

Non-contact Photoacoustic Tomography using holographic full field detection

Jens Horstmann*^a, Ralf Brinkmann^{a,b}

^aMedical Laser Center Lübeck, Peter-Monnik-Weg 4, 23562 Lübeck, Germany;

^bInstitute of Biomedical Optics, University of Lübeck, Peter-Monnik-Weg 4, 23562 Lübeck, Germany

ABSTRACT

An innovative very fast non-contact imaging technique for Photoacoustic Tomography is introduced. It is based on holographic optical speckle detection of a transiently altering surface topography for the reconstruction of absorbing targets. The surface movement is obtained by parallel recording of speckle phase changes known as Electronic Speckle Pattern Interferometry. Due to parallelized 2-D camera detection and repetitive excitation with variable delay with respect to the image acquisition, data recording of whole volumes for Photoacoustic Imaging can be completed in times far below one second. The size of the detected area is scalable by optical magnification. As a proof of concept, an interferometric setup is realized, capable of surface displacement detection with an axial resolution of less than 3 nm. The potential of the proposed method for in vivo Photoacoustic Imaging is discussed.

Keywords: Photoacoustic Imaging, Holographic Interferometry, Electronic Speckle Pattern Interferometry

1. INTRODUCTION

Photoacoustic Tomography becomes more and more popular, a recent review is given by Hu and Wang [1]. Photoacoustic Imaging is based on the emission of pressure waves due to thermoelastic expansion resulting from pulsed laser light absorption [2] in a less absorbing environment. Therefore, an excitation wavelength should be chosen which provides a high absorption contrast. The excited pressure waves propagate through the tissue and can be detected at the surface. Photoacoustic Imaging combines aspects of optical and ultrasound imaging and, consequently, combines some of their particular advantages: Imaging of specific tissue components in a depth up to several centimeters becomes possible with a high image contrast. However, many of the existing approaches share the problem of a relatively high acquisition time often in the range of minutes, which only allows in vitro or in vivo imaging of anesthetized animals. Furthermore, acoustic contact or, in some cases, total immersion is needed for the sake of impedance matching. The state of science shows a variety of different approaches regarding the recording of the pressure waves:

The most straight forward strategy to produce photoacoustic images is pointwise excitation and detection in a scanning mode. In order to increase resolution, excitation and detection geometry can be used in a focused mode. Due to the need for scanning both the excitation- and detection unit over the object, or the object itself, the time consumption for data acquisition is generally high, e.g. several minutes [3]. Due to the high resolution of up to 5 μm , this technique is referred to as Photoacoustic Microscopy (PAM).

In order to increase the acquisition speed, excitation and detection can be parallelized partly. A whole tissue volume can be excited at a time; all absorbers within the excited volume are emitting pressure waves simultaneously. The resulting pressure field can be detected by a transducer array. Methods like *back projection*, which are based on triangulation, can be used to reconstruct the position of the acoustic sources after data acquisition [4]. Non-scanning approaches are referred to as Photoacoustic Tomography (PAT). The simultaneous digitizing of a high number of transducer elements after excitation requires significant electronic effort. Often multiplexing and therefore repetitive measurements are required [5].

*horstmann@mll.uni-luebeck.de, phone: +49-451-500-4695, www.mll-luebeck.de; www.bmo.uni-luebeck.de

Recent progress in data acquisition speed has been shown with a handheld ultrasound head, as presented by Buehler et.al. [6]. Using fast tunable laser sources, the system provides a framerate of 50 Hz, capable of imaging several tissue chromophores in real-time.

An alternative to piezoelectric detection are optical pressure acquisition techniques. The pressure can be measured by the use of a plane-parallel film on the object surface serving as a Fabry-Pérot-Interferometer. The polymer film is transmissive for the excitation light. An interrogation laser beam at a different wavelength is scanned across the surface. Incident pressure affects the interrogation beam reflection intensity; the oscillation in the signal can be detected by a broadband photo diode [7].

Another method is the non-contact detection of the pressure induced surface displacement, as introduced by Carp and Venugopalan [8]. In this case, a single beam interferometer is used to detect small surface oscillations in the nm regime due to photoacoustic pressure waves using a fast broadband photodiode. In general, the method is scalable in the size of the scanned area, however, still requires long acquisition time for larger areas.

In order to combine non-contact free surface measurements with high speed real-time imaging, we propose holographic optical parallel image acquisition of the transiently changing surface topography with acquisition times of ten to hundred milliseconds. This method will be highly useful for in vivo imaging even of non-fixated targets.

2. NON-CONTACT DETECTION SCHEME

A sketch of the introduced non-contact detection scheme is shown in figure 1 (left). An excitation laser illuminates the whole volume in order to excite embedded absorbers for thermoelastic pressure wave emission. The pressure waves propagate to the surface and transiently deform the free boundary. The altering topography is recorded in parallel by a holographic-interferometrical setup. The data are recorded with a fast high speed digital camera.

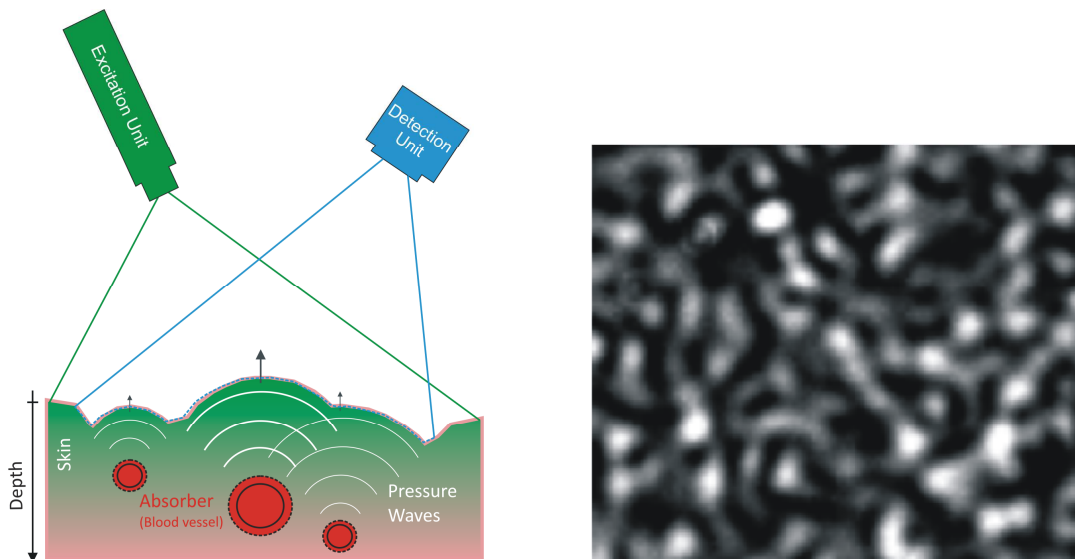


Figure 1. left: Illustration of the introduced method. Excitation pulses are applied to the whole volume. Pressure induced surface displacements owing to thermoelastic expansion of absorbers are recorded by an optical-holographical detection unit. right: Optical speckles appear due to local interference when a rough surface is illuminated coherently and imaged.

The basic method applied for measuring the surface displacement, which is expected to be in the scale of nm only, is Electronic Speckle Pattern Interferometry (ESPI). Speckles appear, when an optically rough surface is illuminated by coherent light. Figure 1 (right) shows a typical speckle field.

The surface is imaged onto a fast camera. If the surface moves, the speckle pattern alters, which is used to record and determine the topography of the irradiated volume. In order to get quantitative data, we make use of the fact that the optical phase within a speckle is constant. When the object surface is displaced, the phase of the corresponding speckles change. This phase change can be determined by speckle interferometry [9] with an axial resolution of only a small fraction of the detection wavelength. The lateral resolution depends mainly on the speckle size and on the imaging scale.

In order to acquire the full time-resolved topography with only one single excitation pulse, a sampling rate of e.g. 10 MHz, which is a typical sampling frequency for Photoacoustic Imaging, is required, which means a full frame acquisition every 100 ns over a period of several μ s. Since those cameras are not available, the problem is solved by repetitive excitation as illustrated in figure 2. Since speckle patterns are very sensitive to smallest movements, always two images are captured. The first is serving as reference before the excitation, and the second in a defined, variable delay after the excitation, respectively. With this double pulse technique and a repetition rate of several kHz, the whole topography can be acquired in several ms.

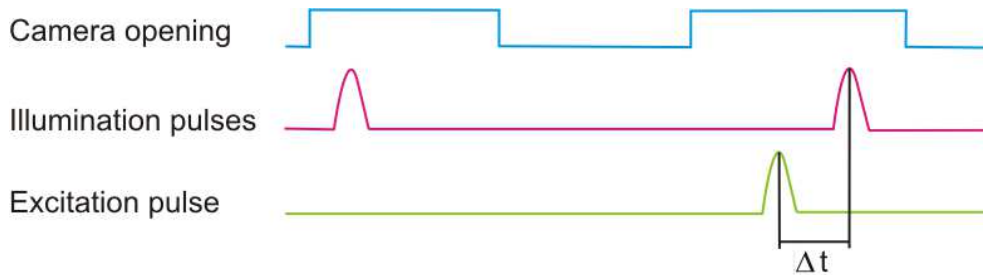


Figure 2. Timeline of the detection scheme. Repetitive procedure with increasing time delay Δt between excitation pulse and second illumination pulse.

The procedure for measuring the surface displacement starts with an initial $\Delta t = 0$. In each subsequent repetition, Δt is increased. The number of repetitions and the stepwise increase of Δt depend on the desired sampling rate.

Once the images are captured, the optical phase of both images is determined and a phase difference image is calculated. From the phase difference image, the geometrical displacement can be derived. Because the phase determination is independent for each speckle, every speckle contributes to the surface position measurement.

In order to reconstruct the target structure, the measured data of a speckle is saved over time and further processes by e.g. a back projection algorithm.

3. PROOF OF CONCEPT

In order to proof the applicability of this detection method for Photoacoustic Imaging, silicone phantoms were produced. Transparent silicone (Wacker Silicones RT604 A/B) served as a non-absorbing, non-scattering phantom in size of $(10 \text{ mm})^3$. Within the cube, a black silicone point absorber of about 1 mm in diameter is located. On the detection side, a 150 μ m film of white silicone was added to increase backscattering of the detection light.

The absorber was excited by a Q-switched Nd:YAG laser (Quantel YG671-10: wavelength 1064 nm, repetition rate 10 Hz, pulse duration 6 ns, pulse energy 20mJ) onto a diameter of about 5 mm. The absorption coefficient of the black silicone was measured to be 16.2 /cm for the used excitation wavelength. Figure 3 shows a sketch of the setup. The time delay between excitation and detection was increased in steps of about 1 μ s.

For detecting the surface movements subsequent to photoacoustic excitation, a Mach-Zehnder-Interferometer based setup was realized with a Q-switched Nd:YAG laser (CryLas FTSS 355-50: wavelength 532 nm, pulse duration 1 ns, pulse energy 100 μ J) serving for illumination. This setup was capable of measuring fast and small surface deformations by use of spatial phase shifting ESPI.

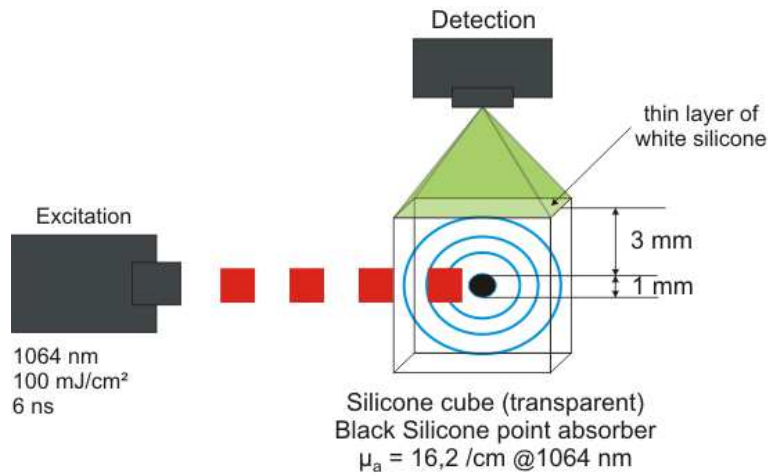


Figure 3. Proof of Concept experiment.

The results are presented as 8 bit gray scale value images. Figure 4 shows a time series as a typical measurements result. The baseline is scaled to a gray value of 128, which corresponds to no displacement. Displacement in the direction of the camera causes a brighter gray value and vice versa. The conversion factor from gray values to nm depends on the detection geometry and was about 0.9 nm per gray value in the presented measurement.

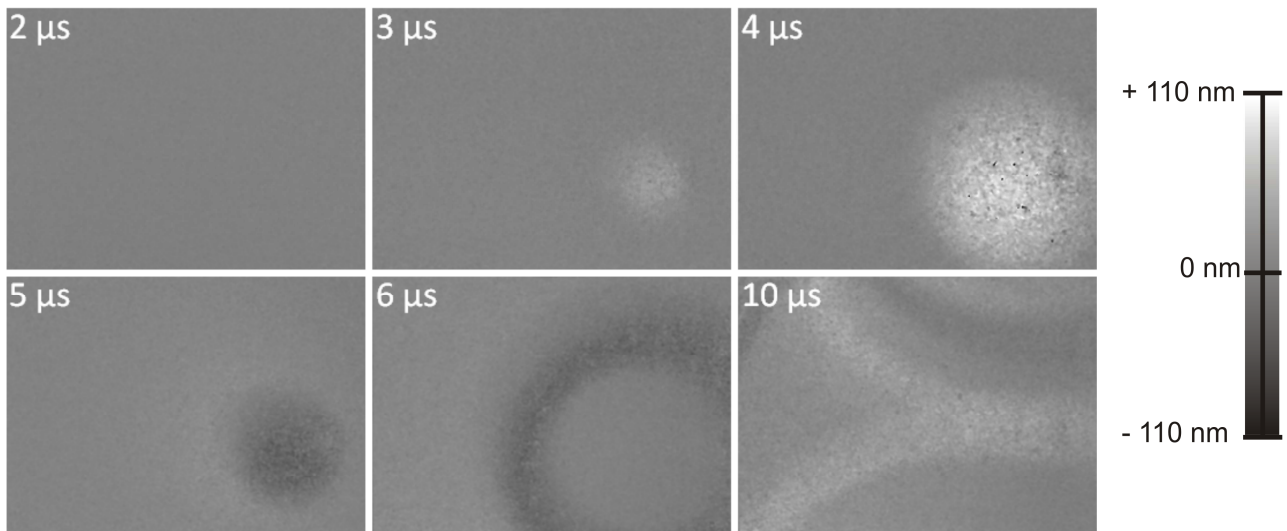


Figure 4. Result frames of the Proof of Concept measurement. Time points are relative to the excitation pulse.

Because the speed of sound in silicone is about 1 mm/ μs and the depth of the absorber is about 3 mm, the first image taken 2 μs after excitation shows no displacement. The surface starts to rise at 3 μs , the signal gets bigger after 4 μs , displaying the rising positive part of the thermoelastic transient. The negative part, starting 5 μs after excitation, lets the surface drop to a level lower than the ground level. The positive and negative parts propagate to the outer regions of the phantom surface later on. Another 4 μs later, when the effect of the actual transient is passed already, reflections from the phantom borders interfere. For a better visual interpretation, the same data are presented in quasi 3D (ImageJ) in Figure 5:

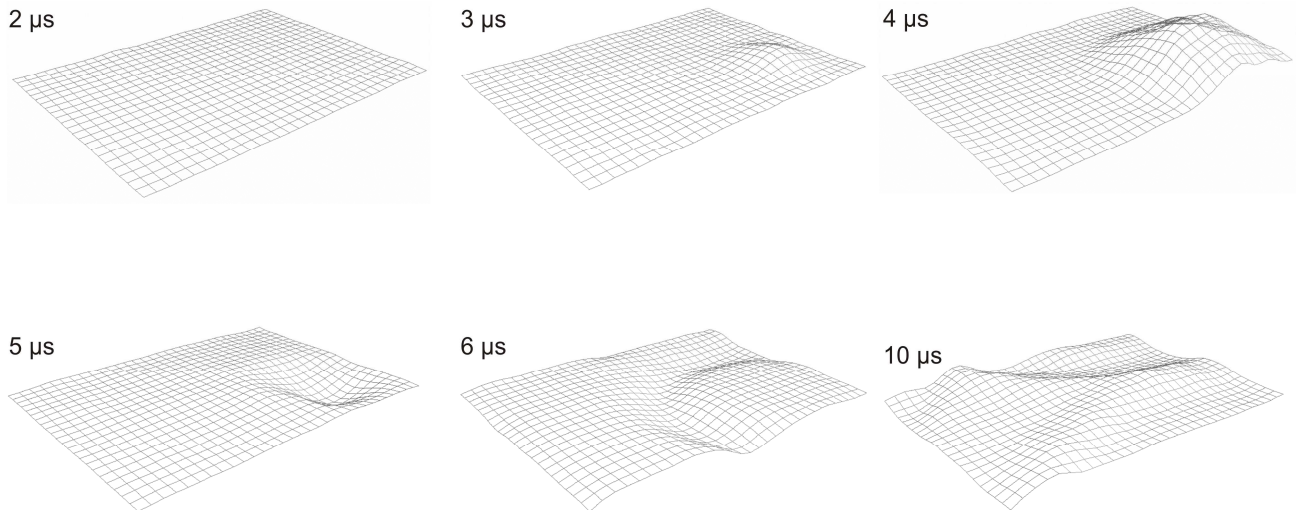


Figure 5. Surface topographies in quasi-3D.

In order to reconstruct a three-dimensional tomography of the absorbing structure from the measured data, time reversal algorithms can be applied in a next step. For this purpose, time-dependent displacement data for every speckle can be obtained. An estimation made with the available data is given in figure 6. A region of interest of one speckle of 10x10 pixels right over the absorber (see marked area in figure 6, left) is averaged and displayed over time (right). The measured signal is alike with thermoelastic transients measured by piezoelectric transducers.

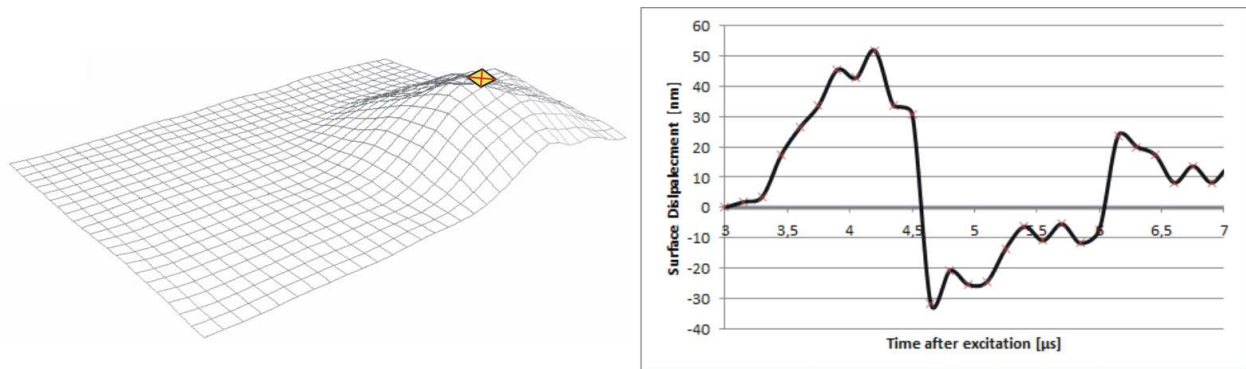


Figure 6. Time-dependent surface displacement of an area of 10x10 pixels right over the absorber.

4. CONCLUSION AND OUTLOOK

We proposed and realized a digital full-field holographic speckle pattern detection system for non-contact PAT. As a proof of concept, measurements on a phantom with embedded absorber show the potential of the proposed detection method for Photoacoustic Imaging. The axial resolution of this first setup investigated is less than 3 nm with a lateral resolution of about 80 μm. The dynamic range of displacement is about +/- 110 nm.

Fully developed with excitation laser and data acquisition camera in the kHz range, respectively, the method is potentially capable of full volume recording with a bandwidth of several ten MHz within times ranging below 100 ms. Further investigations will be carried out towards characterizing the potential and limitations of the technique. The method seems very versatile in terms of spatial and temporal scalability of the investigated field and resolutions, respectively. However, the possible axial and spatial resolutions of reconstructed tomographies can only be estimated by

now. One expects that the transition from pressure to surface displacement will affect the signal as a low pass in time and in space, depending on the surface tension and elasticity.

The potential for the method in the field of Photoacoustic Imaging is very high. The non-contact mode opens up new application fields for Photoacoustic Tomography since it is suitable for in vivo imaging, particularly for interventions where contact mode applications are impossible like endoscopy in the gastrointestinal tract or neurosurgery, where coupling to an operational microscope is conceivable. Another advantage is the high speed image acquisition time with few ten to hundred milliseconds in the double pulse delay technique, where smaller motion artifacts are negligible or can be compensated. This allows Photoacoustic Imaging of non-fixed or sedated targets even over larger distances.

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