Camera based photoacoustic imaging: sensitivity and resolution improvement

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Background – Recently, we have shown that an optical camera in combination with a phase contrast Schlieren detection method can be used for biomedical photoacoustic imaging [1,2]. This approach allows projection images of the initial pressure source to be recorded in the shortest possible time, typically in the microsecond range, only limited by the required sound propagation time from inside the sample to the surrounding volume. The reconstruction of the images is performed by backpropagating the recorded wave pattern images that are located within the field of view (FOV) of the camera in Fourier- or Time-Domain. The generation of a 3D image requires the recording of several projection images from different directions, ideally distributed over a semicircle, of the sample with subsequent application of the inverse Radon transform. In view of the achievable resolution and the flexibility for different lighting schemes for the excitation process, due to the optical transparency of the detector, the proposed approach should be preferable compared to conventional methods. However, for many applications these are not the main issues. Rather, sensitivity, compactness and ease of use are decisive, which is why piezo-arrays are still mostly used. In this work it is shown how the sensitivity can be significantly improved without degrading the resolution and maintaining a compact arrangement.

Methods – The basic principle of camera based photoacoustic projection imaging is shown in Fig. 1a. An expanded probe laser pulse projects the 3D pressure field *p(x,y,z,t)* at a defined time instant onto an optical camera. Since a phase contrast detection approach is used, the achievable contrast is directly proportional to the pressure field induced phase variation $\Delta\varphi$ [3]:

$$\Delta\varphi(x,z,t) = \frac{2\pi}{\lambda_P}\cdot\frac{\partial n}{\partial p}\cdot\int_0^L p(x,y,z,t)\partial y \qquad \text{Eqn. 1}$$

Beside the amplitude of the pressure field, determined by the photoacoustic source, the strength of $\Delta\varphi$ is dependent on the wavelength λ_P of the probe laser pulse, the elasto-optic coupling coefficient *dn/dp* of the material in which the waves propagate, and the interaction length *L* as stated by Eqn.1. These three parameters can be tweaked to improve the sensitivity, but the most effective way is to replace the interaction material with one with a better *dn/dp* value. So far, deionized water has mostly been used as the coupling liquid in order to fulfill the approximation of a homogeneous sound velocity distribution for a fast single-step reconstruction. Replacing water with Fluorinert Liquid (FL), which has an almost four times larger elasto-optic coupling coefficient ($\partial n/dp = 5.13 \cdot 10^{-10} Pa^{-1}$), would boost the sensitivity by the same factor, neglecting any transmission losses due to acoustic impedance mismatches. However, due to the small speed of sound (SoS) value of FL (660m/s), refraction effects at the interface must be considered in the reconstruction process to avoid degradation of the image quality. Adding reflecting walls also helps to improve the overall image quality while keeping at the same time the setup compact [4]. To show the effect of these measures, simulations were performed using modified functions from the k-wave toolbox adapted for the spatial data [5]. In a first step, the forward problem was simulated for the two cases with and without reflecting walls, a defined source distribution (Fig. 1b), different acoustic properties for the upper and lower half space and a wave propagation time of 45 µs. The upper half space of the simulation domain was considered as water with

properties similar to biological tissue (1500 m/s, 1000 kg/m3) and the lower half space is FL (660 m/s, 1793 kg/m3). The properties of the reflecting steel walls were assumed with a SoS value of 5100 m/s and a density of 7850 m/s. In a second step, the adapted time reversal (TR) algorithm from the k-wave toolbox was applied considering the acoustic inhomogeneities for the cases with and without reflecting walls. Only the region of the wave pattern that can be recorded by the camera (FOV) in a typical experimental setting was used as input dataset.

Results – Figure 1 shows the assumed initial source distribution, the simulated wave pattern structure for both cases, with and without reflecting walls, and the reconstruction results. Applying a standard backpropagating algorithm in frequency domain to the wave pattern, with an assumed average sound speed (1080 m/s), the reconstruction completely fails resulting in an extremely blurred image, depicted in Fig. 1e. The TR reconstruction results (Fig. 1c and 1d), on the other hand, show a qualitative good agreement with the ground truth (Fig.1b). Negative pixel values and horizontal distortions of the structures stem from the limited detection aperture. The result obtained with the reflecting wall (Fig.1d) is slightly better. This is explained by the back-reflection of the wave into the camera's FOV, increasing the detection aperture, which results in an improved image quality.

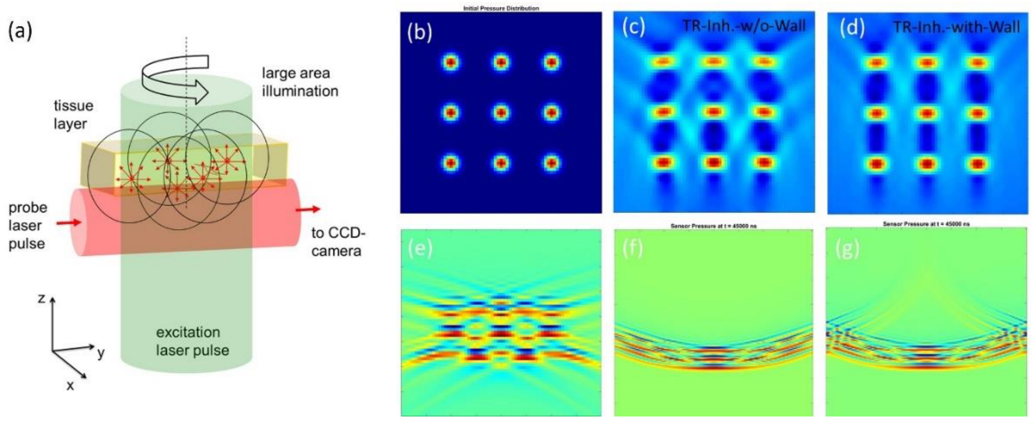

Fig. 1. Schematic of the camera based photoacoustic imaging system **(a)**, the assumed initial pressure source **(b)**, the reconstruction results with TR considering the SoS inhomogeneities without **(c)** and with **(d)** reflecting walls, corresponding simulated wave pattern structures **(f)** and **(g)** and the reconstruction result without considering the SoS inhomogeneities **(e)**.

Conclusions – In summary, the results indicate that water can be replaced with any liquid material that has a better elasto-optic coupling coefficient for a sensitivity improvement as long as it is transparent for the probe laser pulse and the introduced SoS inhomogeneity is considered in the reconstruction process. The disadvantage is that reconstruction methods such as TR, in which the SoS inhomogeneities can be taken into account, are usually not as fast as the standard frequency domain methods, limiting the real-time imaging capability. However, a four times improvement of the detection sensitivity will push forward the application field of the camera based photoacoustic imaging system.

References

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