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PULSE OXIMETER: AN UNIQUE DEVICE FOR MONITORING OF OXYGENATION OF HAEMOGLOBIN IN BLOOD

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ABSTRACT

Pulse oximetry is a noninvasive method for monitoring a person's oxygen saturation. Though its reading of peripheral oxygen saturation (SpO_2) is not always identical to the more desirable reading of arterial oxygen saturation (SaO_2) from arterial blood gas analysis, the two are correlated well enough that the safe, convenient, noninvasive, inexpensive pulse oximetry method is valuable for measuring oxygen saturation in clinical use. In its most common (transmissive) application mode, a sensor device is placed on a thin part of the patient's body, usually a fingertip or earlobe, or in the case of an infant, across a foot. The device passes two wavelengths of light through the body part to a photodetector. It measures the changing absorbance at each of the wavelengths, allowing it to determine the absorbances due to the pulsing arterial blood alone, excluding venous blood, skin, bone, muscle, fat, and (in most cases) nail polish. Reflectance pulse oximetry is a less common alternative to transmissive pulse oximetry. This method does not require a thin section of the person's body and is therefore well suited to a universal application such as the feet, forehead, and chest, but it also has some limitations. Vasodilation and pooling of venous blood in the head due to compromised venous return to the heart can cause a combination of arterial and venous pulsations in the forehead region and lead to spurious SpO2 results. Such conditions occur while undergoing anesthesia with endotracheal intubation and mechanical ventilation or in patients in the Trendelenburg position.

KEYWORDS: Haemoglobin, Oxyhaemoglobin, Deoxyhaemoglobin, Haeme, Hypoxia, SaO_2, SpO_2.

INTRODUCTION

Pulse oximeters measure how much of the haemoglobin in the blood is carrying oxygen (oxygen saturation). They are more commonly used in the areas such as operating rooms, recovery, critical care, wards, and ambulances. They have the following advantages for which they are extensively used:

1) Non-invasive
2) Cheap to buy and use
3) Compact nature
4) Detects hypoxemia earlier than naked eye to see cyanosis.

Figure-1: Takuo Aoyagi.

Takuo Aoyagi, a Japanese engineer whose pioneering work in the 1970's led to the modern pulse oximeter, a life saving device that clips on a finger and shows the level of oxygen in the blood and that has become a critical tool in the fight against the novel coronavirus. While many coronavirus patients do feel chest pain, fever and other symptoms the pulse oximeter will continue are a blessing to human race and to people who do not sense low oxygen saturation alone. Moreover, many covid patients are asymptomatic. As a result, when moderately or mildly ill patients test positive for the coronavirus, they may be sent home with a pulse oximeter so that they can track their oxygen level and return to the hospital when the level drops.

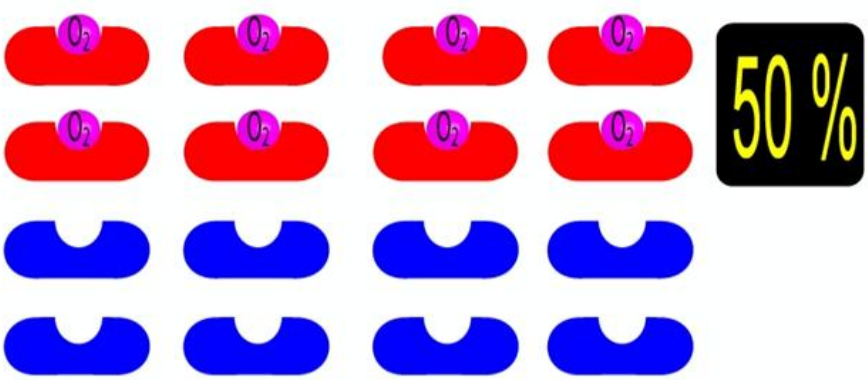

Figure-2: Oximetry.

Oxygen saturation: Oxygen enters the lungs and then is passed on into our blood. The blood carries the oxygen to the various organs in our body. The main way oxygen is carried in our blood is by means of haemoglobin. The haemoglobin without oxygen we will call de oxygenated haemoglobin (deoxy Hb). The haemoglobin with oxygen, we will call oxygenated haemoglobin. Oxygen saturation simply refers to the percentage of the available haemoglobin that carries oxygen. In the above diagram, 8 out of 16 Hb have oxygen. The oxygen saturation is therefore 50%.

Physical properties used in pulse oximetry

Pulse oximetry uses light to work out the oxygen saturation. Light is emitted from light sources which goes across the pulse oximeter probe and reaches the light detector. If the finger is placed in between the light source and the light detector, the light will now have to pass through the finger to reach the detector. Part of the light will be absorbed by the finger and the part not absorbed reaches the light detector.

Figure-3: Detection of oxygen content in blood.

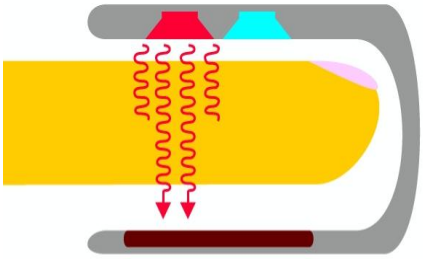

Figure-4: Passage of photon through finger point.

Figures-3 and 4 will help in understanding the above statement with precision.

The amount of light absorbed depends on the following:

1) Concentration of the light absorbing substance
2) Length of the light path in the absorbing substance
3) Oxyhaemoglobin and deoxyhaemoglobin absorbs read and infrared light differently.

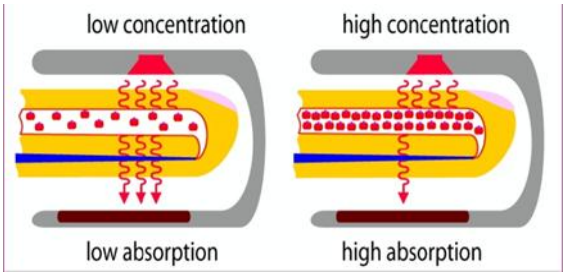

Figure-5: Mechanism of pulse oximetry.

Explaination to the physical properties

(1) Haemoglobin (Hb) absorbs light. The amount of light absorbed is proportional to the concentration of Hb in the blood vessel. The following diagram will prove that the blood vessels in both fingers have the same diameter. However, one blood vessel has a low concentration of Hb while the other blood vessel has a high concentration of Hb. More the amount of Hb in a particular area, more the light is absorbed. This property is described using the law in physics called "Beer's Law". [*Beer's Law is an equation that relates the attenuation of light to properties of a material. The law states that the concentration of a chemical is directly proportional to the absorbance of a solution.*]

(2) We consider two arteries. Both the arteries have the same concentration of Hb. However one artery is wide which means have a wider diameter and the other one is narrow implying it has a narrow diameter. The light emitted from the source has to travel through the artery. The light travels in a shorter path in the narrow artery and travels through a longer path in the wider artery. Though the concentration of Hb is same in both arteries, the light meets more

Hb in the wider artery, since it travels in a longer path. This property is described in a law in physics called "Lambert's Law". [*Lambert's Law is an equation that relates the attenuation of light to properties of a material. The law states that the absorbance of a solution is directly proportional to the path of solution.*]

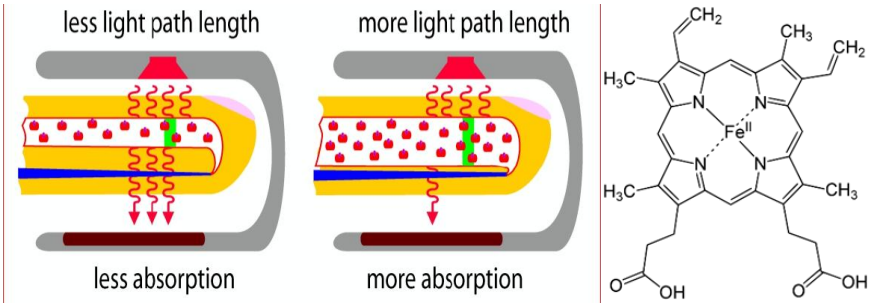

Figure-6: Heme and light absorption.

(3) Oxyhaemoglobin absorbs more infrared light than red light and deoxyhaemoglobin absorbs more red light than infrared light. The pulse oximeter makes use of another important property to calculate oxygen saturation. That is oxyhaemoglobin and deoxyhaemoglobin absorb light of different wavelengths in a specific way.

What is Oxyhemoglobin: Oxyhemoglobin is the oxygen-bound form of hemoglobin. During respiration in the lungs, the hemoglobin component of the red blood cells is exposed to oxygen and loosely bound to it. The binding of oxygen into hemoglobin occurs at high pH, low carbon dioxide, and high-temperature conditions of the blood, which generally occurs inside the lungs. With the binding of the first oxygen molecule to the iron (II), the heme pulls the iron (II) into the porphyrin ring. This slight conformational shift encourages the binding of another three oxygen molecules to the hemoglobin. Ultimately, oxyhemoglobin contains four bound oxygen molecules in its fully saturated form. Therefore, oxyhemoglobin is considered to be in the relaxed (R) state of hemoglobin.

Difference Between Oxyhemoglobin and Deoxyhemoglobin

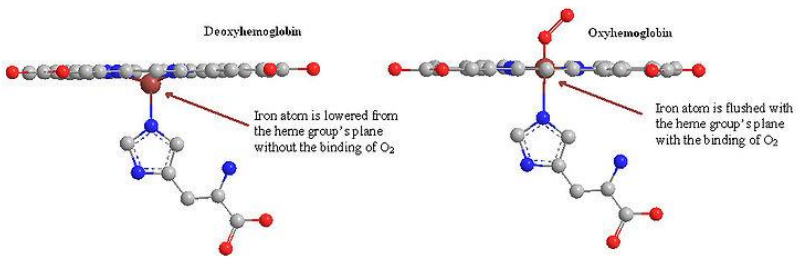

Figure-7: Deoxygenated and Oxygenated Hemoglobin Structure.

Blood that carries oxyhemoglobin is called oxygenated blood. Oxygenated blood flows through arteries, away from the heart under the force generated by the heart. The color of oxygenated blood is bright red. When oxyhemoglobin drops oxygen at the cells, oxygen is used as the final electron acceptor by a process known as oxidative phosphorylation during the production of ATP. The removal of oxygen from the blood causes a drop in the pH of the blood.

What is Deoxyhemoglobin: Deoxyhemoglobin is the hemoglobin that has released oxygen. The release of oxygen occurs at the metabolizing tissue due to the low pH, high carbon dioxide concentration, and low temperature. Deoxyhemoglobin is the tensed (T) state of hemoglobin due to the release of oxygen molecules.

The pulse oximeter uses the property that oxyhaemoglobin and deoxyhaemoglobin absorb light of different wavelengths in a specific way. If we study the absorbance graph of oxy Hb and the absorbance graph of deoxy Hb together we will see that how each of them absorbs light of different wavelengths very differently. The graph shown below will illustrate the statement.

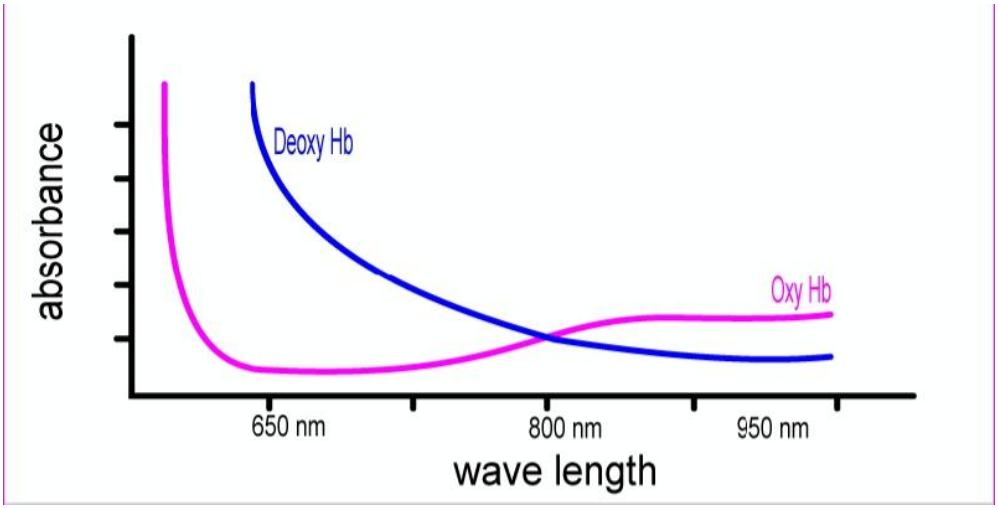

Figure-8: Absorption spectra of deoxy Hb & Oxy Hb

The pulse oximeter uses two lights to analyze haemoglobin. One is a red light which has a wavelength of 650nm (nanometer) and the other is infrared light which has a wavelength of 950nm.

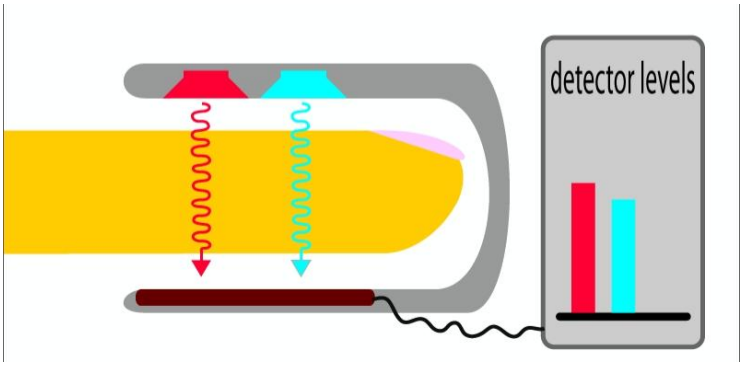

Figure-9: Detection of haemoglobin through pulse oximeter.

To make the comparision of absorbance of oxy Hb and deoxy Hb easier, here is a composite graph showing the absorbance of both. Oxy Hb absorbs more infrared light than red light whereas Deoxy Hb absorbs more red light than infrared light.

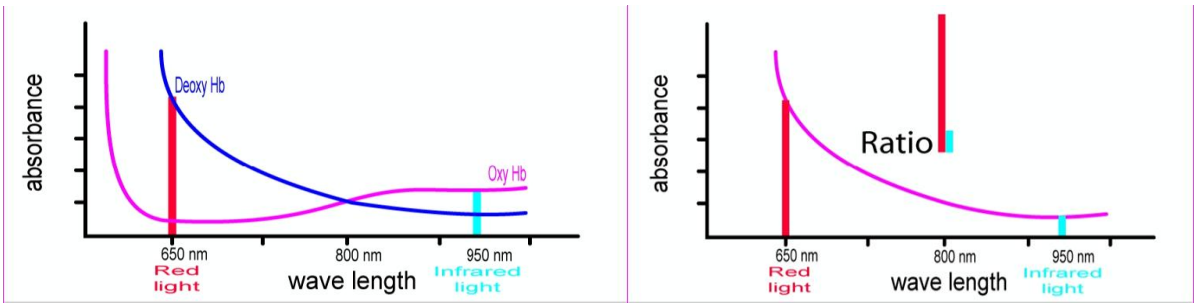

Figure-10: Absorbance of Deoxy Hb & Oxy Hb in visible UV spectra.

The pulse oximeter works out the oxygen saturation by comparing how much red light and infrared red light is absorbed by the blood. Depending on the amounts of oxy Hb and deoxy Hb present, the ratio of amount of red light absorbed compared to the amount of infrared light absorbed changes.

For an example if we compare the graphs at 100% saturation and 0% saturation we can make the following deductions.

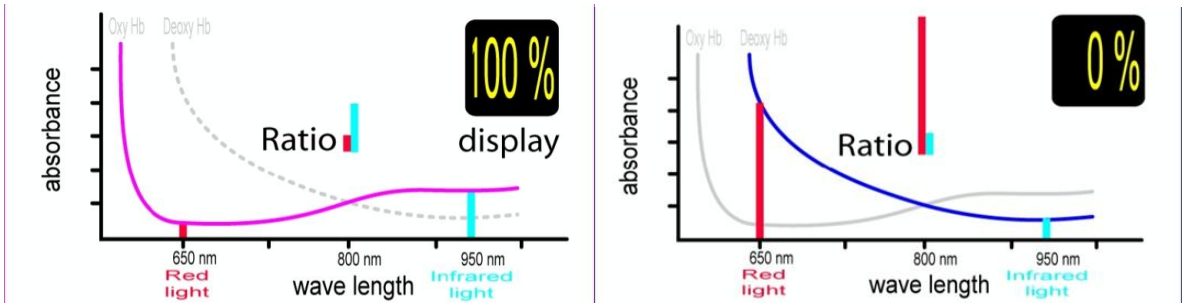

Figure-11: Absorption difference between Oxy Hb & Deoxy Hb in blood.

Accuracy of Pulse Oximetry: In critically ill patients with SaO_2 values of 90 % or higher, the mean difference between SpO_2 and SaO_2 (that is, bias) measured by a reference standard (CO-oximeter) is less than 2%; the standard deviation of the differences between the two measurements (that is, precision) is less than 3%.[1-3] The bias and precision of pulse oximetry readings, however, worsen when SaO_2 is lower than 90%.[4,5] Although pulse oximetry is accurate in reflecting one-point measurements of SaO_2, it does not reliably predict changes in SaO_2, particularly in intensive care unit (ICU) patients.

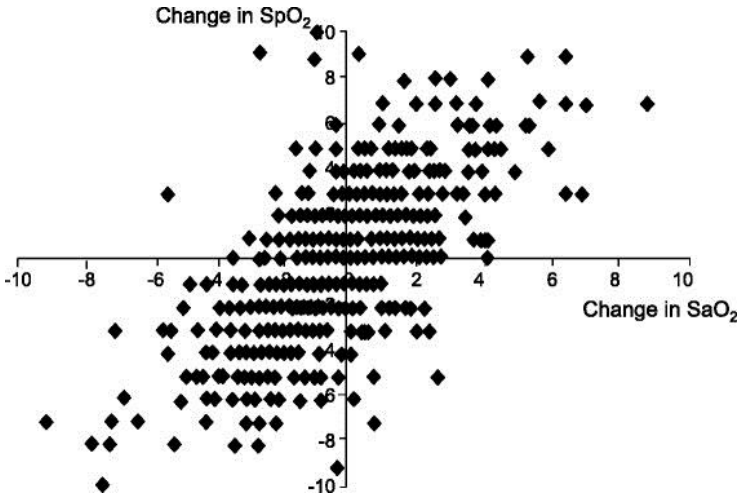

Figure-12: Changes in oxygen saturation measured by pulse oximetry (SpO_2) compared with arterial oxygen saturation measured by a CO-oximeter (SaO_2) in critically ill patients. The pulse oximeter consistently overestimated the actual changes of SaO_2.

The conventional pulse oximeters use transmission sensors in which the light emitter and detector are on opposing surfaces of the tissue bed. These sensors are suitable for use on the finger, toe, or earlobe; when tested under conditions of low perfusion, finger probes performed better than other probes.[6] Recently, pulse oximeter probes that use reflectance technology have been developed for placement on the forehead.[7] The reflectance sensor has emitter and detector components adjacent to one another, so oxygen saturation is estimated from back-scattered light rather than transmitted light. In critically ill patients with low perfusion, the bias and precision between SpO_2 and SaO_2 were lower for the forehead reflectance probe than for the finger probe.[8,9] The superiority of forehead reflectance probes over conventional digital probes, however, was not observed in patients with acute respiratory distress syndrome (ARDS) during a positive end-expiratory pressure (PEEP) recruitment maneuver.[10]

The response time of conventional oximeter probes varies; ear probes respond quicker to a change in O_2 saturation than finger probes.[11,12] A recent study compared the response time of the conventional finger probe with the reflectance forehead probe in patients undergoing general anesthesia (Figure-4).[13] The lengths of time it took to detect a decrease in SpO_2 to 90% after apnea was induced (desaturation response time) were 94 seconds for the forehead probe and 100 seconds for the finger probe. After mask ventilation was started, the lengths of time it took to detect an increase in SpO_2 to 100% (re-saturation response time) were 23.2 seconds for the forehead probe and 28.9 seconds for the finger probes. The investigators speculated that the shorter response time with the reflectance forehead probe was most likely due to the location of the probe rather than to the workings of the reflectance technology. The forehead probe monitors O_2 saturation from the supraorbital artery in which blood flow is abundant and is less likely to be affected by vasoconstriction than is a peripheral artery.

Clinical applications: Pulse oximetry can provide an early warning of hypoxemia.[14.15] In the largest randomized trial involving more than 20,000 perioperative patients, rates of incidence of hypoxemia (SpO_2 of less than 90%) were 7.9% in patients who were monitored with pulse oximetry and only 0.4% in patients without an oximeter.[16] The anesthesiologists reported that oximetry led to a change in therapy on at least one occasion in up to 17% of the patients. Using 95,407 electronically recorded pulse oximetry measurements from patients who underwent non-cardiac surgery at two hospitals, Ehrenfeld and colleagues reported that during the intraoperative period, 6.8% of patients had a hypoxemic event (SpO_2 of less than 90) and 3.5% of patients had a severe hypoxemic event (SpO_2 of not more than 85%) lasting more than 2 minutes.[17] Hypoxemic events occurred mostly during the induction or emergent phase of anesthesia; these time periods are consistent with the clinical view that anesthesia-transitional states are high-risk periods for hypoxemia.[18] In patients undergoing gastric bypass surgery, continuous monitoring of SpO_2 revealed that episodic hypoxemia (SpO_2 of less than 90% for at least 30 seconds) occurred in all patients. For each patient, desaturation lasted as long as 21±15 minutes.[19]

Pulse oximetry has been shown to be reliable in titrating the fractional inspired oxygen concentration (F_IO_2) in patients requiring mechanical ventilation; aiming for an SpO_2 of 92% is reasonable for ensuring satisfactory oxygenation in Caucasian patients.[4] To determine whether the ratio of SpO_2 to F_IO_2 (S/F) can be used as a surrogate for the ratio of PaO_2 to F_IO_2 (P/F), SpO_2 and PaO_2 data from 1,074 patients with acute lung injury or ARDS who

were enrolled in two large clinical trials were compared.[20] An S/F ratio of 235 predicted a P/F ratio of 200 (oxygenation criterion for ARDS), a sensitivity of 0.85, and a specificity of 0.85. An S/F ratio of 310 reflected a P/F ratio of 300 (oxygenation criterion for acute lung injury), a sensitivity of 0.91, and a specificity of 0.56. In patients undergoing surgery, the S/F ratio was shown to be a reliable proxy for the P/F ratio (correlation coefficient (r) of 0.46), especially in those patients requiring PEEP levels of greater than 9 cm H_2O (r = 0.68) and those patients with a P/F ratio of 300 or less (r = 0.61).[21] In the ICU, the S/F ratio can also be a surrogate measure for the P/F ratio when calculating the sequential organ failure assessment score, which measures the severity of organ dysfunction in critically ill patients.[22]

Limitations: Oximeters have limitations which may result in erroneous readings (Table-1). Because of the sigmoid shape of the oxyhemoglobin dissociation curve, oximetry may not detect hypoxemia in patients with high arterial oxygen tension (PaO_2) levels.[12]

Conventional pulse oximeters can distinguish only two substances: reduced hemoglobin and oxyhemoglobin; it assumes that dyshemoglobins—such as carboxyhemoglobin (COHb) and methemoglobin (MetHb)—are absent (Figure-1). Studies showed that the presence of elevated levels of COHb and MetHb could affect the accuracy of SpO_2 readings. Accordingly, multiwavelength oximeters that are capable of estimating blood levels of COHb and MetHb have recently been designed. In healthy volunteers, the accuracy of a multiwavelength oximeter (Masimo Rainbow-SET Rad-57 Pulse CO-oximeter; Masimo Corporation, Irvine, CA, USA) in measuring dyshemoglobins was evaluated by inducing carboxyhemoglobinemia (levels range from 0% to 15%) and methemoglobinemia (levels range from 0% to 12%). Bias between COHb levels measured with the pulse CO-oximeter and COHb levels measured with the laboratory CO-oximeter (standard method) was −1.22%; the corresponding precision was 2.19%. Bias±precision of MetHB measured with the pulse CO-oximeter and MetHb measured with the laboratory CO-oximeter was 0.0% ± 0.45%. The accuracy of pulse CO-oximeters in measuring COHb levels was also assessed during hypoxia. In 12 healthy volunteers, the pulse CO-oximeter was accurate in measuring COHb at an SaO_2 of less than 95% (bias of −0.7% and precision of 4.0%); however, when the SaO_2 dropped below 85%, the pulse CO-oximeter was unable to measure COHb levels. In patients evaluated in the emergency department with suspected carbon monoxide poisoning, the bias between pulse CO-oximetric measurement of COHb and laboratory CO-oximetric

measurement of COHb was less than 3%. The limits of agreement between the measurements, however, were large (−11.6 % to 14.14%) leading some authors to conclude that these new pulse CO-oximeters may not be used interchangeably with standard laboratory measurements of COHb.

Inaccurate readings with pulse oximetry have been reported with intravenous dyes used for diagnostic purposes, low perfusion states (that is, low cardiac output, vasoconstriction, and hypothermia), pigmented subjects and in patients with sickle cell anemia. Because the two wavelengths (660 and 940 nm) that pulse oximeters use to measure SpO_2 can be produced by various ambient light sources, the presence of such sources could produce false SpO_2 readings. To test the accuracy of pulse oximetry in the presence of ambient light, Fluck and colleagues performed a randomized controlled trial in healthy subjects in which SpO_2 measurements were obtained in a photographic darkroom under five separate light sources: quartz-halogen, infrared, incandescent, fluorescent, and bilirubin light. The largest difference in SpO_2 between the control condition (that is, complete darkness) and any of the five light sources was less than 5%. Nail polish can interfere with pulse oximetry readings. In addition to the light from the LEDs, ambient (room) light also hits the detector. For good functioning of the pulse oximeter, the strength of the LED light falling on the detector should be good when compared with the strength of the ambient light falling on the detector. Therefore, it is important to minimise the amount of ambient light falling on the detector. One can try and move away strong sources of room light. One can also try and cover the pulse oximeter probe and finger with a cloth etc. When the peripheral perfusion is poor (e.g. in hypotension), the arteries are much less pulsatile. The change in absorbance is therefore less and the pulse oximeter may then find the signal inadequate to correctly calculate oxygen saturation. Motion artifact is considered an important cause of error and false alarms. In the 1990s, several signal processing techniques were incorporated in pulse oximeters in an attempt to reduce motion artifact. One such technique is Masimo signal extraction technology (SET™). During motion and hypoxia, the Masimo SET oximeter performed better than the Agilent Viridia 24C (Agilent Technologies, Santa Clara, CA, USA), the Datex-Ohmeda 3740 (Datex-Ohmeda, Madison, WI, USA), and the Nellcor N-395 (Covidien Corporation, Dublin, Ireland) oximeters.

The knowledge about pulse oximetry among clinicians continues to be limited. When 551 critical care nurses were recently interviewed, 37% of them did not know that oximeters were

more likely to be inaccurate during patient motion, 15% did not know that poor signal quality can produce inaccurate readings, and 30% considered that SpO_2 readings could be used in lieu of arterial blood gas samples when managing ICU patients. When you think of problems associated with pulse oximeters it is important to remember that the signal that is analyzed is really tiny. As explained before, it is only about 2% of the total light that is analyzed. Which such a small signal, it is easy to see how errors can occur. Pulse oximeters are very vulnerable to motion, such as a patient moving his hand. As the finger moves, the light levels change dramatically. Such a poor signal makes it difficult for the pulse oximeter to calculate oxygen saturation.

The pulse oximeter operates best when all the light passes through arterial blood, as shown in the upper finger in the image below. However, if the probe is of the wrong size or has not being applied properly, some of the light, instead of going through the artery, goes by the side of the artery (shunting), (lower finger in image below). This reduces the strength of the pulsatile signal making the pulse oximeter prone to errors. It is therefore important to select the correct sized probe and to place the finger correctly in the chosen probe for best results. So there remains the problem of optical shunting.

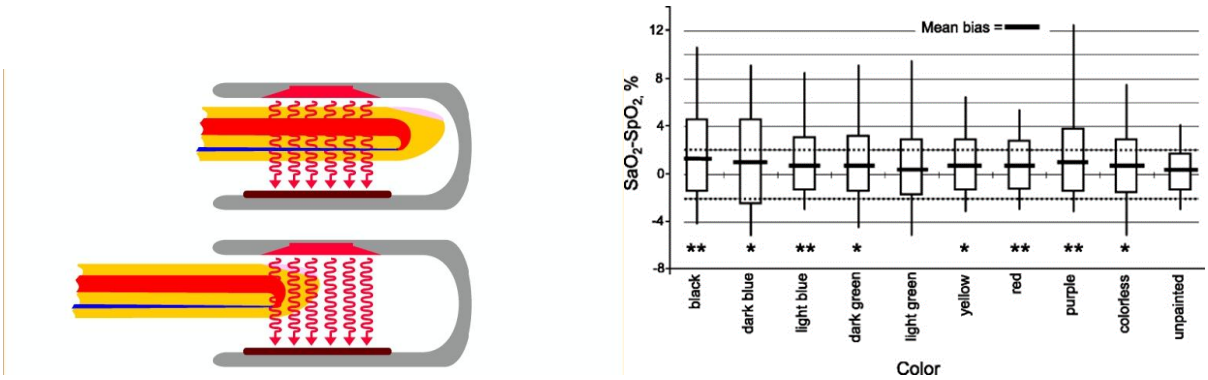

Figure-13: (Optical Shunting) and Bias of O_2 saturation pulse oximetry (SpO_2) and arterial O_2 saturation (SaO_2) of various nail polish colors in critically ill patients. Thick horizontal lines represent mean bias, the whiskers represent maximum and minimum bias; the bottom and top of the boxes represent the first and third quartiles. *P < 0.05 ,P < 0.01 when compared with arterial oxygen saturation.**

Cost effectiveness: Studies have shown that the presence of pulse oximetry may reduce the number of arterial blood gas samples obtained in the ICU and in the emergency department. However, the lack of incorporating explicit guidelines for the appropriate use of pulse oximetry may lessen the cost-effectiveness of pulse oximetry in the ICU.

CONCLUSION

Pulse oximetry is universally used for monitoring respiratory status of patients in the ICU. Recent advances in signal analysis and reflectance technology have improved the performance of pulse oximeters under conditions of motion artifact and low perfusion. Multiwavelength oximeters may prove to be useful in detecting dyshemoglobinemia. Monitoring with pulse oximetry continues to be a critical component of standard of care of critically ill patients despite the paucity of data that such devices improve outcome. In the midst of a respiratory pandemic, it makes sense to have a pulse oximeter at home – just as you might have a thermometer to track fevers. If you have symptoms of COVID-19, he says, like weakness, muscle aches or fever, you could use the device to measure blood oxygen levels. That 92% figure (or lower) is a sign that "you should get evaluated because this disease kills silently and you don't have to have significant shortness of breath to be at risk.

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The author **Mr Shouvik Sarkar** studying in BPharm Semester-VIII at School of Pharmacy, Techno India University, Kolkata, West Bengal, India got inspired to publish article on *Pulse oximeter: a unique device for monitoring of oxygenation of haemoglobin in blood* to pay tribute to the great Japanese inventor **Takuo Aoyagi** who is the inventor of pulse oximeter, a device which just uses infrared light and laws of physics [Beer's Law & Lambert's Law] to calculate the oxygen saturation and pulse rate; a miracle in the field of science. The author is associated with his esteemed project guide Prof. Dr. Dhrubo Jyoti Sen to complete a small project during final semester of BPharm under his guidance on the topic *Comparative logarithmic partition coefficient comparison study of synthesized hydrazine and phenyl hydrazine series of urea, thiourea and guanidine to form amide and lactam units* with co-researcher **Fatima Khatun** and this work has been published in peer reviewed international journal **European Journal of Pharmaceutical and Medical Research**: 7(5), 733-740, **2020** with high impact factor (6.222). The author pays homage to the eternal soul of his loving mother who is always giving support to make a milestone by removing all the agonies.

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