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Review Article

Pitfalls, Myths, and Errors in Pulse Oximetry: Understanding False Readings in Severe Hypoxemia

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Abstract

Pulse oximetry is a widely used, non-invasive method for monitoring oxygen saturation (SpO_2) in clinical and specialized settings, including maritime and high-altitude medicine. However, several pitfalls and misconceptions can lead to false readings, particularly in cases of severe hypoxemia. This mini-review explores the limitations of pulse oximetry, the role of perfusion index (PI) in assessing peripheral circulation, and common sources of measurement errors, such as low perfusion states, motion artifacts, and skin pigmentation. The clinical interpretation of SpO_2 levels is discussed, emphasizing the need for caution when readings fall below 65%, where peripheral cyanosis is evident, rendering further saturation assessment redundant. Additionally, a nomogram illustrating the relationship between SpO_2, partial pressure of oxygen (PaO_2), pH, and $PaCO_2$ is presented, aiding in the understanding of respiratory acidosis and alkalosis. The review also highlights the importance of SpO_2 monitoring in critical conditions, including cytokine storm syndromes, and discusses the integration of Bluetooth-enabled pulse oximeters for real-time data transmission. Understanding the limitations and proper interpretation of SpO_2 readings is crucial for avoiding misdiagnosis and ensuring accurate clinical decision-making.

Keywords: *Oxygen Saturation (SpO_2); Pulse Oximetry; Hypoxemia; Perfusion Index (PI)*

Introduction

Oxygen saturation (SpO_2) is a fundamental parameter in clinical medicine, used to assess a patient's oxygenation status [1]. It represents the percentage of hemoglobin bound to oxygen and is commonly measured using pulse oximetry, a non-invasive and widely available method. While pulse oximetry is a valuable tool in everyday clinical practice, it is subject to significant limitations, particularly in cases of severe hypoxemia [2]. The reliance on pulse oximeters without understanding their potential errors can lead to misinterpretations, incorrect clinical decisions, and unnecessary interventions [3,4].

Pulse oximeters operate by emitting light at two wavelengths-red (660 nm) and infrared (940 nm)-to differentiate between oxygenated and deoxygenated hemoglobin. However, one of the major pitfalls of this technology is its inability to distinguish between oxyhemoglobin (HbO_2) and carboxyhemoglobin (COHb) [5]. This leads to falsely elevated SpO_2 readings in patients with carbon monoxide poisoning, as COHb absorbs light in a similar manner to HbO_2 [5]. As a result, a patient with severe carbon monoxide poisoning may appear to have a normal or mildly reduced SpO_2, despite critical tissue hypoxia. This fundamental flaw makes pulse oximetry unreliable in conditions involving abnormal hemoglobin species [5,6].

Another key limitation of pulse oximetry is its inaccuracy in extreme hypoxemia. At saturations below 80%, the device's performance declines significantly, with increasing measurement errors. SpO_2 values below 65% become unreliable, often displaying inaccurate or inconsistent readings due to signal degradation [6]. Clinicians sometimes report SpO_2 readings as low as 50 - 55%, which is physiologically implausible and often results from measurement artifacts rather than actual oxygen saturation. Furthermore, cyanosis-a clinical sign of severe hypoxemia-typically manifests when SpO_2 drops to around 65%, meaning that extremely low SpO_2 readings should always be interpreted with caution and correlated with clinical findings [6,7].

Other common sources of pulse oximetry error include low perfusion states, where conditions such as shock, hypothermia, or severe hypotension reduce peripheral blood flow, leading to weak signals and inaccurate SpO_2 readings [7]. Skin pigmentation and nail polish can also interfere with light absorption, as darker skin tones, nail polish, and artificial nails may result in falsely high or low SpO_2 values [7,8]. Motion artifacts caused by patient movement, shivering, or tremors can disrupt the sensor's ability to detect an accurate signal. Methemoglobinemia is another source of error, as elevated levels of methemoglobin (MetHb) cause pulse oximeters to converge toward an SpO_2 reading of 85%, regardless of true oxygen saturation [8]. Additionally, ambient light interference from bright overhead lights, surgical lamps, and phototherapy in neonatal care can affect the sensor's light absorption, leading to erratic SpO_2 readings.

Despite these limitations, pulse oximetry remains a crucial tool in clinical practice, but its readings must always be interpreted in context. This manuscript aims to highlight the pitfalls, myths, and errors associated with pulse oximetry, providing clinicians with a deeper understanding of when and why this technology fails. Recognizing these limitations can improve patient safety, prevent misdiagnoses, and encourage the use of supplementary methods, such as arterial blood gas analysis, in cases of uncertainty [5-7].

Figure 1 and 2 display the LCD screens of a commercial finger pulse oximeter, showcasing real-time measurements of SpO_2, perfusion index (PI), heart rate (BPM), battery status, and a spectrogram of plethysmography. Additionally, the device features Bluetooth connectivity, allowing for wireless data transmission to compatible medical applications for further analysis and monitoring.

Figure 1: *Commercial pulse oximeter with bluetooth connectivity: Displaying SpO_2, heart rate, perfusion index, and battery status.*

Perfusion index (PI) is a numerical value displayed on some pulse oximeters that indicates the strength of blood flow at the sensor site. It is calculated as the ratio of pulsatile (arterial) blood flow to non-pulsatile (static) blood flow in peripheral tissue. A higher PI suggests stronger perfusion, while a lower PI may indicate compromised peripheral blood flow. Factors such as low perfusion states, sensor placement, and patient movement can affect PI readings. Therefore, while PI can provide useful information about peripheral perfusion, it should be interpreted in conjunction with other clinical assessments [8]. A higher PI% suggests stronger blood flow at the measurement site, while a lower PI% may indicate weak perfusion due to conditions such as vasoconstriction, hypothermia, or low cardiac output. PI% values vary between individuals and body sites [8,9]. Generally, a PI% above 1.0% is considered good, while values below 0.5% may indicate poor circulation. Clinically, PI% helps assess the reliability of SpO_2 readings, as low PI% may make pulse oximeter readings less accurate. It is also used in anesthesia and intensive care to monitor peripheral circulation and can assist in detecting conditions like shock or poor peripheral perfusion [9].

Despite its usefulness, PI% has limitations. It is affected by movement, skin temperature, and sensor placement. It is not a direct measure of oxygenation or blood pressure but rather a perfusion marker, meaning it should always be interpreted alongside other clinical parameters [9,10].

Figure 2: *Commercial pulse oximeter with bluetooth connectivity: Displaying SpO_2, heart rate, perfusion index, battery status, and real-time perfusion fluctuations on a spectral diagram.*

Perfusion index (PI%) values vary based on individual physiology, measurement site, and clinical conditions. However, general reference ranges and their interpretations are as follows: A PI% value of less than 0.3% indicates very low perfusion, suggesting poor peripheral circulation, possibly due to vasoconstriction, hypothermia, low cardiac output, or shock [10,11]. In such cases, pulse oximetry readings may be inaccurate. A PI% ranging from 0.3% to 0.9% reflects low perfusion, often seen in patients with cold extremities or peripheral vascular disease, where SpO_2 readings may be less reliable [11,12]. Moderate perfusion is generally represented by a PI% between 1.0% and 2.0%, which is considered adequate for reliable SpO_2 measurements and is commonly observed in healthy individuals at rest [11]. Good perfusion, characterized by a PI% between 2.0% and 5.0%, signifies strong peripheral blood flow, ensuring accurate pulse oximetry readings and is frequently seen in well-perfused, healthy individuals [12,13]. A PI% greater than 5.0% indicates high perfusion, often observed in conditions with increased blood flow such as fever, hyperdynamic circulation, or exercise [13]. While this does not necessarily indicate pathology, it should always be correlated with the clinical context.

Clinically, PI% is useful for assessing the reliability of pulse oximetry readings, particularly in anesthesia and intensive care settings for monitoring peripheral perfusion [13]. It plays a role in evaluating patients with circulatory shock, sepsis, or other forms of hemodynamic instability and is also applied in neonatal care to assess circulation in preterm infants.

Correlation of SpO_2 and perfusion index (PI%) with blood gas analysis

Pulse oximetry provides a non-invasive estimate of arterial oxygen saturation (SpO_2), while blood gas analysis directly measures key respiratory and metabolic parameters, including partial pressure of oxygen (PaO_2), partial pressure of carbon dioxide ($PaCO_2$), bicarbonate (HCO_3^-), and pH. Although SpO_2 and PaO_2 are related, their correlation is non-linear, particularly in cases of hypoxemia [14]. The oxyhemoglobin dissociation curve, which describes the relationship between PaO_2 and hemoglobin saturation, is influenced by factors such as pH, temperature, $PaCO_2$ and 2,3-DPG levels. A PaO_2 above 80 mmHg typically corresponds to an SpO_2 of 95% or higher, but in severe hypoxemia, small changes in PaO_2 can lead to large drops in SpO_2 [14,15].

PI% reflects the strength of peripheral blood flow and can affect the reliability of SpO_2 readings. In patients with low PI% due to vasoconstriction, shock, or hypothermia, pulse oximeters may struggle to detect pulsatile signals, leading to inaccurate SpO_2 readings [16]. Blood gas analysis remains the gold standard in assessing oxygenation, ventilation, and acid-base balance, as it provides direct PaO_2 and $PaCO_2$ measurements, which SpO_2 alone cannot differentiate [15,16] Discrepancies between SpO_2 and PaO_2 may arise in conditions such as carbon monoxide poisoning, methemoglobinemia, and anemia, where abnormal hemoglobin species interfere with SpO_2 readings [14,16]. Therefore, while SpO_2 and PI% offer valuable real-time monitoring, their interpretation must be complemented by arterial blood gas analysis in critical clinical scenarios [17]. Pulse oximetry and blood gas analysis are essential tools in managing patients experiencing a cytokine storm, a severe hyperinflammatory response often associated with infections like COVID-19 [18].

Figure 3 below illustrates these relationships. Here is a nomogram illustrating the relationship between oxygen saturation ($SpO_{2)}$, partial pressure of oxygen (PaO2), pH, and PaCO2 [19]. The blue curve represents the oxygen dissociation curve (PaO2 vs. SpO2), while the red markers show the PaCO2 vs. pH correlation, highlighting respiratory acidosis and alkalosis. Let me know if you need modifications or additional parameters.

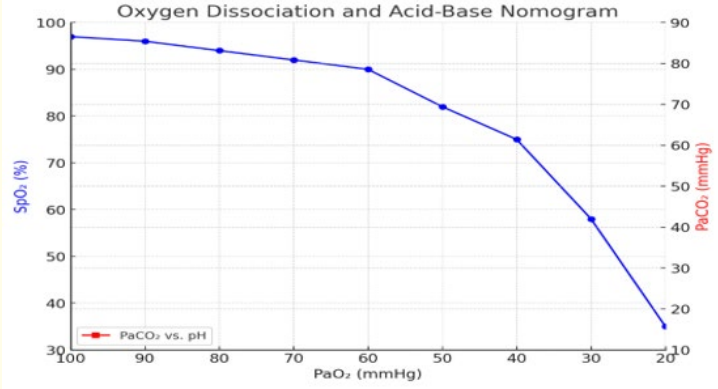

Figure 3: *Nomogram depicting the relationship between oxygen saturation (SpO_2), partial pressure of oxygen (PaO_2), pH, and $PaCO_2$: Visualizing the effects of respiratory acidosis and alkalosis on oxygen dissociation.*

A good level of SpO_2 generally depends on the clinical context. The normal range for healthy individuals is 95 - 100%. Mild hypoxemia occurs between 90 - 94% and may require monitoring. Moderate hypoxemia, ranging from 80 - 89%, often necessitates oxygen therapy. Severe hypoxemia is defined as SpO_2 below 80% and requires urgent medical intervention. A critical level below 65% is usually incompatible with consciousness and is accompanied by clear peripheral and central cyanosis. In maritime medicine, including diving and high-altitude operations, oxygen saturation below 90% is concerning, while levels below 85% indicate serious hypoxia requiring immediate intervention.

Figure 4 presents oxygen saturation levels and their clinical relevance, illustrating the physiological and medical implications of varying SpO_2 values. Additionally, the figure highlights the significance of oxygen saturation in maritime medicine, where levels below 90% are concerning, and values under 85% indicate serious hypoxia requiring immediate intervention. A sample plethysmography waveform is also included to illustrate saturation fluctuations.

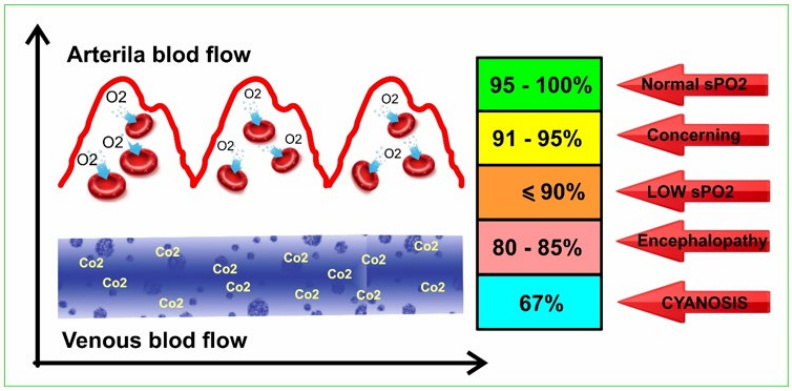

Figure 4: *Oxygen saturation levels and their clinical relevance. The diagram illustrates different SpO_2 levels and their physiological and clinical implications, ranging from normal oxygenation to encephalopathy and cyanosis, along with a sample diagram of plethysmography.*

Conclusion

Pulse oximetry remains an essential, non-invasive tool for monitoring oxygen saturation in clinical practice. However, its reliability is significantly affected by various physiological and technical limitations, particularly in cases of severe hypoxemia. Understanding the pitfalls, myths, and common errors associated with pulse oximetry is crucial for accurate interpretation and clinical decision-making. Factors such as low perfusion states, abnormal hemoglobin species, motion artifacts, skin pigmentation, and ambient light interference can all contribute to false readings, potentially leading to misdiagnosis or inappropriate management.

Additionally, the reliance on SpO_2 alone without correlation with arterial blood gas analysis (ABG) may mask critical hypoxemia, particularly in conditions such as methemoglobinemia or carbon monoxide poisoning. The perfusion index (PI%) offers valuable insight into signal quality and peripheral circulation, but its interpretation should be integrated with other clinical parameters.

Given these limitations, clinicians must remain vigilant in recognizing misleading SpO_2 values and supplement pulse oximetry with arterial blood gas measurements when precise oxygenation status is required. Furthermore, any clinical interpretation of SpO_2 values below 65% is unnecessary, as such profound desaturation is always accompanied by evident peripheral cyanosis, rendering pulse oximetry readings redundant and almost comical. A comprehensive understanding of these challenges will enhance patient safety and improve the clinical utility of pulse oximetry in diverse medical settings.

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