An efficient image formation algorithm for real-time linear-array photoacoustic tomography

Mozaffarzadeh, Moein; Periyasamy, Vijitha; Upputuri, Paul Kumar; Pramanik, Manojit;
Makkiabadi, Bahador

2019

Mozaffarzadeh, M., Periyasamy, V., Upputuri, P. K., Pramanik, M., & Makkiabadi, B. (2019).
An efficient image formation algorithm for real-time linear-array photoacoustic
tomography. Proceedings of SPIE - Photons Plus Ultrasound: Imaging and Sensing 2019.

<https://hdl.handle.net/10356/102649>

<https://doi.org/10.1117/12.2511088>

© 2019 Society of Photo-optical Instrumentation Engineers (SPIE). All rights reserved. This
paper was published in Proceedings of SPIE - Photons Plus Ultrasound: Imaging and
Sensing 2019 and is made available with permission of Society of Photo-optical
Instrumentation Engineers (SPIE).

Downloaded on 26 Apr 2023 18:58:21 SGT

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

An efficient image formation algorithm for real-time linear-array photoacoustic tomography

Moein Mozaffarzadeh, Vijitha Periyasamy, Paul Kumar Upputuri, Manojit Pramanik, Bahador Makkiabadi

Moein Mozaffarzadeh, Vijitha Periyasamy, Paul Kumar Upputuri, Manojit Pramanik, Bahador Makkiabadi, "An efficient image formation algorithm for real-time linear-array photoacoustic tomography," Proc. SPIE 10878, Photons Plus Ultrasound: Imaging and Sensing 2019, 108785D (27 February 2019); doi: 10.1117/12.2511088

SPIE.

Event: SPIE BiOS, 2019, San Francisco, California, United States

An Efficient Image Formation Algorithm for Real-time Linear-Array Photoacoustic Tomography

Moein Mozaffarzadeh^{a,c}, Vijitha Periyasamy^b, Paul Kumar Upputuri^b, Manojit Pramanik^b,
and Bahador Makkiabadi^{*a,d}

^aResearch Center for Biomedical Technologies and Robotics, Institute for Advanced Medical Technologies, Tehran, Iran

^bSchool of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang Drive, Singapore

^cDepartment of Biomedical Engineering, Tarbiat Modares University, Tehran, Iran

^dDepartment of Medical Physics and Biomedical Engineering, School of Medicine, Tehran University of Medical Sciences, Tehran, Iran

ABSTRACT

In photoacoustic (PA) imaging using commercial ultrasound transducers, two dimensional PA images are produced by commonly used delay-and-sum (DAS) as the reconstruction method. However, the reconstructed image is affected by noise and artifacts. Here, we investigate the performance of a nonlinear (NL) beamforming method for linear-array PA image formation. The proposed algorithm uses the p^{th} root of the recorded signals and imposes a computational complexity in the order of DAS ($O(M)$). We have evaluated the performance of the proposed method numerically, having a signal-to-noise ratio of 30 dB and -10 dB. It is shown that at the depth of 15 mm, the NL_3 (NL beamformer with a $p=3$) outperforms DAS, DMAS and NL_2 for about 26 dB, 11 dB and 11 dB, in terms of level of sidelobe, respectively. In addition, DAS, DMAS, NL_2 and NL_3 lead to a full-width-half-maximum of about 1.4 mm, 1.04 mm, 1.04 mm and 0.86 mm, respectively. The proposed method can be a great choice for sentinel lymph node imaging.

Keywords: Photoacoustic imaging, photoacoustic tomography, linear array transducer, beamforming, nonlinear beamformer.

1. INTRODUCTION

Photoacoustic imaging (PAI) is based on the photoacoustic (PA) effect and provides structural, functional and potentially the molecular information of tissue.^{1,2} In PAI, a laser pulse irradiates the sample/tissue, which results in a local temperature rise. Due to the thermoelastic expansion, broadband pressure waves (in the form of ultrasound waves) are generated.³ The ultrasound waves (also known as photoacoustic wave) travels within the medium. The waves are recorded using ultrasound(US) transducer. Finally, these PA waves are reconstructed to obtain the optical absorption map of the tissue.⁴

In PAI, different types of array transducers can be used to detect the PA waves; linear, arc, circular and spherical.⁵⁻¹⁰ One of the challenges in linear-array based PAT is the image reconstruction.¹¹⁻¹³ Due to the limited view of the linear-array transducer (in comparison with the ring-array transducer, which get a full 360 degree view) reconstructed image quality is poor.¹⁴⁻¹⁶ In other words, linear-array transducers have a view of approximately only 60°,¹⁷ and the image quality is lower compared to circular tomography.¹⁷⁻¹⁹

There are some studies conducted to use a single beamforming algorithm for the integrated US/PA imaging systems.^{17,20,21} Delay-and-Sum (DAS) can be considered as the most common beamforming algorithm in US

Further author information: (Send correspondence to B. Makkiabadi)
Bahador Makkiabadi: E-mail: b-makkiabadi@tums.ac.ir

and PAT.^{22–24} Delay-Multiply-and-Sum (DMAS) suppresses the noise and sidelobes, and improves the image quality.²⁵ To address the low noise suppression of DMAS at the presence of high level of noise, Double-Stage DMAS (DS-DMAS), in which two stages of DMAS is used, which is recently introduced for linear-array US and PAT.^{26,27} It is shown that DS-DMAS is a reliable PA image formation algorithm for LED-based system as well.²⁸ Considering all the achievement in DS-DMAS and DMAS, they have a low power in resolution improvement compared to Minimum variance (MV). This problem is investigated and addressed using the MV-Based DMAS (MVB-DMAS).^{7,29}

In this work, a novel image formation algorithm for linear-array PAT is proposed. We have previously investigated the properties of this algorithm in reference³⁰ and used it for sentinel lymph node (SLN) imaging.^{5,9,30} The proposed algorithm is a Nonlinear (NL) beamformer, and it uses the p^{th} root of the detected PA signals. The main improvement gained by the proposed method is lower sidelobes and noise while the complexity of the algorithm is in the order of DAS ($O(M)$). The results presented in this study show that the proposed algorithm can be an appropriate choice for linear-array PA image formation, especially when a high level of noise affect the image quality.

2. METHODS AND MATERIALS

2.1 Beamforming

The PA image (indicating the optical absorption distribution of the tissue) can be formed by DAS which can be written as follows:

$$y_{DAS}(k) = \sum_{i=1}^M x_i(k - \Delta_i), \quad (1)$$

where $y_{DAS}(k)$, k , M are the output of the beamformer, the time index and the number of elements of the array, respectively. In addition, $x_i(k)$ and Δ_i are the detected signals and the corresponding time delay for the detector i , respectively. DAS results in a low quality image and is commonly used due to its simple implementation. The sidelobes and artifacts result from the non-adaptiveness of DAS. To put it more simply, DAS considers all the samples the same as each other. To improve the contrast gained by DAS, DMAS is introduced:²⁵

$$y_{DMAS}(k) = \sum_{i=1}^{M-1} \sum_{j=i+1}^M x_i(k - \Delta_i) x_j(k - \Delta_j). \quad (2)$$

The dimensionally squared problem of (2) is addressed as follows:²⁵

$$x'_{ij}(k) = \text{sign}[x_i(k - \Delta_i) x_j(k - \Delta_j)] \sqrt{|x_i(k - \Delta_i) x_j(k - \Delta_j)|}. \quad (3)$$

$$y_{DMAS}(k) = \sum_{i=1}^{M-1} \sum_{j=i+1}^M x'_{ij}(k). \quad (4)$$

The new components appear in the spectrum due to the similar ranges of frequency for $x_i(k - \Delta_i)$ and $x_j(k - \Delta_j)$, and the multiplication procedure in the DMAS algorithm. A band-pass filter is applied on the beamformed output signal to only pass the necessary frequency components, while keeping the one centered on $2f_0$ almost unaltered. As a results of the used filter, it is named Filtered-DMAS (F-DMAS), extensively evaluated in the reference.^{25,26,28}

DMAS uses a correlation process to weight the calculated samples and improve the image quality in terms of sidelobes. In the previous publications, the superiority of the DMAS has been proved in the terms of sidelobes, resolution and contrast. However, all the advantages are achieved at the expense of a higher computational burden. DMAS is a nonlinear beamformer as a results of its correlation procedure. In this paper, it is proposed

Figure 1: Reconstructed numerical images using the point-target phantom. (a) DAS, (b) DMAS, (c) NL_2, (d) NL_3. All the images are shown with a dynamic range of 60 dB. Noise was added to the detected signals considering a SNR of 30 dB.

to use the p^{th} root of the detected signals to improve the contrast of the PA images.³¹ The p^{th} root of the signals are used as the input of the DAS algorithms. The proposed method formula can be written as follows:

$$y_{NL-p}(k) = \left(\frac{1}{M} \sum_{i=1}^M \text{sign}(x_i(k - \Delta_i)) \sqrt[p]{|x_i(k - \Delta_i)|} \right)^p \quad (5)$$

As can be seen in the (5), the p^{th} root of the detected signals are used in the summation procedure. The same as DMAS algorithms, which changes the dimension to the order of Volt^2 , the dimension of the signals would be changes to $\text{Volt}^{1/p}$ in the NL algorithm. This problem is addressed by the (p^{th}) power finally used (bringing back the dimension to the Volt). It should be noticed that for $p = 2$, the NL algorithm would be a close approximation of the DMAS beamformer. The results in the next section show that (5) would be a close approximation of DMAS. In fact, the performance of DMAS has been achieved at the expense of a computational complexity close to DAS .

3. RESULTS

A numerical study has been conducted to evaluate the performance of the proposed method. We have used the k-Wave Matlab toolbox.³² Six point targets with a radius of 0.1 mm are positioned at the depth of 15 mm until 40 mm, separated 5 mm in axial axis. A linear-array having $M=146$ elements operating at 8 MHz central frequency and 77% fractional bandwidth is used to detect the PA signals. The speed of sound is assumed to be 1540 m/s during simulations. The sampling frequency is 51.3 MHz. It should be noticed that this sampling frequency was chosen by k-Wave.

The reconstructed images are shown in Figure 1 where artifacts caused by the off-axis signals and the imaging noise affect the formed image by DAS. Results of DMAS (Figure 1(b)) and NL_2 (Figure 1(c)) are similar. Both of them provide a better quality compared to result of DAS (Figure 1(a)); lower sidelobes and better-detectable point targets. However, the image is still affected by the sidelobes. As shown in 1(d), the sidelobes are better degraded by the NL_3, compared to NL_2 and DMAS.

We have provided the lateral variations of the reconstructed images in Figure 2; at two depths of imaging. As expected, the NL_3 provides a lower sidelobes compared to other methods. Consider the depth of 15 mm where DAS, DMAS, NL_2 and NL_3 provide -36 dB, -51 dB, -51 dB and -62 dB, respectively. In addition, we

Figure 2: Lateral variations of DAS, DMAS, NL_2 and NL_3 at the depths of (a) 15 mm and (b) 35 mm using the images shown in Fig. 1.

have calculated the full-width-half-maximum (FWHM) of the images. DAS, DMAS, NL_2 and NL_3 lead to a FWHM of about 1.4 mm, 1.04 mm, 1.04 mm and 0.86 mm, respectively. It is true that the proposed method with a $p=3$ outperforms other methods in terms of FWHM, but the sidelobe reduction is the main improvement obtained.

In order to show the performance of the proposed method at the presence of a high level of noise, we have presented Figure 3. The effects of noise and artifacts are clearly seen in the images obtained by DAS, DMAS and NL_2 while NL_3 highly suppressed these negative effects, as seen in Figure 3(d). As mentioned before, the proposed method has already been investigated in³⁰ with application in SLN imaging. In reference,³⁰ it is mentioned that the selection of parameter p is a key matter. It is hard to define this parameter since it directly changes the dynamic range of the detected PA signals. Based on simulations, the higher the p , the better the image quality. However, based on the experimental results presented in reference,³⁰ p cannot be higher than a threshold. Defining such a threshold can be a topic for future studies.

4. CONCLUSIONS

In this paper, we have introduced a NL beamformer for PAI. Using numerical evaluation, it is shown that the proposed method with a $p=2$ provides a quality too close to DMAS while the computational complexity is close to DAS. In addition, with a $p=3$, a higher quality PA image compared to other methods has been obtained. For instance, at the depth of 15 mm, NL_3 outperforms DAS, DMAS and NL_2 for about 26 dB, 11 dB and 11 dB, in terms of level of sidelobe, respectively. The proposed NL beamformer provided a great noise suppression at the presence of high level of noise as well. The NL beamformer can be an appropriate choice for SLN imaging as shown in reference.³⁰

REFERENCES

- [1] Mehrmohammadi, M., Joon Yoon, S., Yeager, D., and Y Emelianov, S., "Photoacoustic imaging for cancer detection and staging," *Current molecular imaging* **2**(1), 89–105 (2013).
- [2] Li, L., Zhu, L., Ma, C., Lin, L., Yao, J., Wang, L., Maslov, K., Zhang, R., Chen, W., Shi, J., et al., "Single-impulse panoramic photoacoustic computed tomography of small-animal whole-body dynamics at high spatiotemporal resolution," *Nature Biomedical Engineering* **1**(5), Art–No (2017).
- [3] Nasiriavanaki, M., Xia, J., Wan, H., Bauer, A. Q., Culver, J. P., and Wang, L. V., "High-resolution photoacoustic tomography of resting-state functional connectivity in the mouse brain," *Proceedings of the National Academy of Sciences* **111**(1), 21–26 (2014).
- [4] Sheng, Q., Wang, K., Matthews, T. P., Xia, J., Zhu, L., Wang, L. V., and Anastasio, M. A., "A constrained variable projection reconstruction method for photoacoustic computed tomography without accurate knowledge of transducer responses," *IEEE Transactions on Medical Imaging* **34**(12), 2443–2458 (2015).

Figure 3: Reconstructed numerical images using the point-target phantom. (a) DAS, (b) DMAS, (c) NL₂, (d) NL₃. All the images are shown with a dynamic range of 60 dB. Noise was added to the detected signals considering a SNR of -10 dB.

- [5] Erpelding, T. N., Kim, C., Pramanik, M., Jankovic, L., Maslov, K., Guo, Z., Margenthaler, J. A., Pashley, M. D., and Wang, L. V., "Sentinel lymph nodes in the rat: noninvasive photoacoustic and us imaging with a clinical us system," *Radiology* **256**(1), 102–110 (2010).
- [6] Park, B., Lee, H., Upputuri, P. K., Pramanik, M., Kim, D., and Kim, C., "Super-resolution photoacoustic microscopy using near-field localization by a plasmonic metal nanoaperture: a simulation study," *IEEE Journal of Selected Topics in Quantum Electronics* **25**(2), 1–7 (2019).
- [7] Mozaffarzadeh, M., Mahloojifar, A., Periyasamy, V., Pramanik, M., and Orooji, M., "Eigenspace-based minimum variance combined with delay multiply and sum beamformer: Application to linear-array photoacoustic imaging," *IEEE Journal of Selected Topics in Quantum Electronics* **25**(1), 1–8 (2019).
- [8] Upputuri, P. K. and Pramanik, M., "Fast photoacoustic imaging systems using pulsed laser diodes: a review," *Biomedical Engineering Letters*, 1–15 (2018).
- [9] Paridar, R., Mozaffarzadeh, M., Periyasamy, V., Basij, M., Mehrmodammadi, M., Pramanik, M., and Orooji, M., "Validation of delay-multiply-and-standard-deviation weighting factor for improved photoacoustic imaging of sentinel lymph node," *Journal of biophotonics*, e201800292 (2018).
- [10] Dean-Ben, X. L. and Razansky, D., "Portable spherical array probe for volumetric real-time optoacoustic imaging at centimeter-scale depths," *Optics Express* **21**(23), 28062–71 (2013).
- [11] Uddin, K. S., Mostafa, A., Anastasio, M., and Zhu, Q., "Two step imaging reconstruction using truncated pseudoinverse as a preliminary estimate in ultrasound guided diffuse optical tomography," *Biomedical optics express* **8**(12), 5437–5449 (2017).
- [12] Lou, Y., Zhou, W., Matthews, T. P., Appleton, C. M., and Anastasio, M. A., "Generation of anatomically realistic numerical phantoms for photoacoustic and ultrasonic breast imaging," *Journal of Biomedical Optics* **22**(4), 041015–041015 (2017).
- [13] Anastasio, M. A., Beard, P. C., and Zhu, Q., "Special section guest editorial: Photoacoustic imaging and sensing," *Journal of Biomedical Optics* **22**(4), 041001–041001 (2017).
- [14] Upputuri, P. K. and Pramanik, M., "Recent advances toward preclinical and clinical translation of photoacoustic tomography: a review," *Journal of Biomedical Optics* **22**(4), 041006 (2016).
- [15] Sivasubramanian, K., Periyasamy, V., Dienzo, R. A., and Pramanik, M., "Hand-held, clinical dual mode ultrasound-photoacoustic imaging of rat urinary bladder and its applications," *Journal of biophotonics* **11**(5), e201700317 (2018).

- [16] Deán-Ben, X. L. and Razansky, D., “On the link between the speckle free nature of optoacoustics and visibility of structures in limited-view tomography,” *Photoacoustics* **4**(4), 133–140 (2016).
- [17] Mercep, E., Jeng, G., Morscher, S., Li, P.-C., and Razansky, D., “Hybrid optoacoustic tomography and pulse-echo ultrasonography using concave arrays,” *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* **62**(9), 1651–1661 (2015).
- [18] Daoudi, K., Van Den Berg, P., Rabot, O., Kohl, A., Tisserand, S., Brands, P., and Steenbergen, W., “Handheld probe integrating laser diode and ultrasound transducer array for ultrasound/photoacoustic dual modality imaging,” *Optics express* **22**(21), 26365–26374 (2014).
- [19] Ke, H., Erpelding, T. N., Jankovic, L., Liu, C., and Wang, L. V., “Performance characterization of an integrated ultrasound, photoacoustic, and thermoacoustic imaging system,” *Journal of biomedical optics* **17**(5), 0560101–0560106 (2012).
- [20] Zhang, H. K., Bell, M. A. L., Guo, X., Kang, H. J., and Boctor, E. M., “Synthetic-aperture based photoacoustic re-beamforming (spare) approach using beamformed ultrasound data,” *Biomedical optics express* **7**(8), 3056–3068 (2016).
- [21] Zueran, L., Huaqin, W., Yongping, L., Zhifang, L., and Hui, L., “The photoacoustic tomography system based on medical ultrasound array,” in [*International Conference on Photonics and Imaging in Biology and Medicine*], W3A–56, Optical Society of America (2017).
- [22] Yang, D., Xing, D., Yang, S., and Xiang, L., “Fast full-view photoacoustic imaging by combined scanning with a linear transducer array,” *Optics express* **15**(23), 15566–15575 (2007).
- [23] Chaigne, T., Gateau, J., Katz, O., Bossy, E., and Gigan, S., “Light focusing and two-dimensional imaging through scattering media using the photoacoustic transmission matrix with an ultrasound array,” *Optics letters* **39**(9), 2664–2667 (2014).
- [24] Wang, Y., Wang, D., Zhang, Y., Geng, J., Lovell, J. F., and Xia, J., “Slit-enabled linear-array photoacoustic tomography with near isotropic spatial resolution in three dimensions,” *Optics letters* **41**(1), 127–130 (2016).
- [25] Matrone, G., Savoia, A. S., Caliano, G., and Magenes, G., “The delay multiply and sum beamforming algorithm in ultrasound b-mode medical imaging,” *IEEE Transactions on Medical Imaging* **34**(4), 940–949 (2015).
- [26] Mozaffarzadeh, M., Mahloojifar, A., Orooji, M., Adabi, S., and Nasirivanaki, M., “Double-stage delay multiply and sum beamforming algorithm: Application to linear-array photoacoustic imaging,” *IEEE Transactions on Biomedical Engineering* **65**(1), 31–42 (2018).
- [27] Mozaffarzadeh, M., Sadeghi, M., Mahloojifar, A., and Orooji, M., “Double-stage delay multiply and sum beamforming algorithm applied to ultrasound medical imaging,” *Ultrasound in Medicine and Biology* **44**(3), 677 – 686 (2018).
- [28] Mozaffarzadeh, M., Hariri, A., Moore, C., and Jokerst, J. V., “The double-stage delay-multiply-and-sum image reconstruction method improves imaging quality in a led-based photoacoustic array scanner,” *Photoacoustics* **12**, 22–29 (2018).
- [29] Mozaffarzadeh, M., Mahloojifar, A., Orooji, M., Kratkiewicz, K., Adabi, S., and Nasirivanaki, M., “Linear-array photoacoustic imaging using minimum variance-based delay multiply and sum adaptive beamforming algorithm,” *Journal of Biomedical Optics* **23**(2), 026002 (2018).
- [30] Mozaffarzadeh, M., Periyasamy, V., Pramanik, M., and Makkiabadi, B., “Efficient nonlinear beamformer based on p^{th} root of detected signals for linear-array photoacoustic tomography: Application to sentinel lymph node imaging,” *Journal of Biomedical Optics* **23**(12), 121604 (2018).
- [31] Polichetti, M., Varray, F., Matrone, G., Savoia, A. S., Béra, J.-C., Cachard, C., and Nicolas, B., “A computationally efficient nonlinear beamformer based on p -th root signal compression for enhanced ultrasound b-mode imaging,” in [*Ultrasonics Symposium (IUS), 2017 IEEE International*], 1–4, IEEE (2017).
- [32] Treeby, B. E. and Cox, B. T., “k-wave: Matlab toolbox for the simulation and reconstruction of photoacoustic wave fields,” *Journal of Biomedical Optics* **15**(2), 021314–021314 (2010).