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Jun Xia
Zijian Guo
Konstantin Maslov
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Jun Xia,a Zijian Guo,a Konstantin Maslov,a Andres Aguirre,b Quing Zhu,b Christopher Percival,c and Lihong V. Wanga

aWashington University in St. Louis, Optical Imaging Laboratory, Department of Biomedical Engineering, St. Louis, Missouri 63130
bUniversity of Connecticut, Department of Electrical Engineering, Storrs, Connecticut 06269
cPennsylvania State University, Department of Anthropology, University Park, Pennsylvania 16802

Abstract. A full ring ultrasonic array-based photoacoustic tomography system was recently developed for small animal brain imaging. The 512-element array is cylindrically focused in the elevational direction, and can acquire a two-dimensional (2D) image in 1.6 s. In this letter, we demonstrate the three-dimensional (3D) imaging capability of this system. A novel 3D reconstruction algorithm was developed based on the focal-line concept. Compared to 3D images acquired simply by stacking a series of 2D images, the 3D focal-line reconstruction method renders images with much less artifacts, and improves the elevational resolution by 30% and the signal-to-noise ratio by two times. The effectiveness of the proposed algorithm was first validated by numerical simulations and then demonstrated with a hair phantom experiment and an ex vivo mouse embryo experiment. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE).

Keywords: photoacoustic computed tomography; 3D reconstruction; mouse embryo; focal line.

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Photoacoustic tomography (PAT) has recently emerged as an important tool for biomedical imaging.1 By combining optical absorption contrast and ultrasonic imaging resolution, this hybrid technology provides high-resolution images beyond the diffusion limit of penetration depth in conventional optical microscopy technologies.1 Recently, a full-ring array-based PAT system was developed for real-time functional mouse brain imaging.2,3 The ultrasonic system is cylindrically focused in the elevational direction, and has 512 ultrasonic transducer elements and 64 data acquisition (DAQ) channels with eightfold multiplexing. A two-dimensional (2D) mouse brain cortex vessel image can be acquired in 1.6 s. In the standard reconstruction algorithm,4 each element is treated as a point detector. This assumption is valid for 2D reconstruction of an in-plane image, since each ultrasonic transducer element has an in-plane width of 0.3 mm (~one acoustic wavelength). For this system, however, the standard reconstruction algorithm cannot directly be extended to three-dimensional (3D) space, because the element height (10 mm) and the elevational focus need to be considered. In this letter, we present a novel 3D reconstruction algorithm by treating the focal line of the transducer as an auxiliary line for applying appropriate delays.

Video 1 shows the 3D spatial response of a single ultrasonic transducer element in our array system. Each point in the spatial response map is the maximum amplitude of the spatial-temporal response obtained from the Field II5, 6 simulation. Without loss of generality, we used the delta function as the ultrasonic transducer’s mechanical-electrical impulse response.

A focal line that goes across the center of the transducer arc (Fig. 1, point O) can be clearly identified in the video. The photoacoustic (PA) wavefront generated from a point in this focal line reaches the entire transducer surface at the same time, maximizing the sensitivity of the receiving aperture. The amount of time delay depends on the position of the point in the focal line. Therefore, we can use this focal line (Fig. 1) as an auxiliary line for applying appropriate delays in the 3D image reconstruction. As shown in Fig. 1, to compute the delay of a point A in the 3D space, we first project A to the x-y plane (B). Point B is then connected to the center point of the transducer (C), crossing the focal line at point D. We then connect A and D, and extend the line to reach the transducer at E. The line AE is always perpendicular to the transducer surface (CD=DE), and is used for calculating the delay time between the imaging point A and the transducer. In the 3D image reconstruction, the original time-domain PA signals from each transducer are back-projected into the 3D imaging space based on the calculated delay times, and are then summed to form the reconstructed image.4 The transducer also has a solid acceptance angle determined by the transducer aperture (Video 1). Only PA waves generated within this solid angle can be detected.

To test the reconstruction algorithm, we first used Field II numerical simulations.5, 6 Four PA point sources were evenly distributed along the radial direction over a distance of 9 mm. This arrangement covers a circular area of 9 mm radius in the x-y plane, which represents our typical imaging area. The ring-array was simulated by rotating a single elevationally focused element around the ring center. A 3D dataset was acquired with elevational scanning. This procedure is equivalent to our experimental configuration, where the ring-array is fixed and the sample is scanned along the elevational direction. The transducer

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Address all correspondence to: Lihong V. Wang, Washington University in St. Louis, Department of Biomedical Engineering, One Brookings Drive, Campus Box 1097, St. Louis, Missouri 63130. Tel: (314) 935–6152; Fax: (314) 935–7448; E-mail: lhwang@wustl.edu.

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parameters are the same as those in the experimental system, i.e.,
the central frequency is 5 MHz (80% bandwidth), the ring radius
is 25 mm, the elevational height is 10 mm, and the elevational
focus for each element is at 19.8 mm. The mechanical–electrical
impulse response, together with the spectral profile of the ultra-
sonic transducer element, can be found in our previous paper.7
We compared the 3D focal-line reconstruction with two other
back-projection algorithms: 2D reconstruction and 3D direct
(without the use of the focal line) reconstruction. In the 2D
reconstruction, in-plane images are reconstructed individually
in 2D space, and then the reconstructed images are stacked to-
gether to form a 3D image. Since the 2D reconstruction assumes
that all signals are generated within the 2D reconstruction plane
\((x-y)\), signal generated from an out-of-plane object \((A)\) is falsely
projected to a point \(A'\) (Fig. 1) in the reconstruction plane with
the same time delay \((A'C = AE)\). Therefore, out-of-plane PA
sources always appear as artifacts in the 2D reconstructed im-
age. In the 3D direct reconstruction, all the elements are treated
as point detectors, and the time delay to the center of the trans-
ducer is employed for back-projection. For a fair comparison
between the 3D direct and the 3D focal-line reconstructions, the
same solid acceptance angle is applied in both methods. The dis-
tances for the time delays employed for the three reconstruction
algorithms are shown in Fig. 1.

Figure 2 shows the resolution analysis along the radial, tan-
gential, and elevational directions. The resolutions are defined as
the full-width-at-half-maximum (FWHM) of the reconstructed
signals in the corresponding directions. It can be seen that when
the point sources are located within the reconstruction plane,
the 2D reconstruction provides satisfactory radial and tangential
resolutions. However, when the point sources are out of the
reconstruction plane, 2D reconstruction generates artifacts and
renders poor elevational resolution, because it assumes all sig-
als are generated within the 2D reconstruction plane (Fig. 1).
The 3D direct reconstruction renders the poorest resolution in
all directions, because it does not consider the element aperture
in the elevational direction and thus employs incorrect delays.
Compared to the 2D reconstruction, the 3D focal-line recon-
struction provides comparable in-plane resolution, and improves
the elevational resolution by 40%. Moreover, the focal-line
method provides a uniform resolution in a larger field of view.8

In addition to improving the image quality, the 3D recon-
struction method also accelerates 3D scanning. To acquire data
from all 512 elements, 64 DAQ channels are multiplexed 8
times, which takes 1.6 s. In the conventional stepwise scan, the
sample must remain still at each elevational location for 1.6 s,
before moving to the next height. With the 3D reconstruction,
continuous scanning can be accomplished, where each group of
64 channels acquires signals at different heights. With an ap-
propriate scanning speed, continuous scanning can record the
same amount of data as in the stepwise scan, while saving the
stepwise transition time.

To experimentally validate the proposed technique, we im-
aged a human hair embedded in a gelatin phantom. The scanning
speed of the motor was set at 0.1 mm per 1.6 s. The illumination
source was an optical parametric oscillator laser, and the laser
light was homogenized by a light diffuser. Figure 3 shows the
2D and 3D focal-line reconstructed images. For a better illus-
tration, the same threshold and color scale have been applied on
both images to enhance the contrast of the hair. By averaging
the elevational \((z\text{-direction})\) FWHM along the hair, we found 3D
reconstruction improved the elevational resolution by 30% (1.05
mm versus 1.34 mm), which is not as great as in the simulated
data, mainly due to noise fluctuation and small variations in the
individual elements’ focusing. The signal-to-noise ratio (SNR)
was evaluated by using the ratio of the hair signal to the standard
deviation of the background. We found that the 3D focal-line
reconstruction improved the SNR by two times. This is because
the 3D reconstruction utilized all signals generated within the
3D acceptance angle.

The efficacy of the proposed technique was also evaluated by
ex vivo mouse embryo experiments. Mouse embryo imaging has
been of particular interest due to its relation to human embry-
onic studies. Because of the strong light scattering, purely optical
imaging techniques normally cannot image embryos older than
12 gestation days.1,8 In this study, we imaged an E15.5 (gesta-
tion day 15.5) C57BL/6 mouse embryo (courtesy of Professor
3D reconstructed images over the whole scanning depth (9 mm) at 532 and 630 nm light illuminations. Because the 630 nm light is less absorbed by blood, internal organs are imaged more clearly.

In summary, the 3D focal-line reconstruction improves the elevational resolution of the concave transducer array, and removes the out-of-focus artifacts in 2D reconstruction. Combined with the multiplexed data acquisition system, it also improves the 3D scanning speed without sacrificing the SNR. The technique was successfully applied to image an E15.5 mouse embryo, where whole body vasculatures and internal organs were clearly imaged.

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References


Fig. 4 In-plane PA images of a mouse embryo at sagittal sections of various depths (Video 2, QuickTime, 1.9 MB): 2.7 mm [(a), (d)], 4.8 mm [(b), (e)], and 6.7 mm [(c), (f)]. Top row: 2D reconstruction. Bottom row: 3D focal-line reconstruction. [URL: http://dx.doi.org/10.1117/1.3625576.2]