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Coherent Multi-Transducer Ultrasound Imaging through aberrating media

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***Abstract*—Transducers with larger aperture size are desirable in ultrasound imaging to improve resolution and image quality. However, in practice inhomogeneities and aberrating layers cause phase errors that limit the benefits of increased aperture size. A coherent multi-transducer ultrasound imaging system (CoMTUS) enables an extended effective aperture through coherent combination of multiple transducers. The optimal beamforming parameters, which include the transducer locations and the average speed of sound in the medium, are deduced by maximizing the coherence of the received radio frequency data by crosscorrelation. In this work, the robustness of the CoMTUS approach in the presence of acoustic clutter and aberration is investigated by both simulated and in-vitro results. Results show that CoMTUS improves ultrasound imaging quality in terms of resolution, and also suppresses phase aberration effects along with clutter, providing benefits to image quality compared with a single probe imaging system. Overall resolution was unaffected by aberration and improved up to 70% in the CoMTUS.**

***Index Terms*—Untrasound Imaging, Plane Waves, Large Aperture, Beamforming, Aberration, Multi-transducers**

I. Introduction

The quality of ultrasound images is often limited by the spatial resolution and restricted field of view (FoV), particularly at large depths in abdominal or fetal imaging applications [1]. Transducers with larger aperture size are desirable in ultrasound imaging to improve resolution and image quality. Nevertheless, it is not clear that a large aperture will overcome the expected resolution loss through depth in the presence of aberration. Indeed, inhomogeneities and aberrating layers cause phase errors restricting the improvements provided by large arrays [2].

Recently, we have demonstrated that multiple synchronized arrays, taking turns to transmit plane waves (PWs) into a common FoV, can be used as one effective aperture to significantly improve imaging resolution and target detectability [3], [4]. In this coherent muti-transducer ultrasound (CoMTUS) method, the optimal beamforming parameters, which include the transducer locations and the average speed of sound in the medium, are deduced by maximizing the coherence of the received radio frequency (RF) data by cross-correlation. So far, the CoMTUS method has been validated only in media with constant speed of sound and little is known about its behavior in more realistic conditions. However, since the average speed of sound is optimized by the CoMTUS method, an improvement in the beamformation with some higher order phase aberration correction is expected. The purpose of this study is to further investigate the feasibility of CoMTUS. In particular, its potential to correct phase aberration errors and improve ultrasound imaging quality in the presence of clutter.

II. Methods

A. Simulations

The k-Wave Matlab toolbox [5], [6] was used to simulate a CoMTUS system formed by two identical linear arrays. Each of the arrays had a central frequency of 3 MHz and 144 active elements in both transmit and receive, with element pitch of 240 μm and kerf of 40 μm. For plane waves the modelled transducer had an axial focus of infinity with all 144 elements firing simultaneously. In total 7 transmit simulations per linear array were performed to produce a PW data set, which covers a total sector angle of 30^o (from -15^o to 15^o, 5^o step). In the case of CoMTUS this results in 14 transmit events in total (7 PWs per array). The spatial grid was fixed at 40 μm (six grid points per wavelength) with a time step corresponding to a Courant-Friedrichs-Lewy (CFL) condition of 0.05 relative to a propagation speed of 1540 m/s. Received signals were downsampled at 30.8 MHz. Channel noise was introduced to the RF simulated data as Gaussian noise with a SNR of 35dB at 50 mm imaging depth.

Heterogeneous scattering media were simulated using tissue maps formed by three different tissues: soft tissue, fat and muscle. A total of 15 scatterers of 40 μm diameter, with random spatial position and amplitude (defined by a 5% difference in speed of sound and density from the surrounding

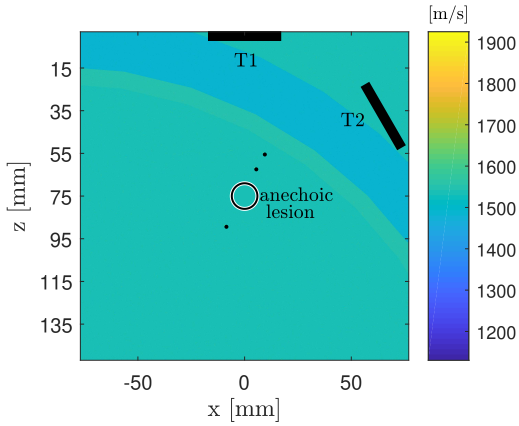

Fig. 1. Example of a tissue map with a muscle layer of 8 mm thickness and a fat layer of 25 mm showing speed of sound. Locations of ultrasound probes, point-like targets and anechoic lesion are shown.

medium), were added per resolution cell, in order to fully develop speckle [7]. Three point-like targets were simulated as circles of 0.2 mm diameter with a 25% difference in speed of sound and density with the surrounding tissue to generate appreciable reflection. A circular anechoic lesion of 12 mm diameter located at the center of the common FoV of both arrays was modeled as a region without scatterers. The same realization of scatterers was superimposed on all maps and through the different simulations to keep the speckle pattern in the CoMTUS system, so any changes in the quality imaging metrics are due to changes in the overlying tissues, the imaging depth and the acoustical field.

TABLE I
TISSUE MAP PROPERTIES.

Tissue type	Speed of Sound [m/s]	Density [kg/m^3]	Attenuation [dB/MHz/cm]	Nonlinearity B/A
Soft tissue	1540	1000	0.75	6
Fat	1478	950	0.63	10
Muscle	1547	1050	0.15	7.4

The control case was simulated using a homogeneous tissue map with sound speed of 1540 m/s and density of 1000 g/cm^3. Then, muscle and fat layers of different thickness were interposed to model aberration effects on the resulting image. The thickness of the muscle layer was set to 8 mm while fat ranged from 0 to 35 mm thickness. The acoustic properties assigned to the tagged tissue types are listed in Table I. A sample tissue map is shown in Fig. 1 with the transducers, point-like targets and lesion locations marked.

B. Experiments

The method was experimentally validated. To induce aberration, a layer of paraffin wax of 20 mm thickness was placed between the probes and a resolution phantom. The imaging system consisted of two synchronised 256-channel Ultrasound Advances Open Platform (ULA-OP 256) systems (University of Florence, Italy) [8] and two identical ultrasonic linear arrays (LA332, Esaote Italy). The two probes were mounted on xyz translation and rotation stage (Thorlabs, USA) and were carefully aligned in the same elevational plane (y = 0). For each probe in an alternating sequence, i.e. only one probe transmits at each time while both probes receive, 7 PWs, covering a total sector angle of 30^o (from -15^o to 15^o, 5^o step), were transmitted at 3 MHz and pulse repetition frequency (PRF) of 1 kHz. RF data backscattered up to 135 mm deep were acquired at a sampling frequency of 19.5 MHz. No apodization was applied either on transmission or reception.

C. Analysis

The data corresponding to the sequence when the array T1 transmits and receives (noted as 1-probe) provides a point of comparison. The RF data were beamformed using the conventional delay-and-sum method for coherent plane wave compounding [9] and assuming a known value of the speed of sound. The CoMTUS beamforming was performed as described in [3]. For each simulated case, the optimum beamforming parameters, which include array locations and average speed of sound in the medium, were used to generate CoMTUS images. Only for the simulated RF data, where the actual position of the arrays in space is known, an additional image (noted as 2-probes) was beamformed by assuming a speed of sound of 1540 m/s and using the spatial location of the array elements.

In order to achieve a comparison between imaging modalities as fair as possible in terms of transmitted energy, the CoMTUS and the 2-probe images are obtained by compounding only 6 different PWs, while the 1 probe system images are generated compounding the total number of the transmit PWs, i.e. 7 PWs from -15^o to 15^o, in 5^o step. In that vein, the CoMTUS and 2-probes images are the results of compounding the RF data when the array T1 transmits PW at zero and positive angles (0^o,5^o,10^o) and the array T2 transmits PW at zero and negative angles (0^o,-5^o,-10^o). For each resulting image, lateral resolution (LR), contrast and contrast-to-noise ratio (CNR) were measured to quantify the impact of both the imaging system and the clutter.

III. RESULTS

A. Simulation results

Fig. 2 and 3 show the simulated images of the PSF and the anechoic lesion for the control case (propagation medium only with soft tissue) and for imaging through aberrating layers of different thickness. The different methods, i.e. 1-probe, 2-probes and CoMTUS are compared. In the absence of aberration (control), resolution improves with increasing aperture size and the worst lateral resolution corresponds to the 1-probe system with 1.78 mm, which is the one with smallest aperture size, while the 2-probe and CoMTUS images are similar with 0.40 mm. However, in the presence of aberration, the PSF and contrast of the 2-probes image significantly degrade when comparing with the control case. This effect is clearly seen in the point targets imaged through

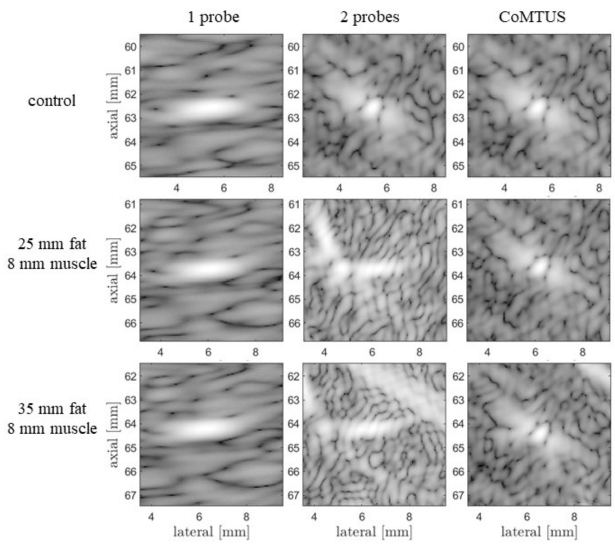

Fig. 2. Imaged PSF at 62.5 mm depth, 60 dB dynamic range. Different imaging methods are compared: 1 probe system, 2 probes without aberration correction and CoMTUS. Three different cases are shown: the control case with no aberrating layer; a medium with a fat layer of 25 mm thickness and a muscle layer of 8 mm thickness; a medium with a fat layer of 35 mm thickness and a muscle layer of 8 mm thickness.

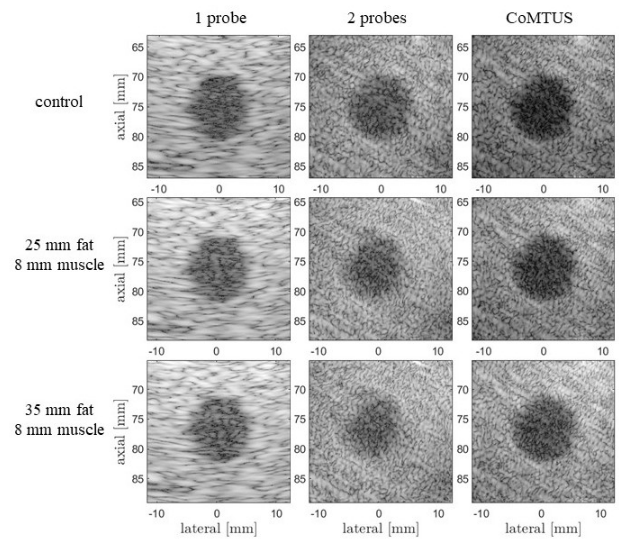

Fig. 3. 12 mm diameter anechoic lesions at 75 mm depth with and without overlying layer clutter, 60 dB dynamic range. Different imaging methods are compared: 1 probe system, 2 probes without aberration correction and CoMTUS. Three different cases are shown: the control case with no aberrating layer; a medium with a fat layer of 25 mm thickness and a muscle layer of 8 mm thickness; a medium with a fat layer of 35 mm thickness and a muscle layer of 8 mm thickness.

a fat layer of 35 mm thickness, where results show that if aberration is not corrected, extended apertures do not show benefits in terms of resolution. Indeed, in the presence of aberration, it is not possible to coherently reconstruct the image using the two separate transducers (2-probes system case). Similar effects are seen in the anechoic lesion (Fig. 3). While differences in the background speckle pattern are observed between the different imaging methods, a higher loss of contrast due to aberration can be appreciated only in the 2-probes images. Nevertheless, no significant changes in imaging quality because of aberration are appreciated in either the 1-probe or CoMTUS systems. Although both systems are able to image through aberrating layers, they show clear differences. The CoMTUS shows more detailed images than the 1-probe system and a reduced speckle size. Quantitative results show that if aberration is not corrected, there are no significant improvements in the imaging metrics related to the aperture size for thicker thickness of fat layers. At clutter thickness larger than 10 mm, image quality of the system formed by 2 transducers without aberration correction (2-probes) is significantly degraded, while CoMTUS imaging metrics are not affected by aberration errors, following the same trend as a conventional aperture (1-probe) and providing a constant value of resolution over clutter thickness without any significant loss of contrast. At the thickest fat layer simulated, resolution is 1.7 mm and 0.35 mm for the 1-probe and CTMUS images, respectively, while in the case of 2-probes images is not longer possible to reconstruct the point-target to measure resolution. Contrast and CNR also show a similar significant loss for the 2-probes image that presents a contrast of -10.84 dB and CNR of 0.69, while those values are significantly better for the 1-probe (-18.44 dB contrast and 0.87 CNR) and CoMTUS (-17.41 dB contrast and 0.86 CNR) images.

B. Experimental results

The value of the calculated optimum speed of sound to beamform the CoMTUS images was 1488.5 m/s and 1482.6 m/s, for the control and paraffin cases respectively. There is a drop in the average speed of sound which agrees with the lower speed of sound of the paraffin wax. The first point target located at 85 mm depth was described using its lateral PSF, with and without the paraffin wax layer (Fig. 4). No significant effects due to aberration are observed in the PSF in any of the cases. The PSF shape is similar with and without the paraffin wax layer and agrees with the one observed in simulations. In general the CoMTUS method leads to a PSF with significant narrower main lobe but also with side lobes of bigger amplitude than the 1-probe conventional imaging system.

Table II summarizes the image metrics computed from the experimental data for both the control and the paraffin cases. Comparison between the control and the paraffin images show little variation in both imaging system, 1-probe and CoMTUS, which agree with the simulation results. Although minimum image degradation by the paraffin layer was observed in the CoMTUS, the overall image quality improved compared with the conventional single aperture and the observed image degradation follows the same trend.

IV. Discussion

Findings presented here agree with previous studies, and in the presence of aberration clutter, aperture size will be limited

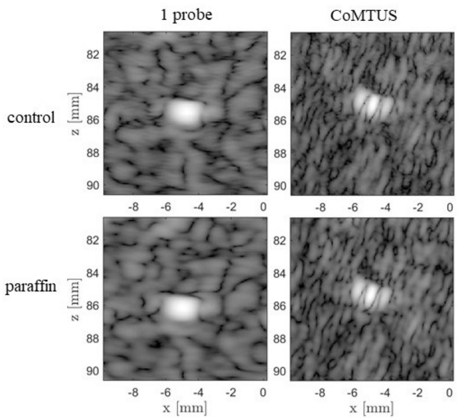

Fig. 4. Experimental imaged PSF at 85 mm depth for the control and paraffin cases, 60 dB dynamic range. Different imaging methods are compared: 1 probe system and CoMTUS.

TABLE II
EXPERIMENTAL IMAGING METRICS.

Imaging method	Lateral Resolution [mm]	Contrast [dB]	CNR [-]	Total PWs [No.]
1-probe control	1.07	-23.24	0.93	7
1-probe paraffin	1.15	-22.36	0.92	7
CoMTUS control	0.40	-20.90	0.91	6
CoMTUS paraffin	0.41	-20.10	0.90	6

in practice [2], [7], [10]. However, CoMTUS shows promise for extending the effective aperture beyond this practical limit imposed by the clutter. This study demonstrates that the CoMTUS approach is robust in the presence of aberration. Both simulated and experimental results show that CoMTUS improves ultrasound imaging quality in terms of resolution in the presence of aberration. Since the average speed of sound is a parameter to optimize in the CoMTUS approach, the technique succeeds in extending the effective aperture of the system in the presence of aberration. More accurate speed of sound estimation would improve beamforming and allow higher order phase aberration correction.

However, other challenges imposed by aberration still remain. Image quality degrades not only by phase aberration but also by reverberation. While phase aberration effects are caused by variations in sound speed due to tissue inhomogeneity, reverberation is caused by multiple reflections within inhomogeneous medium, generating clutter that distorts the appearance of the wavefronts from the region of interest [11]. Finally, in real situations resolution and contrast will be influenced by a complex combination of probe separation and angle, aperture width, PW angle and imaging depth. In the future, we will focus on further investigating these different factors that determine the image performance of the system.

V. Conclusions

In this work, the robustness of the CoMTUS approach in the presence of acoustic clutter and aberration is investigated by both simulated and in-vitro results. Preliminary results show that, CoMTUS improves ultrasound imaging quality in terms of resolution and also suppresses phase aberration effects along with clutter, providing benefits to image quality compared with a single probe imaging system. Overall resolution was unaffected by aberration and improved up to 70% in the CoMTUS.

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References

[1] V. A. Zimmer, A. Gomez, Y. Noh, N. Toussaint, B. Khanal, R. Wright, L. Peralta, M. van Poppel, E. Skelton, J. Matthew, and J. A. Schnabel, "Multi-view image reconstruction: Application to fetal ultrasound compounding," in Melbourne A. et al. (eds) Data Driven Treatment Response Assessment and Preterm, Perinatal, and Paediatric Image Analysis. PIPPI 2018, DATRA 2018. Lecture Notes in Computer Science, vol 11076, pp. 107-116, 2018.

[2] N. Bottenus, W. Long, M. Morgan, and G. Trahey, "Evaluation of large-aperture imaging through the ex vivo human abdominal wall," Ultrasound in Medicine & Biology, vol. 44, no 3, p. 687–701, 2018.

[3] L. Peralta, A. Gomez, Y. Luan, B. Kim, J.V. Hajnal, and R.J. Eckersley, "Coherent Multi-Transducer Ultrasound Imaging," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 66, no. 8, pp. 1316-1330, 2019.

[4] L. Peralta, A. Gomez, J.V. Hajnal, and R.J. Eckersley, "Feasibility study of a coherent multi-transducer US imaging system," In 2018 IEEE International Ultrasonics Symposium (IUS) (pp. 1-4). IEEE.

[5] B.E. Treeby, and B.T. Cox, "k-Wave: MATLAB toolbox for the simulation and reconstruction of photoacoustic wave fields," Journal of biomedical optics, 2010, vol. 15, no 2, p. 021314.

[6] B.E. Treeby, J. Jaros, A.P. Rendell, and B.T. Cox, "Modeling nonlinear ultrasound propagation in heterogeneous media with power law absorption using a k-space pseudospectral method," The Journal of the Acoustical Society of America, 2012, vol. 131, no 6, pp. 4324-4336.

[7] L. Peralta, A. Gomez, J.V. Hajnal, and R.J. Eckersley, "Coherent multi-transducer ultrasound imaging in the presence of aberration," In Medical Imaging 2019: Ultrasonic Imaging and Tomography (Vol. 10955, p. 109550O). International Society for Optics and Photonics.

[8] E. Boni, L. Bassi, A. Dallai, F. Guidi, V. Meacci, A. Ramalli, S. Ricci, and P. Tortoli, "ULA-OP 256: A 256-channel open scanner for development and real-time implementation of new ultrasound methods," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 63, no. 10, pp. 1488–1495, 2016.

[9] G. Montaldo, M. Tanter, J. Bercoff, N. Benech, and M. Fink, "Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 56, no. 3, pp. 489–506, 3 2009.

[10] P. J. S. Tsai, M. Loichinger, and I. Zalud, "Obesity and the challenges of ultrasound fetal abnormality diagnosis," Best Practice & Research Clinical Obstetrics & Gynaecology, vol. 29, no. 3, pp.320–327, 2015.

[11] F. Ali, E.A.R. Berg, and A. Rodriguez-Molares, "Studying the Origin of Reverberation Clutter in Echocardiography: In Vitro Experiments and In Vivo Demonstrations," Ultrasound in medicine & biology, 2019.