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Conformable Row-Column Ultrasound Arrays for Abdominal Imaging

Jian-yu Lu
Ultrasound Lab, Department of Bioengineering
The University of Toledo
Toledo, OH 43606, USA
Email: jian-yu.lu@ieee.org

Xiaoning Jiang
Micro/Nano Engineering Lab (MNEL)
North Carolina State University
Raleigh, NC 27695, USA
Email: xjiang5@ncsu.edu

Abstract – **Fully-addressable two-dimensional (2D) array ultrasound transducers have issues such as a large number of elements, difficult to interconnect with an imaging system, high acoustic impedance of each array element which leads to a low signal-to-noise ratio (SNR), and high cost for medical ultrasound imaging systems, especially, for a 2D array of a size close to 300 mm by 300 mm with more than one million elements for imaging of a large area such as the abdomen of big patients and pregnant women. Despite the issues above, an array of a large size is necessary to reconstruct a large 3D volumetric image for artificial intelligent (AI) assisted medical diagnoses with minimal human interventions, which is especially desirable in countries or areas where there are few highly trained medical professionals to operate ultrasound imaging systems.**

To address the issues associated with large fully-addressable 2D array transducers, row-column (RC) arrays have been proposed to reduce the number of elements of the 2D arrays and reduce the acoustic impedance of each array element to increase SNR.

Although a RC array can address some issues of the fully-addressable 2D arrays and simplify the imaging system greatly, the array must be rigid to avoid introducing phase aberrations due to deformation of the array. To solve the problem, in this paper, 36 sub-arrays of 25.6 mm by 25.6 mm each are proposed to form a large conformable RC array of a size of about 281.6 mm by 281.6 mm. To simplify the imaging system by further reducing the number of elements, a 25.6-mm gap filled with flexible materials between the sub-arrays is introduced. To cover the space between the sub-arrays in imaging, a 2D acoustic lens of 30° divergence is applied to each sub-array. To determine the position of each sub-array in the space for image reconstruction, 3 markers are placed on each sub-array to allow a position-reading camera to determine the position of the sub-array.

Computer simulation with limited-diffraction array beam method was performed to calculate the ultrasound fields produced by a sub-array and the results show that the beam width of each sub-array of 2.5-MHz center frequency is about 2.6 mm at a depth of 70 mm and 0° steering angle. Thus, the pulse-echo beam dimension is about 2.6 mm by 2.6 mm in the plane that is perpendicular to the ultrasound wave propagation.

This demonstrates that the proposed RC array is capable of 3D imaging of a large volume for AI-assisted medical diagnoses with minimal human intervention. Although, as compared to the fully-addressable 2D arrays, the RC arrays can only focus in one dimension in both transmission and reception, leading to lower image resolution and higher sidelobe (reduced image contrast), the proposed RC array is a good compromise and make it feasible for intelligent imaging of a large area such as the abdomen of big patients or pregnant women.

Keywords – ***2D arrays, row-column arrays, medical ultrasound imaging, artificial intelligence, camera positioning, and minimal human interventions.***

I. INTRODUCTION

There has been a tremendous development in medical ultrasound imaging techniques in the past few decades and the medical ultrasound imaging, which is one of the major imaging modalities, is now implemented with a low-cost system routinely used in hospitals worldwide [1][2]. In addition to its low cost, ultrasound imaging does not produce ionizing radiation [3]. However, the current medical ultrasound imaging systems are operated by highly trained professionals and their skills are critical for the quality of medical diagnoses.

Artificial intelligence (AI) is a promising technique to lower the dependence of skills of trained professionals who operate the medical ultrasound systems and speed up ultrasound examination procedures [4]-[6]. In some countries or areas, there simply are not enough supplies of trained medical ultrasound professionals and thus AI would help to provide medical ultrasound imaging services to the populations of those countries and areas.

To increase accuracy of AI in medical diagnoses with ultrasound imaging, there are two keys issues: (1) Develop an ultrasound imaging system that can obtain as much diagnostic information from the patients as possible. (2) Obtain a large number of training data sets for AI algorithms. Between the two issues above, the first is fundamental. To obtain more information from patients, three-dimensional (3D) ultrasound imaging techniques are preferred than the two-dimensional (2D) techniques since 3D imaging provides one more dimension of information from human body. With 3D ultrasound imaging, high-quality data sets can be obtained to train the AI algorithms to make accurate medical diagnoses.

3D ultrasound imaging of the highest quality is achieved using a fully-addressable 2D array transducer [2][7]. However, 2D array transducers for medical ultrasound imaging have several main challenges: (1) The number of elements of a 2D array is usually very large which increases the imaging system complexity and thus the costs greatly (for example, a 128 by 128 2D array has a total of 16,384 elements). To cover a large area such as the entire abdomen of a big patient or a pregnant woman to collect data for automated analyses with AI algorithms and minimal human interventions, the number of elements may be more than 1 million for a 1,024 by 1,024 2D array transducer. (2) Interconnections of a large number of array elements with an ultrasound imaging system are difficult. (3) The impedance of each array element is high due to the small size of the element, which in turn significantly reduce the signal-to-noise ratio (SNR) when connecting to an imaging system.

To reduce the complexity of the 2D array for 3D medical ultrasound imaging, row-column (RC) arrays have been proposed [8]-[10]. With a RC array, the number of elements of a 128 by 128 fully-addressable 2D array is reduced from 16,384 to 128+128=256 and the impedance of the each element of the RC array is reduced by a factor of 128 in this case, significantly increasing the SNR while greatly reducing the complexity and cost of the imaging system.

Although a RC array has the advantages mentioned above, it is not possible to compensate for deformations within each of its large array element. The deformation causes phase aberration within each element and may render the signal from the element unusable for imaging. This is especially true when a large RC array, say, of 1,536+1,536 elements with about 300 mm in length for each element, is used since the long elements must be bent to conform to the curvatures of the abdomen of different patients.

Thus, the problem of deformation of the large element of the RC array needs to be addressed to make it feasible for the AI-assisted medical ultrasound diagnoses with minimal human interventions.

II. METHOD

To address the issues of a large RC array, in this paper, we propose a design that uses modular RC arrays to form a large conformable RC array (281.6 mm x 281.6 mm) (see the Figure 1(a)). Flexible binding materials are used to interconnect 36 sub-arrays, each of which is rigid and has 128 rows and 128 columns, to conform to irregular surfaces such as the abdomen of big patients or pregnant women. The central frequency of each sub-array is 2.5 MHz, the dimension of the sub-array is 25.6 mm x 25.6 mm, and the distance between adjacent sub-arrays is also 25.6 mm. To cover the space between the sub-arrays, an acoustic lens with 30^{o} diverging angle is applied in both row and column directions and each sub-array is able to steer +/-30^{o} angles. To assist image reconstructions, three camera-readable position markers are attached to each sub-array (see pink dots illustrated in Figure 1(a)) to determine the position of each sub-array in space so that the reconstructed images from all sub-arrays can be properly stitched together to form an image of a large 3D volume of human body.

III. SIMULATION

Computer simulations were performed to obtain the beam shapes of a sub-array along both the row and column directions at a transmission focal distance of 70 mm using the limited-diffraction array beam method [11]-[14]. Due to the symmetry, either the row or column can be used in transmission and another is used in reception. In the simulation, the bandwidth of the transducer was assumed to be 81% of the center frequency, and a 1.5-cycle sine wave pulse was used in transmission.

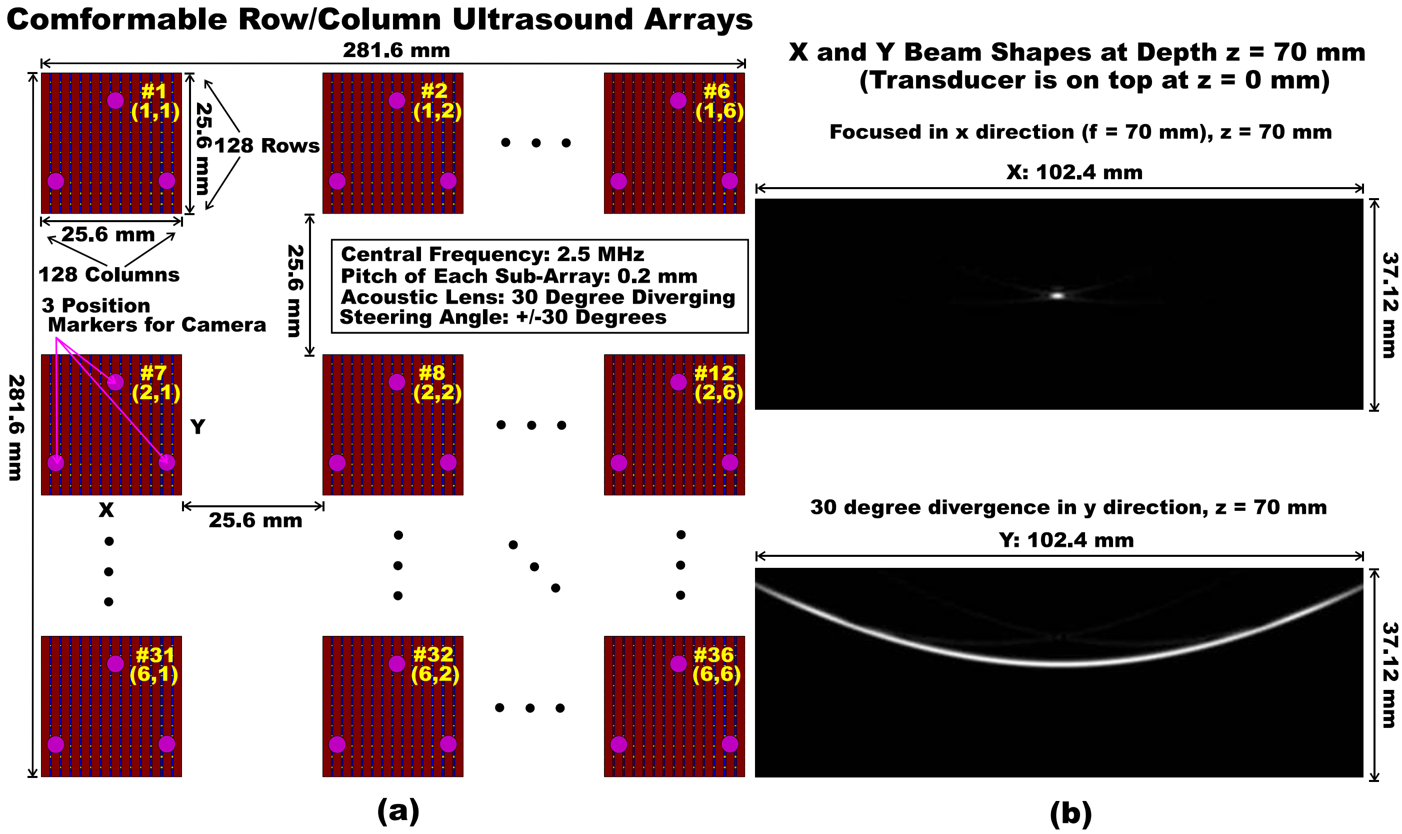

Figure 1. Proposed large row-column (RC) arrays for 3D imaging of a large volume such the abdomen of big patients or pregnant women. (a) A layout of the large RC array using a modular design, consisting of 36 RC sub-arrays to cover an area that is larger than 281.6 mm by 281.6 mm. The dimension of each sub-array is 25.6 mm by 25.6 mm in the row and column directions respectively and each sub-array has 128+128=256 elements. The space between the sub-arrays is also 25.6 mm. 3 position markers are placed on each sub-array to determine the position of the sub-array in the space. An acoustic lens is added to both the row and column directions to allow the ultrasound beam to be diverged about 30° to cover the space between the sub-arrays. Each sub-array has a pitch of about 0.2 mm and a center frequency of about 2.5 MHz to allow the ultrasound beam to be steered over +/-30° angles. (b) Ultrasound beam simulated using the limited-diffraction array beam method [11]-[14]. The top panel shows the focal point in the x direction at a depth of 70 mm at 0° steering angle. The bottom panel shows the 30° diverged wave at 70 mm depth in the y direction using the acoustic lens.

Table 1. Beam widths in x and y directions of each row-column sub-array (see Fig. 1(a)). The beam widths were measured at a depth of 70 mm and 0° steering angle. The axial beam width depends on the bandwidth of the sub-array and the transmit pulse length.

Beam Patterns	**X Direction**	**Y Direction**
	Beamwidth at 0° Steering Angle and 70 mm	**Beamwidth at 0° Steering Angle and 70 mm**
Transmission	2.6 mm	30° divergence
Reception	30° divergence	2.6 mm
Pulse-Echo Response	2.6 mm	2.6 mm
Transmit or Receive	Axial beam width is about 1.07 mm	

IV. RESULTS

Results show that the transmit beam has about 2.6 mm beam width (x direction) at a depth of 70 mm and the axial width (z or depth direction) of the pulse is about 1.07 mm (see Figure 1(b) and Table 1). The beam pattern in both x and y directions are the same due to the reciprocal principle of ultrasound waves in transmission and reception. As seen from Figure 1(a), the rows and columns of a RC array is perpendicular to each other and the overall pulse-echo beam pattern viewed on the x-y plane is roughly the multiplication of the beam patterns in the x and y directions, which gives a rectangular focal spot of roughly 2.6 mm by 2.6 mm (see Table 1). In the axial direction (or z direction), the ultrasound pulse convolves with itself and thus the beam width is increased from

1.07 mm due to a reduction of the pulse-echo bandwidth of the sub-arrays.

V. DISCUSSION AND CONCLUSION

Due to the symmetry of each RC sub-array, the role of transmission and reception can be switched between the rows and columns of the array to obtain two sets of 3D images that can be combined coherently and incoherently to improve image quality and reduce speckle noise respectively. To compensate for the acoustic lens, additional time delays should be added in either transmission or reception to allow the beams to focus and steer by +/-30^{o}.

The computer simulation results show that the beam pattern of a RC sub-array in either transmission or reception can achieve a high resolution. Thus, the pulse-echo response of the sub-array also has a high resolution since it is a convolution of the transmission and reception beam patterns in the time domain. As compared to fully-addressable 2D array transducers, RC arrays have lower resolution and higher sidelobes (lower image contrast) because the arrays can only focus in one dimension in either transmission or reception. However, the benefits of dramatically reduced complexity of imaging systems outweigh the drawbacks and make the AI-assisted 3D imaging of a large area (larger than 300 mm by 300 mm) such as the abdomen of big patients or pregnant women with minimal human interventions feasible.

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