the image lateral resolution and whereas the number of active transmit elements directly influences the transmitted energy and the SNR. These parameters define the ultrasound image quality. Therefore, the optimization of a multielement STA imaging system can be formulated as an optimization problem of the location and the number of the transmit elements. The main optimization criterion in the multielement STA method is the minimal width of the main-lobe combined with the minimum side-lobe level. This optimization leads to increasing image depth penetration and high lateral resolution.

For an N-element array, the transmit aperture is split into N_s subapertures with K_t=N/N_s elements each. Each subaperture transmits a prefocused beam with focus point near the middle of the region of interest. Echo signals reflected from objects are received at a full or dynamically varying receive aperture with dynamic focusing, and stored in memory. All data recordings must then be focused synthetically with dynamic transmit focusing.

Fig. 2 shows the geometry of the transmission and the reception for a STA system, where (r; θ) is the point of focus.

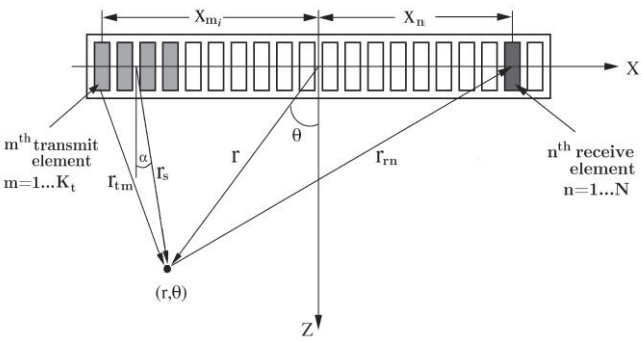

Fig. 2. Geometric relation between the transmit and receive element combination and the focal point

The transmit delay has two parts. The first part is the delay to focus all the elements in the subaperture towards the focusing point. The second part is the delay to focus all the subaperture dynamically. The first part of the delay for the m'th element in the subaperture is

$$\tau_m = \frac{r_s - r_{tm}}{c} \tag{1}$$

$$r_{tm} = \sqrt{\left[\left(-\frac{K_t - 1}{2} + m\right)d\right]^2 + r_s^2 - 2\left(-\frac{K_t - 1}{2} + m\right)d r_s \sin\alpha}$$

and

$$\alpha = \cos^{-1}\left(\frac{r\cos\theta}{r_s}\right).$$

The second part of the delay for the i'th subaperture is

$$\tau_i = \frac{r - r_s}{c} = \frac{1}{c}\left(r - \sqrt{(r\cos\theta)^2 + (xm_i - r\sin\theta)^2}\right) \tag{2}$$

$$= \frac{1}{c}\left(r - \sqrt{\left[K_t\left(-\frac{N_s - 1}{2} + i\right)d\right]^2 + r^2 - 2K_t\left(-\frac{N_s - 1}{2} + i\right)dr\sin\theta}\right)$$

The receive delay τ_n for the STA can be obtained in a similar way as for the phased array

$$\tau_n = \frac{(r - r_{rn})}{c}. \tag{3}$$

Thus, the total delay is $\tau_m + \tau_i + \tau_n$.

For each image point (r; θ), the A-scan signal is

$$A_{STA}(t) = \sum_{n=0}^{N-1} \sum_{i=0}^{N_s-1} \sum_{m=0}^{K_t-1} s_{K_t i+m,n}(t - \tau_n - \tau_i - \tau_m) \qquad (4)$$

where $s_{m,n}(t)$ is the echo signal. The first summation corresponds to the receive beamforming, while the second and the third summations corresponds to transmit synthetic aperture beamforming.

3. COMPUTER SIMULATION

Simulation is a fundamental way of testing the developed 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 with 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 using a powerful software *Field II* [1].

To simulate a measurement numerous parameters have to be set. The transducer used in the measurements, described later, is the linear transducer LA510 from Echoson. The parameters used in the simulations are set to be similar to those of transducer. The medium in the simulation is homogenous and such parameters as the attenuation and the speed of sound were set to be the same as in the experiment. Since, echoes far from the transducer become weaker and have a lower amplitude because the energy is spread out.

In Fig. 3 the 2D ultrasound images of phantom obtained by computer simulation for the case of 32-element linear transducer array with 0.48 mm inter-element spacing and one-cycle burst pulse at nominal frequency 5 MHz are shown. In the case of multielement STA method every subaperture consists of the two elements and transmits an unfocused ultrasound wave. The phantom medium attenuation is 0.5 dB/[MHz×cm] and consists of the collections of point targets spaced 4 pitches apart laterally and the collections themselves are spaced 5 mm apart axially.

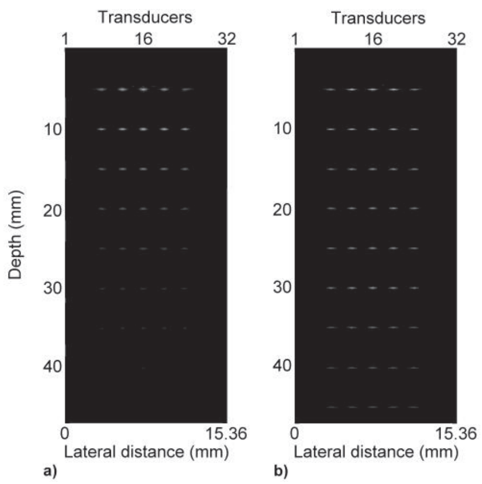

Fig. 3. 2D ultrasound images of tissue mimicking phantom with point targets for STA method (left) and multielement STA (right)

It can be easily seen, that penetration depth increases in the case of the multielement STA method maintaining axial and lateral resolutions in all region of the images.

4. ULTRASOUND IMAGING SYSTEM

A simplified ultrasound imaging system is shown in Fig. 4.

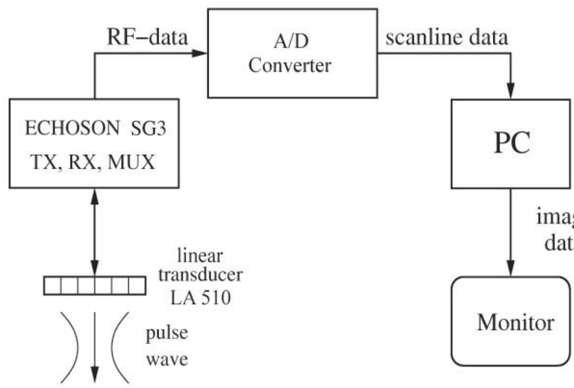

Fig. 4. Block diagram of an ultrasound imaging system

The transducer transmits pulses of the ultrasound waves, and receives reflected echo signals. Echoson SG3 enables full control of selected 32 consecutive transducers of a linear array. 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 send to the PC. Next, the collected digital data are processed offline and displayed on the monitor. All post processing and display is done on the computer using Matlab. The processing creates 2D ultrasound imaging focused in every point of image.

The system allows to perform simulated multichannel acquisition for synthetic aperture imaging. Using a single channel digitizer and switching receiving transducers the system is capable of gathering RF data for up to 32 lines. Repeating this procedure for each transmitted subapertures M of the N-element transducer the M×N data recordings are obtain needed for image reconstruction that are the input to the synthetic aperture algorithm.

Synthetic aperture image reconstruction requires considerable amount of data storage and processing power. In synthetic aperture processing all scan lines (full image) are created in each and every firing, where in standard beamforming only single line is created. The amount of raw RF data needed in multielement STA imaging for reconstruction of a single image is proportional to $D_{RF} * M * N$ and the number of delay-and-sum operations is $D_{RF} * M * N^2$, where D_{RF} is the number of samples in a single RF line. For 32 elements linear array and 2 elements in subaperture (M=16) with 15 cm penetration (D_{RF}=8000 at 40 MHz sampling frequency) storage requirements ≈ $4.1*10^6$ samples, delay-and-sum operations ≈ $131*10^6$ are obtained. It is two times less than in the case of traditional STA method.

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 elements were used for both transmitting and receiving. In the case of the STA method one single element in the transducer transmitting aperture was used to generate an ultrasound wave covering the full image region. In the case of multielement STA method the two elements in subaperture transmitted a flat ultrasound wave and shifted by one element. Each time the elements transmit all elements receive the echoes. The transmit and receive elements combination gives a total of 16×32 possible RF A-lines. All these possible A-lines echo signals were sampled independently at 50 MHz and input to the synthetic aperture algorithm (4).

The tissue mimicking phantom model 525 Danish Phantom Design with attenuation of background material 0.5 dB/[MHz×cm] was used in the experiments. It consists of several nylon filaments twists 0.1 mm in diameter positioned every 1 cm axially. This phantom allows to examine the axial and lateral resolution at various depths in the ultrasound image.

The comparison of the 2D ultrasonic images of a tissue phantom obtained by conventional phased array and multielement STA method are shown in Fig. 5.

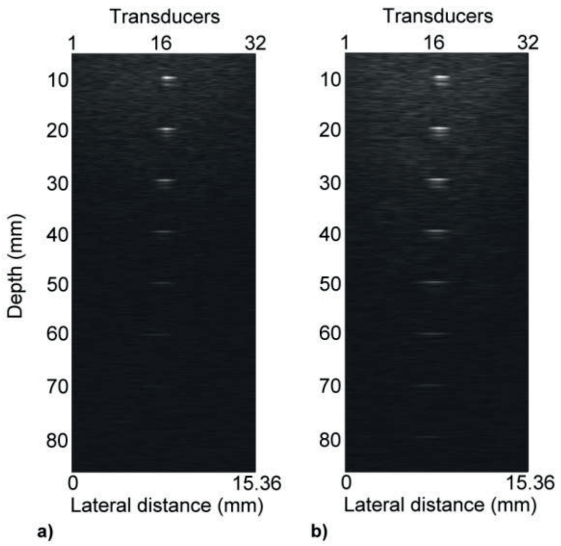

Fig. 5. 2D ultrasound images of tissue mimicking phantom: a) using STA method; b) using multielement STA method

Obtained 2D ultrasonic images clearly demonstrate the advantage of the multielement STA method. With the elongation of the transmit aperture the acoustical power increases yielding a higher SNR, that leads to an increase in penetration depth while maintaining both axial and lateral resolution. The last resolution depends on transducer acoustic field and is discussed in [3].

In order to compare quantitatively the SNR gain the central RF-lines of the 2D ultrasound images shown in Fig. 5 are shown in Fig. 6 and the SNR is calculated.

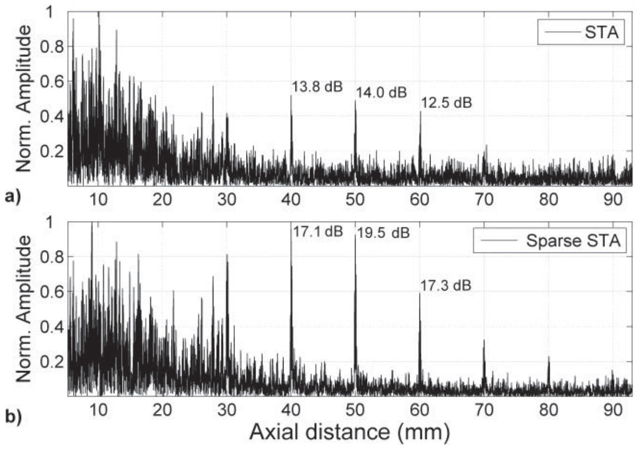

Fig. 6. The RF-lines of the tissue mimicking phantom: a) using STA method; b) using multielement STA method

6. CONCLUSION

The work concerns the development and investigation of the multielement STA imaging method algorithm where only a small number of elements is used to transmit a pulse but all array elements receive the echo signals. This approach allows to increase the system frame rate and penetration depth maintaining the resolution of images. Improvement in the penetration depth can be achieved by increasing transmitted energy that allows to increase the SNR and in its turn to make ultrasound image more contrast.

The paper has given example of how medical synthetic aperture ultrasound imaging can be acquired and processed. The multielement STA method was investigated both by simulation and experimentally. The tissue mimicking phantom was used to test image quality.

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

ACKNOWLEDGEMENTS

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