Hypoxaemia associated with one-lung anaesthesia: new discoveries in ventilation and perfusion

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One-lung ventilation is required when providing anaesthesia for operative procedures in the thoracic cavity. During this process, hypoxaemia is reported to occur with an incidence of approximately 5–10%. Unfortunately, hypoxaemia affects postoperative outcome as there is an increased risk of complications such as cognitive dysfunction, atrial fibrillation, renal failure, and pulmonary hypertension. Thus, prevention and treatment of hypoxaemia associated with one-lung ventilation is a priority for anaesthetists. By enhancing our understanding of the airway, ventilation, and perfusion, this editorial explores how the results of recent studies may refine future clinical practice.

Previously, considerations of hypoxaemia associated with one-lung ventilation have related to airway complications. In the past 50 yr, there have been innovations in the design of airway devices that enable correct lung isolation, ventilation, and suction. Fibreoptic bronchoscopy to check precise positioning of double-lumen endobronchial tubes has been recommended to enhance the safety of one-lung ventilation. More recently, data show that malpositioning of double-lumen endobronchial tubes is still a problem, with an incidence of more than 32%, for anaesthetists with limited experience of thoracic anaesthesia. Analysis of automated anaesthetic records has provided some clarification concerning the perceived difficulty of right-sided double-lumen endobronchial tubes which have a slotted cuff. In an observational study, fibreoptic bronchoscopy was used routinely, and no association was found between the side of double-lumen endobronchial tube and hypoxaemia during one-lung ventilation.

In addition to airway considerations, ventilation strategies in relation to hypoxaemia have been studied. From past data, we understand that the application of positive end-expiratory pressure may reduce atelectasis, decrease intrapulmonary shunt, and improve oxygenation during one-lung anaesthesia. Whilst this technique may be beneficial to the atelectatic lung after a recruitment manoeuvre, it may be harmful in patients with hyperinflated lungs as these reside above the lower inflection point of the compliance graph. In addition, data from a recent randomized controlled trial (RCT) show that mode of ventilation, that is to say, volume or pressure control, does not appear to affect oxygenation during one-lung ventilation.

Our understanding of the relationship between one-lung ventilation and pathogenesis of hypoxaemia is improving as a result of studies evaluating lung inflammation. For instance, compared with a low tidal volume of 5 ml kg\(^{-1}\), one-lung ventilation at a high tidal volume of 10 ml kg\(^{-1}\) has been shown to be associated with a significantly augmented inflammatory response. With an increased duration of exposure to one-lung ventilation, there is production of inflammatory mediators, recruitment of neutrophils, and possible damage to the alveolar capillary membrane. Fortunately, data from two recent RCTs suggest that this inflammatory process may be attenuated by inhalational agents. In one of them, alveolar granulocytes, IL-8, and sICAM-1 (soluble intercellular adhesion molecule) in fluid obtained by lavage of the ventilated lung were significantly lower in patients receiving desflurane than in those who had propofol. These results are supported by another RCT.
in which lavage fluid was obtained from the non-ventilated lung in patients who received sevoflurane or propofol. Importantly, tumour necrosis factor-α, interleukin (IL)-6, IL-8, and Monocyte Chemoattractant Protein-1 in fluid obtained by lavage from the collapsed lung were significantly lower in patients receiving sevoflurane than in those who had propofol. Furthermore, a rise in neutrophil count in the bronchoalveolar lavage was correlated significantly with an increase in IL-1β, IL-6, and IL-8 in patients who had propofol but not sevoflurane.

Further to inflammation, lung injury and hence hypoxaemia can be sustained during one-lung ventilation. In comparison with being supine, the lateral decubitus position is associated with better matching of ventilation with perfusion, and thus less hypoxaemia. The dependent, ventilated lung receives the majority of intrapulmonary perfusion owing in part to gravity and to hypoxic pulmonary vasoconstriction of the pulmonary vessels supplying the collapsed, non-dependent lung. However, the dependent, ventilated lung is also susceptible to lung injury and subsequent hypoxaemia. Recent studies in pigs show cyclic tidal recruitment during one-lung ventilation and features of injury that are significantly greater in the ventilated, dependent lung than in the collapsed, non-dependent lung; these include alveolar oedema, interstitial oedema, micro-haemorrhage, inflammatory infiltration, micro-atelectasis, and overdistension. Whilst these findings in the dependent lung may be caused by ventilation, they may also be attributable to hyperperfusion.

In addition to new information on ventilation, recent data related to perfusion have become available. Previously, hypoxaemia during one-lung ventilation was in part attributable to inhalational agents: they are known to reduce matching of ventilation and perfusion by attenuating hypoxic pulmonary vasoconstriction in the collapsed lung. Whilst this effect may be true, we now understand that inhalational agents do not aggravate intrapulmonary perfusion and hypoxaemia when compared with equi-anaesthetic doses of intravenous propofol. In a RCT of patients receiving either sevoflurane or propofol at equivalent doses, as measured by bispectral index, no significant difference in oxygenation between the two types of anaesthetic was found. These results support previous data showing similar shunt values for both methods during one-lung anaesthesia.

Most procedures performed in patients requiring one-lung anaesthesia are major. They include oesophagectomy, lung resection, diaphragmatic hernia repair, and decortication. These procedures require thoracotomy and a thoracic epidural is widely used for analgesia. Further data are emerging on the effect of thoracic epidural analgesia on control of perfusion and hence hypoxaemia during one-lung ventilation: they clarify the dichotomy of opinion regarding the effect of local anaesthetics on intrapulmonary perfusion. One theory is that thoracic epidural local anaesthetics may cause greater sympathetic block to blood vessels supplying the non-ventilated lung than to the ventilated lung; this effect leads to a reduction in hypoxic pulmonary vasoconstriction in the non-dependent lung and exacerbation of hypoxaemia. The antithesis is that epidural local anaesthetics lead to generalized vasodilatation. Pooling of blood occurs in the ventilated lung rather than in the non-ventilated lung, resulting in improved matching of ventilation and perfusion, with attenuation of hypoxaemia. We now have evidence that elucidates the balance of these two theories. One RCT comparing patients receiving epidural bupivacaine 0.25%, epidural sufentanil, and intravenous remifentanil for analgesia found that oxygenation and shunt were not significantly different. In another RCT, different concentrations of epidural ropivacaine were administered. Shunt and hypoxaemia were significantly increased in patients who received ropivacaine 0.75% compared with those who had ropivacaine 0.25% or normal saline. These data suggest that epidural local anaesthetics of high but not low concentration influence intrapulmonary perfusion, by reducing the effect of hypoxic pulmonary vasoconstriction and exacerbating hypoxaemia during one-lung anaesthesia.

Development of hypoxaemia may also occur as a result of non-dependent lung compression and reduction in cardiac output. In theory, non-dependent lung compression should attenuate ventilation–perfusion mismatch by redirecting blood to the ventilated, dependent lung. Unfortunately, recent data show that there is a concomitant reduction in cardiac output, raising the possibility of impairment in tissue oxygen delivery. The relationship between cardiac output and hypoxaemia is defined by the equation which is derived from the combination of the shunt and Fick equations:

$$\text{CaO}_2 = \text{CcO}_2 - \left[ \frac{\text{Qs}}{\text{Qt}} \times \frac{\text{VO}_2}{\text{Qt}} \right]$$

It can be seen that arterial oxygen content (CaO2) and hence risk of hypoxaemia are determined by several inter-related factors, that is to say, capillary oxygen content (CcO2), shunt fraction (Qs/Qt), oxygen consumption (VO2), and cardiac output (Qt). In the presence of low cardiac output, the ratio of oxygen consumption to cardiac output is increased. When this ratio is multiplied by a high shunt ratio which occurs during one-lung anaesthesia, a product of high magnitude (contained in parenthesis of the above equation) is obtained. Reduction in arterial oxygen content occurs when this product is subtracted from capillary oxygen content. Thus, we find that suboptimal cardiac output could result in low arterial oxygen content especially in the presence of increased shunt. Prevention of reduction of cardiac output and hence oxygen delivery may be attenuated by administration of inotropic agents such as ephedrine.

In addition, haemoglobin (Hb) may influence hypoxaemia by affecting capillary oxygen content as shown in the following equation, in which SaO2 is arterial oxygen saturation, and PaO2 is alveolar oxygen partial pressure:

$$\text{CcO}_2 = (\text{Hb} \times 1.34 \times \text{SaO}_2) + (0.0031 \times \text{PaO}_2)$$
After haemodilution, capillary oxygen content and hence arterial oxygen content may decrease possibly in patients with impaired lung function.26

In conclusion, hypoxaemia during one-lung ventilation may be attenuated by manipulation of ventilation and perfusion independently. From a ventilatory perspective, various preventative strategies such as appropriate alveolar recruitment, positive end-expiratory pressure, and avoidance of high tidal volumes are useful in some patients. We suggest that low concentrations of local anaesthetics in thoracic epidurals, maintenance of cardiac output, and avoidance of excessive haemodilution in patients with impaired lung function are beneficial. In future, as evidence emerges for attenuation of acute lung injury during one-lung ventilation, inhalational agents may be preferred over total intravenous anaesthesia. Furthermore, anaesthesiologists who have limited or occasional experience of thoracic anaesthesia may require additional training to prevent mal-positioning of lung isolation devices. Careful consideration and implementation of these factors will go some way to attenuating hypoxaemia and minimizing adverse patient outcome associated with one-lung anaesthesia.

Conflict of interest
None declared.

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