considerably increases the risk for post-operative respiratory complications, mainly due to impaired mucociliary transport system, decreased macrophage function, lowering of FEV1/VC and increased tracheobronchial glandular secretion. Smoking also increases the tracheal, bronchial and laryngeal irritability. The anesthetic agents and stasis of respiratory secretions often increase the risk for peri-anesthetic laryngospasm and bronchospasm in heavy smokers [14]. Current smokers have a higher risk for post-operative pulmonary complications, even in the absence of chronic lung disease [15]. Co-morbidities such as coronary vascular disease, peripheral vascular disease, and COPD may also warrant special attention in management [14]. Anesthetic agents may cause post-operative respiratory depression in heavy smokers, which make loco-regional anesthesia a safer option in these patients.

A study showed the incidence of complications such as re-intubation, laryngospasm, bronchospasm, aspiration, hypoventilation and hypoxemia during anesthesia was 5.5% among smokers, compared to 3.3% in non-smokers [16].

Moller et al. reported a higher rate of ICU admission after surgery, among patients with a history of heavy and long-term smoking [17]. In a prospective cohort study on 410 patients who underwent non-cardiac elective surgery, Bluman et al. reported a six-fold higher incidence of post-operative pulmonary complications in smokers compared to non-smokers [18].

Hulzebos et al. who studied 117 patients undergoing elective Coronary Artery Bypass Graft, reported that a history of cigarette smoking as a risk factor for post-surgical pulmonary complications [19].

In a study on 118 patients, Kinugasa et al. observed that elderly patients with a history of heavy smoking and poor lung function had a higher risk for pneumonia following esophagectomy [20].

Agostini et al. who studied 234 patients who underwent thoracic surgery observed that smoking was an independent risk factor for post-operative pulmonary complications [21].

A retrospective cohort analysis of 393,794 patients undergoing elective surgery, reported a higher incidence of post-operative pneumonia among current smokers, compared to never- and prior-smokers [22]. The authors observed a dose-dependent increase in pulmonary complications, with the use of more than 20 packs per year associated with a greater frequency of surgical complications. Recently, in a retrospective analysis of 117 patients, observed that age above 70 years, heavy smoking and presence of COPD significantly increased the risk for pulmonary complications following liver resection [23].

Hirsch et al. reported that exposure to smoke and mechanical ventilation may synergistically act to increase neutrophil influx and the risk of acute lung injury [24]. Reports have revealed that smoking is a risk factor that adversely affects the incidence and prognosis of acute lung injury and other respiratory complications in the peri-operative and ICU settings [25-31].

Iribarren et al. in a large epidemiological study reported a close association and dose-dependent effect of, smoking on acute respiratory distress syndrome (ARDS) [26].

Studies show that stopping smoking 48 hours before surgery reduces a cough, pathogen burden in lower airways, normalizes carboxyhemoglobin (COHb) levels, neutralizes cardiovascular effects of nicotine, and improves respiratory ciliary function. However, abstinence for 1-2 weeks is required to reduce sputum production while improving symptoms and lung function may require as long as 4-6 weeks [32]. An earlier study reported a lower incidence of post-operative complications in patients who quit smoking 8 weeks prior to surgery, than those who did not [33-35].

A contrasting study by Bluman et al. reported that abstinence for 4 weeks did not reduce the complications in smokers compared to non-smoker [18]. The minimum duration of abstinence/quitting required preventing post-operative complications are not known precisely [36].

Conventional Pulse Oximetry and its Limitations

Monitoring the oxygen saturation in peripheral circulation is critical for optimal surgical outcomes, and this is commonly done either directly by arterial blood gas analysis, or non-invasively by pulse oximetry.

Arterial blood gas (ABG) analysis involves measurements of the pH, arterial oxygen partial pressure (PaO_2), arterial carbon dioxide partial pressure ($PaCO_2$), bicarbonate ion (HCO_3-) concentration, base excess and oxygen saturation (SaO_2). While it remains the gold standard, ABG analysis is invasive, cumbersome, painful and expensive.

Conventional pulse oximetry was developed in 1972 and offers non-invasive, safe and inexpensive measurement of oxygen saturation. In pulse oximetry, a probe is placed over a vascular bed (fingertip or ear lobe). Light Emitting Diodes (LED) in the probe emits light of two wavelengths (red and infra-red), which is absorbed by the arterial and venous blood as well as the tissue. Subsequently, a photodetector detects the light that passes through the tissue. Oxyhemoglobin absorbs more infra-red light compared to hemoglobin, and the differences in absorption are measured, and the absorbance ratio compared with the SpO_2 values.

Conventional pulse oximeters employ transmission sensors with light emitters and detectors located on opposite sides of the tissue bed, and suitable for measurements from fingertips, toes or earlobes [37,38]. Pulse oximeter probes using reflectance sensors (with emitter and detector placed adjacently) have also become available, which can obtain measurements from the forehead [39].

Reflectance forehead probes have a shorter response time, compared to fingertip probes, as they obtain the readings from the supraorbital artery which has abundant blood flow and is less subject to peripheral vasoconstriction [40].

Studies show the bias (difference between SpO_2 and SaO_2) and precision of pulse oximetry measurements deteriorate at SaO_2 levels less than 90% [41,42]. Though pulse oximetry shows high accuracy in one-point measurements of SaO_2, it has poor reliability in predicting trends in SaO_2, especially in ICU patients [42,43].

However, pulse oximetry has a number of limitations. The oximetry readings can be affected by the presence of dyshemoglobins (carboxyhemoglobin and methemoglobin), intravenous dyes, low perfusion states, skin pigmentation, anemia, use of nail polish, motion artifacts as well as poor operator knowledge [38].

In particular, the accuracy of pulse oximetry can be compromised by high concentrations of carbon monoxide. Carbon monoxide combines readily with hemoglobin, with an affinity 245 times higher than oxygen, forming carboxyhemoglobin (COHb). In non-smokers, COHb is found in concentrations less than 1.5%, while the levels range between 3 to 15%, in current smokers [32].

In a preliminary study on 50 non-smoking subjects in a non-smoking environment reported an average COHb level of 1%. The authors subsequently studied COHb levels in 33 smokers and 27 non-smokers in a smoking environment, using Rad-57 pulse co-oximeter. The results showed that the non-smokers had a mean COHb level of 2.49% (range, 1-6%) while it was 5.04% (range, 1-16%) in the smokers [44].

An earlier study revealed that methemoglobinemia is a common clinical entity, and occurs in patients over a broad range of ages-from 4 days to 86 years [45]. Many drugs, including benzocaine, lidocaine, nitroglycerin, inhaled nitric oxide and dapsone can cause methemoglobinemia.

Methemoglobin and carboxyhemoglobin are incapable of oxygen transport and can reduce blood oxygenation and produce tissue hypoxemia. Methemoglobinemia and carboxyhemoglobinemia often manifest as flu-like symptoms and hence go undiagnosed, till very high levels of arterial carboxyhemoglobin saturation ($SpCO_2$) and arterial methemoglobin saturation (SpMet) are reached. Low levels of methemoglobin do not have significant clinical effects, but morbidity increases with increase in concentration, and death may occur at high levels.

Several reports show that pulse oximetry may lead to overestimation of arterial oxygenation in patients with higher levels of COHb, the extent of overestimation approximately being equal to the level of COHb [46-48].

Pulse CO-Oximetry

Pulse CO-oximetry is technology developed by Masimo Corp (Irvine, CA, USA) that enables continuous, non-invasive estimation of hemoglobin, carboxyhemoglobin, methemoglobin, oxygen level and Pleth Variability Index along with oxygen saturation, pulse rate and perfusion index [49]. The measurements are obtained using multi-wavelength sensors (single-use, adhesive type for continuous monitoring; or re-usable finger-clip sensors for spot checking) [50]. Radical-7 and Rad-87 are two versions of devices with this technology that aid bedside monitoring, while Rad-57 and Pronto are hand-held devices suitable for spot checking.

Erroneous readings and false alarms caused by patient movement have been a drawback of pulse oximeters [51-55]. However, devices with improved signal processing techniques (e.g., Masimo signal extraction technology (SETTM) has addressed this problem effectively [56-58].

Berkow et al. reported comparable accuracy of continuous non-invasive monitoring of hemoglobin (SpHb) with that of laboratory CO-oximetry, upon analysis of 130 arterial blood gas samples from patients who underwent spine surgeries [59]. Causey et al. also reported similar findings in surgical and intensive care patients [60].

In a comparison of SpHb measurements with capillary hemoglobin and laboratory methods, Lamhaurt et al. observed that the techniques yielded comparable results, though the non-invasive monitoring produced a marginal increase in outliers [61].

Lindner and Exadaktylos suggested that the real utility of SpHb measurement lies in its capability as an indicator for subtle changes in hemoglobin trends during occult bleeding or following blood transfusion. The authors remarked that the technology can improve clinical care by augmenting conventional laboratory-based monitoring [51].

A randomized controlled study on 327 surgical patients revealed that addition of SpHb monitoring to the standard care reduced blood transfusion rates from 4.5% to 0.6%, and the number of mean units (0.1 *vs.* 0.01) transfused per patient [62].

In a prospective observational study on 28 surgical patients, Yamaura et al. reported that SpHb measurements in anesthetized patients were significantly affected by thermoregulatory vasoconstriction and perfusion state [63]. Similar findings were reported by Isosu et al. in a study on Japanese surgical patients [64].

Yamada et al. reported good relative trending accuracy of SpHb measurements made using a Radical-7 pulse co-oximeter in a series of 12 patients undergoing hemodialysis in an ICU, reflecting the potential of pulse co-oximetry in evaluating relative changes in blood volume [65].

Barker et al. evaluated the accuracy of Masimo Rainbow-SET Rad-57 pulse co-oximeter (Masimo Corporation, Irvine, CA, USA) in measuring dyshemoglobins, in healthy volunteers receiving induction of carboxyhemoglobinemia (0 to 15%) and methemoglobinemia (0 to 12%). A comparison of the COHb values estimated using the instrument and a standard laboratory CO-oximeter revealed a low bias (-1.22%), and a precision of 2.19%. The corresponding values for MetHb measurements were 0.0% and 0.45%, respectively [66].

The study by Feiner et al. showed a bias and precision of -0.7% and 4.0%, respectively, in pulse CO-oximeter-based measurements of COHb at SaO_2 levels less than 95%. However, the technique failed to detect COHb when the levels were lower than 85%. [67] A low bias (3%) was also reported between CO-oximeter-based and laboratory CO-oximeter based estimation of COHb in patients with suspected carbon monoxide poisoning [68,69].

Since the limits of agreement between the two types of measurements were large, some authors have recommended against replacing laboratory CO-Hb measurements by pulse CO-oximeter readings [68-70].

According to Hare et al. anesthesia-transition periods are associated with a high risk for hypoxemia (SpO_2 less than 90%) [71]. Pulse oximetry may facilitate early detection of hypoxemia in these settings [41,72].

Another important application of pulse oximetry could be in the reliable titration of fractional inspired oxygen concentration (FIO_2) in patients receiving mechanical ventilation. Rice et al. analyzed data from 1074 patients with acute lung injury or ARDS to evaluate whether the ratio of SpO_2 to FIO_2 (S/F ratio) can be a surrogate for the ratio of PaO_2 to FIO_2 (P/F ratio). They observed that the S/F ratio was a reliable proxy for P/F ratio in surgical patients requiring mechanical ventilation [73].

A subsequent study reported that S/F ratios can be a reliable surrogate for P/F ratio in the calculation of sequential organ failure assessment score, in critically ill patients [74].

Pulse oximetry can also be a cost-effective strategy in the emergency and ICU settings, compared to ABG analysis; [75,76] however, explicit guidelines for its optimal use are still lacking.

A randomized study on 1219 surgical patients compared the utility of pulse oximetry in determining the requirement for ICU transfer of

the patients from a surgical floor [77]. The authors noted that the rate of ICU transfer for pulmonary complications was lower among the patients monitored by oximetry, compared to a control group. Oximetry-based monitoring also reduced the total estimated cost of the study ($15,481 compared to $18,173 in control group).

Despite the obvious advantages of pulse oximeters, clinical trials thus far have failed to show improvement in clinical outcomes with their use. This is attributed to the signal-to-noise ratio, [41,78] and the requirement for a larger sample size [41].

However, in view of its ability to yield multiparametric data, facile operation and cost-effectiveness, pulse oximetry may still hold considerable value in the post-operative monitoring for pulmonary complications in patients with a history of smoking.

Conclusion

Smoking exerts a heavy toll on human morbidity and mortality worldwide, and on healthcare expenditure in most countries. Patients with a history of heavy smoking face a greater risk for perioperative pulmonary complications, and systematic monitoring for these is essential for optimal clinical outcomes. Compared to ABG analysis, pulse oximetry affords a non-invasive, cost-effective and facile technology to monitor multiple parameters important to clinical monitoring of these patients. Pulse-CO-oximetry can aid early detection of hypoxemia, and reliable measurements of multiple parameters, even during periods of patient movement and low peripheral perfusion. The utility of this technology needs to be evaluated further in broader settings and larger cohorts of surgical patients.

Disclosures

- The authors declare that they have no conflict of interest.
- This article does not contain any studies with human participants or animals performed by any of the authors.
- There was no prior publication or presentation of this study.
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