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Brief Report

Principles, Utility and Limitations of Pulse Oximetry in Management of COVID-19

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ABSTRACT

Pulse oximetry is an essential component of the standard care of COVID-19 patients. In the context of the spreading COVID-19 pandemic for which no targeted therapy or vaccines are yet available, early identification of the severe cases or cases with high risk of severe disease and appropriate supportive treatment are of paramount importance to save lives. Pulse oximetry is a cheap, fast, easy to use, noninvasive, painless and accurate tool that allows real-time monitoring of hypoxemia. As the primary target of the disease is the respiratory system pulse oximetry provides an unparalleled way to assess the severity of the disease, guide supportive therapies and monitor the clinical status and response to treatment with greater benefits in the low-resource settings. All settings from the quarantine facilities at the ground level to the ICUs in the highest level hospitals can utilize it to achieve their goals. To get the best of this tool, it needs to be used properly and the findings interpreted carefully. Role of basic understanding of the physiological principles and technology behind its use and awareness of its limitations cannot be overemphasized. The pulse oximetry readings are interpreted in the context of blood hemoglobin concentration, tissue perfusion, arterial blood carbon dioxide concentration and oxygen supplementation status.

Keywords: COVID-19, Limitations, Nepal, Pulse oximetry, Utility

Background

The World Health Organization (WHO) recommends that pulse oximetry be available in all settings caring for patients with severe acute respiratory infections including COVID-19 (coronavirus disease 2019).[1] In the context of spreading pandemic of COVID-19, the present article attempts to summarize the principles, utility and limitations of pulse oximetry to optimize clinical outcomes.

Physiology behind pulse oximetry

Pulse oximetry is one of the tools used to assess respiratory functions. It gives an estimate of the level of oxygen saturation of hemoglobin in the arterial blood (SaO_2). SaO_2 provides an important information about the oxygen content of the arterial blood that has been oxygenated in the lungs. Reversible binding of hemoglobin with oxygen allows hemoglobin to carry oxygen from the lungs and release it in other tissues for their functioning and survival. While breathing room air, most of the oxygen in the arterial blood is in the form bound to hemoglobin and remaining three percent is carried in the dissolved form.[2] However, the dissolved form is responsible for partial pressure of oxygen in blood and determines how much oxygen binds with hemoglobin to form oxyhemoglobin. Hemoglobin not bound to oxygen is called deoxyhemoglobin. The ratio of the actual amount of oxygen that has bound with hemoglobin relative to the maximum amount of oxygen that the total amount of hemoglobin could bind with is called oxygen saturation of hemoglobin and is expressed as percentage. The graphical relationship between oxygen saturation of

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hemoglobin and partial pressure of oxygen in blood is depicted by oxygen-hemoglobin dissociation curve (Fig. 1) and its sigmoid shape has major physiological and clinical significance.[3] Normally oxygen saturation of the arterial blood (SaO_2) is about 97%. As partial pressure of oxygen is less in the peripheral tissues, oxygen dissociates from the hemoglobin and is used by the tissues. On the same basis, if oxygenation of blood is impaired in the lungs, oxygen saturation of arterial blood (SaO_2) falls which can be detected by pulse oximetry.

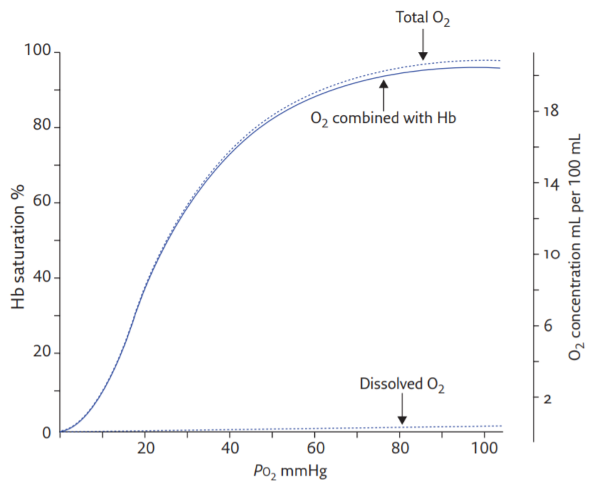

Fig. 1. Oxygen hemoglobin dissociation curve (solid curve); Total oxygen content of blood (top dotted curve) and amount of oxygen in the dissolved form (bottom dotted line) assuming normal hemoglobin (Hb) concentration (15 g/dL). PO_2: Partial pressure of oxygen in blood. [Reproduced from Collins J-A et al. European Respiratory Society 2015 (CC BY-NC 4.0)]

Besides oxygenation of blood, respiratory system is also responsible for removal of carbon dioxide. Of note, carbon dioxide concentration in the blood or extracellular fluid has a major influence on another important parameter that is pH. Gas exchange in the lungs is affected by alveolar ventilation, diffusion of the gases across the respiratory membrane, perfusion of the lungs and level of match between ventilation and perfusion.[2] Diffusing capacity of the respiratory membrane for carbon dioxide is about 20 times that for oxygen and hence carbon dioxide elimination is relatively less affected in conditions that impair diffusion.[2]

Furthermore, oxygen transport from the lungs to the tissues and carbon dioxide transport back from the tissues to the lungs depends on rate of blood flow or cardiac output. Therefore, respiratory functions need to be assessed along with the cardiovascular status.

Pathophysiology of respiratory insufficiency in COVID-19

Though the knowledge about the details of pathophysiology of COVID-19 is still evolving, primary involvement of the respiratory system is now well known. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), a virus from the Coronaviridae family is responsible for the disease.[4] SARS-CoV-2 initially enters the respiratory epithelial cells after binding with the angiotensin converting enzyme type 2 (ACE2) receptors initially in the nasal cavity and then the lower respiratory tract as well.[5, 6] Direct attack to the alveolar epithelial cells by the virus causes cellular injury and initiates immune response including leukocyte infiltration, local vasodilation, increased capillary permeability, edema and exudation. Peripheral lung areas have been found to be involved in the initial stage and in more severe cases, bilateral multifocal widespread involvement has been documented.[7] Initial interstitial edema is later complicated by alveolar edema and local abnormal blood coagulation in the pulmonary vessels worsens the scenario. Pulmonary embolism has also been observed in some cases.[5, 6] These all pathological changes compromise respiratory functions by affecting gas exchange between the alveoli and the pulmonary capillary blood and also causing ventilation-perfusion mismatch.[8] Primarily, hypoxemic respiratory failure does occur in severe cases. Regarding the effect on lung compliance, there are conflicting findings.[8, 9] Though it is possible to have normal lung compliance at least during some stage of the disease progression or recovery, low compliance that is not uncommon increases the work of breathing and dyspnea.

The overwhelming immune response also known as cytokine storm has been pointed to complicate the pathogenesis and to cause widespread involvement including other systems for instance cardiovascular and renal systems. Due to widespread expression of ACE2 receptors in many organs in the body, direct injury by the virus is also possible.[5, 6] Direct viral or indirect immunological injury to the heart and blood vessels compromises blood circulation and further reduces oxygen delivery to the tissues. Resulting compromised coronary circulation can initiate vicious positive feedback cycle of low cardiac output, lower coronary blood flow and so on culminating into death.[5]

Depending on the degree of damage to the respiratory system, clinical presentation of COVID-19 is variable. Asymptomatic infection or mild disease occurs in about 80-90% of the cases. Fever, cough, difficulty breathing are the common initial presenting complaints. Serious complications occur in about 10% of the cases and critical ones in about 5% which include rapid progression to severe pneumonia, acute respiratory distress syndrome (ARDS), respiratory failure, septic shock and multi-organ failure. Case fatality rate varies from 2-5%.[4] Co-morbid conditions like diabetes mellitus, hypertension, renal diseases, chronic obstructive pulmonary diseases, cancers etc. increase the risk of severity and death. Unlike other respiratory illnesses, COVID-19 might present with mild clinical symptoms and signs but severe fall in oxygen saturation.[4,10]

Strategies for management of COVID-19

Considering the unavailability of targeted drugs or vaccines with proven efficacy against COVID-19 till date, public health measures to prevent transmission are the mainstay of the strategies to combat COVID-19 at present. Almost the entire globe is under lockdown of variable degree with the hope to minimize transmission while buying time for better preparation to uphold the capacity of the health facilities and develop specific drugs and vaccines. For now, early detection of the cases and identification of severe cases or cases with high risk of severe disease; their isolation and treatment; tracing the contacts; quality quarantine and monitoring of the suspected contacts are the available strategies stressed by the WHO.[11] In the context of the low-resource settings like Nepal, rapid spread of the disease, limited capacity of the health care facilities and risk of infection to the frontline healthcare and support staff who are already limited in number make the abovementioned strategies invaluable both from the public health and the clinical viewpoints. Despite the enforced public health measures, it has not been possible to control transmission. New cases are on rise and so is mortality. In the absence of the specific therapy, appropriate symptomatic and supportive treatment are the only available modalities of treatment.[4] Understandably, oxygen therapy and ventilator support are among the major life-saving interventions as the disease primarily targets the lungs.

Role of pulse oximetry in management of COVID-19

Pulse oximetry is an invaluable tool for assessing respiratory functions. In contrast to arterial blood gas analysis that is the gold standard technique to evaluate respiratory insufficiency and acid-base status, pulse oximetry is a cheap, fast and easy to use technique. Pulse oximetry is reasonably accurate and allows non-invasive real time monitoring of hypoxemia.[1] These all qualities of pulse oximetry make it the best available tool for detection and continuous real time monitoring of hypoxemia.[12] These remarkable features can be utilized in management of COVID-19 from the ground levels i.e. quarantine facilities to the ICUs in the highest levels of the hospitals caring for COVID-19. Its value is even greater in low resource settings like Nepal.

Pulse oximetry can detect respiratory insufficiency that in some COVID-19 patients may not be detected on clinical examination in the early stage.[10] As evident from the discussion above, early detection and referral of the severe cases is an important step toward saving lives. Well managed quarantine facilities can help achieve this goal and pulse oximetry can be an easy to use cost-effective valuable tool and more so for people with risk factors for severe diseases. Basic orientation to pulse oximetry of all health care workers caring for people under quarantine and provision of communication with the clinicians on duty or on call may improve the outcomes. Population-wide use of pulse oximetry was not recommended in the pre-COVID-19 period.[13] However, this pandemic has raised the question if it can be used for monitoring mild cases being cared for in home isolation under guidance of telehealth facility when in-hospital care is not feasible.[6]

Use of pulse oximetry to monitor patients being transported in the ambulance is a well-known one. Similarly, it can be used for spot examination of the patients in the fever clinics, outpatient departments and monitoring in the emergency departments, isolation wards and ICUs.

Pulse oximetry aids in diagnosis of severe pneumonia. Furthermore, it can be reliably used to diagnose ARDS in resource-limited settings.[1,14] It also guides therapies like oxygen supplementation or ventilator support, the lifesaving supportive therapies for severe COVD-19. It also minimizes the use of arterial blood gas analysis.[13]

Technology behind pulse oximetry and its implications

A transmittance pulse oximeter uses a probe with a light emitter and a sensor facing each other between which a perfused tissue (finger or earlobe) is placed.[13] A modification of Beer-Lambert law is exploited to assess oxygen saturation of hemoglobin in the arterial blood flowing through the tissues. Beer-Lambert law enables determination of concentration of a light absorbing substance in a solution when intensity and wavelength of the incident light, transmission path length and absorbance characteristics of the substance are known.[15] The fact that absorbance characteristics of oxyhemoglobin and deoxyhemoglobin are different for red and near infrared light is utilized to make a differentiation between the two forms of hemoglobin. However, as significant scattering of light does occur with the current model of the pulse oximeter, some modifications to calculations from the Beer-Lambert law are introduced to minimize the error in the measurements.[16] In addition, the ability of the oximeter to analyze the pulsatile component separating it from the background absorbance of the tissues and venous blood makes it possible to estimate the oxygen saturation of hemoglobin in the arterial blood.[16] It is called SpO_2 (in contrast with SaO_2) for oxygen saturation being measured by the pulse oximeter. However, carboxyhemoglobin and methemoglobin (normally present in very low concentrations) cannot be distinguished by the usual pulse oximetry. Pulse oximetry thus overestimates oxygen saturation in carbon monoxide poisoning making the findings invalid. Multi-wavelength or laboratory CO-oximetry on the blood sample is useful in such cases as it is the gold standard.[15,16] Pulse oximeters using lights of multiple wavelengths are also available from some manufacturers with variable results.[17] Designs that do not require empirical calibration are also under consideration.[17]

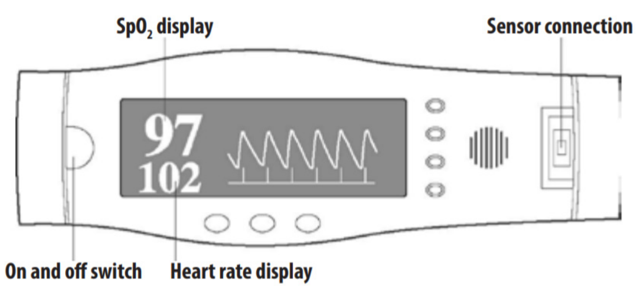

Fig. 2. Valid pulse oximeter reading with normal pulse trace; SpO_2: Oxygen saturation of hemoglobin in the arterial blood as estimated by the pulse oximeter. [Reproduced from WHO 2020. (https://www.who.int/publications-detail/clinical-care-of-severe-acute-respiratory-infections-tool-kit) (CC BY-NC-SA 3.0 IGO)]

Nail polish and excessive ambient light are also the sources of error. Besides this, motion of the probes while recording and low perfusion status add errors to the estimates.[13] Also, abnormal shape of the pulse wave displayed on the screen should question the validity of the record. The health care worker can apply the oximeter to his/her own finger to make sure that the tool is functioning well.[18] Normal reading and pulse wave is shown in Fig 2.[18]

Reflectance pulse oximeters also work on a similar principle but both the emitter and the sensor are placed on the same surface e.g. forehead.[16] They are more useful than the transmittance pulse oximeters in the conditions when the fingers are poorly perfused due to local vasoconstriction.[17]

The accuracy of pulse oximetry

Clinical studies have shown that SpO_2 readings differ from the SaO_2 readings obtained from the gold standard multi-wavelength CO-oximetry by 2-4%.[17] As it is a significant difference, cut off level of SpO_2 to diagnose hypoxemia is set at 93% to make it parallel with the SaO_2 of 90%. Regarding the use for continuous monitoring, pulse oximetry can detect sudden drop of SpO_2 by 3-4%.[17] The manufacturers use findings from healthy volunteers subjected to induced hypoxemia (but not less than SpO_2 of 70% due to ethical considerations) to validate their recordings. Therefore, findings in the critically ill patients at the extremes of age with oxygen saturation below 70% may not be so accurate.[15,16,17] From clinical viewpoint, however, it does not limit its use as the target SpO_2 is above 90%.[3] When these aspects are analysed together with its other benefits that are already mentioned, pulse oximetry is considered as an essential part of the standard critical care.[17,18]

Interpretation of the readings and limitations of pulse oximetry

Normally SpO_2 reading is 96% or greater while breathing room air at rest. A patient with SpO_2 of 94% or higher on room air is considered stable if the patient is otherwise stable. SpO_2 values of 93% or less (90% or less for patients with chronic hypoxic conditions) are considered to have high risk of developing severe illness though other risk factors also need to be considered.[14] SpO_2 less than 90% in an acutely ill patient is a clinical emergency.[18] The target SpO_2 values with oxygen therapy are 93-96%. For patients with chronic type II respiratory failure the target levels are 88-92%.[14]

Despite the remarkable utility of pulse oximetry as explained above, the best possible outcomes are achieved only when it is used properly and the findings are interpreted carefully being aware of its limitations.[13,15] Basic understanding of the technology behind the tool and the physiology of the parameter that it intends to measure and evaluate are essential.

When oxygenation of blood in the lungs is impaired, partial pressure of oxygen in arterial blood (PaO_2) decreases and oxygen saturation of arterial blood (SaO_2) also decreases but not as much as PaO_2 in mild to moderate cases (as shown by the flat top portion of the curve in Figure 2).[3] It means that even a small fall in SaO_2 reading indicates a greater fall in PaO_2 in this portion of the curve. For example, SaO_2 of 90% (normal about 98%) corresponds to PaO_2 of 60 mmHg (normal about 95 mmHg). Further decrease in PaO_2 (below 60 mmHg) due to pulmonary lesions reduces SaO_2 more rapidly as shown by the slippery slope of the curve. On the positive side, oxygen supplementation can raise PaO_2 and SaO_2 to a greater extent in such cases.

Moreover, SaO_2 gives an important but not the complete information about oxygen delivery to the tissues. Oxygen delivery to the tissues depends on oxygen content of the arterial blood and rate of blood flow to the tissues or cardiac output.[1,3] Besides SaO_2 and PaO_2, oxygen content of blood also depends on concentration of normal hemoglobin in blood. Hence, normal SaO_2 in severely anemic patients does not meet the oxygen demands of the tissues. Lack of validity of the pulse oximetry reading in elevated levels of carbon monoxide and methemoglobin have already been discussed. Another important factor to be considered to evaluate oxygen delivery to the tissues is the rate of blood flow to the tissues. Hence, SpO_2 value can falsely reassure one of the adequate oxygen delivery to the tissues. Fortunately, patients suffering from severe anemia or poor perfusion as in septic shock, benefit from oxygen supplementation as it increases oxygen delivery to the tissues by increasing the amount of oxygen dissolved in the arterial blood. Though quantitatively small, this additional dissolved oxygen may be life-saving in critically ill patients.[2]

Moreover, pulse oximetry alone does not reflect the overall ventilation status particularly in patients on oxygen supplementation. Carbon dioxide status and pH need to be determined by other techniques e.g. end tidal CO_2 or arterial blood gas analysis. Other scenarios that decrease the reliability of pulse oximetry are extremes of oxygen saturation as already mentioned.

The pulse oximetry readings also need to be interpreted in the context of the altitude of the place from the sea level. The reference values mentioned in the literature are generally for measurements on people breathing room air at sea level at rest unless mentioned otherwise. With increase in altitude, the SpO_2 values decrease even in healthy people. For example, at an altitude of 1400 m (altitude of Kathmandu), SpO_2 values are 1.5% less than those at sea level.[13] Moreover, SpO_2 values should be interpreted in the context of oxygen supplementation to evaluate the severity of the disease. The status of a patient with SpO_2 of 90% with oxygen supplementation at 10L/min is obviously more critical than the status of another patient with the same value on room air.[1]

As COVID-19 is a highly infectious disease, hand hygiene and dedicated use of pulse oximeter or if not possible, gentle cleaning and disinfection of the probe with soap water or alcohol swab after each use are integral components of infection prevention and control measures.[18]

In sum, pulse oximetry is an essential component of the standard care of COVID-19 patients in all settings. Its value is even greater in low-resource settings. And for best clinical outcomes, the pulse oximetry readings need to be interpreted in the context of hemoglobin status, tissue perfusion, arterial blood carbon dioxide concentration and oxygen supplementation status.

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