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Synergistic enhancements of ultrasound image contrast with a combination of phase aberration correction and dual apodization with cross-correlation

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Abstract

Dual Apodization with Cross-correlation (DAX) is a novel adaptive beamforming technique, which utilizes two distinct apodization functions in suppressing sidelobes and clutter. Previous studies have shown that the performance of DAX in minimizing the effects of phase aberration diminishes with increasing aberrator strength. To achieve greater improvement in image contrast, we propose, in this paper, to combine DAX with a phase aberration correction algorithm based on nearest neighbor cross-correlation (NNCC). Our simulation and experimental results presented in this work showed that the proposed method allows for synergistic enhancements of image contrast and achieves greater improvement in image quality than using DAX alone or phase aberration correction alone in the presence of weak and strong aberrators. Compared to standard delay-and-sum (DAS) beamforming, using the proposed method on simulated data with weak and strong aberrations increased the contrast-to-noise ratio (CNR) values from 3.6 to 9.5 and from 1.5 to 8.5, respectively. Experimental results were obtained using pork tissues of 4 mm and 10 mm thickness and a tissue-mimicking phantom. The CNR values increased from 3.7 to 9.7 for the 4 mm pork aberrator and from 1.3 to 8.2 for the 10 mm pork aberrator.

I. Introduction

The goal of ultrasonic pulse-echo beamforming utilized in current medical ultrasound imaging systems is to focus all the available acoustic energy to a single point in the imaging field. However, off-axis sidelobes and clutter inherent in conventional delay-and-sum (DAS) beamforming used in array systems degrade image quality by lowering contrast-to-noise ratio (CNR) and image resolution. A number of techniques including apodization, spatial compounding, and frequency compounding were proposed in the past as solutions to reduce such undesirable side effects of DAS beamforming and achieve an improvement in ultrasound image quality, but at the expense of increased computational burden, worse lateral resolution or frame rate [1-3].

Recently, Seo and Yen developed a novel beamforming method known as Dual Apodization with Cross-correlation (DAX), which improves ultrasound image contrast by suppressing side lobes and clutter [4]. Since any ultrasound echo signal can be treated as a combination of one signal from mainlobe and another signal from clutter, DAX aims to improve ultrasound image contrast by first differentiating clutter signals from mainlobe-dominated signals and then minimizing their contributions to the ultrasound echo signal. Instead of a single receive (RX) apodization utilized in conventional DAS beamforming, DAX uses two distinct RX apodizations to generate two different point spread functions having similar mainlobe signals but very different clutter patterns. Since DAX does not require a second apodization on transmit, there is no loss of frame rate. By cross-correlating between beamformed RF signals from the two different RX apodizations at zero lag followed by a thresholding operator, a weighting matrix composed of cross-correlation coefficients ranging from the threshold value $\epsilon=0.001$ and 1 is created. Since mainlobe-dominated

signals are highly correlated, coefficients associated with these signals are close to 1. Uncorrelated clutter signals have coefficients close to the threshold value. By multiplying the resulting weighting matrix by the combined RF data, DAX achieves a dramatic improvement in image contrast by attenuating signals dominated by clutter.

Previously, DAX achieved contrast improvement of 139% in simulation and 123% experimentally without sacrificing either lateral or axial resolution [4]. In a follow-up study, the robustness of DAX was evaluated in the presence of different levels of aberration and signal-to-noise ratios (SNR) [5]. It was shown that although the performance of DAX is highly robust in minimizing effects of weak- and medium-strength phase aberrations, a decrease in CNR improvement and lesion visibility was observed in both simulation and experiment as the aberration strength was increased [5]. In addition, simulation results showed that DAX had a tendency to generate irregularly shaped cysts with increased aberration strength, which could lead to misdiagnosis [5].

To address the challenges in ultrasonic imaging posed by phase aberration, a segment of ultrasound imaging community has developed methods to restore the image quality lost due to aberration. Unlike DAX, which operates by minimizing the undesirable aberration effects on image quality, phase aberration correction (PAC) attempts to restore coherence by estimating and correcting phase errors caused by sound speed inhomogeneities in tissue. There are a number of aberration estimation and correction methods including time shift compensation based on element-to-element [6] or element-to-beamsum correlations [7], backpropagation of the received pressure field [8], time reversal focusing [9], and speckle brightness as a quality factor [10]. Previous studies have shown that PAC methods based on near-field phase screen models use element-to-element or element-to-beamsum correlations. Such methods, though shown to be promising, exhibit limitations, including increased computational burden and reduced frame rate, as they are often iterative in nature. The accuracy in estimating aberration profiles also decreases with increasing aberration strength and correlation lengths.

Although both DAX and PAC showed decreased performance with increasingly strong aberrations, one way to maximize improvements in image quality is to use a combined approach in which phase correction on individual channel RF signals is followed by DAX on the phase corrected, beamformed RF signals. Since the contrast enhancement mechanisms of DAX and PAC are different, it is expected that the two methods, when integrated, will generate synergistic effects that will increase contrast beyond that achievable by DAX alone or PAC alone. In this paper, we propose combining DAX with a PAC method based on nearest-neighbor cross-correlation (NNCC) described by O' Donnell et al [11,12] and examine its performance in terms of image resolution and contrast.

II. Methods

A. Computer Simulations

Computer simulations for a point target and an anechoic cyst were performed using Field II [13] to compare the performance of the proposed method with that of DAX alone and PAC alone in terms of lateral bandwidth and image contrast. The imaging parameters used are summarized in Table I. To simulate the effects of aberrating layers on the beam, zero-mean, random electronic near-field phase screens were generated by convolving Gaussian random numbers with a Gaussian function as described by Dahl et al [14]. 25ns RMS 5mm full-width half-maximum (FWHM) and 45ns RMS 5mm FWHM aberrator profiles were created as shown in Figure 1, and applied on both transmit and receive for point target and anechoic cyst simulations.

For anechoic cyst simulations, images of a 3mm-diameter cylindrical cyst located at a depth of 30 mm were generated and image contrast was assessed for standard DAS beamforming, DAX alone, PAC alone, and DAX combined with PAC in the presence of weak and strong aberrators using the equation for contrast-to-noise ratio (CNR) [15]:

$$CNR = \frac{\bar{S}_t - \bar{S}_b}{\sigma_b} \quad (1)$$

where $\bar{S}_t$ is the standard is the mean of the target, $\bar{S}_b$ is the mean of the background and σ_b deviation of the background of the envelop-detected, log compressed image in dB.

B. Experiments in Tissue Mimicking Phantoms

To validate the results from computer simulations, imaging experiments with both electronic and physical aberrators were performed. Full synthetic aperture radio frequency (RF) data sets were acquired from an ATS ultrasound phantom (ATS laboratories, Bridgeport, CT, Model 549) containing 3 mm-diameter anechoic cysts located at 30 mm in depth and sampled at 45 MHz for offline processing. This serves as the control data set for comparison and it was also used to generate data sets with electronic aberrators by applying the aberrator profiles shown in Figure 1 on both transmit and receive. To mimic near-field aberrating layers composed of skin, muscle, and fat commonly encountered in clinical ultrasound imaging, tissues of thickness 4 mm and 10 mm from pork belly were placed in between the transducer and the ATS cylindrical lesion phantom. These RF signals were collected using a Verasonics data acquisition system (Verasonics, Redmond, WA) with a 128-element, 298 μm pitch L7-4 linear array. A 1-cycle transmit pulse with a center frequency of 5 MHz and a sub-aperture size of 64 elements were used. Data from each channel were collected 12 times and averaged to minimize the effects of electronic noise. All individual channel RF signals were band-pass filtered using a 64-tap finite impulse response (FIR) band-pass filter with frequency range limited to the -6 dB bandwidth of the transducer and low-pass interpolated by a factor of 4 to achieve finer delay quantization and estimation. Offline beamforming was then performed using Matlab (The MathWorks, Inc. Natick, MA) with a constant f-number of 2. For control and electronically aberrated data sets, the transmit focus was always set to a depth of 30 mm where a 3 mm-diameter anechoic cyst is located, but it was moved down by the thickness of the pork tissue in the presence of pork belly. Dynamic receive focusing was used with focal updates every 1 mm in range and an image line spacing of 100 μm .

Phase Aberration Correction—The NNCC-based phase aberration correction algorithm was implemented as described by O' Donnell et al [11,12]. The cross-correlation function between any two neighboring elements with channel RF signals $x(n)$ and $y(n)$ was calculated as:

$$A(k) = \sum_{n=-\frac{M}{2}}^{\frac{M}{2}-1} x(n) y(n+k) \quad (2)$$

where M represents the total number of samples which contribute to the cross-correlation function $A(k)$. The cross-correlation function was computed for every channel over a segment length of 13 mm centered at the transmit focus, which is equivalent in wavelengths to what was used by O' Donnell and Flax at a center frequency of 3.3 MHz [11]. The differential delay error between all neighbors was then calculated by computing the time shift between two neighboring elements that results in maximal normalized cross-correlation coefficient. The delay error at any channel $n > 0$ in the N-element subaperture ($N = 64$) was

computed by unwrapping the differential time delays and removing any unwanted linear component using the following equation:

$$\Delta\tau_n = \sum_{k=0}^{n-1} \Delta t_k - n \left[\frac{\sum_{k=0}^{N-2} \Delta t_k}{N-1} \right] \quad (3)$$

where we set $\Delta\tau_n = 0$ for $n = 0$. For simulated and experimental data sets with electronic aberrators, the estimated phase error on every channel were corrected only on receive by time-shifting the channel RF signals. For experimental data sets with pork aberrators, however, correction was performed on both transmit and receive to yield comparable results.

DAX—For all results shown in this study, an 8-8 alternating pattern, in which a set of two complementary apodizations functions with 8 alternating elements are enabled on one but disabled on the other, was selected as it has been shown to achieve the greatest CNR improvement without creating undesirable black artifacts near the transmit focus in the presence of diffuse scatterers [5]. The two receive apodization functions for DAX are shown in Figure 2. Use of such apodization functions on the receive aperture creates grating lobes that are 180 degrees out of phase with respect to one another such that the mainlobe-dominated signals can be distinguished from clutter signals by means of normalized cross-correlation.

A segment of 2 wavelengths was empirically chosen for zero-lag, normalized cross-correlation (NCC) between the two beamformed RF signals obtained with the two complementary apodization functions. To minimize the artifacts in the form of black spots which may arise due to the random nature of speckle, the weighting matrix composed of normalized cross-correlation coefficients ranging from $e = 0.001$ to 1 after thresholding was median filtered with a window size of $0.6 \text{ mm} \times 1.2 \text{ mm}$. The size of the median filter was also empirically selected such that the effect of most artifacts is removed with minimal blurring of the weighting matrix.

The Combined Method—The PAC and DAX combined method proposed in this paper is demonstrated in Figure 3. The two block diagrams labeled as PAC and DAX summarize the details and steps of each method described in the previous sections. PAC was first applied on the RF data which had been delayed with geometric delay profiles calculated based on array geometry to gain increased coherence of the beam. For simulation and electronically aberrated experimental data sets, phase correction was performed once only on receive. For experimental data with pork tissues, phase correction was first performed on transmit and then on receive using phase error estimates obtained with a corrected transmit beam. Next, DAX was performed to suppress any sidelobes and clutter.

III. Results

A. Simulation Results

1. Point Target Simulations—The performance of the NNCC-based PAC method, DAX, and the combined method for weak and strong aberrators are shown by lateral beamplots in Figures 4 and 5, respectively. In all figures, the lateral beamplot for standard DAS beamforming with uniform apodization in the absence of an aberrator is shown as a control.

Figure 4 shows lateral beamplots for different processing methods in the presence of weak aberration. The aberration resulted in an increase in sidelobe level to -8.6 dB for DAS beamforming with no DAX or PAC (Figure 4a). Although DAX successfully suppressed

most of clutter down to -80 dB or lower, the high sidelobes near the mainlobe still remain (Figure 4c). However, PAC proved to be useful in lowering the high sidelobes, which DAX failed to suppress, down to -20 dB (Figure 4b). Finally, with the help of PAC, DAX was able to achieve additional sidelobe suppression of 6.5 dB near the mainlobe and yield a beam comparable to or even better than the control in terms of -6 dB beamwidth and first sidelobe level (Figure 4d). This is possible because PAC reduces the high sidelobes that DAX fails to suppress.

Similar patterns were observed in the case of a strong aberrator as shown in Figure 5. The -6 dB beamwidth was increased and the sidelobes were raised to 0 dB with conventional DAS beamforming (Figure 5a). Again, DAX was not able to suppress the high sidelobes located approximately 1 mm away from the main lobe (Figure 5c). PAC, on the other hand, lowered these high sidelobes by 17 dB. Moreover, a minimum reduction of 10 dB was observed with clutter signals farther away from the mainlobe (Figure 5b). Finally, the combined PAC and DAX resulted in a beam with sidelobes much lower than what DAX alone or PAC alone could achieve and beamwidth comparable to that obtained by PAC alone (Figure 5d).

2. Anechoic Cyst Simulations—Anechoic cysts simulated in the presence of weak and strong aberrators are shown on a 50 dB dynamic range in Figures 7 and 8, respectively. CNR values were calculated and shown in Figure 9. For each aberration, CNR values for standard DAS beamforming, and DAX were calculated with and without PAC. CNR values with no aberrator were used as a control. Standard DAS beamforming yielded a progressive decrease in CNR from 5.3 with no aberrator, to 3.6 with a weak aberrator, and to 1.5 with a strong aberrator. DAX yielded CNR improvements of over 130% in all three cases while PAC achieved improvements of 6% for no aberrator, 19% for a weak aberrator, and 97% for a strong aberrator. The combined method achieved the best results with CNR values of 11.8 for no aberrator, 9.5 for a weak aberrator, and 8.5 for a strong aberrator.

B. Experimental Results

1. Electronic Aberrator Study—Figures 10-12 show the experimental images of the ATS tissue-mimicking phantom containing anechoic cysts with no aberrator, and weak (25ns RMS, 5mm FWHM) and strong (45ns RMS, 3mm FWHM) electronic aberrators. All images are shown on a 50 dB dynamic range. Calculated CNR values are shown in Figure 13. Similar to the trends shown by the anechoic cyst simulations, standard DAS beamforming yielded a progressive decrease in CNR from 5.4 with no aberrator, to 4.0 with a weak aberrator, and to 3.1 with a strong aberrator. DAX yielded CNR improvements of 91% for no aberrator and 81% for a weak aberrator, but resulted in a reduction in CNR with severe image artifacts for a strong aberrator. PAC slightly lowered CNR for no aberrator, but improved CNR by 21% for a weak aberrator and 15% for a strong aberrator. Although the combined method obtained a CNR value of 9.5 for no aberrator, it outperformed both PAC and DAX when aberration is present, yielding CNR values of 10.0 for a weak aberrator and 8.6 for a strong aberrator.

2. Pork Tissues as Physical Aberrators—Figures 14 and 15 show the experimental images of the ATS tissue-mimicking phantom containing anechoic cysts acquired with 4 mm and 10 mm pork tissues as weak and strong physical aberrators, respectively. All images are shown on a 50 dB dynamic range. The CNR values were calculated and shown in Figure 16. The CNR values for the standard DAS beamforming decreased from 5.4 to 3.7 for 4 mm and to 1.3 for 10 mm pork tissues. DAX increased the CNR value to 9.0 for 4 mm, but only to 1.8 for 10 mm pork. PAC, on the other hand, increased the CNR values to 5.0 for 4 mm and to 3.0 for 10 mm pork tissues. Lastly, the combined method further increased the

CNR values to 9.7 for the weak aberrator and 8.2 for the strong aberrator with high lesion visibility for both cases.

IV. Discussion

6 dB Beamwidth and First Sidelobe Level

Figure 6 summarizes and compares the effects of weak and strong aberrators on (a) -6 dB beamwidth and (b) first sidelobe level. Figure 6a shows that the -6 dB beamwidth in the presence of a weak aberrator was similar to that with no aberrator. However, a greater amount of mainlobe broadening was observed with an increase in -6 dB beamwidth from 0.46 mm to 2.13 mm in the presence of a strong aberrator. The smallest -6 dB beamwidth of 0.69 mm was achieved by the combined method. However, the majority of the improvements in -6 dB beamwidth obtained by the combined method was contributed by PAC. This shows that DAX, which could only produce an improvement in -6 dB beamwidth to 1.81 mm, gained large benefits from using PAC.

The benefit of integrating DAX and PAC is not fully apparent until its effect on the sidelobe level is compared with those for DAX alone and PAC alone. In Figure 6b, DAX did not suppress the first sidelobes, which was raised to -9 dB and 0 dB in the presence of weak and strong aberrations. PAC, however, successfully lowered them by 11 dB and 17 dB for the two cases. In the case of a weak aberration, the majority of the sidelobe suppression of 18 dB achieved by the combined method still comes from PAC. But, DAX combined with PAC had an additional 7 dB of suppression. With a strong aberration, the amount of additional suppression achieved by the combined method was 21 dB, which is even greater than the suppression PAC alone could achieve. Therefore, the synergistic enhancement becomes more pronounced with increased aberration strengths. Furthermore, the performance of the combined method in terms of improvements in -6 dB beamwidth and the amount of sidelobe suppression was always higher than those of the standard DAS beamforming, DAX alone, and PAC alone.

Anechoic Cyst Simulations

The results summarized in Figure 9 show that the results with DAX were always better than those with PAC. DAX performed in a highly robust manner and increased the CNR from 5.3 to 12.3 with no aberrator and from 3.6 to 8.4 with a weak aberrator. Since these CNR values are already far greater than that of an unaberrated cyst with standard DAS beamforming, additional CNR improvement accomplished by integrating the two methods in these cases is not of major importance. Also, the images were free of artifacts as shown in Figure 7. However, in the presence of a strong aberrator, the performance of DAX diminished as shown by a reduced improvement in CNR, and resulted in an irregularly shaped cyst as well as artifacts in the form of black spots near the cyst. PAC was able to avoid such undesirable artifacts and enhance lesion visibility with CNR increased to 2.9. But neither DAX alone nor PAC alone was able to achieve a CNR value above that of an unaberrated cyst with standard DAS beamforming. The limitations of the two methods were overcome and synergistic enhancement of image contrast without any artifacts was observed when the combined method was used. The CNR was increased to 8.5, which is greater than those obtained with DAX alone and PAC alone. This is in good agreement with the results for point target simulations, which showed that the combined method was most beneficial in suppressing sidelobes and clutter with increased aberration strength.

Experimental Data with Electronic Aberrators

The results from electronically aberrated experimental data sets were consistent with the trends shown by the point target and anechoic cyst simulations. The combined method

yielded CNR values of 9.5, 10.0, and 8.6 for the three aberration strengths, which were comparable to the simulation results. The increased CNR values were further verified by the speckle brightness improvements of 3 % and 41 % at the transmit focus for the weak and strong aberrations. The irregular shape and black artifacts as a result of applying DAX on a simulated cyst with a strong aberrator shown in Figure 8 was reproduced with experimental data with the same aberrator applied electronically. The shape and amount of artifacts found in the experiments may vary from those in simulation mainly due to the random nature of speckle. In the absence of aberration, the combined method resulted in a CNR value of 9.5, which is slightly lower than that obtained with DAX alone. This is expected and is associated with the jitter error, which places a fundamental limit on the performance of the delay estimation algorithm based on the array element uniformity, channel SNR, the segment length, and the size and strength of the aberration across the array [16]. However, the combined method still guarantees a significant improvement in CNR since the standard deviation of the jitter error was measured to be only 8.3 ns and causes a reduction that is less than 10 % of what was achieved by DAX alone.

Experimental Data with Pork Aberrators

Since physical aberrators are more reflective of clinical scenarios than electronic aberrators, which do not account for signal attenuation and distortion that may occur with body tissues, evaluation of the performance of DAX, PAC, and the combined method using pork tissues as physical aberrators is important especially for human in-vivo studies in the future. The results with pork aberrators were in good agreement with our simulation and electronic aberrator study. The CNR values for all methods were comparable to those obtained for the simulation and electronic aberrator studies. A more coherent summation of the waves as a result of phase correction was also confirmed by speckle brightness improvements of 27% and 58% for pork tissues of thickness 4 mm and 10 mm. Again, the anechoic cyst, which was completely masked by the effects of 10 mm-thick pork aberrator, was clearly visible when the combined method was applied while DAX alone and PAC alone failed. These results confirm the synergistic enhancements of image contrast predicted by our simulation and electronic aberrator studies. Particularly, our results consistently showed and confirmed that the combined method is most useful and achieves the greatest amount of contrast enhancement when a strong aberrator is present. Considering the fact that DAX alone had a tendency to create image artifacts and the contrast enhancements achieved by either DAX alone or PAC alone, if any, were not sufficient in the presence of a strong aberrator, the achievement of the proposed method is very compelling and shows strong potentials to outperform some of the most widely used adaptive phase aberration correction algorithms.

V. Conclusion and Future Work

In this work, we compared the performance of DAX, PAC, and combined DAX and PAC in terms of CNR improvement in the presence of different levels of aberration. The results presented in this study confirmed the findings reported in Seo and Yen [5] that DAX is capable of reducing sidelobes and clutter and achieves a 140% improvement in CNR compared with standard DAS beamforming in the presence of weak aberration, but only improves CNR by 38% and can cause artifacts in the presence of strong aberrators. This is due to the fact that the sidelobes are raised to a level where DAX is unable to make distinctions between the mainlobe-dominated signals and the side-lobe-dominated signals. We have shown in this work that this problem could be overcome by integrating it with an NNCC-based PAC algorithm, which is effective in lowering high sidelobes. The improvements in cyst contrast as well as the visualization of the lesion boundaries using the proposed method were presented in this work.

In conclusion, we have shown that phase correction combined with DAX is an effective way to improve image contrast. The results shown in this work suggest that just one or two iterations of phase correction combined with DAX can achieve improvements of 543% in image contrast even in the presence of a strong aberrator. Furthermore, DAX is also computationally inexpensive because calculation of cross-correlation coefficients only at zero-lag on a 23-sample segment of RF data at 45MHz sampling frequency is necessary. Future work will involve evaluating the performance of the proposed algorithm on in-vivo data sets from human subjects and making any necessary modifications to the algorithm to further increase its robustness. Other correlation-based PAC methods, such as a least-squares algorithm [14] and one that incorporates both element-to-element and element-to-beamsum correlations [17] may be explored. Particularly, for in-vivo applications, the use of more sophisticated PAC methods based on a distributed aberrator model [18] may be investigated as a way to achieve optimal performance of the proposed method.

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Figure 1. Aberrator profiles of 25 ns RMS 5mm FWHM (dashed line) and 45 ns RMS 3mm FWHM (solid line).

Figure 2.
The two apodization functions used for DAX.

Figure 3.
A system block diagram for the PAC and DAX combined method.

Figure 4. Simulated lateral beamplots for (a) no PAC, no DAX, (b) PAC, (c) DAX, and (d) combined PAC and DAX in the presence of weak (25ns RMS, 5 mm FWHM) aberration.

Figure 5. Simulated lateral beamplots for (a) no PAC, no DAX, (b) PAC, (c) DAX, and (d) combined PAC and DAX in the presence of strong (45ns RMS, 3mm FWHM) aberration.

Figure 6.

Comparison of (a) -6 dB beamwidth and (b) first sidelobe level for DAS, DAX, PAC, and combined DAX and PAC in the presence of weak (25ns RMS 5mm FWHM) and strong (45 ns RMS 3mm FWHM) aberrators. DAS beamforming in the absence of an aberrator is also shown as a control.

Figure 7. Simulated cysts for standard DAS beamforming with uniform apodization and DAX with (right column) and without (left column) PAC in the presence of a 25 ns RMS 5mm FWHM aberrator.

Figure 8. Simulated cysts for standard DAS beamforming with uniform apodization, and DAX with (right column) and without (left column) PAC in the presence of a 45ns RMS 3mm FWHM aberrator.

Figure 9.

Comparison of CNR values for simulated anechoic cysts obtained with standard DAS beamforming, DAX, PAC, and combined DAX and PAC. CNR values are shown for no aberration, and weak (25ns RMS 5mm FWHM) and strong (45 ns RMS 3mm FWHM) aberrations.

Figure 10. Experimental cysts for standard DAS beamforming with uniform apodization, PAC, DAX, and combined PAC and DAX for data sets acquired with no aberrator.

Figure 11.

Experimental cysts for standard DAS beamforming with uniform apodization, PAC, DAX, and combined PAC and DAX for data sets acquired with a 25nsRMS 5mm FWHM aberrator.

Figure 12.

Experimental cysts for standard DAS beamforming with uniform apodization, PAC, DAX, and combined PAC and DAX for data sets acquired with a 45 ns RMS 3mm FWHM aberrator.

Figure 13.

Comparison of CNR values for experimental anechoic cysts obtained with standard DAS beamforming, DAX, PAC, and combined DAX and PAC. CNR values are shown for no aberration, and weak (25 ns RMS 5 mm FWHM) and strong (45 ns RMS 3 mm FWHM) electronic aberrations.

Figure 14. Experimental cysts for standard DAS beamforming with uniform apodization, PAC, DAX, and combined PAC and DAX for data sets acquired with pork tissues of thickness 4 mm.

Figure 15.

Experimental cysts for standard DAS beamforming with uniform apodization, PAC, DAX, and combined PAC and DAX for data sets acquired with pork tissues of thickness 10 mm.

Figure 16.

Comparison of CNR values for experimental anechoic cysts obtained with standard DAS beamforming, DAX, PAC, and combined DAX and PAC. CNR values are shown for no aberration, and 4 mm (weak) and 10 mm (strong) pork aberrations.

TABLE I

Field II Simulation Parameters

Parameters	Value
Number of Elements in Subaperture	64
Center Frequency	5 MHz
Bandwidth	50%
Azimuthal Element Pitch	305 μm
Elevation Element Height	5 mm
Sound Speed	1540 m/s
Transmit Focus	30 mm
Lateral Beam Spacing (Point target)	100 μm
Lateral Beam Spacing (Cyst)	120 μm
Receive Focal Delay Step	0.1 μm