Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Oximetry considerations in the small source detector separation limit

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Abstract— **Oximetry is a common blood monitoring technique, useful for the assessment of blood flow and blood oxygen saturation information. Commercial oximeters generally utilize an optical transmission measurement scenario which necessitates the use of wavelengths residing in the optical absorption window (650-1100 nm) which are capable of traveling long distances before absorption. When the source and detector fibers are brought close together (≤ 1 mm) such wavelengths undergo too few scattering events for meaningful data abstraction. Small source-detector separation scenarios are becoming more common as tissue spectroscopy is conducted using catheter and small surface probes. This paper will demonstrate the insufficiencies of present oximetry techniques and the need to use visible wavelengths when conducting oximetry at small source-detector separations. It will begin with a theoretical derivation of the problems with NIR wavelengths in the small source detector separation limit. The theory will be compared to Monte Carlo derived data and *in vivo* data collected with a surface probe with ≤ 1 mm of separation between the source and detector fibers. The study demonstrates that visible wavelengths are more than two orders of magnitude more sensitive to changes in hemoglobin saturation when small source detector fiber separations are used for oximetry measurements.**

I. Introduction

Optical spectroscopy is a promising, noninvasive medical tool. Using various wavelength ranges and optical setups, nonionizing radiation has been used for high resolution superficial and retinal imaging [1], low resolution deep tissue imaging [2], and measurements of tissue composition, including blood oxygen saturation [2]. One of the common uses of optical spectroscopy in the medical field is oximetry.

There are several issues associated with oximetric techniques. With precise calibration, oximetry can be used to measure absolute hemoglobin saturations. These measurements are highly suspect, however, if the optical probe is repositioned and the geometry of the tissue-probe system is altered, even slightly. Such sensitivities make oximetry prohibitive for precise, repeatable experimental measurements of oxy/deoxy-hemoglobin concentrations. Also, it is generally insensitive to small blood oxygenation changes. The ratio of intensities at two or more wavelengths can be affected easily by changes in blood volume and changes in the scattering properties of the tissue sample. While scattering properties rarely change, blood volumes are constantly changing as vessels dilate and constrict to control the flow of oxygen to tissue.

Even though there are several issues of precision and consistency, oximetry is still a good tool for quick and qualitative measurements of blood oxygenation. When great effort is extended to stabilize the probe-tissue contact, oximetry can provide a stable and quick reflection of local tissue oxygenation dynamics. This has been shown using a multiple regression model relying upon a third order diffusion equation to return the absolute oxy and deoxy hemoglobin concentrations [3]. The regression method required hours to compute the hemoglobin concentrations and scattering coefficients while the oximetry measurements are nearly instantaneous.

Oximetry devices generally rely upon NIR and deep red wavelengths for blood oxygen measurements. Use of such wavelengths is ideal when the source fiber(s) and detector fiber(s) are separated by distances larger than 1 mm. Wavelengths in this range are said to reside in the tissue optical window because photons in this wavelength range can travel large distances before absorption. In other words, their Mean Free Path (mfp′ ≡ $(\mu_a + \mu_s')^{-1}$ is very long, sometimes on the order of several centimeters, depending on the exact scattering and absorption properties of the specific tissue sample.

The long mfp′ is ideal for large source detector separations because large amounts of light can propagate through the tissue and arrive at the detector, carrying information regarding the absorption and scattering properties of the tissue along the photons' paths. When an optical probe has small source detector fiber separations, such as catheter tissue probes, the long mfp′ is not preferable. Photons in the optical window undergo too few scattering events before collection for sensitive and precise measurements of the hemoglobin saturation [4].

When probes with less than 1 mm source detector separations are used, photons with wavelengths in the visible range have greater numbers of scattering events before collection than NIR photons and carry more information regarding the tissue absorption and scattering properties. They have a mfp′ on the order of the source detector separation and are affected greatly over short distances by small (~ 20%) changes in tissue hemoglobin saturation.

II. Methods and Materials

A. Diffusion Approximation of Diffuse Reflectance

Diffuse optical techniques are governed fundamentally by the Beer-Lambert relationship:

Manuscript received April 24, 2006. This work was supported in part by the U.S. National Institutes of Health, National Cancer Institute Grant No. CA107860.

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$$I = I_0 e^{\mu_a \langle \rho \rangle} \quad (1)$$

with ρ being the source detector separation and μ_a being the absorption coefficient along the average path of the photon. The radiative transfer equation details more specifically the average behavior of photons in scattering objects or tissue. This equation can be solved using the diffusion approximation which is applicable for source detector separations greater than 1 mm and for wavelengths in the NIR where the scattering coefficient is much greater than the absorption coefficient. Other works have demonstrated that a third order solution (P_3) to the radiative transfer equation satisfies these limitations of the diffusion approximation [5].

For various source-detector separations, the reflectance can be derived from the radiative transfer equation in the limit of the diffusion approximation to be:

$$R(\rho) = \frac{z_0 A_d}{2\pi}\left[\frac{\alpha}{\rho^2 + z_0^2} + \frac{1}{\left(\rho^2 + z_0^2\right)^{3/2}}\right] \times e^{\left[-\alpha\left(\rho^2 + z_0^2\right)^{1/2}\right]} \quad (2)$$

Where $\alpha = [3\mu_a(\mu_{st} + \mu_a)]^{1/2}$ and $z_0 = K/\mu_{st}$. μ_{st} and μ_a are the reduced scattering and absorption coefficients, respectively, and K is a dimensionless constant dependent on the anisotropy constant and the surface reflection coefficient [6].

B. Monte Carlo Simulations

To demonstrate the properties of diffuse optical spectroscopy, a simple multi-layer Monte Carlo algorithm was employed [7]. Absorption coefficients [8] and scattering coefficients [9] were assumed for a tissue sample with various hemoglobin oxygen saturations (10%-90%) and an average hemoglobin tissue concentration of 10%, as measured in murine muscle samples in Ref. 3. All simulations were conducted for ten million photons and surface reflectance data were collected for eight continuous centimeters with 0.02 cm bins.

C. In Vivo data collection

We have previously described the experimental apparatus for collecting and analyzing *in vivo* diffuse reflectance light [3]. Briefly, a broadband light source was delivered to the surface of the murine hind leg using a six plus one fiber probe. The six fibers surrounding the central fiber were the source fibers. The source detector separation was uniformly 1 mm. The center fiber was connected to a 2048 channel room temperature CCD spectrometer. The data were collected for 500 ms intervals and compared to spectra collected from a standard diffuse reflectance source for calibration. The oximetry measurements were conducted with both visible and NIR wavelength couplets. The spectra additionally were analyzed with a P_3 regression analysis similar to that in Ref. 5 for the purpose of more accurately measuring changes of the hemoglobin oxygen saturation.

To generate a change in the hemoglobin oxygen saturation, a standing wave acoustic field was focused and pulsed in the murine hind leg muscle [3]. The stationary ultrasound wave was discovered to create a large temporary drop in the hemoglobin oxygen saturation which often rebounded soon (seconds) after the ultrasound ended. Pulses were temporally separated in order that the blood flow would be restored.

III. Results

In the limit of small (≤ 1 mm) source detector separations, NIR photons undergo too few scatting events to reliably demonstrate a change in response to a change in the hemoglobin oxygen saturation. Figs. 1 and 2 detail how wavelengths in the visible range (540 and 560 nm) are affected by changes in the hemoglobin saturation even at small source detector separations while wavelengths in the NIR require much larger source detector separations before a noticeable change is recorded.

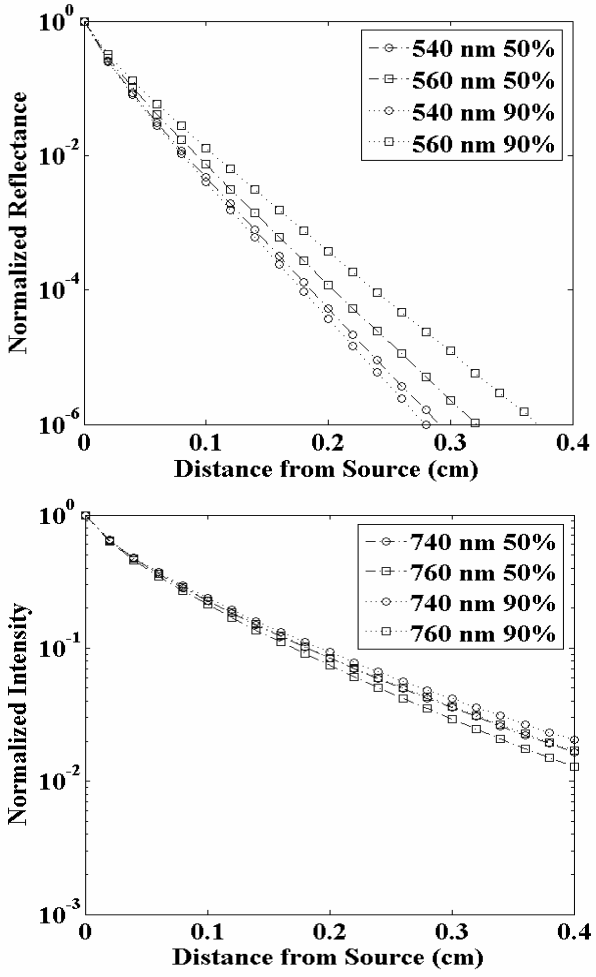

Fig. 1: Monte Carlo simulations of the diffuse reflectance as a function of source detector separation for wavelengths in the visible and NIR. Notice the more rapid separation of reflectance signals in the visible range.

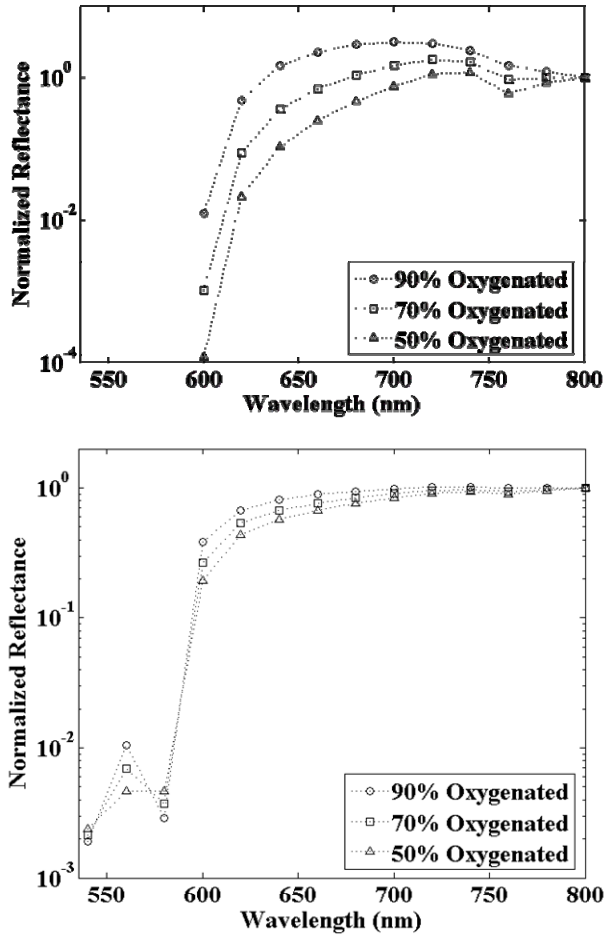

Fig 2: Monte Carlo simulations of broadband diffuse reflectance at source detector separations of 1 cm (top) and 1 mm (bottom). Notice that at 1 cm, the visible light is nearly absorbed and NIR carries the most information but at 1 mm, the NIR light is absorbed very little while the visible light is sensitive to small changes in the hemoglobin oxygen saturation.

The results of the *in vivo* experiments demonstrated that NIR photons carry very little information when collected at small distances. The oximetry measurements demonstrated this point even very strongly (Fig. 3). The effects of the ultrasound pulses were evident when the oximetry measurements were taken and the change of hemoglobin oxygen saturation was verified using the P_3 regression analysis.

IV. Conclusion

In the limit of small source detector separations, tissue properties such as hemoglobin oxygen saturation can be measured with greater sensitivity with visible wavelengths. NIR wavelengths have been shown to carry very little information when the source detector separations are small, such as in catheter probes and small surface probes, due to the long mfp′ of NIR photons.

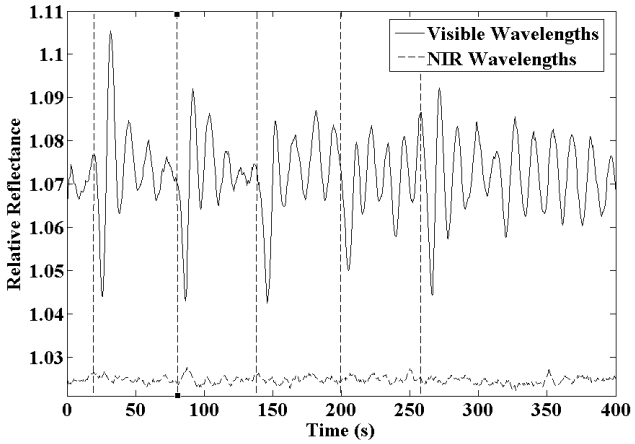

Fig. 3: Oximetry measurements at small source detector separations for wavelengths in the visible and NIR wavelengths. The visible wavelengths provided a very strong signal sensitive to changes in the hemoglobin oxygen saturation when NIR wavelengths were insensitive to these same changes. The vertical lines denote the times of ultrasound pulses.

Acknowledgment

B.A. Winey thanks J. Wilson, Prof. A. Berger, and Prof. T. H. Foster for their insight regarding photon migration, Prof. W. O'Dell for use of his computing facilities and V. Misic for his assistance with computer programming questions.

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