Methods in eye research

Photoacoustic tomography imaging and estimation of oxygen saturation of hemoglobin in ocular tissue of rabbits

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This study evaluated in vivo imaging capabilities and safety of qualitative monitoring of oxygen saturation of hemoglobin ($sO_2$) of rabbit ciliary body tissues obtained with acoustic resolution (AR) photoacoustic tomography (PAT). AR PAT was used to collect trans-scleral images from ciliary body vasculature of seven New Zealand White rabbits. The PAT $sO_2$ measurements were obtained under the following conditions: when systemic $sO_2$ as measured by pulse oximetry was between 100% and 99% (level 1); systemic $sO_2$ as measured by pulse oximetry was between 98% and 90% (level 2); and systemic $sO_2$ as measured by pulse oximetry was less than 90% (level 3). Following imaging, histological analysis of ocular tissue was conducted to evaluate for possible structural damage caused by the AR PAT imaging. AR PAT was able to resolve anatomical structures of the anterior segment of the eye, viewed through the cornea or anterior sclera. Histological studies revealed no ocular damage. On average, $sO_2$ values (%) obtained with AR PAT were lower than $sO_2$ values obtained with pulse oximetry (all $p < 0.001$): 86.28 ± 4.16 versus 99.25 ± 0.28, 84.09 ± 1.81 vs. 95.3 ± 2.6, and 64.49 ± 7.27 vs. 71.15 ± 10.21 for levels 1, 2 and 3 respectively. AR PAT imaging modality is capable of qualitative monitoring for deep tissue $sO_2$ in rabbits. Further studies are needed to validate and modify the AR PAT modality specifically for use in human eyes. Having a safe, non-invasive method of in vivo imaging of $sO_2$ in the anterior segment is important to studies evaluating the role of oxidative damage, hypoxia and ischemia in pathogenesis of ocular diseases.

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1. Introduction

Numerous studies have identified oxidative damage as an important event in the pathogenesis of ocular diseases such as macular degeneration (Kinnunen et al., 2012), cataract (Varma et al., 2011), and glaucoma (Abu-Amero et al., 2006; Alvarado et al., 1981; Chang, 2006; Chen and Kadlubar, 2003; Ferreira et al., 2004; Gabelt and Kaufman, 2005; Holekamp et al., 2005; Izzotti et al., 2003; Izzotti et al., 2006; Izzotti et al., 2009; Kong et al., 2009; Liton et al., 2009; Sacca et al., 2005, 2007; Sacca and Izzotti, 2008; Shui et al., 2006; Siegfried et al., 2010; Tomarev, 2001; Wang et al., 2001; Zhou and Yue, 1999). Two important hemodynamic parameters of oxygen metabolism include oxygen partial pressure ($pO_2$) and oxygen saturation of hemoglobin ($sO_2$). $pO_2$ represents the amount of free oxygen concentration available to cells. $sO_2$ represents the amount of oxygen carried by hemoglobin. The relationship between $pO_2$ and $sO_2$, referred as the
hemoglobin oxygen dissociation curve, describes how blood carries and releases oxygen for tissue metabolism under physiological and pathological conditions (Wang, 2008). We demonstrated that redistribution of oxygen in the anterior segment following vitrectomy and cataract surgery leads to increased \( pO_2 \) in the posterior chamber (PC) and anterior chamber (AC) angle, which is potentially damaging to the trabecular meshwork cells. Hence, measuring \( pO_2 \) in the PC and AC angle may identify eyes at risk for development of glaucoma (Holekamp et al., 2005; Shui et al., 2006; Siegfried et al., 2010).

Since \( sO_2 \) and \( pO_2 \) are related, it is reasonable to postulate that \( sO_2 \) similar to \( pO_2 \) may play an important role in early diagnosis of glaucoma. A novel powerful optical imaging modality called photoacoustic tomography (PAT) is capable of non-invasive in vivo imaging of intra-vascular total hemoglobin concentration (HbT) and \( sO_2 \) (de la Zerda et al., 2010; Hoelen et al., 1998; Hu et al., 2010; Jiao et al., 2009, 2010; Jiang et al., 2010; Kong et al., 2009a, 2009b; Maslov et al., 2008; Yao et al., 2010; Rosenwaig, 1982; Silverman et al., 2010; Song et al., 2013; Wang et al., 2003, 2006; Wang and Wu, 2007; Wang, 2008; Wang et al., 2011; Xie et al., 2009; Xing et al., 2013; Yao and Wang, 2011; Zhang et al., 2006, 2007, 2010, 2010).

In addition to measuring \( sO_2 \), PAT can also provide structural imaging at a higher resolution than coherence tomography (OCT) and deeper penetration than ultrasound (US). Because OCT relies on ballistic photon detection, the penetration depth is limited to \( \sim 1 \) mm in biological tissue due to high optical scattering. On the contrary, US has very small scattering in the soft tissue, and thus it has deeper tissue penetration but lower resolution than OCT (Kong et al., 2009a; Yao and Wang, 2011). PAT overcomes limitations of OCT and US. Thus, deep embedded structures (such as ocular tissue in the rabbit eye) can be successfully detected by PAT.

PAT obtains in vivo cross-sectional three-dimensional high-resolution structural, functional, and molecular images by utilizing the photoacoustic effect discovered by Alexander G. Bell in 1880 (Yao and Wang, 2011). When tissue is irradiated by a laser beam, locally absorbed light is converted into heat. The heat causes thermoelastic expansion of the tissue and rise in pressure. The pressure rise propagates in the tissue as an ultrasonic wave, also known as a photoacoustic wave. The photoacoustic wave is detected by ultrasonic transducers that convert it into electrical signals. The electric signals are amplified, digitalized, and analyzed by a computer to form images (Wang, 2008). Because the amplitude of the photoacoustic wave is proportional to the energy absorbed by the object, multiple optical wavelengths can be used in PAT to provide spectral information of optical absorption. In addition, because oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (Hb) have different absorption spectrum, \( sO_2 \) can be estimated by solving the following equations:

\[
\begin{align*}
\mu_s(\lambda_1) &= 2.303 \times (e_{ox}(\lambda_1)C_{ox} + e_{de}(\lambda_1)C_{de}) \\
\mu_s(\lambda_2) &= 2.303 \times (e_{ox}(\lambda_2)C_{ox} + e_{de}(\lambda_2)C_{de})
\end{align*}
\]

where \( \mu_s(\lambda_1) \) and \( \mu_s(\lambda_2) \) are absorption coefficients of the blood at two wavelengths; \( e \) and \( C \) are the molar extinction coefficients and concentrations, respectively; \( ox \) and \( de \) refer to oxy- and deoxygenated hemoglobin.
deoxyhemoglobin, respectively. The oxygen saturation of hemoglobin can be obtained as following:

$$sO_2 = \frac{C_{ox}}{C_{ox} + C_{de}} \times 100$$

In each imaging procedure, two wavelengths, 578 nm or 563 nm, were chosen to differentiate Hb and HbO2. Although wavelength dependent scattering could cause errors in calculating the sO2 values, wavelengths we used were very close. Therefore the difference in path length was negligible. Thus, there was no need for a calibration factor (Zhang et al., 2006). Wavelengths were switched between b-scans (cross-sectional image) and the acquisition rate of each b-scan was 2 Hz. The system spatial resolutions, determined by the ultrasonic transducer, were about 70 μm in the lateral direction and 54 μm in the axial direction, both smaller than the dimension of ciliary body. To ensure that we detected signal solely from the ciliary body we only chose only that area for analysis. Since we selected AR PAT to work at greater depth, this lead to loss of resolution of the individual vessels. Therefore, instead of measuring sO2 from a single blood capillary, we calculated an average value from all blood vessels in the measured area based on the PAT detection.

3. Results

We were able to successfully resolve the anatomy of the anterior segment of the rabbit eye including iris, ciliary body, and anterior choroid (Fig. 2). Histological evaluation using light microscopy and hematoxylin and eosin stains demonstrated no laser damage to the ocular tissue up to one week following AR PAT imaging (Fig. 1). In the non-survival experiments, on average, sO2 values obtained with AR PAT were lower than sO2 values (%) obtained with pulse oximetry (all p < 0.001): 86.28 ± 4.16 versus 99.25 ± 0.28, 84.09 ± 1.81 vs. 95.3 ± 2.6, and 64.49 ± 7.27 vs. 71.15 ± 10.21 in the settings of: oxygen percentage in breathing gas between 99% and 100% (level 1); oxygen percentage in breathing gas between 90% and 98% (level 2); and oxygen percentage in breathing gas less than 90% (level 3) respectively (Fig. 4).

4. Discussion

The current study demonstrated that AR PAT imaging can successfully, non-invasively, and safely resolve the anatomy of the anterior segment of the eye. The laser energy was carefully controlled and focused towards the sclera in order to avoid direct exposure of the lens and retina. Further protection such as application of a contact lens covering the iris is possible.

We also demonstrated that AR PAT can qualitatively monitor the sO2 change in blood vessels of the ciliary body. We found that sO2 qualitative monitoring obtained with AR PAT yielded values that were significantly lower than sO2 measurements obtained with pulse oximetry. These results would be expected since systemic pulse oximetry only measures arterial sO2 whereas AR PAT calculates an average value from both arterial vessels (that have high oxyhemoglobin concentration hence high sO2) and venous vessels, which contain both oxyhemoglobin and deoxyhemoglobin resulting in lower overall sO2. Further, due to imaging of deep tissue AR PAT couldn’t resolve individual vessels. Instead it qualitatively monitored an averaged sO2 of the entire vascular bed. A reliable qualitative monitoring with ranges that correlate with hyperoxia, normoxia and hypoxia would be especially valuable for early detection and monitoring of the conditions that affect tissue saturation. Our study showed that AR PAT is a promising method for qualitative monitoring of the deep tissue, which also might be useful for monitoring oxidative damage studies in eyes.

Our technique should work similarly in pigmented animals or humans. Because our AR PAT system has high spatial resolutions, the pigment would not interfere with the sO2 imaging of deeply embedded ocular vasculatures. However, we would have to consider changing the imaging wavelengths to avoid strong attenuation due to the pigments. For an example, for a melanin-rich sample, a longer wavelength would be used, because melanin has smaller absorption at longer wavelength.

Previously we performed PAT imaging of rat brains in vivo under normoxic, hyperoxic, and hypoxic conditions. We successfully demonstrated simultaneous assessment of the blood volume, HbT, and sO2 of the cerebral vasculature (Wang et al., 2006). We recently developed a dual-modality microscope integrating PAT and fluorescence confocal microscopy (FCM) that can simultaneously image sO2 and pO2 in vivo in a single blood vessel (Wang et al., 2011). Other investigators demonstrated the ability of PAT to successfully image blood distribution in live rats and rabbits (de al Zerda et al., 2010; Jiang et al., 2010; Xie et al., 2009; Zhang et al., 2010a). We previously demonstrated the feasibility of PAT imaging of microvasculature of the ear, brain, and skin (Maslov et al., 2008; Rao et al., 2010a).
PAT is also capable of evaluating the metabolic rate of oxygen (MRO2). Although other modalities can also evaluate MRO2, they have limitations. Magnetic resonance imaging only detects temporal changes in hemoglobin concentration. Positron emission tomography requires exogenous radioactive tracers to image MRO2 (Yee et al., 2006). Diffuse optical tomography has low spatial resolution (Culver et al., 2003). In contrast, PAT has a potential to become a single modality to image in vivo MRO2, blood vessels and other structures of interest, and estimate blood flow without exogenous contrast (Wang, 2008). Currently, MRO2 measurements can’t be obtained in the AR PAT system because of its limited detection of flow rate. However a new cross-correlation based method which measures blood-flow velocity by using photoacoustic microscopy may achieve in vivo deep flow monitoring by increasing the detection time and thus providing a potential solution for MRO2 measurement (Liang et al., 2013; Zhou et al., 2013).

The eye has an abundance of endogenous contrasts such as hemoglobin, melanin, and vascular tissue. All can be readily quantified and imaged by the PAT technique (de la Zerda et al., 2010; Hu et al., 2010; Jiao et al., 2010; Jiang et al., 2010; Rao et al., 2010; Silverman et al., 2010; Song et al., 2013; Xie et al., 2009; Zhang et al., 2010a, 2010b). PAT imaging of ex vivo sectioned pig eyes demonstrates that using focused laser beam short pulse irradiation with a ring ultrasonic transducer provides sharper ocular images than an unfocused laser (Kong et al., 2009a). Laser with
1064 nm near infra-red wavelength provides better penetration but lower sensitivity than laser with 532 nm green wavelength, which provides shaper images of cornea, lens surface, iris, ciliary body, and zonules (Silverman et al., 2010). We previously demonstrated the capability of PAT to image the microvasculature of the iris (Hu et al., 2010; Rao et al., 2010). Other investigators evaluated OCT guided PAT (Jiao et al., 2010; Song et al., 2013) and laser-scanning optical-resolution PAT for retinal vasculature imaging and adaptive optics PAT to image single retinal pigment epithelium cells (Jiang et al., 2010; Xie et al., 2009). In the current study, we successfully imaged and resolved $\text{sO}_2$ in the ciliary body of the rabbit eye with AR PAT.

Our pilot study has limitations. Due to strong scleral scattering, we used AR PAT (Zhang et al., 2006) in the experiment. The lateral resolution of AR PAT is 80 microns, which is larger than the diameter of microvasculature, so it is not possible to resolve individual blood vessels with a diameter less than 80 microns. However, the system can integrate the optical-resolution capability to get deep vessel images of the ciliary body (Xing et al., 2013). Because the laser only has an 1 kHz repetition rate, there were strong motion artifacts, which reduced current measurement accuracy. In the future, a video-rate AR PAT system can be employed to increase the monitoring speed and thus decrease motion artifacts (Wang et al., 2012). And last but not least our study did not demonstrate the accuracy of AR PAT’s $\text{sO}_2$ values. Future studies involving tissue phantoms would help to determine the accuracy of $\text{sO}_2$ values obtained with AR PAT.

Despite these limitations, our pilot study found that the AR PAT imaging modality is capable of obtaining non-invasively in vivo $\text{sO}_2$ qualitative monitoring correlated with pulse oximetry under various oxygen blood levels in rabbits. Further studies are needed to validate and modify the PAT modality specifically for ophthalmic use. Safe, non-invasive in vivo PAT imaging of the anterior segment and, potentially, the posterior segment of the eye, would be useful for evaluating the role of oxidative damage, hypoxia and ischemia in pathogenesis of various ocular diseases such as glaucoma, diabetic retinopathy, age-related macular degeneration and cataract.

**Dedication**

We dedicate this manuscript to David Beebe, PhD, who’s recent passing from ALS deeply shocked and saddened all of us. David Beebe was an energetic, passionate, and insightful scientist and a wonderful mentor for many of us. He was someone who never wasted a moment of his life. He was a sterling example of how compassion, motivation, and kindness can change the world. But most of all he was such a great person. People like David change the world because everyone tries to do a little more and do a little better because of his example. He will be greatly missed.

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**Conflicts of interest**

Stella N. Hennen: none; Wenxin Xing: none; Ying-Bo Shui: none; Yong Zhou: none; Kalishman Jennifer: none; Andrews-Kaminsky, Lisa: none; Michael Kass: none; Beebe, David: none; Maslov, Konstantin: Microphotoacoustics, Inc., which, however, did not support this work; Wang, Lihong: Microphotoacoustics, Inc. and Endra, Inc., which, however, did not support this work.

**References**


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**Fig. 4.** Oxygen saturation ($\text{sO}_2$) qualitative monitoring of rabbit ciliary body vasculature obtained by photoacoustic tomography (PAT) under the following conditions: systemic $\text{sO}_2$ as measured by pulse oximetry between 100% and 99% (level 1); systemic $\text{sO}_2$ as measured by pulse oximetry between 98% and 90% (level 2); and systemic $\text{sO}_2$ as measured by pulse oximetry less than 90% (level 3). Red dashed line: systemic $\text{sO}_2$ as measured by pulse oximeter. Blue solid line: $\text{sO}_2$ qualitative monitoring by PAT. (a) Time trace of $\text{sO}_2$ qualitative monitoring, (b) $\text{sO}_2$ mean value and corresponding standard deviations of $\text{sO}_2$ in those conditions. Systemic pulse oximetry values are plotted on axis Y.