Review Article

Airway closure and intraoperative hypoxaemia: twenty-five years later

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Purpose: *The literature describing the pulmonary mechanisms of increased P_A-PaO_2 during general anaesthesia was examined to define the role of airway closure and sub-radiological atelectasis.*

Source: *A Medline search was designed to include articles dealing with the stated purpose, which is thus selective rather than a meta-analysis. The MeSH consisted of the following words: Anesthesia: general / inhalational; Pulmonary gas exchange; Ventilation:perfusion ratio; Lung Physiology; Lung Volume measurements; Closing Volume/Capacity; Functional Residual Capacity; Atelectasis; Diaphragm. Also, Dr H. Rothen and Prof. G. Hedenstierna supplied raw data.*

Principal findings: *Changes in shape and dimensions of the thorax and abdomen immediately after induction of anaesthesia result in marked alterations in the efficiency of oxygenation. Three pathways can be described: increased effects of airway closure, increased low ventilation: perfusion in dependent lung zones, and frank atelectasis. The magnitude of the alterations is determined by the patients' age and body habitus. Some of the changes may carry-over into the postoperative period. The data suggest that increasing tidal volume during anaesthesia will reduce the effects of airway closure and that vital capacity breaths will re-expand atelectatic areas.*

Conclusion: *Airway closure and atelectasis contribute equally to the increased ventilation: perfusion mismatching that occurs during general anaesthesia.*

Key words

LUNGS: closing volume/capacity, airway closure, atelectasis, ventilation: perfusion ratio.

OXYGEN: anaesthesia, hypoxaemia, tension.

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Objectif: *La littérature médicale portant sur les mécanismes pulmonaires de l'augmentation de la P_A-PaO_2 pendant l'anesthésie a été révisée dans le but de préciser le rôle de la fermeture des voies aériennes et de l'atélectasie indétectable par examen radiologique.*

Source: *La recherche sur Medline était destinée à inclure tous les articles traitant du sujet, donc plutôt une sélection qu'une méta-analyse. Les mots clés étaient les suivants: Anesthésie: générale par inhalation; Échanges gazeux pulmonaires; Rapport ventilation/perfusion; Physiologie pulmonaire; Mesures des volumes pulmonaires; Volume/capacité de fermeture; Capacité résiduelle fonctionnelle; Atélectasie; Diaphragme. En outre, le Dr H Rothen et le Pr G Hedenstierna ont fourni des données brutes.*

Principales observations: *Les changements morphologiques et dimensionnels thoraciques survenant immédiatement après l'induction de l'anesthésie altèrent profondément l'efficacité de l'oxygénation. Trois étapes sont décrites: augmentation des effets de la fermeture des voies aériennes, augmentation de la restriction ventilatoire; perfusion des zones pulmonaires inférieures; atélectasie évidente. L'importance des altérations est déterminée par l'âge du patient et son habitus physique. Quelques uns des changements peuvent se perpétuer dans la période postopératoire. Ces données suggèrent que l'augmentation du volume courant pendant l'anesthésie peut réduire les effets de la fermeture des voies aériennes et que les inspirations égales à la capacité vitale permettent la ré-expansion des zones atélectasiées.*

Conclusion: *La fermeture des voies aériennes et l'atélectasie contribuent également à la perturbation du rapport ventilation/perfusion pendant l'anesthésie générale.*

The suggestion that the closure of small airways may contribute to intraoperative hypoxaemia [expressed as an enlarged alveolar – arterial PO_2 difference (P_A–PaO_2)] was first published in an anaesthesia journal, the Journal of the *Canadian Anaesthetists Society*, in 1971.[1] In the intervening 25 yr, the mechanisms caus-

ing the increased P_A–PaO_2 have been more clearly identified, aided particularly by technological advances in the determination of ventilation to perfusion relationships and the detection of sub-radiological atelectasis by computerized tomographic (CT) scanning. This article will summarize the current state of knowledge regarding these mechanisms, with the primary focus on the role of airway closure.

The magnitude and mechanism of intraoperative hypoxaemia

The three principal mechanisms of increased total venous admixture [measured as an enlarged P_A–PaO_2] are : (a) increased shunt, (b) increased number of lung zones with low ventilation to perfusion ratios and (c) decreased mixed venous PO_2. Mixed venous PO_2 reflects metabolic and cardiovascular function, whereas shunt and low ventilation to perfusion ratios reflect the efficiency of pulmonary gas exchange. A recent major technological advance in the past few years is the graphic representation of quasi-continuous ventilation to perfusion ratios. This allows the differentiation and quantification of shunt and low ventilation to perfusion ratios. Figure 1a is a graphic representation of typical values of shunt and low ventilation to perfusion ratios measured before and during anaesthesia.[2] The figure shows the increase in both components of the P_A–PaO_2 gradient during anaesthesia, in particular, the increase in low ventilation to perfusion ratios. Figure 1b gives the relationship between shunt and low ratios and age during anaesthesia.[3] Both components have a direction correlation with age but that for low ventilation to perfusion is much more marked, suggesting an age-related mechanism. The changes occur shortly after the induction of general anaesthesia, which is known to cause immediate alterations in the shape and dimensions of the thoracic cage. These alterations cause the reduction in functional residual capacity (FRC), pulmonary compliance (C_L), the increased airways resistance (Raw) and the changes in the distribution of ventilation that follow the induction of general anaesthesia.[4] The dependent portion of the diaphragm is displaced cephalad. Cardiac output is decreased simultaneously. The net effects of the alterations in lung function on gas exchange can be described by considering three pathways to cause relative hypoxaemia. These are: increased effects of airway closure, new or increased lung zones with low ventilation to perfusion ratios without demonstrable airway closure, and increased shunting (Figure 2). The areas of low ventilation to perfusion ratios can augment the effects of airway closure on oxygenation. Also, if areas of low ventilation to perfusion ratios are filled with soluble gases, they may, in due course, become atelectatic

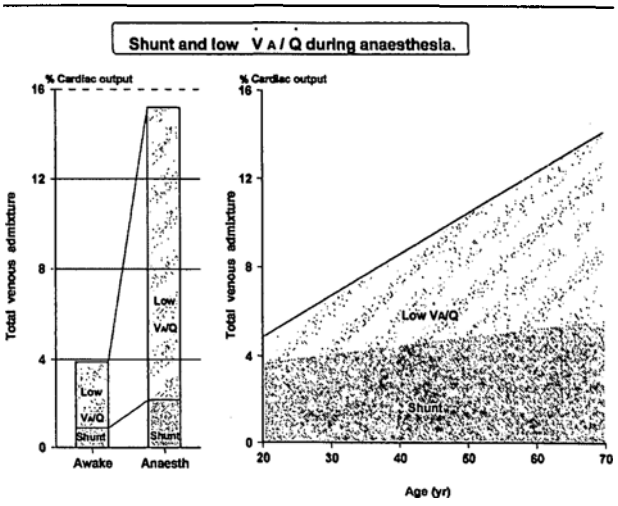

FIGURE 1 (A) *Left.* Typical values of shunt and ventilation:perfusion ratios before and during anaesthesia. (B) *Right.* Relationship between shunt, ventilation:perfusion ratio and age.

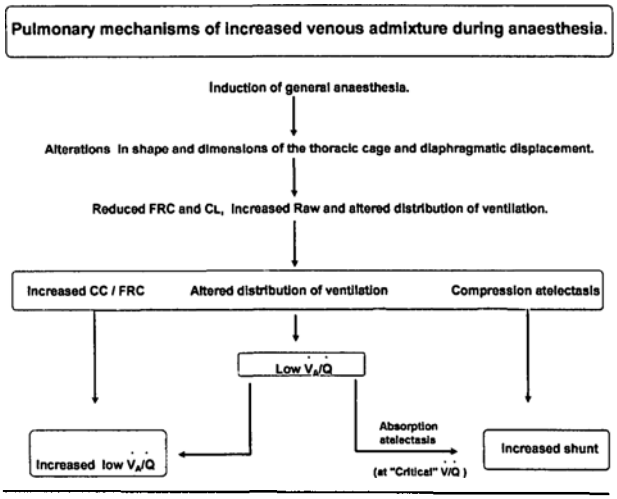

FIGURE 2 Pulmonary mechanisms of increased venous admixture during anaesthesia.

following absorption of the contained gas. This depends on the effectiveness of hypoxic pulmonary vasoconstriction. The "critical" ventilation to perfusion ratio necessary for absorption atelectasis to occur depends on the composition of inspired gases, being lower with highly soluble gases. Thus, there are two mechanistic explanations, both related to the initial sequence of events, to account for part of the enlarged P_A–PaO_2 gradient.

Individual components

Airway closure

Small peripheral airways that are devoid of cartilage-

nous support are maintained open by three forces : the tethering effect of elastic recoil of the lung parenchyma, the elastic properties of the terminal airways and the subatmospheric ("negative") intrapleural pressure (Ppl). Thus, airway closure will occur with the loss of any of these influences, or by increased pulmonary extravascular water. The magnitude of airway closure is expressed as either closing volume (CV) or closing capacity (CC), which is CV plus residual volume. Airway closure becomes clinically important when CC is greater than FRC (i.e., CC/FRC > 1.0 or CC-FRC is positive).[5,6] Pulmonary elastic recoil decreases and Ppl becomes less "negative" with age. Thus CC and CC/FRC increase with age and the increase is accentuated by obesity,[5] or any condition leading to increased Ppl.

The initial clinical investigations revolved around the influence of surgical position on CC, FRC and oxygenation.[1,6,7] The principal findings were:

1 Closing capacity increases with age but is not influenced by surgical position. The critical CC/FRC ratio of 1.0 occurs at 49 yr in the seated position but at 36 yr when supine.
2 Gas trapping behind closed airways occurs when CC > FRC
3 Arterial oxygenation deteriorates when CC > FRC following changes in surgical position. The deterioration is less marked in patients with extensive airway closure (CC/FRC > 1.25), suggesting a natural protective mechanism, possibly collateral ventilation.

The possibility that airway closure may adversely affect oxygenation during anaesthesia was also examined by measuring the amount of gas trapped behind closed airways[8] and P_A–PaO_2 at various tidal volumes.[9] The measured volume of trapped gas during anaesthesia could, theoretically, be sufficient to explain the expected amount of venous admixture.[8] Subsequent analysis of the data revealed that the volume of trapped gas increased exponentially with increasing preoperative CC / intraoperative FRC.[5] Large tidal volumes (10 $ml \cdot kg^{-1}$) decreased P_A–PaO_2 gradient from the values at small tidal volumes (5 $ml \cdot kg^{-1}$). This was due to the provision of intraoperative inspiratory lung volumes (= FRC plus tidal volume) greater than preoperative closing capacity.[9]

These studies suggest that airway closure may cause increased P_A–PaO_2 .Central to the issue of the effects of airway closure is whether CC changes during anaesthesia. The two initial papers reported that CC was unchanged during anaesthesia with spontaneous[10] and with controlled ventilation.[11] The latter investigators repeatedly and consistently reported that CC was unchanged in healthy patients[12] and in the obese[13] and that the "marker" gas for the measurement made no difference.[12] They also reported a relationship between P_A–PaO_2 and CC/FRC.[11,13] The increased lung recoil during anaesthesia might be expected to decrease CC, but Ppl becomes less subatmospheric and the two factors cancel each other out. Although one study reported that CC was decreased during anaesthesia,[14] the bulk of the evidence is that CC is constant. Thus the influence of airway closure will primarily depend on changes in FRC. Functional residual capacity is reduced by 10–20% during anaesthesia, with greater reductions in obese subjects.[4] Placing anaesthetized and artificially ventilated patients in the lateral decubitus position influences FRC and CC/FRC. The dependent lung has a lower FRC (0.92 L vs 2.15 L) thus CC is >FRC, with total CC almost evenly split between the two lungs.[15]

A number of authors have reported a correlation between P_A–PaO_2 and CC/ FRC.[11,12,16] In patients in whom CC/FRC during anaesthesia was >1.0, shunt was approximately five-fold that in patients with CC/FRC <1.0.[17] A very marked adverse influence of body mass index on the CC/FRC was also noted. The lung volume at which shunting started is that at which CC is greater than FRC.[17] It was noted above that large tidal volumes can overcome the influence of CC on oxygenation. The application of positive end expiratory pressure (PEEP) can, by increasing FRC, be beneficial,[15,18,19] although most of the increase in FRC will affect the non-dependent lung zones.[15] The regional transpulmonary pressure required to open closed airways is 0.6 kPa (6.1 cm H_2O).[15] The high pressures in the breathing system required to attain this transpulmonary pressure may, however, adversely affect cardiac output. A better option is to use large tidal volumes (10–12 $ml \cdot kg^{-1}$). The data summarized above indicate the role but not the relative contribution of airway closure to overall mismatching of ventilation to perfusion.

Pregnancy has specific effects on pulmonary physiology. Closing capacity during pregnancy, however does not change whereas FRC is reduced by 20–25%.[20] The increased CC/FRC during pregnancy[20,21] explains the reduced PaO_2 occasionally noted in pregnant women.

Lung zones with low ventilation:perfusion ratios

This consists of the portions of the lung without demonstrable airway closure or compression atelectasis (vide infra). The alveoli have a low FRC and compliance and are prone to absorption collapse if the effectiveness of hypoxic pulmonary vasoconstriction is reduced and if highly soluble gases are used. The efficiency of O_2 transfer decreases progressively with increased inspired oxygen concentrations (FIO_2).[22] Hyperinflation of the lungs by a vital capacity breath can eliminate atelectasis.[22] The mean airway pressure required to deliver a

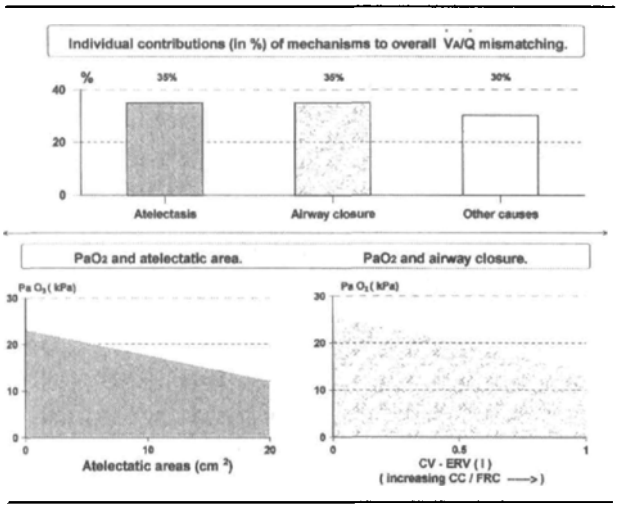

FIGURE 3 *Upper*: Contribution of atelectasis and airway closure to venous admixture. *Lower*: Relationship between atelectasis (*left*) and airway closure (*right*) and oxygenation.

vital capacity in healthy young patients is 40 cmH_2O per breath.[23] However, when high FiO_2 (>0.4) is used, the effect is transient.[24]

Atelectasis.

Small areas (3–5% of the transverse area of the lungs) of atelectasis have been repeatedly demonstrated by computerized tomographic scanning shortly after induction of general anaesthesia.[25] These areas of increased density appear in the most caudal and dependent portions of the lung and are most likely due to mechanical compression by the cephalad displacement of diaphragm. The densities occur in the lung tissue proper.[26] The densities do not appear after ketamine induction, which does not reduce FRC, but do appear after muscle paralysis.[27] They occur in the most dependent portion of the lungs and move to the lowermost lung zones following changes in posture.[25] These observations support the proposal that the densities represent "compression" atelectasis, particularly since the magnitude correlates best with indices of obesity.[28] It was noted above that FRC is markedly reduced in obese patients.[4] Since perfusion to these collapsed alveoli persists,[26] shunt increases. Indeed a high correlation between the extent of compression atelectasis and shunt has been repeatedly reported.[27,29–32] The application of PEEP reduces the extent of atelectasis but the effects of PEEP on oxygenation are variable.[31] In 90% of cases, the atelectatic areas persisted into the immediate postoperative period, and were present in 50% of patients 24 hr after surgery.[30]

The combined effects of airway closure and atelectasis

The studies presented so far have dealt with each of the two mechanisms separately. The combined effects of the two mechanisms on oxygenation in the same patients was recently reported.[32] The authors confirmed the expected direct relationships between airway closure and low ventilation-to-perfusion ratios, and between the extent of atelectasis and shunt. Their main observation was the relative contribution of the various mechanisms. This is based on the value of the coefficients of partial correlation following multiple linear regression analysis of the data. On the basis of that analysis, 35% of the total increase in venous admixture was found to be due to the effects of airway closure and 35% was the consequence of atelectasis (Figure 3). The magnitudes of airway closure and of the atelectatic areas were inversely correlated with PaO_2. Figure 3 is the graphic representation of the data.

General discussion and conclusions

The data examined indicate that the initial changes in the geometry of the thorax trigger the increase in mismatching of ventilation-to-perfusion ratios. The increase in P_A–PaO_2 ,therefore, largely depends on the individual patient's age and body habitus. These changes occur with all methods of induction of anaesthesia, except for ketamine. However, subsequent neuromuscular blockade results in the same pattern. The changes are unavoidable. The relative hypoxaemia that results can be corrected by increasing FiO_2 but that may increase atelectasis, as noted above.[22–24] Atelectasis during anaesthesia may persist into the postoperative period.[30] Periodic vital capacity breaths can open collapsed alveoli. The reappearance of atelectasis following that manoeuvre depends on the composition of the carrier gases.[24] Large tidal volumes and judicious levels of PEEP increase PaO_2. Both methods can have undesirable effects on cardiac output and on $PaCO_2$. These can be corrected by adjusting frequency and inspiratory flow rates to maintain $PaCO_2$ at acceptable levels.

The role of airway closure in causing relative hypoxaemia during anaesthesia has been confirmed and accounts for approximately 35% of the increase in venous admixture. Larger contributions from airway closure should be anticipated in older and more obese patients.

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