

Blood oxygenation measurements by multichannel reflectometry on the venous and arterial structures of the retina

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The aim of the present study was to propose a model and a method to derive the oxyhemoglobin blood content in the retinal veins and arteries by full spectrum reflectometry measurements in the spectral zone from 430 to 680 nm. We proposed a mathematical equation expressed as a linear combination of two terms $S_{\text{OHb}}(\lambda)$ and $S_{\text{Hb}}(\lambda)$ representing the normalized spectral absorption functions of the hemoglobin and the oxyhemoglobin, one term λ^{-n} representing the ocular media absorption with scattering, and a family of multi-Gaussian functions, which usefully compensate for the noncompatibility of the model and the experimental data in the red spectral zone. The present paper suggests that the spectral reflection function in the area from 520 to 580 nm is optimal in calculating the oxyhemoglobin concentration of the blood contained in the endothelial structures of retinal vessels. The model calculation needs a function $(1/\lambda)^{-n}$ that corrects for the ocular media absorption and light scattering on the vessels' structures. For the spectral area of lights with wavelength larger than 580 nm, the reflected light represents mainly the light scattering on the red blood cells. © 2011 Optical Society of America

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1. Introduction

Alterations of retinal blood flow are the cause of the majority of ocular diseases. Blood flow and blood oxygenation represent the most important parameters to characterize the retinal metabolism. Presently, there is a large interest in measuring these parameters *in vivo* by noninvasive methods. While the methods proposed to estimate blood flow in retinal structures seem to be useful [1,2], the existing methods utilized for the noninvasive blood oxygenation measurements in retinal vessels have inherent limitations, making a clinical application currently impracticable [3].

Several technologies have been proposed to measure retinal blood oxygenation by photometric methods by using specific wavelengths from the visible or near-infrared spectrums [4–7]. These technologies are based on theoretical studies [8] that propose that, by using three specific wavelengths, it is possible to estimate the blood oxygenation in a sample of blood without calibration. However, the retinal vessels represent a heterogeneous medium in continuous motion. Thus, the measurements of retinal blood oxygenation by photometric methods using only a few specific wavelengths represent a rough estimation.

Recent developments in this field suggest estimating the retinal blood oxygenation by full spectrum reflectometry measurements using multichannel

spectrometers that perform fast photometric measurements for a large range and a high number of wavelengths [9,10]. It was demonstrated [11] that by increasing the number of wavelength measurements, the precision of the blood oxygenation evaluation increases with about the square root of the considered wavelength number.

Spectral reflectometry measurements using the multichannel technique have shown that the reflectometry function obtained from a retinal structure represents a combined complex of different scatter and absorption functions. So the overall reflection function contains the spectral absorption components of the blood mixed with the spectral absorption components of all eye structures, traversed by the light towards the retina and from back reflection towards the exit of the eye. Furthermore, the light scattered by the red blood cells and vessel structures represents an important contribution to the overall reflection function [10].

In fact, the reflectometry function in the visible spectral region from veins and arteries was not completely explained by any recent model [10]. In consequence, Schweitzer *et al.* [10] proposed to derive the oxyhemoglobin blood content in veins and arteries by using the reflectometry data from the spectral zone of 510 to 586 nm. In this spectral zone, the blood absorption has a major contribution to the overall reflectometric function while the ocular media absorption and erythrocytes scattering are minimal. The same authors concluded that for wavelengths larger than 590 nm, the spectral reflectometry data is largely affected by the light reflected by the red blood cells.

A particular condition was exposed by Diaconu [12], who discovered that the reflectometry function obtained from the optic nerve capillary structures involves the same spectral characteristics as the reflectometry function from a sheet of white paper tinted with blood. He proposed a linear mathematical model that fully explains the reflectometry functions from the capillary structures of the optic nerve area in the visible spectral zone from 430 to 680 nm. The proposed procedure consists of applying the mathematical model to only one wavelength zone of the reflectometry function and to use the results to explain the other wavelength zone of the reflectometry function. By using this procedure, it can be verified if the model results represent a valid solution for all the experimental data that contain noise.

The aim of the present study was to derive the oxyhemoglobin blood content in the retinal veins and arteries by reflectometry measurements in the spectral zone from 430 to 680 nm using the model and method proposed by Diaconu [12] for the optic nerve capillary structures.

In fact, we consider that the structural composition of the limiting membrane of the blood vessel and its diameter represent the principal physiological characteristics that change the optical reflection properties on the different vessel types. By examining the

retina using a simple ophthalmoscope, it is evident that the light reflected from an artery or a vein is of less intensity compared to the light reflected from the microcapillaries' structures.

The veins and the arteries have relatively large diameters that allow a more important blood volume in a deeper path to be exposed to the illumination. In fact, under white light retinal illumination, the veins and arteries appear red (light red for the arteries and dark red for the veins), whereas the coloring of the capillaries' structures from the optical nerve zone appear more of a reddish white, demonstrating that the long wavelengths are relatively more reflected by the veins' and arteries' structures when compared to the zone containing the capillaries' structures.

2. Methods

The reflectometry spectral function was continuously recorded by the multichannel technique, as shown in Fig. 1 (800 wavelengths from 430 to 680 nm for each 500 ms), on arteries, veins, and the optic nerve capillary zone, during 20 s at 0.5 s integrals for a steady-state intensity of a white light retinal illumination from six healthy subjects. More details on a similar apparatus and the measurement technique were presented previously [12]. In the actual apparatus, the coupling between the fundus camera, the CCD video camera, and the spectrograph was accomplished using a pinhole mirror that reflects the whole image of the retina to the video camera except for the axial zone, where a pinhole 0.5 mm in diameter lets the light enter through to the spectrograph. The electron multiplication CCD camera for spectroscopy has been programmed in a special horizontal binding mode where four horizontal elements are grouped together. This horizontal binding mode reduces the measured wavelength number from 1600 to 800 and improves the signal–noise ratio.

Three different measurement sessions were obtained from each subject at 1 h intervals. Before and

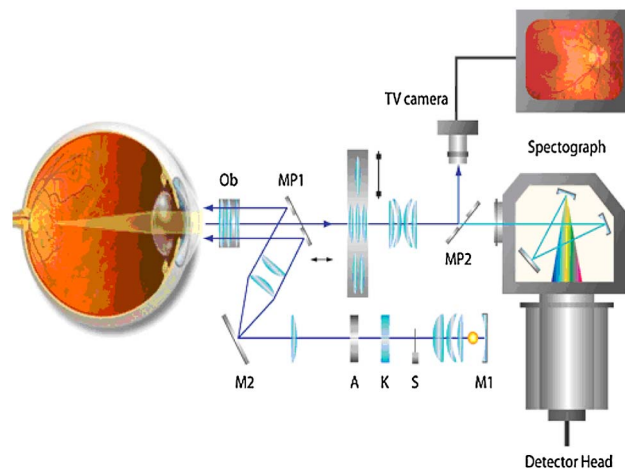


Fig. 1. (Color online) Schematic view of the multichannel reflectometry system for the eye. Ob, lens; MP1, mirror pinhole 1; MP2, mirror pinhole 2; M1, mirror 1; M2, mirror 2; A, aperture; K, neutral filter; S, shutter.

after each measurement session, the spectral intensity of the incident light was measured using an artificial eye with a matte surface of BaSO₄ considered as a neutral reflector at the site of the retinal fundus. The incident spectral light and the reflected light from the retinal structures were corrected for the dark signal.

3. Model

The mathematical equation used to derive the hemoglobin and the oxyhemoglobin contribution spectra to the overall reflectometry absorption function $A(\lambda)$ from the optic nerve, veins, and arteries, was expressed as a linear combination of two terms, $S_{\text{OHb}}(\lambda)$ and $S_{\text{Hb}}(\lambda)$, representing the normalized spectral absorption functions of the hemoglobin and the oxyhemoglobin and one term λ^{-n} representing the ocular media absorption with scattering. One constant factor k was also included in the model,

$$A(\lambda) = m_1 * S_{\text{Hb}}(\lambda) + m_2 * S_{\text{OHb}}(\lambda) + m_3 * \lambda^{-n} + m_4 * k. \quad (1)$$

The m_1, \dots, m_4 parameters represent the contribution of each term from Eq. (1) to the overall reflectometry absorption function $A(\lambda)$. Oxyhemoglobin concentration has been calculated using the formula $\text{OHb}\% = m_2 / (m_1 + m_2)$. The model has been applied to only one wavelength zone of the reflectometry spectral function, and the results of the model have been used to explain the other wavelength zone of the reflectometry function.

In the second model, we include in a multi-Gaussian function to compensate for the noncompatibility of the model and the experimental data in the red spectral zone,

$$A(\lambda) = m_1 * S_{\text{Hb}}(\lambda) + m_2 * S_{\text{OHb}}(\lambda) + m_3 * \lambda^{-n} + m_4 * k - \sum_{i=1}^n m_{4+i} * N(\mu_i, \sigma^2). \quad (2)$$

The role of the multi-Gaussian function was to subtract the noise from the overall reflectometry function and to protect the model for any given interfering signal. The noise may be created by the light scattered or absorbed on any given structure not predicted by the model.

The laboratory simulations showed that such a model predicts a null multi-Gaussian function when the model is applied to the spectral data without noise or additional interfering signal. However, the multi-Gaussian functions can reconstitute and separate any given spectral signal induced into the data formerly not predicted by the model.

In the present study, μ represented a vector of 18 equidistant elements on the wavelength scale from 580 to 670 nm with an interval of $\sigma = 5$ nm.

Then, $\mu = [580 \text{ nm} : 5 \text{ nm} : 670 \text{ nm}]$ and $n = \text{length}(\mu) = 18$.

4. Results and Discussions

Figure 2 shows an example of reflectivity absorption function (430 to 640 nm) from the optic nerve, vein, and artery, as well as the model fit contributions predicted by the Eq. (1) system applied to the spectral data from 530 to 590 nm.

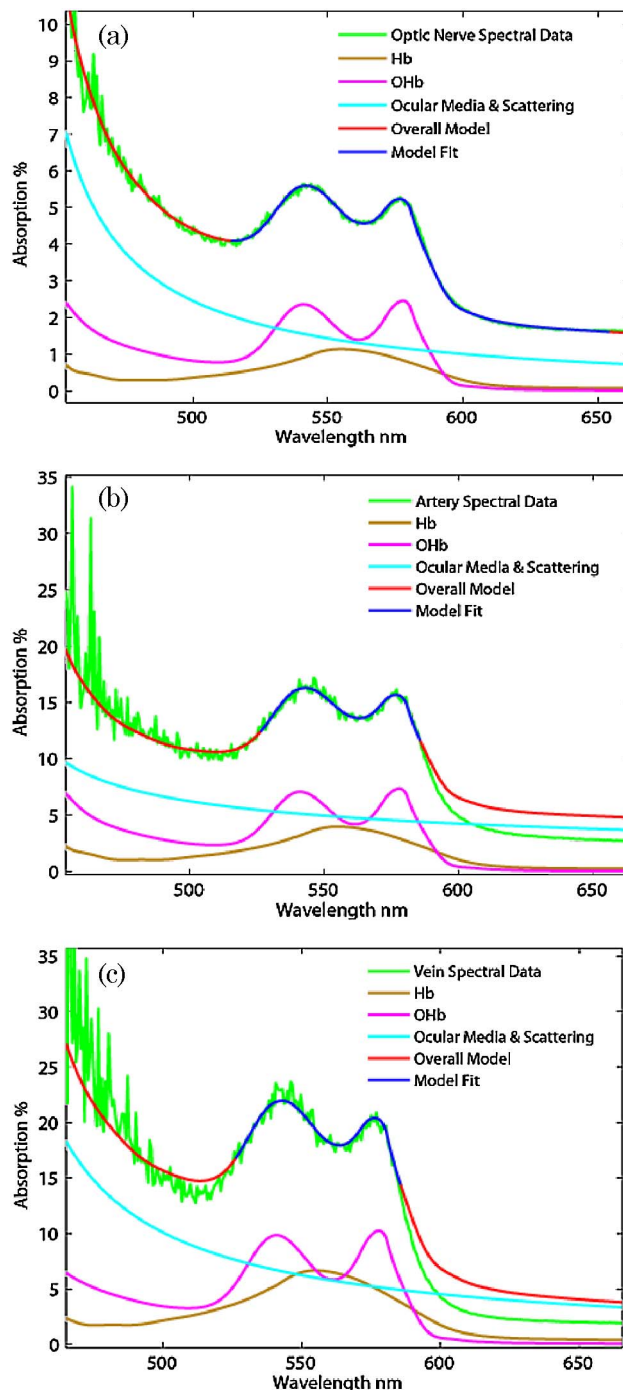


Fig. 2. (Color online) Graphical representation of the model fit applied to the experimental data obtained from (a) optic nerve capillaries, (b) arteries, and (c) veins. The contributions of hemoglobin, oxyhemoglobin, and optical medium absorption including the scatterings are shown.

Figure 2 also illustrates the contributions of the hemoglobin, the oxyhemoglobin, and the ocular medium absorption with light scattering predicted by the model to explain the overall reflectivity absorption function.

The results shown in Fig. 2 reveal that the model results represented by Eq. (1) applied for the spectral data from 530 to 590 nm can well explain the entire reflectometry function (430 to 640 nm) from the optic nerve structures [12]. However, the model results cannot explain the reflectivity function on the veins and arteries in the red spectral zone.

From the model results presented in Fig. 2, we understand that the reflectometry spectral data from veins and arteries include two reflectivity mechanisms. One mechanism is evident in the spectral zone from 430 to 590 nm where the light reflection on the veins and arteries is similar with the reflection mechanism on the microcapillary structures. A linear model can explain the reflectometry function in this spectral zone. A distinct reflection mechanism is evident in the red spectral zone where the absorption function is reduced when compared with the model prediction applied to the spectral data from the 430 to 590 nm zone. In fact, the model predicts that there are relatively more red light reflections on the veins and arteries than on the capillary structures. This result confirms the Schweitzer *et al.* [10] proposal, so that in the red spectral zone, the light scattering the red blood cells is important and depends on the blood volume exposed to the light path.

To explain the mechanisms involved in light reflection and absorption on veins and arteries, we propose a hypothetical model represented by Eq. (3), where the reflected light from the blood vessels represent two different scattering and absorption mechanisms:

$$I_S(\lambda) = I_{S1}(\lambda) + I_{S2}(\lambda). \quad (3)$$

One mechanism is represented by the light scattered and absorbed on the frontal structure of the blood vessels in which a very small fraction of the incident light is absorbed by a very thin film of the blood contained in endothelial structures [Eq. (4)]. This mechanism is similar to the model suggested by Diaconu [12] to explain the light scattering and absorption of the microcapillaries structures.

$$I_{S1}(\lambda) = K * I_0(\lambda) * [m_1 * S_{HB}^{-1}(\lambda) + m_2 * S_{OHb}^{-1}(\lambda)], \quad (4)$$

where K represents the fraction of incident light (I_0) scattered on the endothelial structures, m_1 and m_2 represent the coefficients for the hemoglobin and oxyhemoglobin blood content, and $S_{HB}(\lambda)$ and $S_{OHb}(\lambda)$ represent the hemoglobin and oxyhemoglobin spectral absorption functions.

In the second mechanism, a very large fraction of the incident light penetrates the blood vessels' volume. This light will be partially backscattered on the red blood cells found inside the blood vessel [10] and partially absorbed by the erythrocytes while

crossing twice the blood volume, following a reflection on the structures of the eye behind the vessel.

$$I_{S2}(\lambda) = K_S * [I_0(\lambda) - I_{S1}(\lambda)] * \{1 - 10 \exp\{-2 * d_v * [m_1 * S_{HB}(\lambda) + m_2 * S_{OHb}(\lambda)]\}\}, \quad (5)$$

where d_v represents the vessel diameter and K_S represents the scattering and reflection fraction.

Equation (5) expresses the mechanism where a fraction of the light is scattered on the red blood cells and another fraction is absorbed by erythrocytes traveling twice the blood volume $2 * d_v$ following a reflection on the structures of the eye behind the vessel [13].

The model results for the two mechanisms of scattering and absorption represented by Eq. (3) are illustrated in Fig. 3.

From Fig. 3, we notice that in the spectral area from 400 to 580 nm, the reflectometry function results mainly from the diffusion on the frontal endothelial structure of the blood vessels. In other words, the light, which will have to cross the blood vessel volume, is strongly absorbed by it. The contribution of this light to the reflectometry function is negligible in the spectral zone from 400 to 580 nm. However, the light of wavelengths larger than 590 nm is less absorbed by the blood, making the blood almost transparent to this light. The data represented in Fig. 3 show that in the spectral area for wavelengths larger than 590 nm, the light that is scattered on the red blood cells or reflected on the retina structures behind the blood vessels could be dominant compared to the light scattered on the frontal structure of the blood vessels.

The model represented by Eq. (2) was proposed to regulate for noncompatibility between the Eq. (1) model and the reflectometry experimental data in the red spectral zone. The multi-Gaussian functions can predict the amount of the light scattered on the red blood cells that depend on the blood vessel diameter.

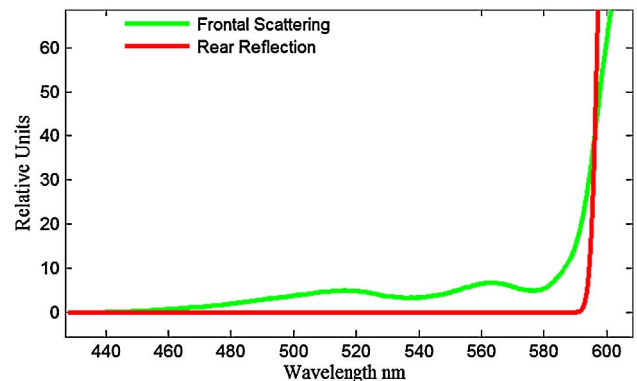


Fig. 3. (Color online) Graphical representation for the two mechanisms representing the frontal scattering on the endothelial structure of blood vessels and the rear reflection with scattering on the hematocrits [Eq. (3)].

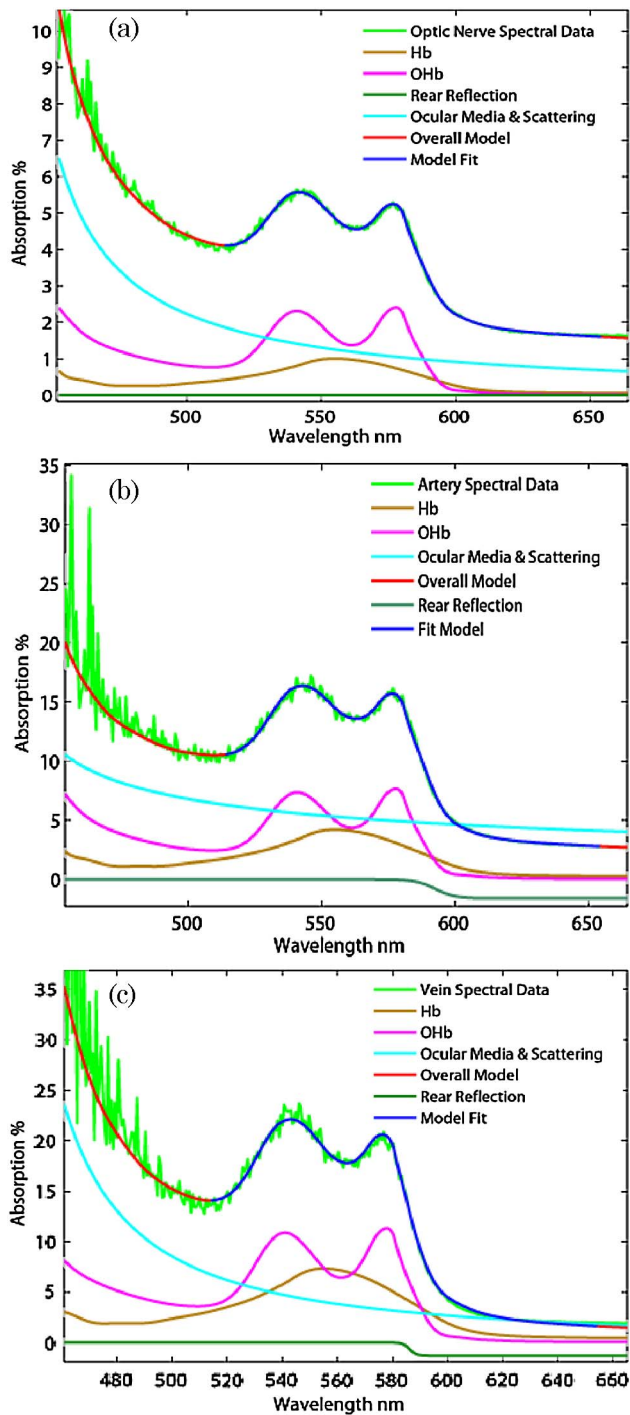


Fig. 4. (Color online) (a) Graphical representation for the calculated fitting curve by the second model [Eq. (2)] applied to the experimental data obtained from the (a) optic nerve, (b) arteries, and (c) veins. The contributions of hemoglobin, oxyhemoglobin, and optical medium absorption including the scatterings are shown. The rear reflection (red scattering light) estimated by the multi-Gaussian function is also represented in the figure.

In Fig. 4 are shown examples of diverse spectral reflectometry absorption functions for the optic nerve, vein, and artery alongside the model fit predicted by the system of Eq. (2) applied for the reflectometry data from the 530 to 680 nm spectral zone.

The results shown in Fig. 4 demonstrate that the system of Eq. (2) can well explain the overall spectral reflectometry function measured from the optic nerve head capillaries', veins', and arteries' structures. The multi-Gaussian functions illustrate the amount of light scattered on the red blood cells, an amount relatively significant for both veins and arteries.

Figure 5 shows an example of the blood oxygenation values derived with the second model applied for 30 consecutive reflectometry measurements on the artery, vein, and optic nerve capillaries of a subject. The results from Fig. 5 can be grouped into three ranges of blood oxygenation values with average values of about 75% for arteries, 50% for veins, and 65% for optic nerve capillaries.

The range of blood oxygenation values in arteries is greater than the oxygenation values found in capillary structures. On the other hand, the venous oxygenation values are always lower than those of capillary structures. It should also be noted that the blood oxygenation values derived from venous and arterial structures present a wide variability compared to the blood oxygenation values derived from capillary structures.

The eye motion represents the primary cause of the variability of blood oxygenation estimation by reflectometry measurements. The optic nerve zone represents the best area in the eye for reflectometry

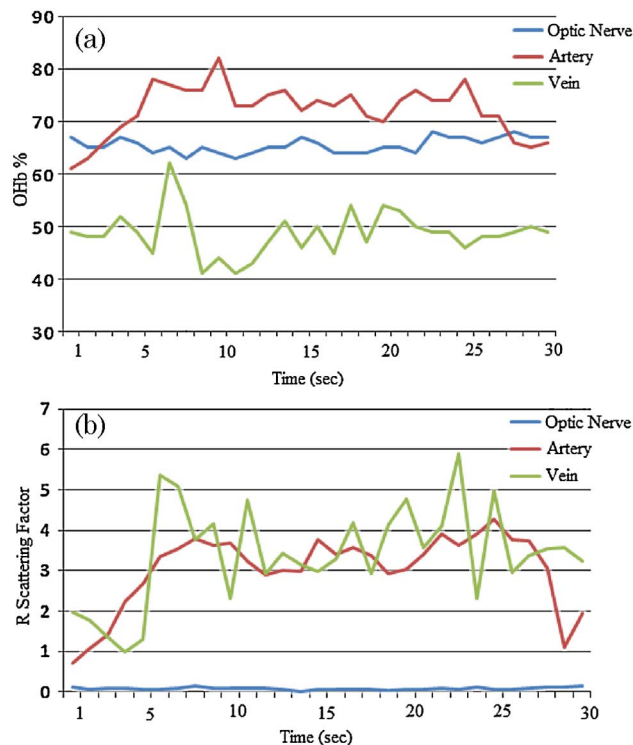


Fig. 5. (Color online) (a) Example of blood oxygenation values derived with the second model and (b) intensity of the light scattered in the red wavelength zone (R scattering factor) of the reflectometry function derived by the multi-Gaussian function from the second model applied for 30 consecutive reflectometry measurements on the arteries, veins, and optic nerve capillaries from one subject.

measurements compared to veins and arteries because of its high reflectivity factor and relatively large and homogeneous area.

The veins and arteries present a curved reflectivity surface. The detection of the light reflected from artery or vein depends greatly on the relative position of the sensor direction to the blood vessel axis. In consequence, the eye motion plays a significant role in the variability of the reflectometry measurements on the veins and arteries and implicitly on the derivative values of blood oxygenation.

Figure 5(b) shows the intensity of light scattered in the red wavelength zone (R scattering factor) derived by the multi-Gaussian function from the second model. The data presented in Fig. 5(b) confirm that the R scattering factor values are in direct correlation with the blood vessel diameter. It is noticeable that for reflectometry measurements from the optic nerve zone, the R scattering factor shows very low values that are consistent with the small diameter of capillaries.

Figure 6 shows possible correlations between the oxygenation values and the R scattering factor derived from 30 consecutive measurements from an artery, a vein, and an optic nerve capillary zone of a

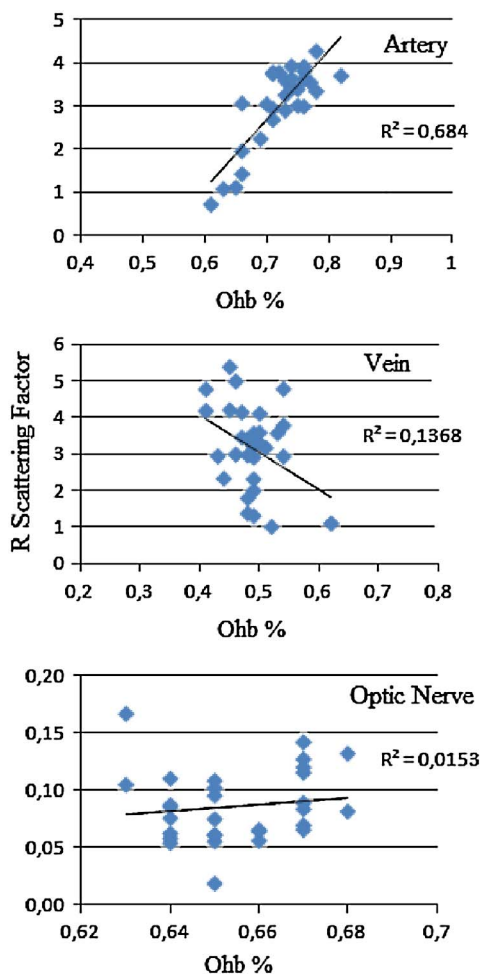


Fig. 6. (Color online) Correlation between the oxygenation values and the R scattering factor for the results from artery, vein, and optic nerve capillaries.

subject. From Fig. 6 we understand that the R scattering factor can be in direct correlation with the arterial blood oxygenation values and in inverse correlation with the venous blood oxygenation values. The correlation between the blood oxygenation values and the R scattering factor from the optic nerve capillaries is low, which is consistent with the homogeneity of the optic nerve zone. From the correlation of the results shown in Fig. 6, we understand that it is possible to select the blood oxygenation values corresponding to the axial position of the sensor direction relative to the blood vessel axis, considering that the maximum values of the R scattering factor are obtained when the sensor's direction is aimed at the blood vessel axis.

In this case, the R scattering factor values will be useful to reduce the variability of blood oxygenation values corresponding to eye motion. However, the data represented in Fig. 6 show that the reflectometry measurements corresponding to the axial position of the sensor's direction relative to the blood vessel axis grant maximum oxygenation values for measurements from the arteries and minimum oxygenation values for measurements from the veins [10]. We suggest that the sensor positions outside of the blood vessel axis will allow the capture of a stray light scattered from the adjacent structures of the vessel that are reflected on the wall vessel. Generally, the blood oxygenation of the capillary structures beside the large retinal vessel is lower than the arterial blood oxygenation and elevated more than the venous blood oxygenation. Then the stray light scattered from the adjacent structures of a vessel contributes to reducing the blood oxygenation estimation in arteries while increasing the estimated value of the blood oxygenation in veins.

Figure 7 shows the results for oxyhemoglobin blood content (percent) measured from arteries', veins', and optic nerve capillaries' zones in 12 subjects.

Similar to the results presented in Fig. 5 from one subject, the results presented in Fig. 7 can be grouped into three ranges of blood oxygenation with average values of about 73% for arteries, 47% for veins, and 63% for optic nerve capillaries.

It is notable that the arterial blood oxygenation values derived by this model are 10% lower than

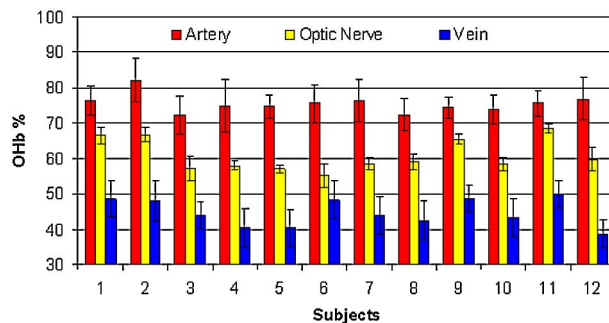


Fig. 7. (Color online) Mean values for oxyhemoglobin blood content (percent) measured from arteries', veins', and optic nerve capillaries' zones in 12 subjects.

the arterial blood oxygenation values reported by Schweitzer *et al.* [10]. This difference could have two causes.

i. The technique of the reflectometry signal measurement could cause it because if the reflectometry signal is collected from a larger area of the artery, more diffused light from the adjacent zone of the vessel is collected, which induces a decrease of the derived blood oxygenation values.

ii. The model for oxyhemoglobin derivation contains the function λ^{-n} , which corrects the reflectometry data for the ocular media absorption and the diffusion of the light on the blood vessel. Without this correction, the derived blood oxygenation values would be higher.

However, the variability of the arterial blood oxygenation values between the various subjects is relatively low compared to that of the venous blood oxygenation variability. One explanation may be that the retinal arterial blood oxygenation depends on the systemic arterial blood oxygenation, which is a uniform parameter for people in good health. The venous blood oxygenation of the retina depends on the arterial blood oxygenation, but also on the retinal metabolism and blood flow. Our results on the venous blood oxygenation suggest that the retinal metabolism or retinal blood flow can be specific to each subject, even if the same quantity of light were employed to illuminate the retina during the measurements [14,15].

5. Conclusions

The results of the model revealed that the retinal spectral reflectometry signal is complex, containing scattering, reflection, and absorption lights, each type of light presenting a specific predominance in the different spectral zones of the retinal reflectometry function.

i. The spectral absorption function of the blood is dominant in the spectral zone from 520 to 580 nm.

ii. The ocular media spectral absorption function and the light scattering on the blood vessels' structures are dominant in the spectral zone with wavelengths shorter than 520 nm.

iii. In the spectral zone of wavelengths larger than 590 nm, the light scattering on the red blood cells and the light reflection from the eye structures behind the vessel is dominant.

The present paper suggests that the spectral reflection function in the area from 520 to 580 nm is optimal in calculating the oxyhemoglobin concentration of the blood contained in the endothelial structures of retinal vessels. The model calculation needs a function $(1/\lambda)^{-n}$ that corrects for the ocular media absorption and light scattering on the vessels' structures. The $(1/\lambda)^{-n}$ function must be modeled so that the model results from the spectral zone of 520 to 580 nm are also a solution for the reflectometry

function in the 430 to 520 nm spectral zone [12]. For the spectral area of lights with wavelengths larger than 580 nm, the reflected light mainly represents the light scattering on the red blood cells.

The quantity of this light (R scattering factor) may be derived using a multi-Gaussian function. The R scattering factor representing the amount of the scattered light in the red wavelength zone may be a useful parameter to estimate the relative variation in retinal vessel diameter and can also be helpful in correcting the errors in blood oxygenation estimation caused by eye motion.

References

1. C. E. Riva and G. T. Feke, "Laser Doppler velocimetry in the measurement of retinal blood flow," in *The Biomedical Laser: Technology and Clinical Applications*, L. Golman, ed. (Springer, 1981), pp. 135–161.11.
2. G. T. Feke and C. E. Riva, "Laser Doppler measurements of blood velocity in human retina vessels," *J. Opt. Soc. Am.* **68**, 526–531 (1978).
3. A. Harris, R. B. Dinn, L. Kagemann, and E. Rechtman, "A review of methods for human retinal oximetry," *Ophthalmic Surg. Lasers Imaging* **34**, 152–164 (2003).
4. R. N. Pittman and B. R. Duling, "A new method for the measurement of percent oxyhemoglobin," *J. Appl. Physiol.* **38**, 315–320 (1975).
5. J. M. Beach, J. S. Tiedeman, M. F. Hopkins, and Y. S. Sabharwal, "Multispectral fundus imaging for early detection of diabetic retinopathy," *Proc. SPIE* **3603**, 114–121 (1999).
6. J. M. Beach, K. J. Schwentzer, S. Srinivas, D. Kim, and J. S. Tiedeman, "Oximetry of retinal vessel by dual-wavelength imaging: calibration and influence of pigmentation," *J. Appl. Physiol.* **86**, 748–758 (1999).
7. H. S. Hardarson, A. Harris, R. A. Karlsson, G. H. Halldorsson, L. Kagemann, E. Rechtman, G. M. Zoega, T. Eysteinnsson, J. A. Benediktsson, A. Thorsteinsson, P. K. Jensen, J. Beach, and E. Stefánsson, "Automatic retinal oximetry" *Invest. Ophthalmol. Visual Sci.* **47**, 5011–5016 (2006).
8. F. C. Delori, "Noninvasive technique for oxymetry of blood in retinal vessels," *Appl. Opt.* **27**, 1113–1125 (1988).
9. D. Schweitzer, E. Thamm, M. Hammer, and J. Kraft, "A new method for the measurement of oxygen saturation at the human ocular fundus," *Int. Ophthalmol.* **23**, 347–353 (2001).
10. D. Schweitzer, M. Hammer, J. Kraft, E. Thamm, E. Königsdörffer, and J. Strobel, "In vivo measurement of the oxygen saturation of retinal vessels in healthy volunteers," *IEEE Trans. Biomed. Eng.* **46**, 1454–1465 (1999).
11. D. Schweitzer, L. Leistritz, M. Hammer, M. Scibor, U. Bartsch, and J. Strobel, "Calibration-free measurement of the oxygen saturation in retinal vessels of men," *Proc. SPIE* **2393**, 210–218 (1995).
12. V. Diaconu, "Multichannel spectroreflectometry: a noninvasive method for assessment of on-line hemoglobin derivatives," *Appl. Opt.* **48**, D52–D61 (2009).
13. M. Hammer, S. Leistritz, L. Leistritz, and D. Schweitzer, "Light paths in retinal vessel oximetry," *IEEE Trans. Biomed. Eng.* **48**, 592–598 (2001).
14. G. Birol, S. Wang, E. Budzynski, N. D. Wangsa-Wirawan, and R. A. Linsenmeier, "Oxygen distribution and consumption in the macaque retina," *Am. J. Physiol.* **293**, 1696–1704 (2007).
15. C. E. Riva, J. E. Grunwald, and B. L. Petrig, "Reactivity of the human retinal circulation to darkness: a laser Doppler velocimetry study," *Invest. Ophthalmol. Visual Sci.* **24**, 737–740 (1983).

Valentina Vucea

Détentrice d'une maîtrise en physique de l'Université de Craiova, en Roumanie, je suis venue m'installer au Québec en 2002 pour y poursuivre mes études à l'Université de Montréal. Ici, j'ai fait connaissance du professeur Vasile Diaconu, et j'ai commencé une maîtrise en 2004 dans son laboratoire à l'École d'Optométrie.

C'est durant ma maîtrise que je me suis intéressé aux méthodes de détermination d'oxygénation sanguines à partir de mesures de spectrorélectométrie dans l'œil. J'ai continué à travailler activement dans cette thématique lors de mon doctorat en génie biomédical, sous la supervision du monsieur Vasile Diaconu, professeur à l'Institut de Génie Biomédical de l'Université de Montréal. À l'aide de mes connaissances acquises et de l'expertise de mon directeur de recherche, j'ai pu allier la physique et l'ophtalmologie dans le cadre de ma thèse doctorale traitant la spectrorélectométrie de l'œil, méthode de mesure non invasive et en continu de l'oxygénation sanguine. Pendant mes études de deuxième et troisième cycle, j'ai obtenu des bourses d'excellence et d'étude, de l'École d'Optométrie et de la Faculté de Médecine de l'Université de Montréal, aussi qu'une bourse de doctorat en recherche de FQRNT (Fonds québécois de la recherche sur la nature et les technologies), pour deux années consécutives. En 2009, j'ai remporté le prix d'excellence pour ma présentation orale lors de la 15^{ème} réunion annuelle du réseau FRSQ de recherche en santé de la vision, et en 2010, le prix d'excellence pour ma présentation par affiche lors de la Journée scientifique du Groupe de Recherche en Sciences de la Vision.

Également, je suis l'auteure d'une vingtaine de présentations institutionnelles, nationales et internationales et de deux publications dont un article récent paru dans la très prestigieuse revue "Applied Optics".

Valentina Vucea

Holder of a Master's degree in Physics from the University of Craiova, in Romania, I arrived in Quebec in 2002 in order to advance my studies at the University of Montreal. Here, I became acquainted with Professor Vasile Diaconu and began my master's degree in 2004 in his laboratory at the School of Optometry. It's during my Masters that I got interested in the methodology behind blood oxygenation determination from measurements taken from the eye with a spectroreflectometer. I continued working actively in this domain during my doctorate in biomedical engineering, under the supervision of Dr. Diaconu, Professor at the Institut de Génie Biomédical de l'Université de Montréal. Along with my background and the expertise of my research advisor, I unified physics and ophthalmology in my doctoral thesis by the use of the spectroreflectometer, a continuous non-invasive method that measures blood oxygenation. During my Master's and Doctorate, I obtained excellence grants from the School of Optometry, and the Faculty of Medicine de l'Université de Montréal and also, a doctoral research bursary from FQRNT (Fonds québécois de la recherche sur la nature et les technologies), for two consecutive years. In 2009, I won the excellence award for my oral presentation during the 15th annual reunion of the "réseau FRSQ de recherche en santé de la vision", and in 2010, the excellence award for my poster presentation during the « Journée scientifique du Groupe de Recherche en Sciences de la Vision ». Also, I am the author of twenty institutional, national and international presentations and two publications, of which one recently appeared in the very prestigious revue "Applied Optics".

Valentina Vuca

