Tissue optics applied to reflectance pulse oximetry.

Graaff, Reindert

Publication date:
1993

Link to publication in University of Groningen/UMCG research database

Summary

This work is part of a research program with the aim of developing a reflectance pulse oximeter that can be used to monitor the fetal oxygen saturation during labour. Reflectance pulse oximetry is a non-invasive optical method to determine the oxygen saturation of arterial blood. For that purpose it makes use of the differences between the absorption spectra of oxygenated and de-oxygenated hemoglobin.

Pulse oximetry differs from oximetry by taking advantage of the pulse-wave induced fluctuations of the fraction of arterial blood in the tissue. When light has propagated through the tissue, fluctuations in the detected photon flux can be found which are approximately proportional to these pulse-wave induced blood volume fluctuations. Moreover, the normalized size of the these fluctuations depends on the absorption coefficient of the arterial blood at the applied wavelength, which provides the essential information used in pulse oximetry. The influence of the size of the blood volume fluctuations is eliminated by determination of the ratio of normalized pulse sizes at two wavelengths. In the simplified Lambert-Beer model for pulse oximetry, the ratio between the normalized sizes of these fluctuations at two different wavelengths equals the ratio of the absorption coefficients of arterial blood for these wavelengths, which is a function of the oxygen saturation.

Pulse oximeters measure the ratio of the normalized pulse sizes for red and infrared light, denoted as R/IR, and display an oxygen saturation which is derived from this ratio by using a calibration curve. Within a decade, pulse oximeters have become widely available for measurements through tissue, for example fingers and earlobes. In these transmission pulse oximeters the light sources are located at one side of the tissue, e.g., the finger, while the detector is located at the opposite side of the tissue.

Application of transmission pulse oximetry is not always possible. This method cannot be used for monitoring the arterial oxygen saturation of the fetus during labour. In infants and adults with a low peripheral perfusion transmission pulse oximetry cannot be used at the extremities as well. In such cases a reflectance approach for pulse oximetry opens perspectives, since more locations for sensor attachment become available. Therefore, we developed a measuring system for reflectance pulse oximetry with the light sources and detector(s) adjacent to each other in a single probe housing. Moreover, with this system it is possible to perform measurements at different distances from the light sources simultaneously.

Chapter 1 gives a brief description of the history of *in vivo* oximetry. Furthermore, the basic principles are given which have been used to develop oximeters, including transmission pulse oximeters. Application of these principles to reflectance pulse oximetry has shown that several discrepancies between the simplified theory and practice occur. It is concluded that light scattering within tissue influences pulse oximetry, in particular reflectance pulse oximetry. The analysis of this influence is the main theme of this thesis.

The studies in **Chapter 2** deal with the physics of light propagation in turbid media. These studies have been performed to determine the attenuation coefficients α, including the deviations of α in the diffusion approximation, and to find similarity rules between the unknown values of the optical properties involved, which often vary between subjects and measurement sites. These similarity rules have shown to be helpful in decreasing the number of variables.

In **Chapter 2.1** light propagation in the unbounded medium has been studied, using isotropic scatterers and anisotropic Rayleigh-Gans scatterers with values for the average cosine of the scattering angle, g, between 0 and 0.9995. Rigorous solutions of the Boltzmann transport equation for the diffusion pattern and the attenuation coefficient α have been obtained for the whole range of absorption. The results have been expressed in absorption and backscattering probabilities, K and S, respectively, similarly to those in Kubelka-Munk theory. The results have been used to quantify the deviations in the attenuation coefficient that are introduced when diffusion theory is used; these deviations increase for increasing absorption. For use in whole blood the deviations of diffusion theory are $< 15\%$ as long as $\lambda > 660$ nm, but for smaller wavelengths the maximum deviations of α in the diffusion approximation rapidly increase.

In **Chapter 2.2** the validity of the similarity parameter $\Sigma_s' \equiv \Sigma_s (1 - g)$, the reduced scattering coefficient, is investigated. Σ_s is the scattering coefficient. Similarity exists when the same distribution of light is obtained in two turbid media, whereas the scattering properties in each medium are different. The attenuation coefficients and diffusion patterns for isotropic scattering and for Rayleigh-Gans scattering, as derived in Chapter 2.1, were used. Similarity has been studied for α, as well as for K and S in the positive and negative directions, and for predictions of the internal reflection at interfaces. Similarity between solutions of the Boltzmann equation for highly forward scattering and isotropic scattering exists only when the diffusion approximation is valid, which is true for relatively small absorption, $\Sigma_a \ll \Sigma_s(1 - g)$. However, similarity between results both with $g > 0.9$ is independent of the value of the absorption coefficient.

Therefore, it is advantageous to simulate highly forward scattering media like biological tissues with $g > 0.9$, e.g., by Monte Carlo simulations of light propagation, and to use similarity only within that range, instead of using isotropic scattering or diffusion theory. Monte Carlo simulations on slabs confirm the deviations from the diffusion approximation and show differences between the behaviour of isotropic scattering particles and highly forward scattering particles near boundaries.

It can be concluded for Rayleigh-Gans scatterers that the similarity parameter $\Sigma_s' = \Sigma_s (1 - g)$ of the medium is sufficient to describe light propagation without knowledge of the values of Σ_s and g separately as long as $g > 0.9$. Under those circumstances similarity can be applied over the whole range of absorption coefficients.

In **Chapter 2.3** the reduced scattering cross section σ_s' of spherical particles has been studied by using Mie theory as a function of the size parameter $x = 2\pi a/\lambda$, where a is the particle radius and λ is the wavelength in the surrounding medium of the particle, and the relative refractive index m. Results show that $\sigma_s' = 3.28 \, \pi a^2 \, x^{0.37} \, (m - 1)^{2.09}$ is true within a few percent when $1 < m < 1.1$ and $5 < x < 50$, respectively. From this relation it was concluded that the ratio of reduced scattering cross sections at different wavelengths for particles within this range is independent of x and m. This is even true for mixtures of differently sized spheres, provided that scattering at a single particle is not influenced by other particles, and that the particles are within the mentioned range. The results seem promising for biomedical applications, since red blood cells are within this range. Moreover, the scatterers in tissues like the human skin are, to a great extent, in this range as well.

In **Chapter 2.4** numerical solutions of the Boltzmann equation are given for Mie scattering patterns with $1 < m < 1.1$ and Henyey-Greenstein scattering, both with $g > 0.9$. The results show that the Mie results are very close to the Rayleigh-Gans results.

In **Chapter 3** a new method is described that can be used to rapidly determine the behaviour of light in tissue from available Monte Carlo simulation results. This technique was used to estimate the optical properties of the human skin from *in vitro* and *in vivo* measurements.

Chapter 3.1 presents a new method for the simulation of light propagation, the condensed Monte Carlo simulation. In this method the results of a single Monte Carlo simulation for a given albedo $c \equiv \Sigma_s/(\Sigma_a + \Sigma_s)$ can be used to obtain results for other albedos; Σ_s and Σ_a are the scattering and absorption coefficient,

respectively. The method requires only the storage of the number of interactions of each photon with the medium. The reflectance and transmittance of turbid slabs can thus be found from a limited number of condensed Monte Carlo simulations. We can use an inversion procedure to obtain the absorption and scattering coefficients from the total reflectance and total transmittance of slabs.

The photon fractions remitted from a semi-infinite medium per mm^2 as a function of the distance r between light source and detector can be found even from the results of a single condensed Monte Carlo simulation. Furthermore, condensed Monte Carlo simulations based on different values of g have shown that the similarity rule can be applied also to the semi-infinite medium, especially when the scatterers in the medium and in the simulation thereof are both within the range $g > 0.9$. This further reduces the number of Monte Carlo simulations that are needed to describe the influence of the distribution of scattering angles.

In **Chapter 3.2** the condensed Monte Carlo simulation technique was used for calculating absorption and reduced scattering coefficients from data in the literature on the measured total transmittance and total reflectance of samples of the human skin *in vitro*. The results of several measuring methods were compared. We also estimated the range for the values of absorption coefficients and reduced scattering coefficients at 660 nm and 940 nm by measuring intensities at several distances from the light sources at the skin surface *in vivo* by using condensed Monte Carlo simulations for a homogeneous semi-infinite medium. These *in vivo* values for the absorption coefficients and the reduced scattering coefficients appear to be much smaller than the values from the *in vitro* measurements, that have been assumed until now. Our *in vivo* measurements are in agreement with *in vivo* measurements that are available in the literature.

In **Chapter 4** the basic knowledge on tissue optics as given in chapter 2 and 3 is applied to reflectance pulse oximetry, assuming a semi-infinite medium with a homogeneous distribution of absorbers, scatterers, and pulsations. The results of measurements were compared with those of Monte Carlo simulations.

Chapter 4.1 starts with a recapitulation of the relevant items described in the preceding chapters. Furthermore, the tissue-optical phenomena that influence the measurements in reflectance pulse oximetry are described systematically for the purpose of making the subject accessible to those who are involved in pulse oximetry but less familiar with tissue optics. The phenomena are presented by using results from condensed Monte Carlo simulations. From the Monte Carlo results it is found that reflectance pulse oximetry does not only depend on the differences in absorption coefficient caused by the blood volume changes, but

also by changes in the reduced scattering coefficient, and by the pulse-independent parts of the absorption and reduced scattering coefficients. The theoretical concepts have been elaborated in Chapters 4.2-4.5.

In **Chapter 4.2** our measuring system is described, and some results of measurements with this pulse oximeter system are given, which were obtained on the volar side of the distal phalanx of the index finger. Our results show that the ratio R/IR, that is used in pulse oximetry to estimate the arterial oxygen saturation, is influenced by light propagation in tissue. Simultaneous measurements at several distances between light sources and detectors show that R/IR depends on this distance. In this study, the influence of the estimated tissue properties on R/IR and its distance dependence are investigated by means of condensed Monte Carlo simulations. A three wavelengths model (660, 900, and 940 nm) was been introduced, because of secundary emission of the red LED around 900 nm. The influence of light absorption by water has been taken into account as well. The simulation results depend on which optical properties are chosen. Results of R/IR for $S_aO_2 = 98\%$ with optical tissue properties derived from *in vivo* experiments agree much better with the measured values than the predictions based on *in vitro* tissue properties.

In **Chapter 4.3** a new concept of reflectance pulse oximetry is presented. Analysis of the experimental data of chapter 4.2 once more has shown that the variation in R/IR between subjects is related to the ratio of the average intensities at adjacent detectors. It confirms that R/IR is also determined by the non-pulsatile parts of the absorption and reduced scattering coefficients.

Condensed Monte Carlo simulations on semi-infinite media were used to estimate the optical properties for all individual measurements. The results demonstrate that the variation in R/IR is mainly caused by variation in the reduced scattering coefficients of the medium. By using the ratio of the average intensities at adjacent detectors for both wavelengths, as determined *in situ*, the absorption and reduced scattering coefficients can be estimated, which makes it possible to develop more accurate reflectance pulse oximeters.

Chapter 4.4 describes the deviations in R/IR that can be expected when the reduced scattering coefficients of blood differ from the assumed values, or when they vary during the heart-cycle. The reduced scattering coefficient of red blood cells has been approximated with the results of Mie-scattering for spheres. For red cell suspensions the contribution for each cell to the reduced scattering coefficient is smaller. Moreover, the reduced scattering coefficient depends on the degree of aggregation, deformation, and orientation of the erythrocytes. The influence of these effects on R/IR can be described with a single parameter χ, which is probably independent of the applied wavelength. Calibration curves for

several values of χ have been obtained. These calibration curves also give an explanation for the deviations that have been found when pulse oximetry is applied to horses, because of the increased tendency of their red blood cells to aggregate.

Chapter 4.5 describes several models for data processing for our measuring system with the aim to correct for the influence of the reduced scattering coefficients during the heart cycle. Based on the theoretical considerations in chapter 4.1 it is possible to determine the correction term for the reduced scattering coefficient of blood, as discussed in chapter 4.4. Such corrections may be important when measurements are performed in areas with vasoconstriction. We suggest to determine the correction term χ from simultaneous measurements obtained at different detectors. The results of the simulations show that the correction term can be obtained from the ratio of normalized pulse sizes at adjacent detectors, provided that the pulsatile fluctuations in the absorption and reduced scattering coefficients are distributed homogeneously over the medium. For the case with no pressure onto the probe this restriction seems to be fulfilled as shown by comparing experimental data from the volar side of the index finger with numerical results. However, with pressure onto the probe we obtained results for estimates of χ and R/IR which were inconsistent. This inconsistency can be understood by assuming that the distribution of pulse sizes is not homogeneous in the tissue under these circumstances.

Conclusions

From the studies in Chapter 2 it is concluded that Monte Carlo simulations are to be preferred to diffusion theory. The studies on similarity show that Σ_a and Σ_s' can be regarded as the variables that determine light propagation in highly forward scattering media with $g > 0.9$, even when the absorption coefficient is relatively large as compared to the reduced scattering coefficient. Separate knowlegde of the values of g and Σ_s is not necessary in that case. Furthermore, knowledge of g, Σ_s or the size-distribution of scatterers is not needed for the prediction of the ratio between the reduced scattering cross sections of Mie scatterers at different wavelengths, provided that the scatterers are within the range $1 < m < 1.1$ and $5 < x < 50$.

The studies in Chapter 3 have shown that condensed Monte Carlo simulations may save much calculation time. Application of this method to tissue *in vivo* and *in vitro* has shown that the *in vivo* values for the absorption coefficients and the reduced scattering coefficients are much smaller than the values from the *in vitro*

measurements, that have been assumed until now to be reliable.

Application of the knowledge obtained in Chapters 2 and 3 to reflectance pulse oximetry has shown that the Monte Carlo simulations can very well describe the ratio of pulse sizes, as well as values for R/IR at different detectors. Corrections for the effects of the average absorption and reduced scattering coefficients of the medium on reflectance pulse oximetry can also be performed. However, for the reduced scattering coefficient of blood and its changes, correction terms with respect to reflectance pulse oximetry cannot yet be determined for all cases.

Experimental research will have to prove whether the models given here will satisfy in practice, and whether further fundamental studies are needed. Such studies may include models where pulse sizes are not distributed homogeneously over the medium. This approach may be needed for measurements on the scalp to take the absence of pulsations of the skull into account. Another fundamental study might be devoted to the influence of blood vessels, as these also contribute to the non-homogeneous distribution of blood within the tissue. In this case too the condensed Monte Carlo method might be used, or variations of it. Anyway, the condensed Monte Carlo simulation has been shown to be a valuable tool for a deeper understanding of reflectance pulse oximetry. Moreover, it provides quantitative support for the estimation of the arterial oxygen saturation by means of reflectance pulse oximetry.