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Research articles

Visualization of photoacoustic images in a limited-View measuring system using eigenvalues of a photoacoustic transmission matrix

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ABSTRACT

Photoacoustic imaging is a unique imaging method that involves extracting information from points at different depths, an advantage of ultrasound imaging, while maintaining functional information, a key feature of conventional photo imaging. This makes it easy to add functional images to ultrasound images by adding a laser pulse source to the conventional ultrasound imaging device and detecting a photo-ultrasound signal via a conventional ultrasound probe. One challenge when using normal one-dimensional (1D) probes and generating photoacoustic images is the limited-view problem, in which artefacts are observed due to the positions of the ultrasound transducers. In this study, we used a photoacoustic transmission matrix (PA-TM) for simulation and performed a verification test using a 1D probe and a phantom. The results confirmed that the eigenvalues of the PA-TM visualized the light absorber itself in the limited-view measurement system, which eliminates reconstruction artefacts and further scattering artefacts, and that visualization is possible by signal intensity amplification through further phase modulation.

1. Introduction

Photoacoustic tomography is an emerging non-invasive hybrid light and ultrasound imaging technique. Illuminating an object with uniform short-pulse laser light leads to thermoelastic expansion at sites of optical absorption. Generated photoacoustic ultrasound waves can be measured using an ultrasound transducer and then reconstructed based on the straightness of the ultrasound wave. Light can provide a functional, metabolic, and molecular contrast signal. However, the ultrasound transducer cannot determine the source of the generated photoacoustic signal, due to diffusion of light in the object. Consequently, ultrasound transducers must be placed in multiple locations around the object to avoid omission of image information. In many practical implementations, ultrasound transducers are placed over an aperture that does not enclose the object, and the result is the limited-view problem [1]. To avoid this problem, arc-shaped and bowl-shaped transducers are employed instead of the generally used 1D ultrasound transducers [2,3]. With ultrasound imaging, the transmitted ultrasound does not have functional interaction with the object; however, with a beam-forming technique, a complex set of control pulses emitted from 1D ultrasound transducers can form arc-shaped sound waves, resulting in a high-quality image.

Several techniques have been proposed to localize the area emitting the photoacoustic signal. The first technique is based on localized vibration tagging at the absorption areas. Induced by the acoustic radiation force in a focused ultrasonic beam, signals of interest can be distinguished by tagging the photoacoustic signal at the origin using localized tissue vibration [4]. This technique can eliminate the clutter signal; however, it is necessary to scan all image areas with a high-energy ARF beam and to acquire photoacoustic signals sequentially.

The second technique is to control the scattering light by combining optical phase conjugation and ultrasound tagging. Ultrasound is used to define a target modulation location, and a phase conjugating mirror (PCM) is used to return time-reversing tagging light to the ultrasound modulation location. Analog [5] and digital [6,7] approaches have been used to create a PCM. With the analog approach, photorefractive crystals are used to record the phase hologram and replay the time-reversing light holographically. Although these crystals have high sensitivity for recording phase holograms, the readout light has higher gain than the recording light and erases the photorefractive holograms. With the digital approach, an interference fringe is captured using a digital

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camera, and the phase hologram is calculated. The phase holograms are subsequently projected onto the spatial light modulator (SLM), and the readout light replays the time-reversing light. These principles are highly elegant, but the system requires accurate alignment [8] and repeated iterative focusing to achieve high gain [9]. Because focusing enhancement is greatly restricted by the size of the focusing area, it is unsuitable for the illumination used for tomography.

The third technique is optical wavefront shaping [10,11]. Using a feedback photoacoustic signal from the target location related to light energy, incident light is optimized using a wavefront control device with an iterative optimization algorithm [12].

Another important technique involves using the photoacoustic transmission matrix (PA-TM). This approach uses the transmission matrix to detect, localize, and selectively focus light on light-absorbing targets through diffusive samples for a photoacoustic system with a single transducer [13], and is based on the coherence of the laser light. However, acquiring the photoacoustic signal observed as a point light source causes a local photoacoustic effect, and the emitted photoacoustic signal can be detected by a 1D transducer as a point spread propagated wave [14]. This technique eliminates reconstruction artefacts. By combining these two techniques, it is possible to derive the PA-TM using a 1D transducer [15].

In this study, we focus on the singular value following derivation of the PA-TM and propose a technique for visualization of the light response distribution and suppression of the reconstruction artefact under a limited-view measurement system. This enables determination of both the presence of light absorbers and the degree of control of the localized light quantity with high contrast by compressing the artefact.

2. Theory

2.1. Photoacoustic transmission matrix

As laser light enters a scatterer, each of the wavefronts (i = 1, 2, . . . , n) is scattered inside the scatterer and then emitted from its surfaces (j = 1, 2, . . . , m) in a random-phase state (Fig. 1(a)). Therefore, if the phase state of the light at each location is uniform, the state of the light at the emitting surface can be expressed as $|t_{ij}|e^{\phi_{ij}}$, which includes a random phase component. In such conditions, observing the surface using a camera reveals a speckle of light particles, which means that light interference occurs at each surface. The light can be modulated if it is possible to modulate the phase of the incident light and cause interference, and to calculate the transmission matrix that expresses the light's response. For coherent light, speckle intensity can be adjusted by modulating the phase at the incident surface. Light can be focused by setting the light source in such a manner that light rays passing through the observed surface are in phase (Fig. 1(b)). It is also possible to create dark spaces using peripheral brightness.

In general, light loses its straightness after travelling a scattering distance longer than the mean free path; for example, it is impossible to observe the phase status inside a living substance, the scatterer, using a camera that captures light intensity. However, if light-absorbing substances are present in the scatterer, a photoacoustic phenomenon is induced by the change in energy associated with light absorption, and it is possible to detect a photoacoustic wave signal, which is proportional to the energy of the absorbed light. Moreover, various reconstruction methods have been proposed based on the transmission time and straightness of an ultrasound signal, which enables identification of the location of the light-absorbing substance. Therefore, it is possible to calculate the response matrix for the light at the light-absorbing substance by modulating the phase of the incident light. We used a light response rate corresponding to a singular value of the response matrix at each position of the light-absorbing substance, and attempted to visualize the light-absorbing substances inside a scatterer.

Furthermore, the photoacoustic wave generated by light irradiation in each pattern is measured using the coherence status of the light; thus, the irradiation has a speckled pattern. Therefore, the photoacoustic wave has essentially an N-type waveform and forms a composite wavefront along its shape. With this irradiation method, the photoacoustic wave is formed from speckle points and propagates [14,15]. Therefore, it is possible to detect signals without the limited-view problem that arises with measurement using a photoacoustic 1D array transducer. In the actual measurement system, however, complete reconstruction is not possible, due to restrictions in aperture and bandwidth arising from the finite diameter of the transducer, and image artefacts are generated during the reconstruction. In the phase measurement, the offset is cancelled and the information is extracted from the phase response, which is not hampered by the artefacts.

2.2. Measurement of the PA-TM eigenvalue

We used the Hadamard matrix to modulate the phase of each input wavefront (Fig. 2(a)). The Hadamard matrix is a square matrix composed of −1 and 1, with π or 0 as the phase. To observe the output status, we used the periphery of the phase-modulating device as the reference phase plane, since interference measurements were taken to obtain the response to the input phase.

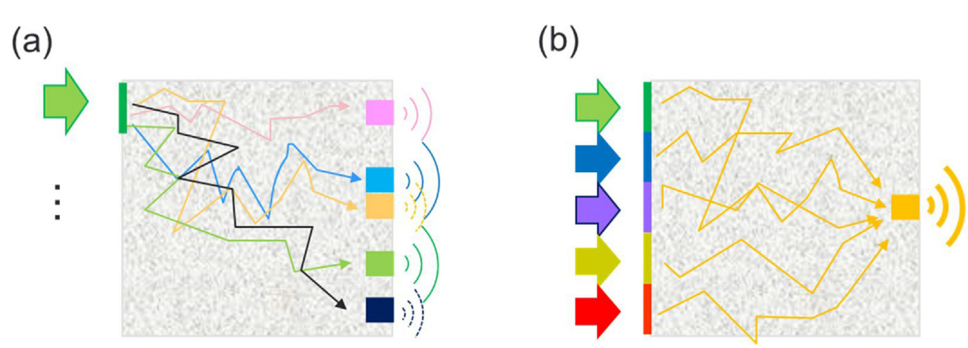

Fig. 1. Transmission matrix focusing through a scattering sample.
(a) Each incident light is scattered in the scattering sample, with each scattered light having a phase state different from that of the incident light state. The transmission matrix, the phase response of light, is simultaneously measured by either changing the whole area of each input light phase or encoding the illumination pattern and phase.
(b) Optical wavefront shaping of the incident wave enables focusing light through the scattering sample with periodic phase matching by modulated incident light phase using the reverse phase of the transmission matrix.