Monitoring tissue oxygenation has a vital role in anaesthesia and intensive care. Oxygenation of arterial blood is monitored clinically with arterial blood-gas analysis and pulse oximetry. Continuous measurement of \( P_{A\text{O}_2} \), using an intra-arterial probe is being developed, but clinical use is limited. Pulse oximetry measures \( S_{P\text{O}_2} \) in arterial capillaries. It does not account for carboxyhaemoglobin or haemoglobin and tends to overestimate \( S_{P\text{O}_2} \) in severe hypoxaemia. While useful clinically to follow changes in arterial oxygenation, it is not equivalent to co-oximetry.

Whole body oxygen delivery (\( DO_2 \)) is derived from the product of arterial oxygen content and cardiac output. This necessitates insertion of a pulmonary artery catheter to measure cardiac output by thermodilution, a method which has variations of 10–15% between measurements. Oxygen consumption (\( VO_2 \)) is the uptake of oxygen from arterial blood, and reflects oxygen consumed by cellular metabolism of the whole body. Direct measurement of \( VO_2 \) using metabolic monitors is more accurate than calculation using the Fick principle (as the product of cardiac output and the arterial–mixed venous oxygen content difference). Modern metabolic monitors allow relatively easy and highly accurate and reproducible measurements. Low \( VO_2 \) values indicate tissue hypoxia.

Recently, the concept of a pathological oxygen supply dependency has been debated. This proposes that patients with severe illness (e.g. sepsis and ARDS) have high critical \( DO_2 \) values. Critical \( DO_2 \) is \( DO_2 \) at which \( VO_2 \) begins to decrease (i.e. when \( VO_2 \) becomes dependent on \( DO_2 \)), and has been demonstrated in experimental haemorrhage to be 8–9 ml kg\(^{-1}\) min\(^{-1}\). Impaired oxygen extraction and utilization is an explanation for pathological oxygen supply dependency in critically ill patients. Thus high ("supranormal") values of \( DO_2 \) have been proposed as therapeutic end-points [1, 2]. Monitoring \( DO_2 \) and \( VO_2 \) then assumes great importance; a significant increase in \( VO_2 \) after measures to increase \( DO_2 \) would indicate that oxygenation was inadequate. However, outcome after use of "supranormal" therapy is not always better [3], and the concept of pathological oxygen supply dependency is not universally accepted [4].

Mixed venous oxygenation represents oxygen that is left after perfusion of the capillary beds in the systemic circulation, and indicates the balance between whole body oxygen transport and consumption. It can be monitored clinically as mixed venous oxygen saturation (\( S_{V\text{O}_2} \)) either continuously using a fibreoptic pulmonary artery catheter, or intermittently by blood sampling. A low \( S_{V\text{O}_2} \) (< 65%) usually indicates tissue hypoxia, but normal values do not guarantee adequate oxygenation to all organs. Mixed venous blood represents blood only from perfused tissue, and maldistribution of microcirculatory flow underlies beds of tissue hypoxia in the face of an acceptable (\( S_{V\text{O}_2} \)).

Other than indices of oxygenation, blood lactate concentration is used clinically to assess tissue oxygenation. In the presence of hypoxia, anaerobic glycolysis metabolizes pyruvate to lactate. Ratios of pyruvate and lactate are probably better indices of the redox state than lactate alone. However, pyruvate measurements are not available routinely, whereas lactate concentrations can be measured promptly by modern lactate analysers. Serious tissue hypoxia is suggested by high blood lactate concentrations, but normal values are not always safe. High concentrations may also occur late in hypoxia, or may be associated with non hypoxic–ischaemic situations, such as when pyruvate substrate is increased by high metabolic rates (Pasteur effect) or inhibition of pyruvate dehydrogenase.

Apart from the inherent problems of measurement and accuracy with each of the above indices, they all reflect global whole body oxygenation. Normal or near-normal values mask poor blood flow and oxygenation to individual tissue capillary beds. The indices do not disclose or measure regional or organ hypoxia. Gastric tonometry, recently introduced to clinical practice, takes one step towards that goal. The principle is simple—inadequate regional perfusion results in anaerobic metabolism and gut intramucosal acidosis which is measured indirectly. A special tube with a carbon dioxide permeable silicone balloon at its tip is placed in the stomach. The balloon is filled with saline, and after 30–90 min equilibration, saline \( P_{C\text{O}_2} \) approaches mucosal \( P_{C\text{O}_2} \). Saline \( P_{C\text{O}_2} \) and actual arterial bicarbonate concentration (from a simultaneously collected arterial blood sample) are measured using a standard blood-gas analyser. Gastric pH (\( pH \)) is then calculated by applying a modified Henderson–Hasselbalch equation. Measurements can also be obtained with the tube inserted in the colon. \( H_2 \) receptor antagonists affect \( pH \) in healthy subjects but not in critically ill patients, and their routine use is unnecessary [5, 6]. The difference between arterial \( pH \) and mucosal \( pH \), \( pH_{\text{muc}}-pH \), may be a more specific measure of gastric mucosal hypoxia.

Gastric tonometry is an attractive technique. It does not require intravascular placement, and splanchnic organs are particularly vulnerable to a failing circulation. Early response to detected gut ischaemia may prevent translocation of bacteria and endotoxin into the blood stream. Using gastric tonometry, gastric mucosal acidosis was reported to be common in critically ill patients [7,8], and was associated with increased complications and mortality in these patients and in those after major surgery [9,10] and trauma [11,12]. Unexpected splanchnic hypoxia was detected in cardiac patients after surgery [13–17], despite increased cardiac output and splanchnic blood flow after administration of doxepamine [16] and dobutamine [17]. The study by Welte and colleagues from Munich [18] found that \( pH \), decreased during orthotopic liver...
transplantation, although $DO_2$, and haemodynamic variables remained unchanged.

Measurement of pH is not without problems. Arterial bicarbonate is not a valid index of intracellular or extracellular bicarbonate in the gut, and its use to compute pH is questioned [19]. Errors in calculated pH can arise from analyses of saline $PCO_2$ with different blood-gas analysers [20]. Cut-off values of pH above which patients met with favourable outcome varied considerably in reported studies. The effects of inotropic agents (e.g. doxepamine) on pH are conflicting [16,21]. The Munich group’s finding that pH was not a good predictor of graft viability [18] contrasted with that of a previous study [22]. Gastric tonometry assumes that gut intramucosal acidosis is invariably caused by hypoxia, but this may not be the case in sepsis [23]. Nevertheless, there are increasing data to suggest that low pH values reflect inadequate perfusion of the gut. This splanchnic hypoperfusion is not indicated by haemodynamic or oxygen transport variables or illness severity scores (APACHE II and ISS) [12]. Although conventional measurements of metabolic acidosis may provide a similar clinical picture [24], pH may be a more sensitive and earlier marker of hypoxia. We now have a new tool to monitor oxygenation. To validate its use, however, many questions still need to be answered, such as whether or not assessment of pH changes in response to therapy or to guide therapy is useful, and what are acceptable pH values?

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References


