

Alveolar Recruitment Maneuvers: Are Your Patients Missing Out?

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Awake, spontaneously breathing humans sigh on average 9 to 10 times per hour. The sigh is a normal homeostatic reflex proposed to maintain pulmonary compliance and decrease the formation of atelectasis by recruiting collapsed alveoli. The induction and maintenance of anesthesia with muscle paralysis and a fixed tidal volume abolish the sigh. Without periodic sighs, patients are left susceptible to atelectasis and its negative sequelae. The prevalence of atelectasis has been estimated to be as high as 100% in patients undergoing general anesthesia. A strong correlation between atelectasis and postoperative pulmonary complications has been demonstrated. Postoperative pulmonary complications lengthen hospital stays and increase healthcare costs. Alveolar recruitment

maneuvers, which make up one component of open lung ventilation, have been described as vital capacity breaths, double tidal volume breaths, and sigh breaths. These simple maneuvers result in a sustained increase in airway pressure that serves to recruit collapsed alveoli and improve arterial oxygenation. This article examines the literature regarding the application of alveolar recruitment maneuvers in the perioperative setting. The format is a series of clinically oriented questions posed to help the reader translate available evidence into practice.

Keywords: Alveolar recruitment maneuvers, open lung ventilation, sigh breaths.

Objectives

At the completion of this course, the reader should be able to:

1. Explain the importance of sigh breaths and the consequences of their absence under general anesthesia.
2. Describe how to perform the 2 major types of alveolar recruitment maneuvers.
3. Discuss the types of surgeries and patients in whom sigh breaths can be used effectively.
4. Discuss pitfalls of solely relying on oxygen saturation as measured by pulse oximetry (SpO_2) as an indicator of adequate gas exchange and to determine the use of alveolar recruitment maneuvers.
5. Identify strategies for evaluating the effectiveness of alveolar recruitment maneuvers.

Introduction

The sigh breath is a normal homeostatic reflex that occurs multiple times every hour in awake, spontaneously breathing humans. Alveolar recruitment maneuvers (ARMs),

which function as sigh breaths under general anesthesia, constitute part of the “open lung ventilation” concept. This article begins with a review of open lung ventilation, which sets the stage for discussing the detrimental loss of the sigh under general anesthesia and the importance of ARMs. It also examines the different methods and recommended frequency for performing an ARM following general anesthesia. To date, there are inconsistencies in the literature regarding the utility of ARMs during surgery. A systematic review, written by the authors and currently under review, is used to support the benefits of ARMs and the various surgical populations in which this maneuver can be used. The pitfalls of relying on the pulse oximeter as an indicator of adequate gas exchange and to guide frequency of ARMs is discussed along with strategies for evaluating the effectiveness of ARMs. Finally, strategies to reduce the development of atelectasis during induction, during emergence, and following extubation are presented to highlight areas for future research. The format for this article is a series of clinically oriented questions posed to

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help the reader translate available evidence into practice.

By the end of this article, the reader should be ready to incorporate ARMs in his or her daily practice. Reducing the incidence of both intraoperative and postoperative pulmonary complications will improve patient safety and reduce future healthcare costs.

What Is "Open Lung Ventilation"?

The term *open lung ventilation* was first coined by Papadakos and Lachmann¹ in 1992. Open lung ventilation consists of ARMs followed by the application of low tidal volumes and high positive end-expiratory pressure (PEEP) to minimize atelectasis and optimize gas exchange. Before 1992, the application of lower tidal volumes had been explored as a strategy to prevent ventilator-induced lung injury, yet barotrauma and biotrauma still occurred because of atelectasis and lung closure.¹ The addition of ARMs and PEEP serves to reinflate atelectatic areas and minimize cyclical alveolar opening and closing.¹ This article will focus on the addition of ARMs and PEEP to minimize atelectasis in the perioperative period.

What Is the Importance of Sigh Breaths?

In 1964, Bendixen et al² found that awake men and women sigh on average between 9 and 10 times per hour. The sigh breath is a normal homeostatic reflex characterized by a complex interaction between vagally mediated input and peripheral chemoreceptors that results in an increase in inspiration.^{3,4} The sigh breath functions to maintain pulmonary compliance.⁵ In a group of spontaneously breathing subjects, pulmonary compliance decreased in the absence of periodic sighs and returned to baseline after only 2 sigh breaths. Sigh breaths minimize the alveolar-to-arterial (A-a) oxygen tension gradient and maintain venous admixture within normal range.⁶ Sigh breaths also release new surfactant and distribute it evenly on the alveolar surface and the distal airways.^{7,8} The fusion pore is the area on the alveolar type II cell that acts as a barrier to block further surfactant release. Sigh breaths open this barrier and replenish the available supply of surfactant.⁸

How Do General Endotracheal Anesthesia and Elimination of Sigh Breaths Affect the Lungs?

General endotracheal anesthesia causes compression and absorption atelectasis by 3 main mechanisms: (1) muscle paralysis, (2) increased fraction of inspired oxygen (FIO₂), and (3) cessation of the sigh breath. Muscle paralysis causes a restriction in the movement of the dependent diaphragm of patients, resulting in a decrease in lung compliance.⁹ It also decreases the dependent movement of the lung, thereby decreasing functional residual capacity.¹⁰ These factors contribute to compression atelectasis, which occurs when the pressure distending the alveolus is

reduced.¹¹ In a study using computed tomography (CT), the occurrence of compression atelectasis was noted to occur in 100% of patients undergoing general anesthesia.¹²

Absorption atelectasis occurs when the flux of oxygen from alveolar gas into capillary blood exceeds waste gas returning to the alveoli (as oxygen diffuses faster than nitrogen). This frequently occurs during induction of anesthesia when the inspired oxygen concentration is increased to 100%. Since oxygenated gas is leaving the alveoli for the blood faster than waste gas (mostly nitrogen) is returning to the alveoli, the alveoli shrink and eventually collapse, increasing atelectasis.¹³

Hedenstierna¹⁴ published an article including CT scans (Figure 1) demonstrating the occurrence of atelectasis immediately following induction of general anesthesia.

In 1964, Bendixen et al⁶ hypothesized that constant ventilation with adequate but static tidal volumes in anesthetized patients would result in progressive atelectasis and shunting when sigh breaths were absent. They found that, on average, arterial oxygen tension fell 22% and pulmonary compliance fell 15% in the absence of sigh breaths. After a few minutes of slow, deep, sustained breaths, arterial oxygen tension rose on average by 150 mm Hg, reducing the shunt created by static tidal volumes. The law of Laplace can explain this increase in oxygen tension or PaO₂:

$$P = \frac{2T}{r}$$

where *P* indicates pressure; *T*, surface tension; and *r*, radius.

When the radius of an alveolus is decreased by atelectasis, the pressure required to reinflate the alveolus increases. Alveolar recruitment maneuvers provide the elevated pressure necessary to reinflate collapsed alveoli.

Is There a Link Between Atelectasis and Postoperative Pulmonary Complications?

Postoperative pulmonary complications (PPCs) are defined as any respiratory condition that adversely influences the clinical course of patients after surgery.¹⁵ Studies show a strong correlation between atelectasis and PPCs. Atelectasis appears to be one of the primary mechanisms underlying acute lung injury, is a major cause of severe postoperative hypoxemia, and is associated with a prolonged length of stay in the intensive care unit and the hospital.^{15,16} Atelectasis may also contribute to serious PPCs such as respiratory failure and pneumonia.¹⁷ Postoperative pulmonary complications represent a substantial economic burden because of lengthened hospital stays and increased healthcare costs.¹⁵ In 2010, PPCs were estimated to add nearly \$3.5 billion to annual healthcare costs.¹⁸

What Are Alveolar Recruitment Maneuvers?

Alveolar recruitment maneuvers are described as vital capacity breaths, double tidal volume breaths, and sigh breaths.¹⁹ They use sustained increases in airway pres-

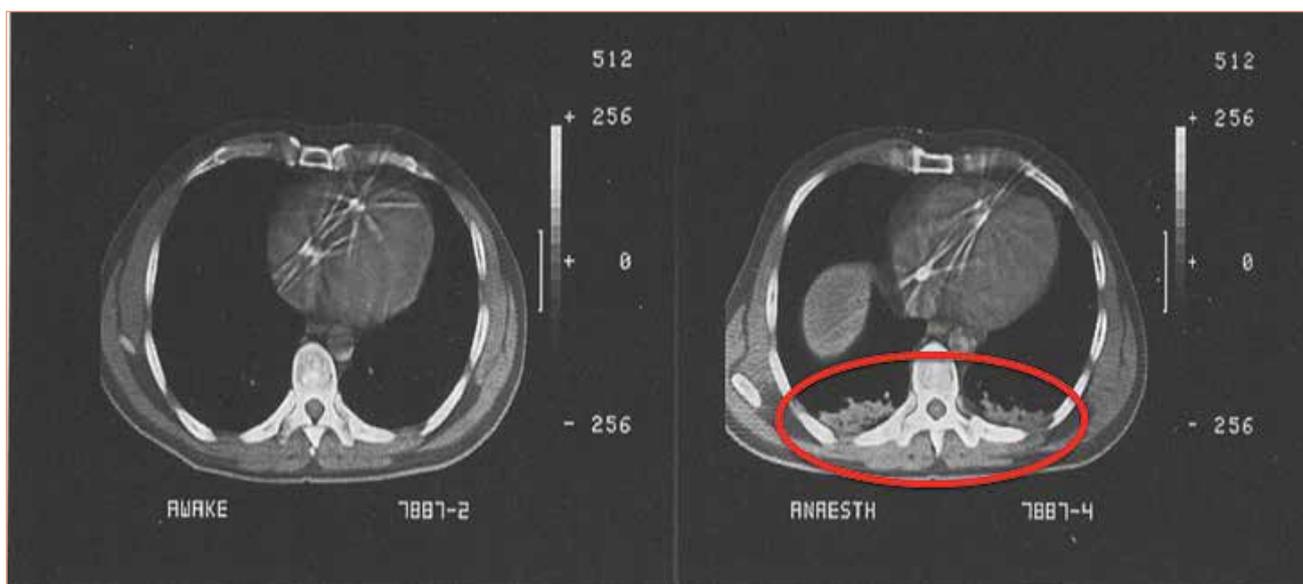


Figure 1. Atelectasis Immediately Following Induction of Anesthesia

Computed tomographic scans of thorax show patient's lungs before (left) and after (right) induction of anesthesia. On left, note clear lung fields in posterior region. On right, note presence of atelectasis in posterior portion of lungs (surrounded by red oval). Reprinted from public domain from Hedenstierna,¹⁴ 1996.

sure (breath holds) to recruit collapsed alveoli, increase lung area available for gas exchange, and improve arterial oxygenation.²⁰ Sigh breaths are to awake, spontaneously breathing patients as ARMs are to anesthetized mechanically ventilated patients.

The method for achieving an ARM tends to fall into 2 major groups. Some authors consider sustained inflation of the lungs (for 5-90 seconds) to a peak inspiratory pressure (PIP) of 40 cm H₂O as representative of ARMs.^{20,21,22} Others describe incrementally increasing positive end-expiratory pressure (PEEP) in a stepwise manner from 4 to 20 cm H₂O as an ARM.^{4,23}

Is There Evidence to Support Alveolar Recruitment Maneuvers?

There is evidence to support the use of ARMs in the intraoperative period. In a systematic review of the literature, 6 randomized controlled trials (of 439 studies) that met inclusion criteria were identified.^{4,21,23-26} The final inclusion criteria consisted of scoring these articles using the Jadad scale. The Jadad scale uses 5 questions to evaluate the quality of randomized controlled trials.²⁷ The answer to each question is given a maximum of 1 point. Randomized controlled trials with 1 and 2 points are considered low-quality studies, and those with 3 to 5 points are considered high-quality studies. The studies included in this systematic review all received a 3 or higher on the Jadad scale. All studies compared the use of an ARM to a control group lacking an ARM in adults who did not have acute respiratory distress syndrome (ARDS) in the intraoperative period. Studies involving cardiac and thoracic surgery were excluded

because of surgical factors affecting normal heart and lung physiology. Studies published before January 2014 were reviewed and were not limited by language. Databases searched included PubMed, Cumulative Index to Nursing & Allied Health Literature (CINAHL), The Cochrane Library, and the National Guideline Clearinghouse, as well as all subsequent research reference lists until January 1, 2014.

Alveolar recruitment maneuvers in the 6 studies consisted of either a stepwise increase in PEEP up to 20 cm H₂O, sustained manual inflations (up to 15 seconds) up to a PIP of 40 cm H₂O, or a stepwise increase in tidal volume to a plateau pressure of 30 cm H₂O using inverse ratio ventilation. Overall, patients in the experimental groups had a higher intraoperative PaO₂ and increased lung compliance compared with patients in the control groups. Control groups included patients receiving zero PEEP,^{21,23,24} PEEP of 4 cm H₂O,^{4,25} and PEEP of 10 cm H₂O.²⁶ None of the patients in the control groups received ARMs. Of the 4 studies that included PPCs as outcome measures, only one found a statistically significant reduction in PPCs in its ARM group (sustained manual inflation to PIP of 40 cm H₂O).²⁶ The other 3 studies found that ARMs did not significantly affect the rate of PPCs.^{4,23,24} Four of the studies reported no complications with the use of ARMs. Complications of ARMs were variably defined as hypotension (MAP <60 mmHg), SpO₂ <90%, pneumothorax requiring a chest tube, and a need to give a fluid bolus or vasoactive medication. The table compares the primary and secondary outcome measures in the 6 studies included in this review.

• *Is There Evidence to Support Alveolar Recruitment*

Maneuvers in Subsets of Patients Who Have an Increased Risk of Experiencing Perioperative Atelectasis? There is evidence to support the use of ARMs in subsets of patients who have an increased risk of experiencing perioperative atelectasis. Examples of patients with increased risk include pediatric patients or those who have ARDS. Sustained manual inflations to a PIP of 30 to 40 cm H₂O significantly reduced the oxygen requirement in mechanically ventilated pediatric patients 6 hours after their implementation without causing significant hemodynamic changes.²⁸

A systematic review published in 2008 showed that patients with ARDS or those with acute lung injury experienced a significant increase in PaO₂ with ARMs while experiencing few serious adverse effects.²⁹ Patients undergoing complex surgical procedures such as cardiac surgery or open thoracic surgery are also at increased risk of perioperative atelectasis. A stepwise increase in PEEP to 15 cm H₂O and tidal volume to a PIP of 40 cm H₂O significantly increased PaO₂ following cardiac bypass surgery with minimal adverse effects.³⁰ Sustained lung inflations to a plateau pressure of 40 cm H₂O before instituting one-lung ventilation has been shown to decrease alveolar dead space, improve arterial oxygenation, and improve the efficiency of ventilation during thoracic surgery.³¹

• **Is There Evidence to Support Alveolar Recruitment Maneuvers in Healthy Patients?** A 2003 study by Pang et al²¹ analyzed the effect of ARMs on patients undergoing laparoscopic cholecystectomy. Inclusion criteria limited the study to patients with ASA classes I-II between the ages of 16 and 70 years. Although body mass index (BMI) was not included in the table of demographics, the average weight of patients in the ARM group and control group was 56 kg and 55 kg, respectively. The researchers in this study found that sustained manual inflations to a PIP of 40 cm H₂O significantly increased intraoperative PaO₂ compared with the control group (PEEP 0, static tidal volumes) without causing cardiovascular or respiratory complications.

Which Method of Alveolar Recruitment Is Most Effective?

Based on the results of the systematic review described earlier, there does not appear to be a difference in effectiveness among the various ARMs described. Compared with the control groups, all types of ARMs were found to be beneficial. The subsequent use of ARMs in this article refers to either a stepwise increase in PEEP/tidal volume or sustained manual inflations up to a PIP of 40 cm H₂O. Manual sustained hyperinflations require a shorter time to perform, whereas stepwise increases in PEEP or tidal volume may prevent untoward patient responses such as straining or coughing when the depth of anesthesia is questionable. Any of the ARMs described can be safely applied at the discretion of the anesthesia provider.

How Frequently Should I Use Alveolar Recruitment Maneuvers?

It is recommended that ARMs followed by the application of PEEP should be applied whenever feasible after induction of general anesthesia. Four studies included in the review used ARMs following the induction of anesthesia. Induction of anesthesia with high FIO₂, paralytic agents, and fixed tidal volumes leave patients highly susceptible to the development of atelectasis.^{6,9,13,14,32}

ARMs should be performed routinely and in the presence of a falling SpO₂, instead of relying solely on increasing FIO₂ during the maintenance phase of anesthesia. The frequency of ARM application varied widely among the studies in this review. Five of the 6 studies incorporated the use of ARMs at least once per hour.^{4,23-26} Intraoperative PaO₂ and pulmonary compliance increased in patients undergoing both single and repeated ARMs. Almarakbi et al²⁶ compared the differences among groups after repeated application of ARMs (sustained manual inflations up to PIP of 40 cm H₂O) at various intervals. One group received an ARM only once, whereas another received ARMs every 10 minutes until completion of surgery. The repeated-measures ARM group showed the greatest improvement in atelectasis, as measured by increased pulmonary compliance and PaO₂.²⁶

Should I Use PEEP Immediately After an Alveolar Recruitment Maneuver?

To maintain the benefits of an ARM, the patient should immediately be placed on PEEP.⁷ In addition to comparing the effects of repeated ARMs (manual inflations up to a PIP of 40 cm H₂O) vs that of a single ARM, Almarakbi et al²⁶ included a third experimental group that received a single ARM followed by zero PEEP. There were no significant differences between the effects in outcomes between this single ARM group without PEEP to those of the control group (PEEP = 10 cm H₂O only). Neither of these groups showed an improvement in respiratory compliance, intraoperative or postoperative PaO₂, or a reduction in hospital length of stay.

In a 2002 study by Dyhr et al,³³ patients following cardiac surgery were randomized to either an ARM group (manual inflations to 45 cm H₂O) followed by PEEP (individualized for each patient) or to the same ARM group with zero PEEP. The researchers noted an increase of 120 mm Hg in the PaO₂ of patients in the ARM group followed by PEEP over the span of 2.5 hours, but no increase in PaO₂ in the ARM group with zero PEEP over this same span.³³

What Is the Danger of Continually Increasing FIO₂ to Treat a Falling SpO₂?

Continually increasing FIO₂ in the face of a falling SpO₂ may maintain an elevated SpO₂, but it may also mask the presence of a major physiological shunt. Oxygenation

Study	Primary outcomes of systematic review				Secondary outcomes of systematic review				
	Intraop PaO ₂	Pulmonary compliance	A-a gradient	PaO ₂ /FIO ₂	PPCs	Postop PaO ₂ /SpO ₂	Complications	Frequency	Airway-resistance
Almarakbi et al, ²⁶ 2009	Increased in RP and RRP only	Increased in RP and RRP only	Not studied	Not studied	Patients in RRP shortest LOS, followed by RP	Highest SpO ₂ in RRP, then RP	None	RP once, RRP every 10 min	Not studied
Pang et al, ²¹ 2003	Increased in ARM group	Not studied	Not studied	Not studied	Not studied	No difference	None	Once	Not studied
Severghini et al, ²⁴ 2013	Not studied	No difference	Not studied	Not studied	Higher in controls on postop day 1, no difference after, no difference in LOS	Controls' SpO ₂ fell on days 1 and 3, ARM group remained same	Comparable to controls	Varied; see study	Not studied
Sprung et al, ²⁵ 2009	Not studied	Higher in ARM group	Not studied	Higher in ARM group	Not studied	No significant difference	None	After intubation, 30 min, 60 min, then every hour after	Decrease in ARM group
Weingarten et al, ²³ 2010	Increased in ARM group only	Increased in ARM group only	Not studied	Higher in ARM group	No difference in LOS	No difference	None	After intubation, 30 min, 60 min, then every hour after	Decrease in ARM group
Whalen et al, ⁴ 2006	Increased more in ARM group	Higher in ARM group initially and after insufflation	Not studied	Higher in ARM group	No difference	No difference	None	Varied; see study	No difference

Table. Primary and Secondary Outcome Measures in the Randomized Controlled Trials

Abbreviations: A-a, alveolar-arterial; ARM, alveolar recruitment maneuver; FIO₂, frequency of inspired oxygen; intraop, intraoperative; PaO₂, partial pressure of arterial oxygen; LOS, length of (hospital) stay; postop, postoperative; PPCs, postoperative pulmonary complications; RP, single ARM group followed by PEEP; RRP, repeated ARM group followed by PEEP; SpO₂, arterial oxygen saturation.

issues related to atelectasis will only be resolved after the institution of ARMs followed by PEEP. High levels of FiO_2 promote absorption atelectasis, which will continue to worsen the A-a gradient.^{14,22} Oxygen can also produce reactive oxygen species capable of damaging cells by reacting with crucial molecular components. Additionally, high concentrations of oxygen can adversely affect respiratory control, ventilation/perfusion ratios, and hypoxic pulmonary vasoconstriction, as well as cause vasoconstriction of systemic arterioles.³⁴

My Patient's SpO_2 is 100%, Why Should I Perform an Alveolar Recruitment Maneuver?

The pulse oximeter measures the saturation of hemoglobin with oxygen. An SpO_2 of 100% means that every gram of hemoglobin is bound to 1.36 mL of oxygen. Despite a 100% SpO_2 , patients may be developing a significant shunt represented by a widening A-a gradient. Significant shunts, represented by large A-a gradients, were shown in patients with 100% oxygen undergoing general anesthesia without PEEP or ARMs.²² Patients in the control group (PEEP 5 cm H_2O , static tidal volumes) were found to have gradients as large as 430 mm Hg. Although the SpO_2 was not reported, it is conceivable that these patients would not have shown a change in SpO_2 . The authors did not state a specific PaCO_2 , however using a PaCO_2 of 45 mm Hg in the alveolar oxygen equation yields a PaO_2 of approximately 660 mm Hg. If the A-a gradient of 430 mm Hg is subtracted, a PaO_2 of approximately 230 mm Hg results. It is unlikely that this value would result in a SpO_2 less than 100% according to the oxygen-hemoglobin dissociation curve.

In a study by Pang et al²¹ in 2003, patients in ARM groups (sustained manual inflations to PIP of 40 cm H_2O) and control groups (PEEP 0, static tidal volumes) had similar SpO_2 values (100% and 99%) on 35% oxygen, but significantly different PaO_2 values. Patients in the ARM group had, on average, a PaO_2 50.1 mm Hg higher than that of the control group despite having almost exact same SpO_2 values. The SpO_2 may be a good indicator of an oxygenation or perfusion problem when it is low, but it does not alert the provider to developing shunts that place the patient closer to substantial oxygenation issues intraoperatively and during emergence.

How Do I Judge the Effectiveness of an Alveolar Recruitment Maneuver?

Aside from obtaining PaO_2 measurements from blood gases before and after an ARM and calculating the A-a gradient, there is a more practical and less invasive approach. Four of the studies in this review reported a statistically significant increase in pulmonary compliance in ARM groups.^{4,23,25,26} Dynamic pulmonary compliance is calculated by dividing tidal volume by the difference between PIP and PEEP. Static pulmonary compliance

Dynamic Compliance =	$\frac{V_T}{(\text{PIP} - \text{PEEP})}$
Static Compliance =	$\frac{V_T}{(\text{PP} - \text{PEEP})}$

Figure 2. Dynamic and Static Pulmonary Compliance

Abbreviations: PEEP, positive end-expiratory pressure; PIP, peak inspiratory pressure; PP, plateau pressure; V_T , tidal volume.

is equal to the tidal volume divided by the difference between plateau pressure and PEEP (Figure 2).

An increase in static or dynamic pulmonary compliance after an ARM shows a reduction in atelectasis and an increase in PaO_2 . To avoid performing the aforementioned calculations, there is a more clinically relevant method for determining whether an increase in compliance has occurred. When using volume-controlled ventilation, the provider would note that the same tidal volume is delivered at a lower PIP following application of ARMs. With pressure-controlled ventilation, the provider would note that an increased tidal volume is delivered at the same PIP setting. Many contemporary anesthesia ventilators include options that allow the user to visualize pressure-volume loops and display calculated dynamic compliance values, making it even easier to measure the effectiveness of ARMs.

What If Alveolar Recruitment Maneuvers Cause Hypotension?

Alveolar recruitment maneuvers that cause hypotension may reveal ongoing hypovolemia and the need for fluid volume resuscitation. Both Monnet et al³⁵ and Silva et al³⁶ studied the use of an end-expiratory occlusion test (EOT) to determine preload responsiveness in mechanically ventilated patients with ARDS. The procedure for the EOT was to hold end-expiratory pressure for 15 seconds at both low and high PEEP levels (similar to ARMs described earlier).³⁶ Patients underwent a passive leg raise test, and those who showed a significant change in their baseline cardiac index were then given an EOT, followed by a 500-mL fluid challenge.³⁶ Changes in cardiac indexes were measured and recorded. Silva et al³⁶ found a significant correlation between changes in the passive leg raise test and the EOT. They also identified a significant correlation between the EOT and responsiveness to a fluid challenge. They concluded that the EOT could predict preload dependence regardless of the level of PEEP in patients with ARDS.³⁶ Similarly, a drop in blood pressure or beat-to-beat variability in the SpO_2 plethysmograph following an ARM indicates the need to reevaluate a patient's fluid volume status.

Patients undergoing cardiac surgery may be more susceptible to hemodynamic changes due to application of ARMs. In 2005, Nielson et al³⁷ found that sustained

manual inflations to a PIP of 40 cm H₂O for 10 and 20 seconds markedly reduced cardiac output and left ventricular end-diastolic volume in hemodynamically stable patients following cardiac surgery. Pulmonary arterial pressures increased, on average, by 12 mm Hg during 10-second ARMs and 9 mm Hg during 20-second ARMs. Cardiac output decreased from 5.6 L/min to 3.0 L/min in 10-second ARMs and to 3.6 L/min in 20-second ARMs. Hypotension following ARMs not responding to fluid resuscitation may reveal the need for reassessment of cardiac function.

What Is the Available Research Regarding Alternative Methods to Reduce Atelectasis Perioperatively?

The idea of decreasing FIO₂ during induction and/or emergence to reduce atelectasis surfaced in the literature in the 1990s, but since then has not been studied extensively. In 1996, Rothen et al³⁸ conducted a study comparing the use of 30% oxygen and 100% oxygen during induction of general anesthesia in 24 healthy patients scheduled for elective surgery. They found a significant decrease in atelectasis measured by CT scans in patients induced with only 30% oxygen. No patients in the reduced oxygen group experienced significant complications during induction. In their conclusion, the researchers did not recommend the routine use of 30% oxygen during induction of anesthesia. They merely suggested that anesthesia providers reexamine their induction techniques, including the routine use of 100% oxygen.

The consequences of a reduced oxygen induction during difficult intubations can be disastrous. Difficult airway management is not always predictable. Without further evidence showing that the benefits far outweigh the risks, it seems prudent to maintain current practices of the application of 100% oxygen before induction of general anesthesia.³⁹

In 2002, Benoît et al⁴⁰ conducted a study comparing the effect of 40% oxygen and 100% oxygen during emergence with 30 patients with ASA classes I and II scheduled for elective surgery. Patients were divided into 3 groups: 100% oxygen (static tidal volume), 100% oxygen and an ARM (sustained manual inflation up to PIP of 40 cm H₂O), and 40% oxygen and an ARM. These researchers found a significant decrease in atelectasis (estimated by CT scans) following extubation in the reduced FIO₂ group. They concluded that a high FIO₂ on emergence contributes to atelectasis in the postoperative period and that further studies should be undertaken to reexamine emergence practices.

Another area of research is the application of continuous positive airway pressure (CPAP) immediately following extubation. The use of CPAP immediately following extubation has been found to maintain the benefits of intraoperative ARMs and prevent additional atelectasis. In

2005, Squadrone et al⁴¹ compared subjects experiencing a postoperative PaO₂/FIO₂ ratio of 300 or less in the immediate postoperative period. Patients who met the qualifications either received 50% oxygen with a Venturi mask or 50% oxygen with CPAP set at 7.5 cm H₂O. There was a significant decrease in the incidence of endotracheal intubations and other severe complications such as pneumonia and sepsis in patients in the CPAP plus oxygen group.

In the future, a study regarding the use of intraoperative ARMs combined with the use of CPAP following extubation may extend the benefits of ARMs into the recovery period. Ideally, ARMs undertaken in the intraoperative period followed by CPAP in recovery would reduce PPCs and improve patient outcomes.

There is sufficient evidence at this time to support the use of ARMs in daily practice. Alveolar recruitment maneuvers are easy to administer, and their benefit can be immediately confirmed by the improvement in a patient's pulmonary compliance. Following induction of anesthesia, ARMs should be performed routinely during maintenance (at least once per hour), and in the presence of a falling SpO₂. Until further research is conducted, the provider can incorporate simple strategies during emergence such as elevating a patient's head, ensuring adequate tidal volumes, maintaining PEEP, and providing adequate reversal of neuromuscular blockade to reduce the formation of atelectasis in the postoperative period.

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