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Photoacoustic Phasoscopy Super-Contrast Imaging Correlating Optical Absorption and Scattering

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ABSTRACT

Phasoscopy is a recently proposed concept correlating electromagnetic (EM) absorption and scattering properties based on energy conservation. Phase information can be extracted from EM absorption induced acoustic wave and scattered EM wave for biological tissue characterization. In this paper, a novel imaging modality, termed photoacoustic phasoscopy (PAPS) imaging, is proposed and verified experimentally based on phasoscopy concept with laser illumination. Both endogenous photoacoustic wave and scattered photons are collected simultaneously to extract the phase information, and phasoscopy image is then reconstructed by mapping phase distribution. The phasoscopy imaging experiments on vessel-mimicking phantom and *ex vivo* porcine tissues demonstrate significantly improved contrast than conventional photoacoustic imaging.

Keywords: Photoacoustic, phasoscopy, optical absorption, scattering, super-contrast

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1. INTRODUCTION

Photoacoustic (PA), also called thermoacoustic imaging is attracting significant research interest in recent years due to its breaking through of optical diffusion limit by "listening to photons", i.e. detecting optical absorption induced thermoacoustic wave [1-3]. PA microscopy and tomography have been well developed to achieve multi-scale multi-contrast imaging performance, probing endogenous chromophores (hemoglobin, melanin, etc.) or exogenous contrast agents [4-6]. Dual-modal imaging approaches combining PA with other imaging modalities, e.g. ultrasound imaging [7-10], optical coherence tomography (OCT) [11-14], and diffuse optical tomography (DOT) [15,16], have also been proposed in recent years to generate multiple images for co-registration by collecting both PA wave, and pulse-echo ultrasound or scattered photons. However, few research works have been done to explore the intrinsic correlation between endogenous PA wave and scattered photons coming from the same object.

In a typical PA imaging system, nanosecond pulsed laser is usually used to illuminate the object. Then the thermoelastically induced acoustic wave due to the optical absorption of chromophores is detected by ultrasound transducers to reconstruct the image. To go beyond the conventional PA imaging approach, here we employ a photodiode to detect the scattered photons simultaneously besides acquisition of PA signal as shown in Figure 1(a). More interestingly, the intrinsic correlation between PA wave and scattered photons is analyzed to extract the phase information based on the phasoscopy concept [17, 18]. In this paper, the PA phasoscopy concept will be briefly introduced, and then PA phasoscopy (PAPS) super-contrast imaging will be proposed and demonstrated on vessel-mimicking phantoms and *ex vivo* porcine tissues.

2. METHODS AND MATERIALS

2.1 Photoacoustic phasoscopy theory

The analysis of PA phasoscopy is based on the energy conservation principle [17], where the total incident optical energy P_{in} should be equal to the total absorbed optical energy P_{absorb} and scattered optical energy P_{scat} :

$$P_{in} = P_{absorb} + P_{scat}. \quad (1)$$

In the real measurement, only one portion of the PA wave and scattered photons could be detected by the ultrasound transducer and photodiode respectively, so we introduce conversion coefficients p and q to represent the conversion ratios of the detected PA energy $\overline{p_{acoustic}^2}$ and detected scattered optical energy $\overline{p_{scat}^2}$ from the total absorbed optical energy P_{absorb} and total scattered optical energy P_{scat} , respectively:

$$\begin{aligned}\overline{p_{acoustic}^2} &= pP_{absorb} \\ \overline{p_{scat}^2} &= qP_{scat}\end{aligned}\quad (2)$$

Substitute Eq. (2) into Eq. (1), then we have:

$$\frac{\overline{p_{acoustic}^2}}{pP_{in}} + \frac{\overline{p_{scat}^2}}{qP_{in}} = 1. \quad (3)$$

According to Eq. (3), it is predicted that for a specific biological tissue, the detected PA wave and scattered photons will follow an ellipse equation with acoustic and optic semi-axes $\sqrt{pP_{in}}$ and $\sqrt{qP_{in}}$, as shown in Figure 1(b). More specifically, when a tissue can absorb more photons to induced PA wave, it will scatter less photons. Interestingly, different tissues will fall on different locations on the ellipse with specific phases ($\theta_1, \theta_2, \theta_3$), and the phase contrast could be derived as:

$$\frac{\tan(\theta + \Delta\theta)}{\tan(\theta)} = \frac{\left(\frac{p_{acoustic} + \Delta p_{acoustic}}{p_{scat} - \Delta p_{scat}}\right)}{\left(\frac{p_{acoustic}}{p_{scat}}\right)} = \frac{\left(1 + \frac{\Delta p_{acoustic}}{p_{scat}}\right)}{\left(1 - \frac{\Delta p_{scat}}{p_{scat}}\right)} \approx \left(1 + \frac{\Delta p_{acoustic}}{p_{acoustic}}\right) \left(1 + \frac{\Delta p_{scat}}{p_{scat}}\right). \quad (4)$$

From Eq. (4) we can see that the PA phasoscopy contrast could be significantly enhanced by multiplying the PA contrast $(1 + \Delta p_{acoustic}/p_{acoustic})$ and scattered optical contrast $(1 + \Delta p_{scat}/p_{scat})$, which is a nonlinear contrast amplification. Based on the PA phasoscopy concept, here we propose a novel imaging approach, termed PA phasoscopy (PAPS) imaging, which could be achieved by receiving both laser-induced PA wave and scattered photons simultaneously under the same laser illumination, and calculating the phase indicator $\tan\theta = p_{acoustic}/p_{scat}$ point by point to form a PA phasoscopy image. Then the intensity at each point fuses both optical absorption and scattering properties, and is expected to give enhanced image contrast than conventional photoacoustic imaging based on optical absorption only. Next we will experimentally demonstrate the super-contrast PAPS imaging on both phantom and *ex vivo* tissues.

Figure 1. (a) Diagram of optical scattering and absorption based on energy conservation. (b) PA phasoscopy for three different tissues.

2.2 Experimental setup

The experimental setup is shown in Figure. 2. A Q-switched pulse laser (FDSS 532-1000, CryLaS, GmbH) with 1 mJ pulse energy, 1.8 ns pulse width and 532 nm wavelength is used to provide the collimated light source, which is attenuated by a neutral density filter (NDC-50C-2M, Thorlabs) and focused into a multi-mode fibre (MHP550L02, Thorlabs) coupler by a condenser lens (LB1471, Thorlabs). The output of the fibre is focused by a pair of lens onto the vessel-mimicking phantom, which is made of a silicone tube (3 mm diameter) filled with blue ink and pumped by a syringe. The phantom is immersed in water for optimum light transparency and acoustic coupling. A focused ultrasound transducer (V303-SU, Olympus) with 1 MHz central frequency is used to detect the PA signal, followed by 54 dB gain preamplifier (5662, Olympus). At the same time, the scattered photons are collected by a photodiode (DET10A, Thorlabs). Both the PA signal and scattered photon signal are averaged 100 times, recorded by a digital oscilloscope (WaveRunner 640Zi, LeCroy) with 5 GHz sampling rate and sent to a PC for post-processing. To acquire an image, the water tank is moved linearly by the XY translation stage (XYR1, Thorlabs) for raster scanning.

Figure 2. Experimental setup of the proposed PAPS imaging. ND: neutral density; ConL: condenser lens; FC: fibre coupler; MMF: multi-mode fibre; PD: photodiode; US: ultrasound transducer.

3. RESULTS

3.1 Vessel-mimicking phantom

To get the cross-sectional image of the vessel-mimicking phantom, the translation stage is scanned 10 mm in X-axis with 0.5 mm step size. The received PA signals $p_{acoustic}$ are subjected to the low-pass filtering and Hilbert transformation for the envelope extraction, which are then mapped to form the PA image shown in Figure 3(a). On the other hand, the phasoscopy signals are obtained by extracting the phase $\tan \theta = p_{acoustic} / p_{scat}$ and are mapped to form the phasoscopy image, as shown in Figure 3(b). To fairly compare the imaging contrast, the intensities of both images are normalized to the same scale, which is clearly shown in Figure 3(c). As expected, the intensities of PA signal and scattered photon signal are changing on the opposite way based on energy conservation principles, i.e. when more light is absorbed, less light is scattered, and vice versa. The imaging results clearly show that the phasoscopy contrast $\tan \theta = 212:1$ (red solid line) fusing optical absorption and scattering contrasts, is more than 9 times larger than the optical absorption contrast (blue dashed line), i.e. the PA imaging contrast. The imaging results prove the feasibility of PAPS imaging to achieve super-contrast performance than conventional PA imaging based on optical absorption only.

Figure 3. (a) Conventional PA imaging result and (b) super-contrast PAPS imaging result of a vessel-mimicking phantom's cross-section. (c) The intensity along the dashed and solid lines in (a) and (b) to show the contrast comparison.

3.2 Ex vivo porcine tissues

To further validate the phasoscopy imaging approach, *ex vivo* porcine tissues are prepared with different optical absorption and scattering properties at fat and muscle parts. As shown in Figure 4(a), the tissue sample is scanned 6 mm across the solid line covering three different parts denoted as 1, 2, 3. After low-pass filtering, envelop extraction and contrast scale normalization, the conventional PA imaging and proposed PA phasoscopy imaging results are shown in Figure 4(b)-(c). It is clearly shown that the image contrast between fat and muscles parts reconstructed by the PAPS imaging in Fig. 4(c) is much better than the PA imaging in Figure 4(b). The image contrast comparison is shown in Figure 4(d), where the intensities along the dashed and dotted lines in Figure 4(b) and (c) are plotted. It shows that the contrast of the PAPS imaging (red solid line) is more than two times larger than the contrast of conventional PA imaging based on optical absorption only (blue dashed line).

Figure 4. (a) Photograph of the *ex vivo* porcine tissues with three different fat and muscle parts. (b) The conventional PA imaging, and (c) proposed PAPS imaging results with same contrast scale. (d) The intensity across the dashed and solid lines in (b) and (c) to show the image contrast comparison.

4. SUMMARY

Existing dual-modal PA imaging approaches include PA plus ultrasound [7-10], PA plus OCT [11-14], PA plus DOT [15,16], and so on. All the above approaches are separately processing the PA signals and ultrasound/photon signals to reconstruct two individual and complementary images, where the intrinsic correlation between them has not been fully explored. The key difference between the proposed PAPS imaging and existing approaches is: PAPS imaging correlates the detected PA signal and scattered phonons to deliver ONE image fusing both optical absorption and scattering properties of the same object based on energy conservation principle and phasoscopy concept, rather than two separate images in conventional dual-modal PA imaging approaches. Moreover, compared with the conventional PA imaging suffering the laser intensity fluctuation, the proposed PAPS imaging is inherently immune to the laser and system variations due to the reason that: when input laser intensity fluctuates, both the PA signal $p_{acoustic}$ and scattered photons p_{scat} fluctuate in the same way, leading to the constant phase:

$$\theta = \arctan(p_{acoustic} / p_{scat}).$$

In conclusion, the concept of PA phasoscopy is briefly introduced and PA phasoscopy super-contrast imaging is proposed and experimentally demonstrated in this paper. It correlates both optical absorption and scattering based on energy conservation to achieve super-contrast performance, rather than conventional PA imaging based on optical absorption only or optical imaging based on scattered photons only. *In vivo* 3D phasoscopy imaging will be studied for both small animal and clinical applications in the future

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