Multiple passive-element enriched photoacoustic computed tomography

Steffen Resink[1,*], Jithin Jose[1,*], Rene G. H. Willemink[2], Cornelis H. Slump[2], Wiendelt Steenbergen[1], Ton G. van Leeuwen[1,3] and Srirang Manohar[1,†]

[1] *Biomedical Photonic Imaging Group, MIRA Institute, Faculty of Science and Technology University of Twente, PB 217, 7500AE, Enschede, The Netherlands*

[2] *Signals and Systems Group, MIRA Institute, Faculty of Electrical Engineering, Mathematics and Computer Science University of Twente, PB 217, 7500AE, Enschede, The Netherlands*

[3] *Biomedical Engineering and Physics, University of Amsterdam, Academic Medical Center P.O. Box 22700, 1100DE, Amsterdam, The Netherlands*

[*] *Equal contribution*

[†] *Corresponding author:s.manohar@utwente.nl*

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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.

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 ns 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 PER-PACT method (passive-element enriched PA computed tomography), 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 2D slices of the SOS and AA distribution in the object. Simultaneously, 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]:

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

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 $\zeta = 40^o$, 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 3 fan beams (or views) are shown for the 1st, 5th and 9th passive-element, with 3 rays per view. It can be appreciated that for every physical rotation angle, multiple views of the 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 signals from inside the object, nor with signals from other passive-elements.

The imager is discussed in detail in Ref. [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 dimensions (10x0.25) 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 concept, we used the same test object as in Ref. [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 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 Ref. [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 9 projections (angular increment 40°). For the cases when 1, 3, 6 and finally 9 passive-elements are used the results are shown in Fig. 2(b), (c), (d) and (e) respectively. When the single passive-element (element 9) is used with 9 projections, we obtain a good reconstruction of the agar cylinder, but not of the inserts. The image with the use of 3 passive-elements (elements 7-9) shows 3 inserts. The 4th insert appears with 6 passive-elements (elements 4-9) with a subtle improvement in image quality when all 9 elements are used.

The maps of AA are shown in Fig. 3. With a single passive-element (element 9) and 9 projections (Fig. 3(a)), streak artifacts dominate the image. The situation is improved with the introduction of progressively more passive-elements till all 9 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 9 passive-element-9 projections case (Fig. 2(e) and Fig. 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-PERPACT 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 9 passive-elements by cutting down the number of views from 80 to 9. The latter situation concerns 9 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 photoacoustic imaging; fast hybrid imaging of samples becomes possible. The multi-PERPACT method thus removes a considerable impediment to practical application in a simple manner. In future we will apply the method to small animal imaging.

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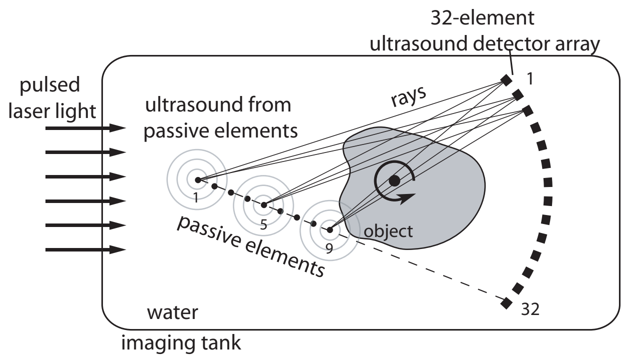

Fig. 1. Schematic of the multiple passive-element approach (multi-PERPACT) in photoacoustic computed tomography which allows short measurement times while maintaining image quality. Nine passive-elements are shown, and for simplicity only a few projection rays of ultrasound propagation are shown.

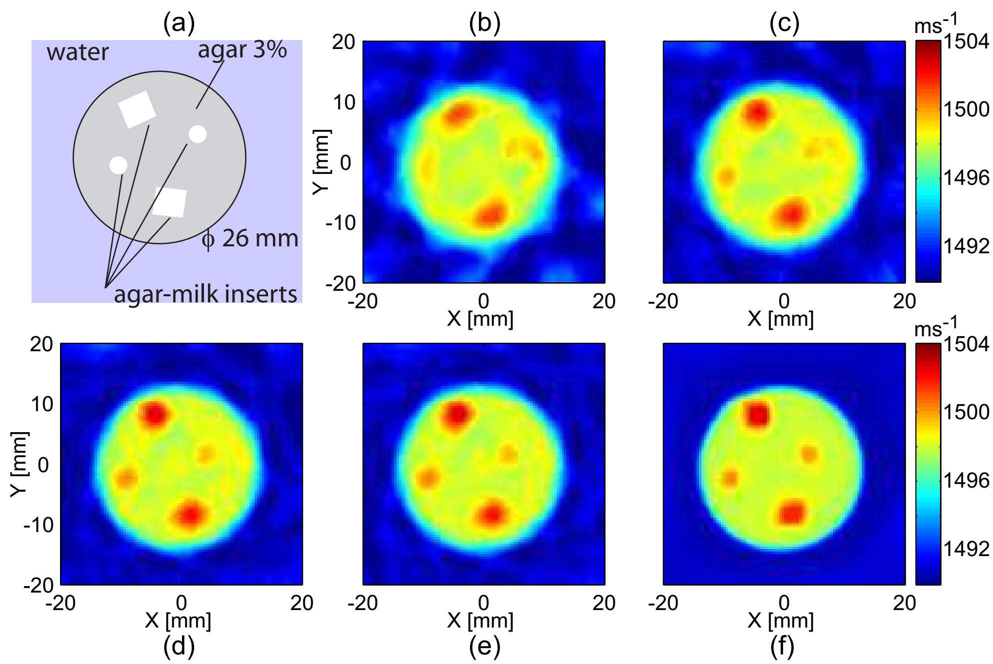

Fig. 2. (a) Agar gel test sample with agar-milk inclusions. Speed of sound tomograms obtained with only 9 projections (measurement time 1.5 minutes) using increasing number of passive-elements (b) element 9, (c) elements 7-9, (d) elements 4-9, and (e) all 9 elements. For comparison (f) used element 1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

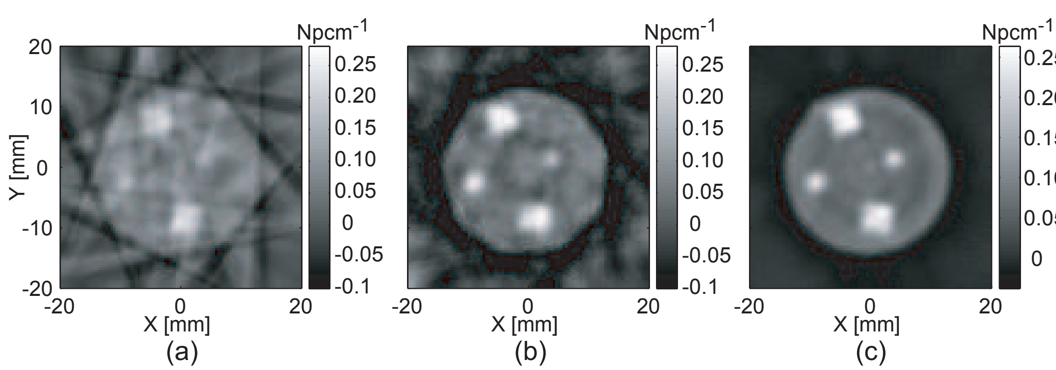

Fig. 3. The acoustic attenuation tomograms obtained with only 9 projections using (a) element 9, and (b) all 9 elements. For comparison (c) used element 1 with 80 projections.