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Review Article

Physical Aspects of Pulse Oximetry in the Context of COVID-19 Pandemic

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Abstract

The COVID-19 pandemic shocked the entire medical community. One of the most severe manifestations of the new coronavirus disease was the rapid damage to the lungs, which was accompanied by a drop in blood oxygen saturation. Since such injuries could be almost asymptomatic, they often led to late hospitalizations and, as a result, serious illness or death. Against this background, the task of monitoring blood oxygen saturation has acquired particular relevance. This function is effectively performed by a pulse oximeter - a portable, non-invasive, relatively inexpensive device that determines saturation almost instantly and is able to do this at any time and in any place. Given the relevance of the topic, let us dwell on the physical foundations of pulse oximetry, which turned out to be so important during the COVID-19 pandemic.

Keywords: *Medical Physics; Biological Physics; Pulse Oximetry; Light Attenuation; Saturation; Hemoglobin*

Introduction

This review article continues our previous study [1] on the application of medical and biological physics and medical informatics for a consistent description of various relevant aspects of the diagnosis and treatment of COVID-19 pandemic.

The measurement of various indicators of arterial blood pulsation is based on photometric methods using the ability of biological tissues to change the degree of absorption, scattering or reflection of the light flux passing through it. According to the Bouguer-Lambert law, the attenuation of light intensity in an object with uniform optical properties depends on the thickness of the layer through which this radiation passes (see, for example, textbook [2]):

$$I = I_0 e^{-\alpha d},$$

Where *I* is the intensity of the light flux passing through the tissue, *I0* is the intensity of the incident light flux, α is the light attenuation coefficient depending on the radiation wavelength and the optical properties of the tissue, *d* is the thickness of the light absorbing and scattering tissue.

In the case of a mixture, such as oxygen in the blood, the attenuation coefficient, as was shown by Beer, depends on concentration C of the solute (oxygen) as follows:

$\alpha = \alpha_1 \tilde{N}$.

Here α_1 is the attenuation coefficient in a solution of unit concentration. Both of the above relations together give the Bouguer-Lambert-Beer law, the use of which underlies the method of pulse oximetry.

If the light flux passes through a biological tissue containing arterial vessels, and the value of the light flux passed through it is estimated, then the attenuation of the light radiation will depend on the thickness of the biological tissue, its internal structure, the size of the blood vessels, and the spectral composition of the light source.

The dependence of light attenuation on time has two components: a pulsating component, due to a change in arterial blood volume with each heartbeat - systole, and a "constant" component, determined by the proportion of light absorbed and scattered in the measured pulse cycle during diastole, and optical characteristics of venous, capillary blood, bones, skin and other biological tissues under study. The maximum attenuation of the light intensity corresponds to the moment of maximum blood supply to the vessel during systole, and the minimum, respectively, during diastole.

Pulse oximeter is a device designed for non-invasive measurement of arterial oxygen saturation in peripheral vessels and heart rate. Oxygen saturation SpO_2 is defined as the ratio of the concentration of oxyhemoglobin [HbO_2] to the total concentration of hemoglobin in the blood [HbO_2] + [Hb] (oxyhemoglobin + reduced hemoglobin).

Oximetry is a term that refers to the optical measurement of oxyhemoglobin saturation, while pulse oximetry describes a special technique that takes advantage of pulsating arterial blood flow.

A pulse oximeter usually contains a dual source of light radiation and emits light through a translucent part of the body (usually a fingernail or earlobe). This device uses two LEDs that generate visible red light (with a wavelength of ≈ 650 nm) and infrared radiation (with a wavelength of ≈ 950 nm), and photodetectors (light detectors) to determine the intensity that has passed through this part of the body (Figure 1).

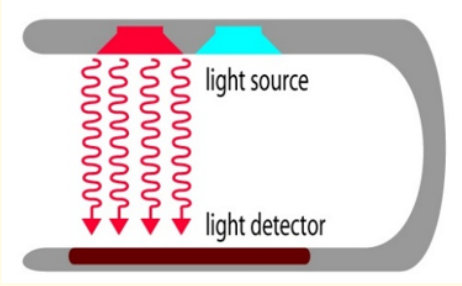

Figure 1: *Schematic representation of a dual source of light radiation and a photodetector (light detector) of a pulse oximeter [3].*

Physical basics of pulse oximetry

Let us assume that a pulse oximeter emits an electromagnetic wave (visible or infrared) of a certain length λ and initial intensity I_0. Such a wave passes through a certain part of the body which periodically changes its thickness due to the heartbeat and attenuates ac-

cording to the Bouger-Lambert -Beer law. Figure 2 shows the moments of the cardiac cycle: (a) when this thickness is the smallest, therefore, the intensity of the transmitted wave I_1, obtained at the photodetector, is the largest; (b) when this thickness is the largest and, correspondingly, the intensity I_2 of the wave received at the photodetector is the smallest.

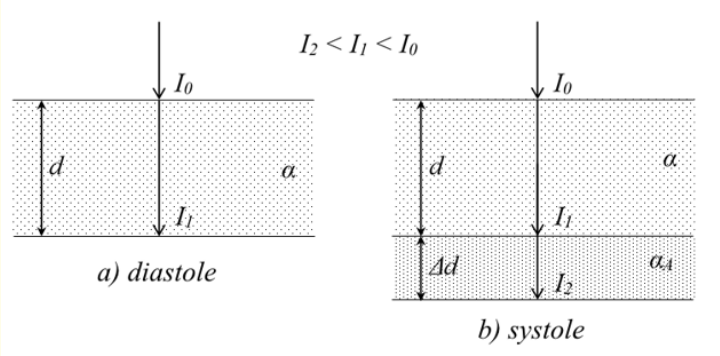

Figure 2: *Change in light intensity after passing through a certain part of the body (nail, earlobe) at the time of: a) diastole; b) systole.*

Measurement of arterial saturation of oxyhemoglobin is a non-invasive measurement and is performed using a finger pulse oximeter.

Here α is the attenuation coefficient of the "constant" (diastolic) component, i.e. venous, capillary blood, bones, skin and other tissues under study, while α_A is the attenuation coefficient of the "pulsating" component, i.e. part of the area is formed due to additional inflow of oxygenated arterial blood with each contraction of the heart.

Figure 3 shows the pulse oximeter recording the intensity I of an electromagnetic wave that has passed through the body region at two wavelengths (λ_R and λ_{IR}) as a function of time t. Then, during several cardiac cycles, the pulse oximeter determines the maximum values of the transmitted intensity I_1 and the minimum I_2 at two wavelengths: λ_R and λ_{IR}.

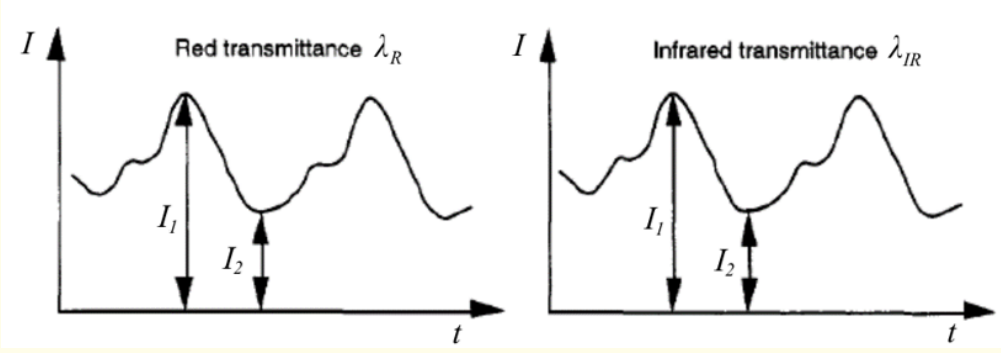

Figure 3: *Dependence of light intensity obtained on a photodetector on time during a pair of cardiac cycles for red and infrared wavelengths [3].*

The internal processor of the pulse oximeter then calculates the quantity Rs the ratio of the logarithms of the transmitted intensities for the red wavelength (λ_R) and the infrared wavelength (λ_{IR}):

$$R_S = \frac{\ln[I_2(\lambda_R)/I_1(\lambda_R)]}{\ln[I_2(\lambda_R)/I_1(\lambda_R)]} = \frac{\alpha_A(\lambda_R)}{\alpha_A(\lambda_R)}.$$

The importance of this formula is that the ratio R_S of the logarithms of the transmitted intensities does not depend on either the initial intensity I_0 or the region thicknesses d and Δd, but depends only on the intensities I_1 and I_2 passing through the region at different wavelengths and recorded by the photodetector.

The idea behind the operation of a pulse oximeter is to exploit the fact that oxyhemoglobin and its deoxygenated form have significantly different luminous attenuations and, therefore, the attenuations of oxygenated hemoglobin (HbO_2) and deoxyhemoglobin (Hb) are significantly different at the two wavelengths λ_R and λ_{IR} (red/ infrared).

Indeed, the emitted wavelengths of red λ_R and infrared λ_{IR} radiation are about 650 nm and 950 nm, respectively (for different models of pulse oximeters, these wavelengths may vary slightly). Figure 4 shows that the extinction coefficient $\alpha_{eD}(\lambda_R)$ of deoxyhemoglobin (Hb) is significantly higher than the extinction coefficient $\alpha_{eO}(\lambda_R)$ of oxyhemoglobin (HbO_2) at a wavelength of $\lambda_R \approx 650$ nm from the visible range.

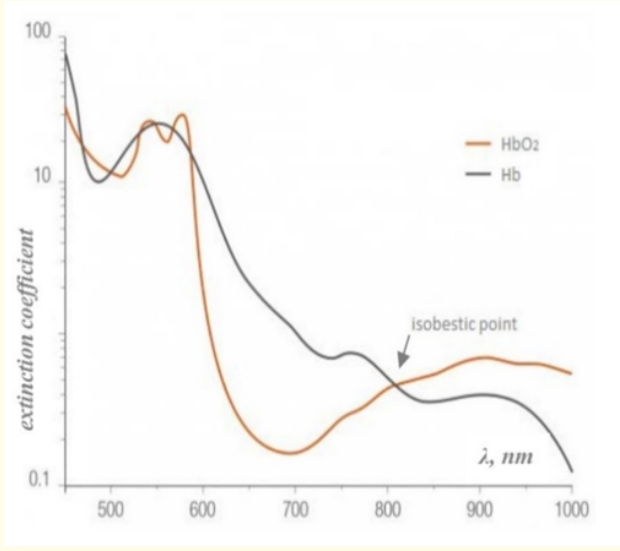

Figure 4: *Dependence of the extinction coefficients Hb i HbO_2 on the avelength of the incident light (the isobestic point is the wavelength at which the same attenuation occurs by two different molecules) [3].*

On the contrary, the extinction coefficient $\alpha_{eO}(\lambda_{IR})$ of oxyhemoglobin (HbO_2) is significantly higher than the extinction coefficient $\alpha_{eD}(\lambda_{IR})$ of deoxyhemoglobin (Hb) at a wavelength $\lambda_{IR} \approx 950$ nm in the infrared range. Thus, a theoretical relationship can be established between saturation SpO_2 and the ratio R_S. Graphically, the dependence of SpO_2 on R_S resulting from the Bouguer-Lambert -Beer law is a hyperbola as it is shown on figure 5.

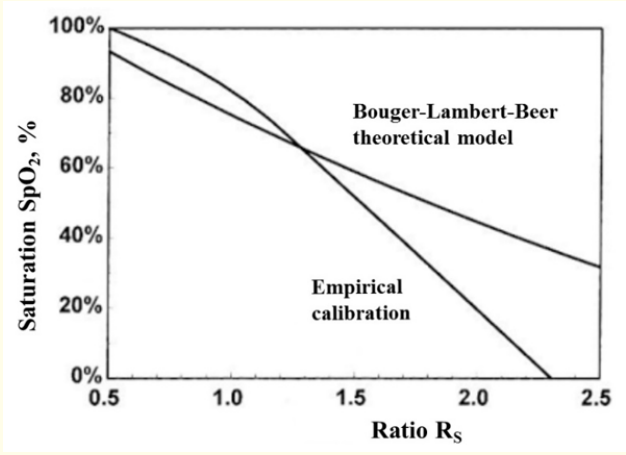

Figure 5: *Theoretical and empirical dependences of SpO_2 saturation on the pulse oximeter ratio RS [3].*

Therefore, the processor calculates the pulse oximeter ratio R_S, then it is supposed to substitute R_S in the theoretical formula to calculate the saturation of SpO_2 and to show its value on the display. But independent measurements of saturation show that theoretical formula is not accurate, especially at sufficiently low values of saturation SpO_2. In this regard, it should be noted that the study of the theoretical foundations of the Bouguer-Lambert-Beer law [4] and the practical application of the pulse oximetry method revealed, along with its advantages, also certain additional disadvantages [5-10]. Therefore, instead of the theoretical formula, an empirical calibration table of SpO_2 and R_S values is used to find SpO_2 saturation at a known R_S ratio, which is stored in the pulse oximeter memory. Data for this table are obtained as a result of inhalation of depleted oxygen mixtures by healthy patients.

Figure 5 shows graphs of $SpO_2(R_S)$ dependence based on two approaches: theoretical formula using the Bouguer-Lambert-Beer attenuation law, and an empirical calibration table. It can be easily seen that theoretical and empirical graphs closely correlate at the region of high saturations which is most common for patients without severe damage of lungs.

Conclusion

Thus, the pulse oximeter measures arterial oxygen saturation and provides vital information about the patient's cardiorespiratory function. The advantages of this method are non-invasiveness, simplicity and constant data availability. It provides a real-time oxygen saturation monitoring mode and can be used for diagnostic purposes in a wide range of medical specialties such as anesthesiology, emergency care, intensive care or even home care.

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