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Review Report

A Review on Pulse Oximetry uses and limitations

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ABSTRACT

Pulse Oximetry, a noninvasive method for continuous monitoring of blood saturation with oxygen. Since then it has gained recognition of medical specialists because of its simplicity and instantaneous presentation of information on the patient's blood oxygenation, which is of great importance in clinical urgencies. As a result, a trend is observed towards improved reliability of measured values of saturation and toward increased user comfort. An increasing number of physicians and medical engineers now consider the patient device combination as an integral system where deviations from normal conditions can be caused by biophysical and technical factors, for instance, by hardware or software failure. Therefore, the main goal is to trace the fault and to try to overcome it. If the fault is intolerable, the hospital physician should be supplied with information on the doubtfulness of the saturation recordings. In this review, we discuss how pulse oximeters are able to distinguish oxygenated hemoglobin from deoxygenated hemoglobin and how they are able to recognize oxygen saturation only from the arterial compartment of blood. Based on these principles, we discuss the various conditions that can cause spurious readings and the mechanisms underlying them.

Keywords: SpO_2, PPG signal, Pulse Oximetry, Hemoglobin.

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ABSTRACT

Pulse Oximetry, a noninvasive method for continuous monitoring of blood saturation with oxygen. Since then it has gained recognition of medical specialists because of its simplicity and instantaneous presentation of information on the patient's blood oxygenation, which is of great importance in clinical urgencies. As a result, a trend is observed towards improved reliability of measured values of saturation and toward increased user comfort. An increasing number of physicians and medical engineers now consider the patient device combination as an integral system where deviations from normal conditions can be caused by biophysical and technical factors, for instance, by hardware or software failure. Therefore, the main goal is to trace the fault and to try to overcome it. If the fault is intolerable, the hospital physician should be supplied with information on the doubtfulness of the saturation recordings.

In this review, we discuss how pulse oximeters are able to distinguish oxygenated hemoglobin from deoxygenated hemoglobin and how they are able to recognize oxygen saturation only from the arterial compartment of blood. Based on these principles, we discuss the various conditions that can cause spurious readings and the mechanisms underlying them.

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1. INTRODUCTION

Blood enters the right atrium and passes through the right ventricle. The right ventricle of the heart pumps the blood to the lungs where red blood cells which contain hemoglobin get oxygenated. The oxygenated blood is brought back to the heart, from their pumped to the various parts of the body through arteries. The percentage of hemoglobin in the blood that is saturated with oxygen is called blood gas saturation or SpO_2.

Oxygen saturation is defined as the ratio of oxy-hemoglobin to the total concentration of hemoglobin present in the blood and is given by

$$SpO_2 = \frac{[HbO2]}{[Hb]+[HbO2]} \quad (1)$$

Where $[HbO2]$ and $[Hb]$ are the concentrations of oxygenated and de-oxygenated haemoglobin in the arteries respectively. SpO_2 has the same value throughout the arterial system, since oxygen is extracted from the blood only in the capillaries.

1.1 Technique

SpO_2 can be estimated by measuring the absorption of light as it passes through the body. Oximetry is the measurement of blood gas saturation. Pulse Oximetry is a non- invasive method of Oximetry which involves flashing two LED's alternately. The pulse oximeter estimates the oxygen saturation by comparing how much red light and infra-red light is absorbed by the blood as shown in fig. 1. Depending on the amounts of $[HbO2]$ and $[Hb]$ present, the ratio of the amount of red light absorbed compared to the infrared light absorbed changes.

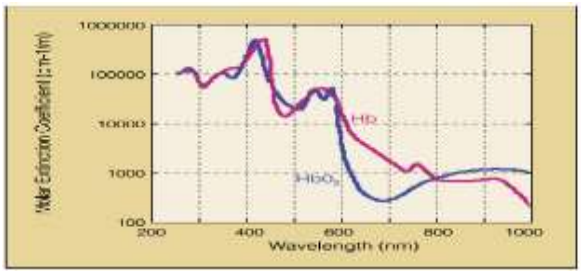

Fig. 1. The Absorption spectra of the oxygenated and deoxygenated hemoglobin molecules.

1.2 Pulse Oximetry

Pulse Oximetry is a technique used to monitor the SaO_2 of hemoglobin. At present, the usual technique to isolate light absorption by arterial blood is based on photo plethysmography (PPG). PPG is the measurement of light absorption changes due to cardiac induced blood volume changes [2], [3]. The PPG signal originates from the arterial blood volume increase during systole, so that the measurement of the PPG signal in several wavelengths—pulse Oximetry—enables the assessment of the SaO_2.

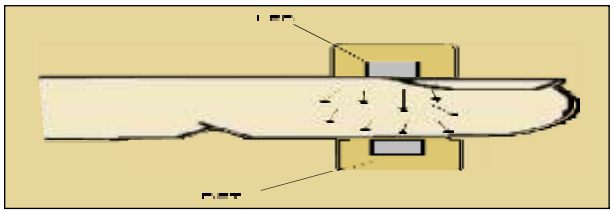

Fig. 2. Illustrates a photo plethysmograph.

The PPG probe consists of a light-emitting diode (LED) directed into finger tissue and a photo detector that measures the light transmitted through the tissue. Blood volume increases in the arteries during systole, which results in a decrease in light intensity through the tissue.

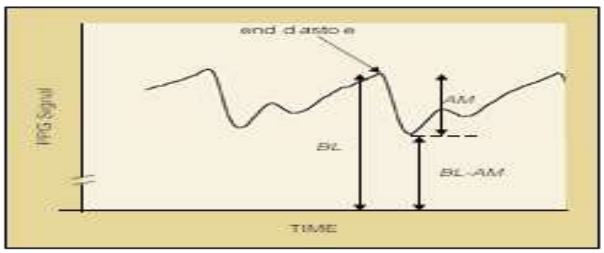

Fig. 3. A PPG signal over time. The baseline, BL, is the maximum of the pulse, and AM is the pulse amplitude

Figure 3 shows a PPG signal. The maximal value of the PPG signal (*BL*) is proportional to the light irradiance transmitted through the tissue at end-diastole, when the tissue blood volume is minimal. In general, the PPG signal is presented in inverted form (Figure 4) so that an increase in the PPG signal corresponds to an increase in arterial blood volume. The theory of pulse Oximetry is described in several textbooks and articles [3], [4]. In short, from the amplitude, *AM*, of the PPG signal and from the baseline, *BL*, of the pulse (see Figure 3) the relative maximal change of the PPG signal, AM/ BL, is calculated. AM/BL does not depend on the intensity of the illuminating light.

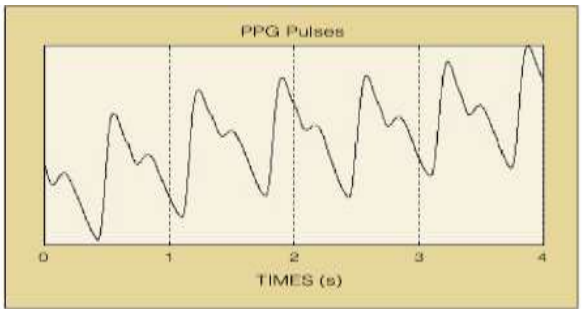

Fig. 4. The inverted PPG signal. The increase in the PPG signal corresponds to increase in tissue blood volume

For each wavelength, *AM*/*BL* is proportional to three factors:

- Maximal arterial blood volume increase during systole
- The extinction coefficient of that wavelength in that increment of blood
- The optical path-length in the tissue for that wavelength.

In order to create a parameter, which depends primarily on the extinction coefficient of the arterial blood (which depends on the oxygen saturation) and only depends slightly on the arterial blood volume increase at systole and on the optical path- length in the tissue, the light transmission is measured for two wavelengths $\lambda 1$ and $\lambda 2$, and the ratio R is defined by

$$R = \frac{(AM/BL)_1}{(AM/BL)_2}$$

R depends primarily on the ratio of the extinction coefficients for the two wavelengths, and this ratio

depends on the arterial oxygen saturation SaO_2 [3], [4]. By dividing the ratios in this fashion, we should, in principle, remove the dependence of the parameter on the blood volume increase through which the light is passing. The division of the ratios reduces the dependence on the optical path-length, but does not eliminate it totally. In order to achieve a larger difference in light transmittance between the two wavelengths, commercial pulse oximeters choose one of the wavelengths in the infrared region, and the other in the red region, where the difference in the extinction coefficient between oxygenated and deoxygenated blood is maximal.

However, for this choice, the red light scattering constant differs significantly from that of the infrared light resulting in a non-negligible difference in optical path-lengths for the two wavelengths. *R*, the ratio of *AM*/*BL* for the two wavelengths, includes two factors: the ratio of the extinction coefficients for the two wavelengths and the ratio of the two path-lengths for the two wavelengths. The latter is not unity, so that SaO_2 cannot be directly derived from *R*. The actual relationship between *R* and SaO_2 for each pulse oximeter sensor is determined by calibration [3]: *R* is measured in several people simultaneously with *in vitro* SaO_2 measurements on extracted arterial blood. The *in vitro* measurements are performed using a co-oximeter, a device that measures oxygen saturation in samples of extracted blood through optical or chemical methods.

For each person, *R* and SaO_2 measurements are taken for several values of SaO_2. These different values of SaO_2 are achieved by changing the partial pressure of oxygen in the air the subjects breathe. The table of the simultaneous measurements of *R* and SaO_2 provides the required calibration for the derivation of SaO_2, the clinical parameter, from *R*, the measured parameter. It should be emphasized that the calibration is possible because arterial blood has the same value of oxygen saturation all over the arterial system, since oxygen is not diffused through the arterial wall.

The assumed reliability of the calibration is based on the assumption that the ratio between the path-lengths for the two wavelengths, $\lambda 1$ and $\lambda 2$, does not change between different people and different physiological and clinical situations. The validity of this assumption is limited, and deviations from this assumption are probably the origin of the inherent inaccuracy of the pulse Oximetry technique for the assessment of SaO_2 in arterial blood. Manufacturers of pulse oximeters for SaO_2 measurement claim accuracies of 2%. That is, the standard deviation of the SaO_2 measurement by pulse Oximetry with respect to the "true value" of SaO_2 found by performing an *in vitro* measurement by co-oximeter is 2%. A standard deviation of 2% means that for 5% of the examinations made, using PPG-based techniques and deviations higher than 4% (two standard deviations) are expected. A deviation of 4% in a SaO_2 measurement is acceptable for monitoring patients during surgical operation or in intensive care units, since the required clinical information is that no dramatic change in respiration or ventilation has occurred.

However, a deviation of 4% in the SaO_2 measurement is too high for the assessment of lung function in pulmonary function units, so that, in general, pulse Oximetry is not used by pulmonologists for the determination of SaO_2.

2. COMMON AREAS FOR USE OF PULSE OXIMETRY

- During anesthesia and post anesthesia care, including both general and conscious sedation
- Intensive care units
- Neonatal care units, including delivery, nursery, and
- neonatal intensive care unit
- Hospital medical units
- Transportation within the hospital and during ambulance or air ambulance transportation
- Diagnostic testing, such as pulmonary function testing, exercise testing, and during sleep studies
- Sub-acute care centers, such as nursing homes and rehabilitation centers
- Home care patients.

3. LIMITATIONS

The inherent limitations of pulse Oximetry in various clinical settings must be recognized in order

to appropriately interpret results. The major limitations can be divided into eight categories: those arising from calibration assumptions, optical interference, and signal artifact, Fingernail polish , Excessive movement , Inherited forms of abnormal hemoglobin, Poor probe positioning resulting in decrease absorption of red and/or IR light and Fetal Hb (HbF)

i) Calibration Assumptions

Initially the conversion from absorbency ratios to arterial oxygen saturation was based directly on Beer-Lambert calculation, but the effects of reflection and scattering of light even within the pulsatile fraction of arterial blood led to gross overestimation of oxygen saturation. Better results have come from using experimentally derived calibration curves (Figure 3). These curves are based on measurements in healthy young volunteers after induction of hypoxemia with coincident determination of oxygen saturation by both pulse oximeter and in vitro laboratory co-oximeter. An unavoidable limitation, therefore, is that pulse oximeters can only be as accurate as their empirical calibration curves. Understandably, researchers were limited in the degree of hypoxemia inducible in these volunteers, to a SaO_2 of approximately 75% to 80%. Therefore, the shape of the curve below these levels must be extrapolated, with obvious implications for the accuracy of pulse oximetry at low oxygen saturations. Early accuracy studies showed such great inaccuracy and bias at low oxygen saturation that manufacturers revised early calibration curves and software. [6] More recent studies, however, continue to show significant bias, increasing as oxygen saturation decreases, [7] although it has been justifiably pointed out that few, if any, clinical treatment decisions will hinge on whether the oxygen saturation is actually 50% or 60%. [4] Healthy young adults have usually comprised the subject groups used for calibration. One manufacturer was even said to have used two Olympic athletes in calibration trials. [5] As such, the applicability of data from such a narrow population to patients at the extremes of ages and with various medical problems has been questioned.

ii) Optical Interference

Many substances in the blood, both endogenous and exogenous, can interfere optically with pulse Oximetry, even when controlling for the contributions of the static components of arterial blood. This interference generally takes the form of false absorbers, or components besides reduced Hb and HbO2 that will absorb light within the red and near infrared wavelengths used in pulse Oximetry.

iii) Signal Artifact

Most commonly, problems in pulse Oximetry arise from signal artifact. The presence of a sharp pulsatile waveform displayed on those oximeter models featuring a plethysmograph is no guarantee against signal artifact. Signal artifact results from false sources of signal or from a low signal-to-noise ratio. False signal can arise from detection of non-transmitted light (ambient sources or optical shunt) or from non-arterial sources of alternating signal. A low signal-to-noise ratio results from inadequate signal complicated by an excess of physiological or technical noise.

iv) Fingernail polish

Earlier reports of pulse oximeters noted that fingernail polish, particularly black, blue, and green color, can lower SpO_2 by up to 10%. [8,9] More recent studies with newer models of pulse oximeters found that fingernail polish has only a minor effect on SpO_2 readings; i.e., black and brown fingernail polish displayed the greatest reduction in the SpO_2 reading but by an average decrease of _2%[10]. In 50 critically ill patients requiring mechanical ventilation, Hinkelbein and colleagues [29] found that the mean difference between SpO_2 and SaO_2 was greatest for black (+1.6 % ± 3.0 %), purple (+1.2 % ± 2.6 %), and dark blue (+1.1 % ± 3.5 %) nail polish; limits of agreement ranged from 6 % (unpainted fingernail) to 14.4 % (dark blue) (Fig. 5). Rotating the oximeter finger probe by 90 ° did not eliminate the error induced with nail polish [11].

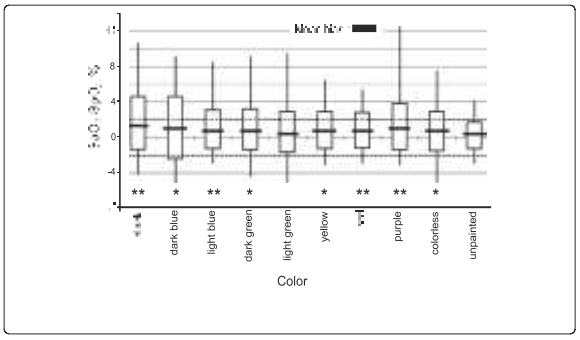

Fig. 5 Bias of O_2 saturation pulse oximetry (SpO2) and arterial O_2 saturation (SaO_2) of various nail polish colors in critically ill patients. Thick horizontal lines represent mean bias, the whiskers represent maximum and minimum bias; the bottom and top of the boxes represent the first and third quartiles. *$P < 0.05$, **$P < 0.01$ when compared with arterial oxygen saturation. Reprinted with permission from Elsevier Inc. [29]

v) Excessive movement

Excessive movement such as tremor or convulsions has been documented to cause spuriously low SpO_2, with desaturations below 50% sometimes observed, [12, 13] though less commonly SpO_2 over estimations can also occur. In theory, motion can cause the normally static tissues in relation to the sensor position to change over the time frame of the arterial pulses. At times, this motion can augment or mimic the cardiac-induced signals as the blood in the veins (and other previously stationary tissues) are now moving, further modulating the red and IR light attenuation in the probed tissue. However, many newer generation pulse oximeters have improved processing algorithms that reduce the occurrence of false SpO_2 readings due to excessive patient movements. [12, 13]

vi) Inherited forms of abnormal hemoglobin

Uncommon Hb variants have been reported to cause spuriously decreased SpO_2 readings, including Hb Lansing[14] Hb Bonn,[15] Hb Koln,[16,17] Hb Hammersmith,[18] and Hb Cheverly.[19] Sarikonda et al. [14] reported a father and daughter with SpO_2 readings that were more than 10% lower than SaO_2 measurements due to an abnormal Hb variant (Hb Lansing) which accounted for 11% of their total Hb. Assessment of oxygen affinity was normal, suggesting that interference of absorbance of red and/or near-IR light by the abnormal Hb accounted for the spurious reduction in SpO_2. [14]

vii) Poor probe positioning resulting in decrease absorption of red and/or IR light

Poor probe positioning resulting in decrease absorption of red and/or IR light Poor probe positioning can result in light shunting wherein the emitted light bypasses tissues and strikes the photo detector. If both transmitted red and/or IR light are largely unabsorbed, the R value can approach 1 (see Red: IR Modulation equation above). As a result, similar to that seen with Methemoglobinemia, the SpO_2 may either overestimate or underestimate the SaO_2. In older models of pulse oximeters, ambient light complicated SpO_2 measurements by directly hitting the photo detector or by increasing the amount of light going through the tissues, making the SpO_2 measurements unreliable. However, most modern pulse oximeters are able to "subtract" the ambient light signals. If effects of ambient light remain a concern, shielding the probe with an opaque material is a simple solution.

viii) Fetal Hb (HbF)

The absorbencies of red and near-IR light by HbF is essentially the same as HbA and thus SpO_2 measurement is as reliable in newborns as in adults. However, HbF may be misread as COHb by co-oximeters, thereby spuriously lowering the FO_2Hb.[20] The degree to which HbF affects FO_2Hb readings depends on the specific co-oximeter used as different co-oximeter models often utilize different sets of wavelengths; in addition, HbA and HbF differ in light absorbance (for both O_2Hb and HHb) primarily in the 450e650 nm spectral range e which coincides with the wavelengths used by most co-oximeters.[21,22] Although simply adding the fictitious COHb level to O_2Hb in an attempt to correct the FO_2Hb (provided there is no evidence of hemolysis or CO poisoning that can cause a true increase in COHb) may work for some systems, some co oximeters can correct the readings in the presence of HbF. While using the oxygen dissociation curve to derive a calculated SaO_2 from the PaO_2 is another option, this can be inaccurate as

the oxygen dissociation curve for HbA and HbF can significantly differ throughout the SaO_2 span; more specifically, the p50, defined as the PaO_2 which correlate with a SaO_2 of 50%, is 19mmHg for HbF and 27mmHg for HbA. Thus, in the presence of HbF, the SpO_2 is at least as accurate, if not more so, than co-oximeter-derived O_2 saturations. Given the variability of how co-oximeters assess SaO_2 in the presence of HbF, clinicians and blood gas technicians should have a practical and mutual understanding of how co-oximeter results may be affected by HbF at their particular institutions.

4. CONCLUSION

The light path in biological tissue is complex and involves multiple scattering that results in higher light absorption due to prolongation of the optical path-length. The extent of light absorption depends on the wavelength of light, tissue characteristics, and the distribution of blood in the tissue through which it propagates. The determination of blood oxygen saturation in a given tissue sample cannot be derived directly from light transmission measurements through that tissue sample because of missing information regarding the scattering. The available pulse oximeters for arterial oxygen saturation measurement use light in two wavelengths, in the red and infrared regions, and calibration is used to account for the difference in optical path-length between them. The accuracy of the commercial pulse oximeters is adequate for monitoring patients during surgical operation, where the clinical information that is needed is the absence of dramatic deterioration in the respiration efficiency. However, the error in pulse oximetry is too high for the clinical assessment of lung function, probably because of the need for calibration in the available.

5. NOMENCLATURE

- SaO_2 is the hemoglobin saturation with oxygen in the systemic arteries of the human body;
- SpO_2 is the hemoglobin saturation with oxygen as measured by pulse oximeter;
- Partial saturation is the ratio HbO_2/ (total Hb);
- Partial pressure of oxygen (PaO_2).
- Fetal Hb (HbF)
- Carboxy- Hb (COHb)
- Fractional O_2Hb

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