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Spatial coherence for multi-angle plane-wave DMAS beamforming in clinical ultrasonic imaging of carotid artery

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1. Introduction

In plane-wave (PW) ultrasound imaging, conventional delay-and-sum (DAS) beamforming suffers from loss of image resolution and insufficient rejection of off-axis clutter interference due to the lack of transmit focusing. To improve the image quality of PW imaging, coherent plane wave compounding (CPWC) uses multiple PW transmits to construct the final image by firstly obtaining low-resolution images at different PW transmit angles and then these sub-images are coherently combined to form the high-resolution image [1]. Though CPWC imaging provides a trade-off between the frame rate and the image quality, its image quality heavily depends on the number of PW transmit angles. With only a few PW angles, the suppression of side-lobe clutter and axial-lobe artifact is generally unsatisfactory [2].

Recently, a novel nonlinear beamforming has been proposed for ultrasound imaging by multiplying echoes between possible channel pairs after time compensation. It is referred to as the delay-multiply-and-sum (DMAS) beamforming [3]. Consequently, the side-lobe clutter and grating lobe artifacts can be suppressed due to the emphasis of spatial coherence in the beamforming output. In this study, the DMAS beamforming [4] is applied in baseband domain to multi-angle PW imaging of clinical carotid artery and the image quality is compared among different DMAS implementations. Specifically, the magnitude of time-delayed channel signal is scaled by p-th root and then restored by p-th power after channel sum. Note that a higher p value introduces higher spatial coherence into baseband DMAS beamforming and thus corresponds to higher image quality.

2. Methods

For each pixel in multi-angle PW imaging, a two-dimensional (2D) echo matrix comprising the received channel signal from every transmit event of different PW angles can be constructed. The echo matrix can be processed to produce the final B-mode output by any combination of DAS and DMAS beamforming in either the dimension of receive channel or the dimension of PW transmit angle. The original CPWC imaging can be understood as the 2D summation of the received echo matrix and is referred to as 2D-DAS in this study. Given the baseband channel data after time compensation and phase rotation $s_{nk} = a_{nk}e^{j\phi_{nk}}$ where n is the index of receive channel (n = 1, 2,…, N) and k is the index of PW transmit angle (k = 1, 2,…, M), the CPWC (i.e., 2D-DAS) can be formulated as:

$$y_{\text{2D-DAS}} = \sum_{k=1}^{M}\sum_{n=1}^{N} s_{nk} \quad (1)$$

On the contrary, the proposed 2D-DMAS method extracts the 2D signal coherence by directly applying DMAS process on the echo matrix. In other words, each entry in the echo matrix is magnitude-scaled by p-th root while maintaining its phase. Then, the signal dimensionality is restored by p-th power after 2D summation as shown in the following:

$$y_{\text{2D-DMAS}} = \left(\sum_{k=1}^{M}\sum_{n=1}^{N} \sqrt[p]{a_{nk}}\, e^{j\phi_{nk}}\right)^{p} \quad (2)$$

Other DMAS beamforming in the literatures such as Rx-DMAS [5] and Tx-DMAS [6] are also considered for comparison. For Rx-DMAS, the echo matrix is firstly summed in the dimension of PW transmit angle for synthetic transmit focusing. Then, the DMAS processing is applied on the channel data to estimate the spatial coherence in the dimension of receive channel. On the contrary, for Tx-DMAS, the DMAS processing is applied in the dimension of PW transmit angle after summing the echo matrix in the dimension of receive channel to achieve dynamic receive focusing:

$$y_{\text{Rx-DMAS}} = \left(\sum_{n=1}^{N} \sqrt[p]{c_n}\, e^{j\phi_n}\right)^{p} \quad with \quad c_n e^{j\phi_n} = \sum_{k=1}^{M} s_{nk} \quad (3)$$

$$y_{\text{Tx-DMAS}} = \left(\sum_{k=1}^{M} \sqrt[p]{b_k}\, e^{j\phi_k}\right)^{p} \quad with \quad b_k e^{j\phi_k} = \sum_{n=1}^{N} s_{nk} \quad (4)$$

3. Results

The aforementioned four beamforming methods for multi-angle PW imaging are compared using the *in-vivo* data of carotid artery on the

PICMUS platform (IEEE IUS 2016). The PICMUS parameters are listed in **Table I**. The performances are evaluated with seven PW compounding (7 PW), uniformly tilted from -16° to +16° with spacing of 5.3°.

Table I. Parameters of PICMUS data

Max. PW angle	±16°	Number of PW angle	7
Element pitch	0.3 mm	Element height	5 mm
Element width	0.27 mm	Elevation focus	20 mm
Number of elements	128	Excitation	2.5 cycle
Center frequency	5.2 MHz	Sampling frequency	20.8 MHz

Ultrasound B-mode images of of *in-vivo* carotid artery in longitudinal and transverse views are respectively demonstrated in the left and right panels of **Fig. 1**, respectively. The display dynamic range is 60 dB. It is clearly shown that both the 2D-DMAS and Rx-DMAS beamforming methods can effectively suppress side-lobe and grating-lobe artifacts within the vessel compared to conventional CPWC imaging (i.e., 2D-DAS) so that their corresponding images appear to be less foggy than the 2D-DAS reference. Moreover, it is also noticeable that the 2D-DMAS outperforms the Rx-DMAS in terms of removal of acoustic reverberation within the vessel and in the peripheral tissue structure. For example, the reverberation artifacts beneath the upper wall of vessel at about 10 mm of lateral position remain visible with Rx-DMAS beamforming while they are not visually detectable with 2D-DMAS beamforming. On the other hand, it should be noted the performance of Tx-DMAS is relatively marginal since the clutter noise remains apparent in both views. Moreover, comparison among all beamforming methods in Fig. 1 also verifies the visually superior image resolution of 2D-DMAS beamforming.

Nonetheless, the improved suppression of clutter artifacts in DMAS beamforming comes at the price of reduced magnitude of tissue background and elevated variation of speckle background. This is expectable since the echoes from speckle scatterers has lower signal coherence and thus the image magnitude of speckle background appears to be relatively suppressed in any DMAS beamforming. Since the 2D-DMAS emphasizes the signal coherence more than the other two one-dimensional DMAS counterpart, it suffers from the most downside of coherence-based beamforming.

4. Conclusions

In this study, multi-angle PW imaging is combined with nonlinear DMAS beamforming to improve image quality. The proposed 2D-DMAS provides enhanced image resolution and better rejection of clutter artifacts. The 2D-DMAS effectively improves the image contrast but at the cost of increased speckle variation. In the future work, speckle reduction techniques can be integrated to smooth the granular image appearance of 2D-DMAS beamforming.

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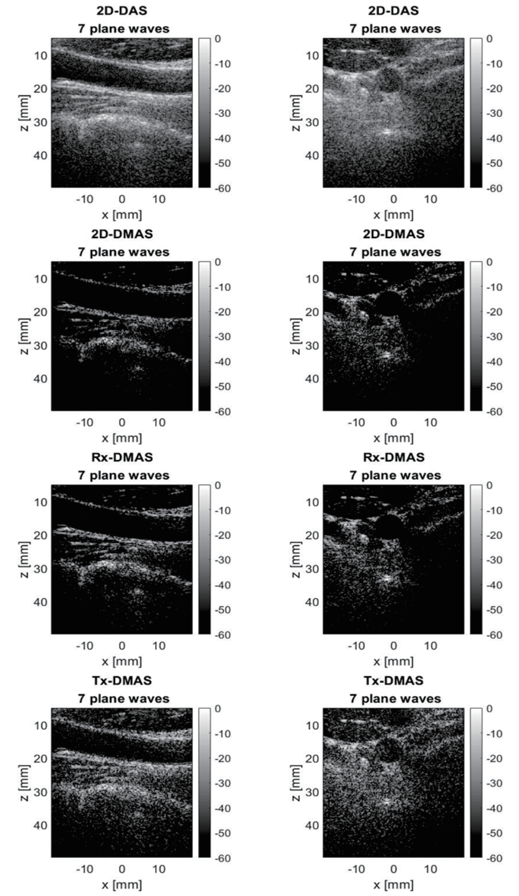

Fig. 1 B-mode images of carotid artery for 2D-DAS, Rx-DMAS, Tx-DMAS and 2D-DMAS beamforming with $p = 2.0$.

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