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DOI

[10.1364/OL.36.002809](https://doi.org/10.1364/OL.36.002809)

Publication date

2011

Document Version

Final published version

Published in

Optics Letters

[Link to publication](#)

Citation for published version (APA):

Resink, S., Jose, J., Willemink, R. G. H., Slump, C. H., van Steenbergen, W., van Leeuwen, T. G., & Manohar, S. (2011). Multiple passive element enriched photoacoustic computed tomography. *Optics Letters*, 36(15), 2809-2811. <https://doi.org/10.1364/OL.36.002809>

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Multiple passive element enriched photoacoustic computed tomography

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Received May 25, 2011; accepted June 7, 2011;
posted June 28, 2011 (Doc. ID 148067); published July 20, 2011

Recently, we presented a method using laser-induced ultrasound from an external absorber (passive element) to image the ultrasound transmission parameters of an object under photoacoustic tomographic investigation. The method suffers from long measurement times due to the requirement for a large number of views and consequently physical projections around the object. Here we propose and validate an approach that permits a multitude of views to be obtained within a limited projection scenario. The approach uses a plurality of spatially distributed external absorbers in the path of the light, that results in multiple laser-induced ultrasound sources to interrogate the object from a number of angles. This reduces the required number of rotation angles or physical projections around the object, permitting a considerable reduction in imaging time without significant degradation in image quality. The approach brings the concept of hybrid imaging of ultrasound transmission parameters together with photoacoustic imaging, into the realm of practical application. © 2011 Optical Society of America

OCIS codes: 110.5120, 120.3890, 170.7170.

Photoacoustic (PA) imaging is attracting much attention due to various advantages observed and foreseen in applications in biology and medicine [1]. The technique is based on detecting ultrasound transients generated by the absorption of nanosecond pulses of light in tissue by pathologies including breast cancer [2,3].

Recently, we presented a method that in addition to conventional PA imaging, permits a simultaneous imaging of ultrasound transmission parameters [4,5]. These parameters, speed of sound (SOS) and acoustic attenuation (AA), constitute additional tissue characterization [6] providing anatomic information in the context of which the functional information from PA can be visualized. Further, the availability of an SOS map can facilitate a correct reconstruction of the PA image using actual local SOS values using acoustic backprojection [7].

This passive element enriched photoacoustic computed tomography (PER PACT) method, uses a small absorber placed in the ultrasound coupling medium, usually water, in the path of the laser light illuminating the object in a PA imager [4]. The laser-induced ultrasound transient created in the absorber by the PA effect, propagates through the water and interacts with the object. The otherwise circular wavefront undergoes distortion as it encounters regions with different SOS in the object. The wave also suffers attenuation to different extents if a heterogeneous distribution of AA is present. At the far-end, the wavefront is sampled at each element of an ultrasound detector array: the times of flight and signal amplitudes at each element are compared to the reference situation in water without the sample. Acquiring a multitude of such projection views around the object applying the appropriate image reconstruction algorithms [7] permits the development of two-dimensional slices of the SOS and AA distribution in the object. Simul-

taneously, PA signals from the object are also recorded by the detector array, since most of the light passes on to illuminate the object, allowing PA tomograms of the object to be reconstructed [6].

A drawback of the PER PACT approach is the long measurement time. A large number of views is required to avoid aliasing problems, which implies a large number of physical rotation angles around the object. The minimum number of views in the PER PACT geometry, (a fan-beam geometry) can be calculated using [8]

$$N_{\min} = \frac{4\pi\nu R}{1 - \sin(\zeta/2)}, \quad \text{with } \nu = \frac{1}{2a} = \frac{M}{2(\pi + \zeta)R}, \quad (1)$$

where ν is the maximum spatial frequency, R the radius of the artifact-free zone of reconstruction, and ζ the fan-beam angle. The factor ν is the Nyquist frequency related to the lowest density of spacing (a) between the “rays” (M) in each view.

For the experimental setup used [6], the number of rays is the number of elements in the detector array, thus $M = 32$. Further, $R = 15$ mm and $\zeta = 40^\circ$, which yields a value for N_{\min} as 80. With 100 times signal averaging per view for a 10 Hz laser repetition rate, the measurement time for a single slice is 13.3 minutes. For the method to be practically applicable, the measurement time should be considerably shortened without compromising resolution and contrast.

In this Letter, we propose a simple solution to the problem. We utilize a plurality of passive elements to act as multiple ultrasound sources. The situation is sketched in Fig. 1, where for simplicity, three fan beams (or views) are shown for the first, fifth, and ninth passive element, with three rays per view. It can be appreciated that for every physical rotation angle, multiple views of the

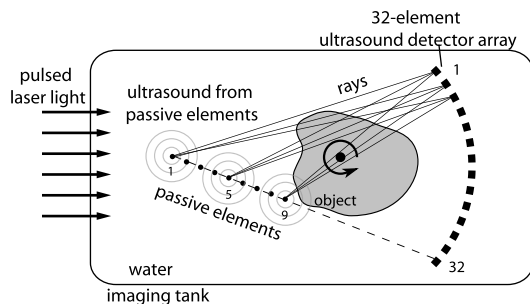


Fig. 1. Schematic of the multi-PER PACT which allows short measurement times while maintaining image quality. Nine passive elements are shown, and for simplicity only a few projection rays of ultrasound propagation are shown.

object are acquired, as multiple fan beams emanate from passive elements to the detector array. The implication is that a lower number of rotation angles compared to the single passive element case is required, while maintaining high image quality.

We inserted nine horse tail hairs with diameters between 200 and 250 μm in a PA computed tomography imager. These passive elements were positioned in the path of the light according to a simple constraint: at a detector element the PA signals from any passive element should not overlap with the signals from inside the object, nor with signals from other passive elements.

The imager is discussed in detail in [6], and here we describe only the essential details. A Q -switched Nd:YAG laser (Brilliant B, Quantel) with a frequency doubler delivering 6 ns pulses at 532 nm was used as a light source. The object was mounted on a rotary stage and immersed in water. A curvilinear array (Imasonic, Besançon, France) comprising 32 piezocomposite elements with the dimensions of 10 mm \times 0.25 mm, possessing a central frequency of 6.25 MHz was used as a detector

array. A 32-channel pulse-receiver system (Lecoeur Electronique, Chuelles) was used for data acquisition. To demonstrate the multiple passive element concepts, we used the same test object as in [6]. The object was a 26 mm diameter agar cylinder with four small SOS and AA contrast inclusions [Fig. 2(a)] made of agar dissolved in milk. The inserts had an SOS of 1505 ms^{-1} and an AA of 0.29 Npcm $^{-1}$, while the cylinder had an SOS of 1498 ms^{-1} and an AA of 0.10 Npcm $^{-1}$.

Estimation of integrated time delay differences between object and reference measurements were performed using a time-domain maximum likelihood method introduced in [6]. The integrated AA was estimated using signal amplitude attenuation between object and reference measurements. The distribution of the acoustic properties, SOS and AA, was reconstructed using a ray-driven discretized measurement model [6].

Experiments were performed with 80 projections around 360° corresponding to angular increments of 4.5°. For the full set of projections with a single passive element (element 1), the SOS tomogram is shown in Fig. 2(f), where the inserts are represented accurately. To investigate the effect of using more passive elements, we used a limited subset of nine projections (angular increment 40°). For the cases when one, three, six, and finally nine passive elements are used, the results are shown in Figs. 2(b)–2(e), respectively. When the single passive element (element 9) is used with nine projections, we obtain a good reconstruction of the agar cylinder, but not of the inserts. The image with the use of three passive elements (elements 7–9) shows three inserts. The fourth insert appears with six passive elements (elements 4–9) with a subtle improvement in image quality when all nine elements are used.

The maps of AA are shown in Fig. 3. With a single passive element (element 9) and nine projections [Fig. 3(a)],

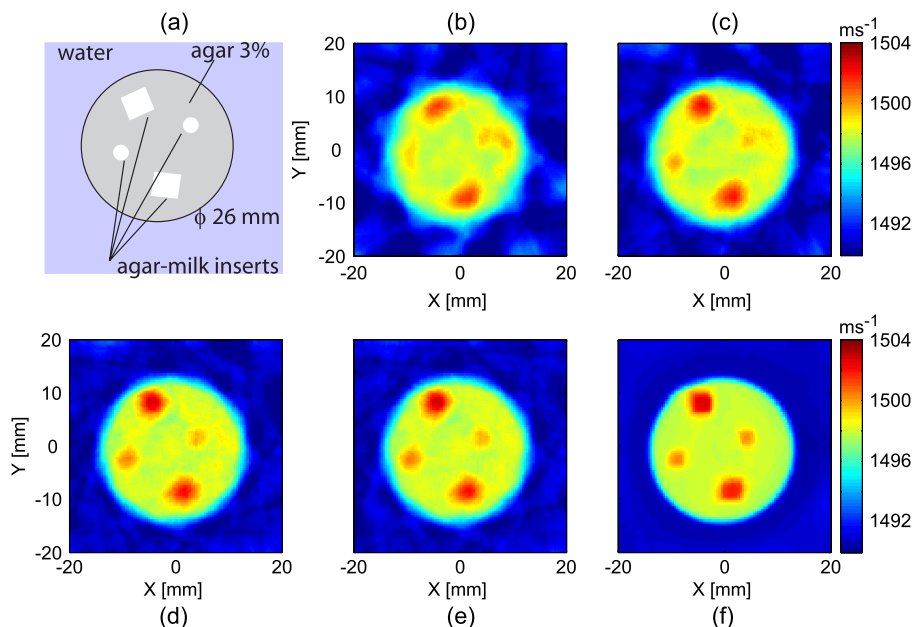


Fig. 2. (Color online) (a) Agar gel test sample with agar milk inclusions. SOS tomograms obtained with only nine projections (measurement time of 1.5 minutes) using an increasing number of passive elements: (b) element 9, (c) elements 7–9, (d) elements 4–9, and (e) all nine elements. For comparison, (f) used element 1 with 80 projections that requires a measurement time of 13.3 minutes.

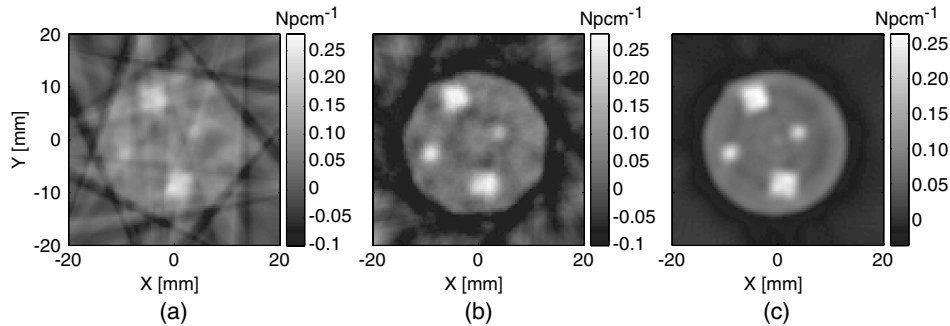


Fig. 3. AA tomograms obtained with only nine projections using (a) element 9 and (b) all nine elements. For comparison (c) used element 1 with 80 projections.

streak artifacts dominate the image. The situation is improved with the introduction of progressively more passive elements until all nine elements finally provide good visualization of the gel cylinder and the inserts [Fig. 3(b)]. The AA image when a single passive element (element 1) is used with all 80 projections is shown in Fig. 3(c) for comparison. Comparing the SOS and AA images for the nine passive element-9 projections case [Figs. 2(e) and 3(b)], the SOS image appears smoother. This is due to a higher smoothing in the regularization [6] applied during reconstruction, which is required since the SOS contrasts exhibited by the inserts are low.

We conclude that the multi-PER PACT approach permits the use of limited projections without compromising image quality in tomograms of SOS and AA. For the examples discussed, we have reduced the measurement time from 13.3 minutes for a single passive element to 1.5 minutes using nine passive elements by cutting down the number of views from 80 to 9. The latter situation concerns nine views times 32 detector elements giving 288 projection angles arranged with an average spacing of 1.25° . This number of projections also offers sufficient spatial sampling for high-resolution conventional PA imaging; fast hybrid imaging of samples becomes possible. The multi-PER PACT method thus removes a considerable impediment to practical application in a simple manner. In the future we will apply the method to small animal imaging.

Daniele Piras and Johan van Hespén helped with various experimental aspects. The research was funded in the NIMTIK project by the MIRA Institute and by AgentschapNL through projects IPD067771 and IPD083374 in the theme IOP Photonic Devices.

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