ANESTHESIOLOGY

Perioperative Pulmonary Atelectasis: Part II. Clinical Implications

David Lagier, M.D., Ph.D., Congli Zeng, M.D., Ph.D., Ana Fernandez-Bustamante, M.D., Ph.D., Marcos F. Vidal Melo, M.D., Ph.D.

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ABSTRACT

The development of pulmonary atelectasis is common in the surgical patient. Pulmonary atelectasis can cause various degrees of gas exchange and respiratory mechanics impairment during and after surgery. In its most serious presentations, lung collapse could contribute to postoperative respiratory insufficiency, pneumonia, and worse overall clinical outcomes. A specific risk assessment is critical to allow clinicians to optimally choose the anesthetic technique, prepare appropriate monitoring, adapt the perioperative plan, and ensure the patient's safety. Bedside diagnosis and management have benefited from recent imaging advancements such as lung ultrasound and electrical impedance tomography, and monitoring such as esophageal manometry. Therapeutic management includes a broad range of interventions aimed at promoting lung recruitment. During general anesthesia, these strategies have consistently demonstrated their effectiveness in improving intraoperative oxygenation and respiratory compliance. Yet these same intraoperative strategies may fail to affect additional postoperative pulmonary outcomes. Specific attention to the postoperative period may be key for such outcome impact of lung expansion. Interventions such as noninvasive positive pressure ventilatory support may be beneficial in specific patients at high risk for pulmonary atelectasis (*e.g.,* obese) or those with clinical presentations consistent with lung collapse (*e.g.*, postoperative hypoxemia after abdominal and cardiothoracic surgeries). Preoperative interventions may open new opportunities to minimize perioperative lung collapse and prevent pulmonary complications. Knowledge of pathophysiologic mechanisms of atelectasis and their consequences in the healthy and diseased lung should provide the basis for current practice and help to stratify and match the intensity of selected interventions to clinical conditions.

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Pulmonary atelectasis contributes to perioperative lung dysfunction[1–3] and potential injury.[4–6] This emphasizes the relevance of an active clinical management based on the identification of risk factors, and implementation of specific diagnostic and therapeutic approaches to optimize lung function and minimize lung injury. Here, we review the clinical implications of perioperative pulmonary atelectasis in both a pathophysiologic and an evidence-based perspective.

Clinical Risk Factors for Perioperative Atelectasis

Risk factors for atelectasis can be categorized as patient-, anesthesia-, and surgery-related. Many risk factors have been identified, either directly with imaging techniques or indirectly through their association with global measurements of gas exchange and respiratory mechanics dysfunction. In this review, we will give special attention to direct evidence from lung imaging. Anesthesiologists should identify such factors to anticipate the risk for perioperative respiratory dysfunction and adapt their management to both patient and surgery (table 1).

Patient-related Risk Factors

Obesity

The increased weight of abdominal and thoracic adipose tissue exacerbates the compressive forces transmitted by the chest wall to the lung and exaggerates the cephalad displacement of the diaphragm.[7] These produce a rightward shift of the respiratory system pressure–volume curve,[8] higher pleural pressure,[9] lower respiratory system compliance,[8,10] and lower functional residual capacity (FRC) before[11] and after induction of general anesthesia.[12] The combined effect of compression of the dorso-caudal lung and the gas absorption in lung units exposed to small airway closure results in greater risk of perioperative pulmonary atelectasis in obese than nonobese patients.[13,14] Postintubation atelectasis at positive end-expiratory pressure (PEEP) 0 cm H_2O assessed by computed tomography linearly relates to body mass index (weight/square of the height) in the 18 to 30 range.[15] Also, during general anesthesia, transpulmonary pressure, *i.e.*, the pressure directly acting to expand the lungs,[16] decreases with body mass index up to 40, corroborating the increased susceptibility to lung collapse with obesity. Indeed, mean PEEP estimates to produce positive end-expiratory transpulmonary pressure during general anesthesia in the overweight and obese were 9.1 cm H_2O for body mass index 25 to 29.9; 11.2 cm H_2O

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Table 1. Clinical Risk Factors for Perioperative Pulmonary Atelectasis

Category	Risk Factors
Patient-related	Body mass index > 25 kg/m^2
	Age-dependent small airway closure
	Acute lung inflammation
	Noninflammatory pulmonary edema
	Diaphragmatic and respiratory muscles dysfunction (amyotrophy, neurologic or neuromuscular disease)
	Abdominal hypertension (ileus, ascites, compartment syndrome, pregnancy)
	Bronchial congestion (*e.g.*, active tobacco consumption, chronic bronchitis)
	Chronic aspiration
Anesthesia-related	Diaphragmatic dysfunction (anesthesia depth, neuromuscular blockade, phrenic nerve block)
	High fractional inspired oxygen tension
	Nitrous oxide
	Lower tidal volume (without positive end-expiratory pressure)
	Inappropriate neuromuscular blockade reversal
	Postoperative respiratory depression due to opioids or sedatives
	Fluid overload
	Transfusion related acute lung injury
Surgery-related	Body position (Trendelenburg, supine, lateral decubitus)
	Pneumoperitoneum
	One-lung ventilation
	Cardiopulmonary bypass
	Surgery duration (cardiothoracic, upper abdominal, and laparoscopy)
	Open abdominal and thoracic surgery (postoperative pain)

for body mass index 30 to 34.9; 12.8 cm H_2O for body mass index 35 to 39.9; and 16.8 cm H_2O for body mass index 40 or greater.[9] Also, after tracheal extubation and during the first 24 postoperative hours, morbidly obese patients present larger atelectasis than nonobese patients.[17]

Age. The susceptibility for airway closure, as judged by the difference between FRC and closing capacity, is minimal at young adulthood (20 yr old) and larger at younger and older ages.[18] Risk for intraoperative atelectasis would be expected to follow a similar pattern as airway closure promotes low ventilation/perfusion ratio ($\dot{V}_A/\dot{Q}$) egions and absorption atelectasis. An association between atelectasis area measured with computed tomography immediately after induction of anesthesia and age has been demonstrated. Atelectasis area increases with age from young adulthood to a peak at about 50 yr old, and decreases after 50 yr old.[15] Such reduction of atelectasis with age greater than approximately 50 yr is presumably due to small airway closure delaying denitrogenation and alveolar collapse during preoxygenation.[15] In children, anesthesia-induced atelectasis is relevant particularly before 3 yr old.[19] The immature chest wall muscles and incompletely developed supporting structures in the lung parenchyma reduce outward tethering forces, while elastic recoil of the lung is fully preserved,[20] resulting in lower FRC and higher levels of required opening pressures.[18,21]

Diaphragmatic Dysfunction

Perioperative diaphragmatic dysfunction as observed after upper abdominal and cardiothoracic surgery substantially increases the risk of atelectasis. For instance, preoperative diaphragmatic thickening fraction measured with ultrasound independently predicts postoperative pulmonary atelectasis, pneumonia, or prolonged mechanical ventilation after cardiac surgery.[22] Similarly, diaphragmatic excursion less than 10 mm on ultrasound at 24 h postoperatively is associated with higher incidence of atelectasis after thoracic surgery.[23]

Intra-abdominal Hypertension

Intra-abdominal hypertension (ileus, ascites, tumor, hematoma) increases pleural pressure, reduces transpulmonary pressures, and can precipitate large pulmonary atelectasis in supine position particularly after loss of diaphragmatic tone.[24] Pregnancy (third trimester) can similarly increase the risk for intraoperative atelectasis.[25]

Pulmonary Conditions

Pulmonary Inflammation and/or Pulmonary Edema. Pulmonary inflammation and/or pulmonary edema substantially increase the risk of perioperative pulmonary atelectasis due to several mechanisms such as surfactant impairment, increased lung weight, and use of high fractional inspired oxygen tension (F_{IO_2}).[26]

Smoking. Active smoking has been associated with perioperative respiratory morbidity and postoperative pulmonary complications (*e.g.*, obstructive atelectasis, pneumonia, and chest x-ray film findings of atelectasis or consolidation),[27–29] even if not consistently related to anesthesia-induced intraoperative atelectasis.[3,30] Increased airway secretions in smokers leading to bronchial or bronchiolar

obstruction, in addition to bronchospasm, can contribute to lung collapse.[31]

Chronic Obstructive Pulmonary Disease. Chronic obstructive pulmonary disease is a risk factor for perioperative pulmonary complications. Specifically regarding lung collapse, chronic obstructive pulmonary disease has been associated with resistance to atelectasis, *e.g.,* from oxygen absorption in awake[32] and surgical[33,34] patients, despite small airway closure and substantial $\dot{V}_A/\dot{Q}$ mismatch.[32,34,35] Such resistance to lung collapse is likely due to the effect of hyperinflation and loss of lung elastic recoil. Perioperatively, the magnitude of atelectasis is determined by the net effect of factors contributing to and preventing lung collapse.

Chronic Pulmonary Hyperperfusion. Chronic pulmonary hyperperfusion encountered in congenital heart disease (*e.g.,* ventricular septal defect) protects from atelectasis as compared to hypoperfused lung (*e.g.,* tetralogy of Fallot) due to the stabilizing tethering effect of filled pulmonary capillaries on alveolar walls.[36]

Anesthesia-related Risk Factors

General Anesthesia Drugs

Sedative-hypnotics. Both intravenous[37] and inhalational anesthetics[38,39] have been associated with intraoperative pulmonary atelectasis. Inhalational anesthesia and total intravenous anesthesia lead to a similar incidence of pulmonary complications after noncardiac surgery.[40] In cardiothoracic surgery, there is no evidence for superiority of any general anesthesia technique in the production of postoperative pulmonary complications as volatile agents have been found either superior,[40,41] equivalent,[42] or inferior[43] to intravenous agents. Nitrous oxide presents higher lipid solubility than nitrogen, promoting alveolar gas absorption[44] and increasing the risk of postoperative atelectasis.[45] Ketamine by itself maintains chest wall muscle tone, thus preventing lung collapse.[46]

Opioids. As respiratory depressants, opioids decrease the central neural drive to the respiratory muscles and the sensitivity to carbon dioxide leading to respiratory depression and cough inhibition. Accordingly, intraoperative systemic opioids have been dose-dependently associated with postoperative atelectasis.[47]

Neuromuscular Blocking Agents and Antagonists. Neuromuscular blockade can compound with general anesthetics to facilitate the compressive effect of the abdomen onto the lungs, change chest wall cross-section, and promote ensuing atelectasis.[3] Postoperatively, residual neuromuscular blockade contributes to respiratory muscle dysfunction, atelectasis, and hypoxemia,[48,49] thus reinforcing the relevance of neuromuscular blockade reversal.[50] This should be accurately done as neostigmine administered at high doses (greater than 60 μg/kg) or not based on neuromuscular monitoring resulted in postoperative pulmonary atelectasis, presumably from neostigmine-induced neuromuscular blockade.[51]

Regional Anesthesia

Use of regional anesthesia as the main anesthetic technique in a spontaneously breathing patient can preserve physiologic diaphragmatic function and reduce intraoperative atelectasis.[3,52]

While regional techniques are associated with less atelectasis than general anesthesia,[53,54] they may still produce respiratory muscle dysfunctions and facilitate lung collapse.

Neuraxial anesthesia has been associated with a significant paresis of abdominal and accessory respiratory muscles (*e.g.*, intercostals) and deterioration of the exhalation force, breathing pattern, or ability to cough.[55] Reduction of lung volumes has been accordingly associated with neuraxial anesthesia, and depends mainly on the level and extension of the blockade (*i.e.*, impairment increases from lumbar to cervical). For example, thoracic epidural anesthesia with T1–T5 sensory block decreases vital and inspiratory capacity.[56,57] Spinal anesthesia similarly reduces vital capacity but contributes to a higher reduction of the expiratory reserve volume (–48% with sensory block at T2) than thoracic epidural anesthesia.[58,59] Of note, reductions in intraoperative lung volumes during spinal anesthesia are greater in the overweight[53] or the obese[60] patient. Due to the higher level of motor block and potential compromise of the diaphragmatic innervation, cervical epidural anesthesia may further deteriorate lung expansion as shown by a significant reduction in diaphragmatic excursion, maximal inspiratory pressure, and tidal volume (V_T).[61] While such respiratory muscle dysfunction associated with both epidural and spinal anesthesia may compound to lung collapse in at-risk conditions,[25] this risk does not appear to be clinically relevant in patients without preexisting lung disease and might not surpass the benefits of avoiding general anesthesia in patients at high respiratory risk.[25,62]

Peripheral nerve blocks can also facilitate lung collapse. The risk of ipsilateral atelectasis due to phrenic nerve palsy and hemidiaphragmatic paresis may limit the use of interscalene block or other injections of local anesthetic in the cervical region (*e.g.*, supraclavicular, cervical plexus blocks) in patients presenting respiratory conditions.[63,64] Importantly, this risk is substantially reduced by the use of ultrasound-guided techniques and lowered volume of local anesthetic.[64,65]

Blood Transfusion

Perioperative blood transfusion has been associated with postoperative pulmonary complications including atelectasis on systematic chest computed tomography after orthopedic surgery.[66,67]

Surgery-related Risk Factors

Body Position

Operating Table Angle. The supine position is associated with a 27% decrease in FRC when compared to the sitting

position (90 degrees)[68] as it facilitates the cephalad shift of the diaphragm induced by the compression of intraabdominal organs. The Trendelenburg position further increases compression of the dorso-caudal lung as shown by additional reduction in FRC (approximately 12%) in anesthetized children.[69] During robotic surgery, steep Trendelenburg reduces end-expiratory transpulmonary pressure[9] independently from patients' body mass index and application of pneumoperitoneum.[9] The reduction in regional ventilation[70] and approximately 12% increase in silent spaces (lung areas with little or no ventilation suggestive of atelectasis) in the dorsal dependent lung have been confirmed by electrical impedance tomography.[71] In contrast, the 40-degree reverse Trendelenburg position relieves lung compression by the abdomen with a marked benefit in obese patients, *e.g.*, homogenization of regional ventilation during bariatric laparoscopic surgery.[72]

Prone Positioning. Normally, the prone position reduces FRC from the sitting posture in awake, spontaneously breathing healthy humans.[73] In the anesthetized surgical patient, the prone position with free abdominal movements (upper chest and pelvic supports) can markedly increase FRC by 53% when compared to supine posture,[74] even more in obese patients.[75] Frequently, anterior chest and abdominal wall movements are restricted in the prone position, and lung expansion is predominantly determined by movement of the dorsal chest wall and diaphragm. The prone position reduces the mass of dependent lung exposed to the effect of gravity, favorably modifies the matching of lung and chest wall shapes, and reduces lung compression by cardiac and abdominal structures. These result in spatial homogenization of lung aeration and less deterioration of lung inflation and regional strain over time[76] due to both gravitational (dorsal greater than ventral expansion) and nongravitational (caudal greater than cranial expansion) mechanisms.[77] Favorable effects on ventilation, $\dot{V}_A/\dot{Q}$,[78–80] and oxygenation are also observed,[81] while perfusion distribution is not significantly affected.[82]

Lateral Decubitus. The dependent lung is exposed to compression from the weight of the nondependent lung, mediastinum, and abdominal organs.[83,84] Thus, atelectasis is almost exclusively located in the dependent lung as detected by computed tomography in anesthetized patients.[83,85] Yet the global FRC is larger in the lateral than in the supine position both before[86] and after[87] induction of general anesthesia due to the contribution of the nondependent lung. This represents a larger nondependent lung volume exposed to lower compression forces and larger transpulmonary pressures than that present in supine conditions.[88] Despite differences in lung size, the effect of lateral decubitus appears similar if the patient is lying on the left or right side.[68,88]

Lithotomy. Lithotomy position has little differential effect on respiratory mechanics and the amount of poorly aerated lung tissue when compared with the supine position.[54,89]

Pneumoperitoneum

Pneumoperitoneum compresses the juxta-diaphragmatic lung regions by increasing intra-abdominal pressure, thus promoting the cephalad displacement of the diaphragm.[90] Peritoneal insufflation independently reduces end-expiratory lung volume (approximately 35% in the nonobese and approximately 15% in the obese),[91] respiratory system compliance,[92] and end-expiratory transpulmonary pressure.[9] These physiologic changes are consistently associated with substantially higher atelectasis volume in the dependent lung (mean increase of 66% by computed tomography).[90,93] This effect was independent of the body position,[9,92] and has been confirmed, in humans, with relatively low intraabdominal pressure (11 mmHg).[90] Combination of pneumoperitoneum and steep Trendelenburg position, as frequently implemented during robotic surgery, is associated with a high risk of severe atelectasis and may require a specific approach to lung recruitment.[70,94,95]

Cardiac Surgery

Lung inflammation and ischemia–reperfusion injury from cardiopulmonary bypass are associated with substantial pulmonary compromise characterized by alveolocapillary membrane injury,[96] surfactant impairment,[97] and mucociliary dysfunction.[98] Alterations of the chest wall function including the effect of sternotomy,[99,100] diaphragmatic dysfunction,[101] and pleural violation compound with those effects with impairment of lung expansion in the intra- and postoperative periods. Accordingly, atelectasis represents a frequent cause of hypoxemia both during and after surgery.[102–104] The predominance of retrocardiac lung collapse in the postoperative period suggests an important contribution to atelectasis from compression by the weight of the heart (fig. 1).[105]

One-lung Ventilation

Atelectasis produced by lung isolation is remarkable for its extension to a lung volume and its continuous character (*i.e.,* no tidal recruitment). Depending on the preoperative respiratory status and the effectiveness of hypoxic pulmonary vasoconstriction, one-lung ventilation may be associated with critical impairment of intraoperative gas exchange and cardiopulmonary function.[106] Lung isolation exposes the collapsed lung to inflammatory,[107,108] ischemic,[109] and reexpansion[110] insults, besides direct surgical trauma. The ventilated dependent lung is also at risk in this setting not only due to the potential systemic inflammatory response but also due to mechanical ventilation injury and compressive atelectasis during lateral decubitus.[111,112] This effect can be exacerbated in the obese or if insufficient PEEP is associated with low V_T.[113] Such intraoperative insults to the collapsed and the ventilated lungs likely contribute to the large number of pulmonary complications, including

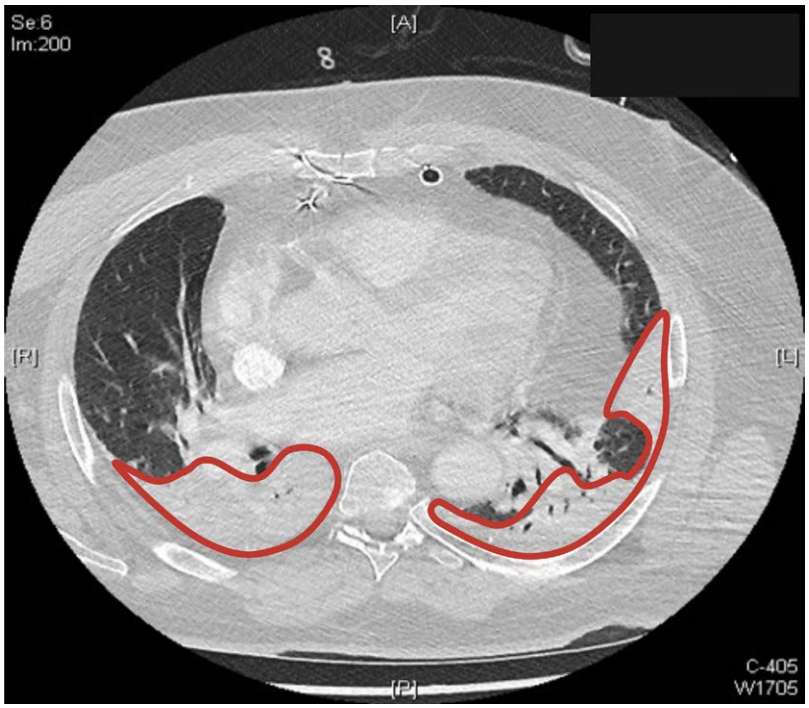

Fig. 1. Lung computed tomography: bilateral opacities of the dependent retrocardiac lung regions (*red lines*) revealing the typical aspect of severe perioperative pulmonary atelectasis in an obese patient requiring reintubation for postoperative respiratory failure 2 days after coronary artery bypass graft surgery.

postoperative atelectasis, observed in the thoracic surgery population.[114–116]

Surgery Duration

General anesthesia is responsible for nearly instantaneous diaphragmatic cephalad displacement in supine and semisitting patients.[71,103,117] Pulmonary atelectasis appears in the early minutes after loss of consciousness,[118,119] particularly when preoxygenation with F_{IO_2} of 1.0 is applied,[120] and additional gas absorption persists along the first 90 min.[121] Experiments in sheep revealed that lung collapse in healthy lungs with aeration heterogeneity comparable to that of humans occurs throughout 16 h after initiation of general anesthesia with low V_T ventilation without PEEP.[6] Such progressive collapse could contribute to the detrimental effect of anesthesia duration on postoperative pulmonary complications.[122] A combined effect of time and site of surgery is likely, as no time dependence of atelectasis volume was found in normal lung patients undergoing intracranial surgery,[123] while gas exchange and FRC progressively deteriorate along cardiac or abdominal surgeries.[124,125]

Minimally Invasive Procedures

Abdominal minimally invasive procedures are frequently associated with the use of pneumoperitoneum and Trendelenburg position, thus increasing the risk of intraoperative pulmonary atelectasis.[9] However, avoiding open thoracic or abdominal surgery may substantially reduce postoperative pain, improve postoperative lung volumes,[126] and lower the rate of postoperative pulmonary atelectasis and other complications.[127,128]

Diagnostic Approach to Pulmonary Atelectasis

While frequently inferred from physiologic measurements (respiratory mechanics and gas exchange), accurate diagnosis of atelectasis, as a primarily morphologic process, should be based on direct quantification of the collapsed pulmonary parenchyma, *e.g.*, using imaging techniques.[129]

Direct Morphologic Assessment

Chest Radiography

Lung deaeration is associated with increased x-ray attenuation. Accordingly, opacification related to a lung segment or lobe is a typical finding of atelectasis. Yet dorsocaudal or retrocardiac opacities can be missed in frontal chest radiography.[130] Mediastinal or hemidiaphragmatic shift together with compensatory overinflation of the expanded lung are additional classical findings.

Computed Tomography

Similar to chest radiography, computed tomography is also based on x-ray attenuation yet with the important addition of three-dimensional high-resolution quantitative assessment. Computed tomography is the accepted standard for diagnosis and quantification of alveolar collapse,[131] and attenuation values of −100 to +100 Hounsfield units correspond to the operational definition of nonaerated lung.[132] Displacement of interlobar fissures; shift of the mediastinum, heart, and pulmonary hilum toward the collapsed area; ipsilateral diaphragmatic elevation; intercostal space narrowing; and overinflation of the remainder aerated lung are typical findings of lobar atelectasis (fig. 1). Computed tomography is also useful to determine the cause of atelectasis by identification of bronchial obstruction, or compressive pleural effusion.[133] The differential diagnosis between pneumonia, alveolar flooding, and atelectasis may be difficult as lung attenuation can also result from fluid accumulation. Differentiation approaches have been investigated although not entirely established, *e.g.*, a threshold of contrast (iodixanol) enhancement 85 Hounsfield units or greater to discriminate atelectasis and pneumonia demonstrated a sensitivity for atelectasis of 90% and specificity of 92%.[134]

Magnetic Resonance Imaging

Magnetic resonance imaging is a nonionizing technique to diagnose and quantify lung atelectasis (fig. 2).[135,136] T1- and T2-weighted images have been used in clinical conditions,[136] and the method validated against computed tomography in a preclinical study.[137] As T2-weighted magnetic resonance imaging allows for the identification of water-based tissue, it could significantly help to differentiate obstructive (hyperintensity due to accumulated secretions and total air resorption) from nonobstructive atelectasis (low signal intensity due to less free fluid and residual air).[136]

Pulmonary Ultrasound

Lung ultrasound has been recently extensively validated for bedside assessment of lung collapse both in the operating room and in the intensive care unit (ICU).[138] As air is a strong ultrasound beam reflector, lung deaeration substantially increases the echogenicity of lung parenchyma. Accordingly, pulmonary atelectasis, similar to other causes of lung consolidation, is visualized as a "tissue-like" or "hepatized" ultrasonographic structure (fig. 3A).[139] Lung ultrasound is highly accurate to diagnose pulmonary atelectasis in both children[140] and adults,[141] and performs better than auscultation or bedside radiography to differentiate important causes of increased density (*e.g.*, pulmonary consolidation *vs.* pleural effusion).[142] Similar to computed tomography, the differential diagnosis of pulmonary consolidation with ultrasound (atelectasis *vs.* pneumonia) remains challenging. The visualization of dynamic air bronchogram, revealed by a ventilation-synchronized, linear, or pinpoint hyperechoic signal inside a lung consolidation, allows for high positive predictive value (86 to 97%) but moderate sensitivity (61%) in the diagnosis of pneumonia.[143,144] Assessment of atelectasis with ultrasound has been proposed for intraoperative individualization of alveolar recruitment[145–147] and postoperative prediction of pulmonary complications.[148] Transesophageal ultrasound may be used if transthoracic acoustic windows are unavailable.[149] Color Doppler interrogation of a lung consolidation can help to evaluate local blood flow and the efficacy of hypoxic pulmonary vasoconstriction (fig. 3B).[150]

Indirect Physiologic Assessment

Electrical Impedance Tomography

Electrical impedance tomography allows for continuous real-time and bedside assessment of lung ventilation and aeration,[151] and has been proposed as a tool to monitor and individualize intraoperative lung recruitment.[152,153] Loss of aeration associated with atelectasis decreases the electrical impedance of lung tissue as air has high electrical impedance. Current devices provide assessment of a cross-sectional thoracic slice approximately 10 to 15 cm thick at the level of the transducer belt and allow for regional comparisons (*e.g.*, ventral *vs.* dorsal or right *vs.* left lung).[71,103] While signals are represented as a two-dimensional lung-shaped image (fig. 4), the image does not derive from a direct morphologic assessment, but is mapped according to a presumed chest geometry.[129] Changes in end-expiratory lung impedance produced by PEEP strongly correlate with changes of end-expiratory lung volumes measured with the nitrogen washout technique.[154] Measurements of the impedance variation produced by tidal ventilation have been used to describe the regional distribution of lung ventilation and estimate regional lung expansion as poorly ventilated regions present less tidal impedance variation than normally ventilated regions.[71,103] An important technical limitation is that pulmonary consolidations and pleural effusion could produce a similar signal, preventing differential diagnoses.

Respiratory System Compliance and Driving Pressure

Pulmonary atelectasis may reduce respiratory system compliance, thus increasing driving pressure.[155,156] Considering their presumed impact on patients' prognosis,[16,155–157] and easy assessment, monitoring of driving pressure during surgery may be particularly valuable. Indeed, large registry-based studies have consistently identified driving pressure equaling 15 cm H_2O or greater as a potential threshold to predict postoperative pulmonary complications and prompt interventions.[157,158] Yet such observations are not specific to atelectasis as lung overdistension could lead to similar changes in compliance and driving pressures. Moreover, respiratory system mechanical properties are determined by both lungs and

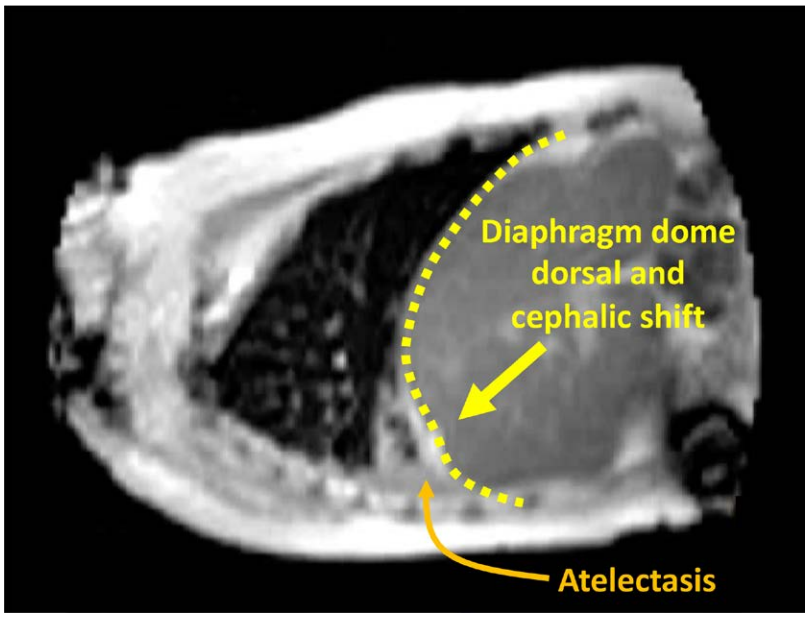

Fig. 2. Sagittal cross-section magnetic resonance images showing the effect of general anesthesia and paralysis in the supine position: dorsal cephalad shift of the diaphragm dome and atelectasis of the dorso-caudal lung.

chest wall. Accordingly, the use of absolute thresholds for respiratory system compliance or driving pressure is limited in patients presenting unphysiological or varying chest wall mechanics (*e.g.*, obesity, pneumoperitoneum, abdominal surgery).[159] In those cases, monitoring intraoperative trends[16] to detect a deterioration (*e.g.*, greater than 20% increase at constant V_T), use of PEEP titration, or additional monitoring for partitioning of lung and chest wall mechanical properties might be helpful (fig. 5).

Transpulmonary Pressure

Transpulmonary pressure is conceptualized as the pressure across the lungs, *i.e.*, the difference between airway opening pressure and pleural pressure. While airway pressure is usually available, pleural pressure is not. Esophageal pressure measurement has been used to estimate pleural pressure.[160] The obtained measurement has been shown to correspond to the pleural pressure surrounding the region where

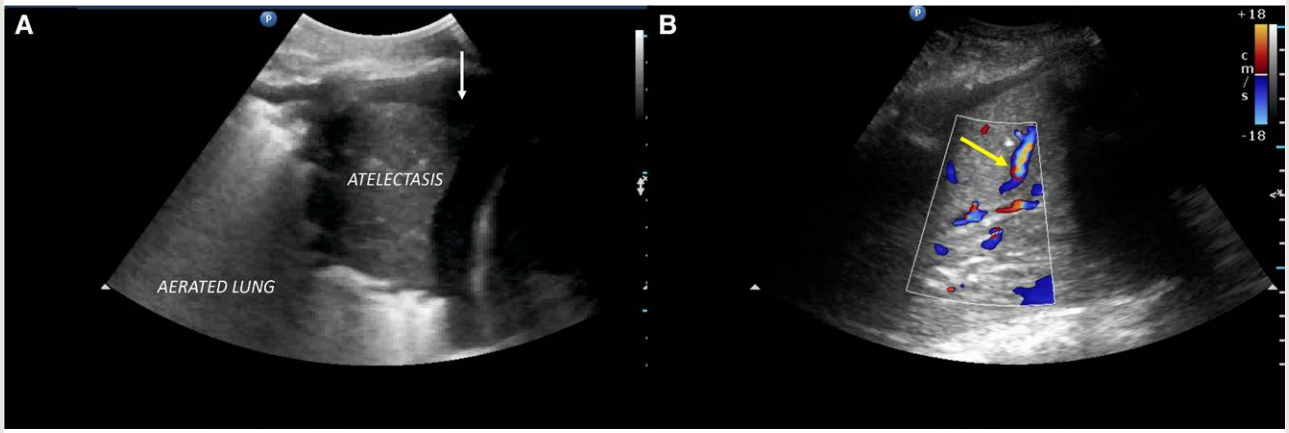

Fig. 3. Detection of pulmonary atelectasis by ultrasound. (*A*) Pulmonary atelectasis revealed by a pulmonary consolidation surrounded by a pleural effusion (*white arrow*). (*B*) Color Doppler imaging showing the persisting pulmonary blood flow within consolidated lung (*yellow arrow*) due to incomplete hypoxic pulmonary vasoconstriction, which may result in a shunt effect.

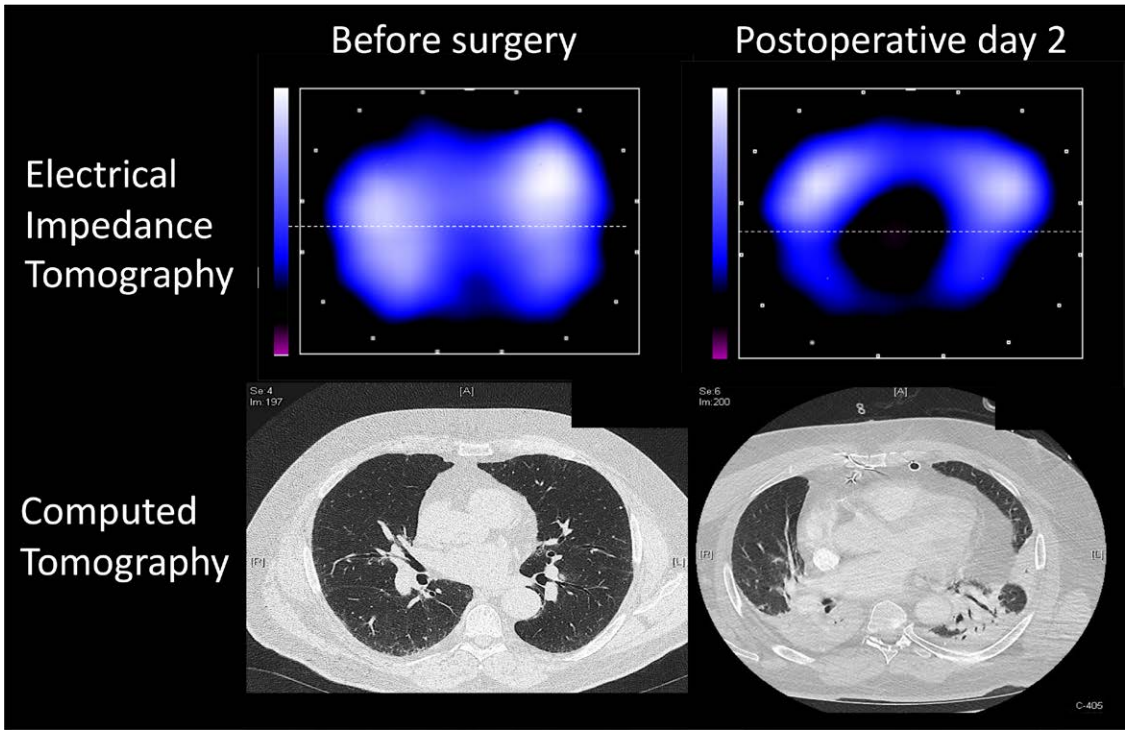

Fig. 4. Pre- and postoperative regional distribution of the tidal impedance variation, assessed with lung electrical impedance tomography, in a patient presenting postoperative respiratory failure 2 days after coronary artery bypass graft surgery. Note that pulmonary atelectasis observed on computed tomography is associated with a reduced impedance variation signal in the dorsal hemithorax.

the pressure is assessed (*i.e.*, dorso-caudal lung according to esophageal balloon location).[161] Exposure to negative transpulmonary pressure, notably at the end of expiration, increases the risk of lung collapse as shown by supine pig and human cadaver imaging studies.[161,162] Negative end-expiratory transpulmonary pressures have also been consistently associated with hypoxemia and lung collapse during acute lung injury[163] and in surgical patients.[95,159] Hence, the continuous monitoring of esophageal pressure, targeting positive transpulmonary pressure,[16] has been proposed as a strategy to individualize airway pressure and maintain lung expansion during mechanical ventilation (fig. 5).[9,164]

Blood Oxygenation

Pulmonary atelectasis correlates with the presence of shunt or regions of low $\dot{V}_A/\dot{Q}$ and contributes to intraoperative hypoxemia.[52,120,165] The magnitude of the hypoxemia will be determined by the degree of ventilation/perfusion mismatch, including the volume of atelectatic lung and the adequacy of regional hypoxic pulmonary vasoconstriction. Pulse oximetry is a simple and usually reliable continuous monitor of oxygenation allowing for the early detection of possible perioperative atelectasis.[166] Because absolute oxygen saturation measured by pulse oximetry (Spo_2) can be normalized by increasing Fio_2, use of the Spo_2/Fio_2 ratio may help to diagnose impaired blood oxygenation better than Spo_2 alone. In injured lung patients, the range of Spo_2/Fio_2 equaling 235 to 315 is associated with Pao_2/Fio_2 of 200 to 300 mmHg.[167]

Therapeutic Management of Perioperative Atelectasis

Several perioperative interventions have been explored to promote lung recruitment, and, ultimately, prevent pulmonary atelectasis. Yet, while studies tested interventions directed to reduce atelectasis, they rarely used its quantitative assessment as their primary endpoint, but instead included postoperative pulmonary atelectasis as a component of pulmonary outcome composites.[168,169] The relevance of interventions directed to minimize atelectasis has been recently emphasized by an international expert panel classifying as highest quality of evidence that "formation of perioperative clinically significant atelectasis" could "be an important risk factor for the development of postoperative pulmonary complications."[168] In this section, we will discuss

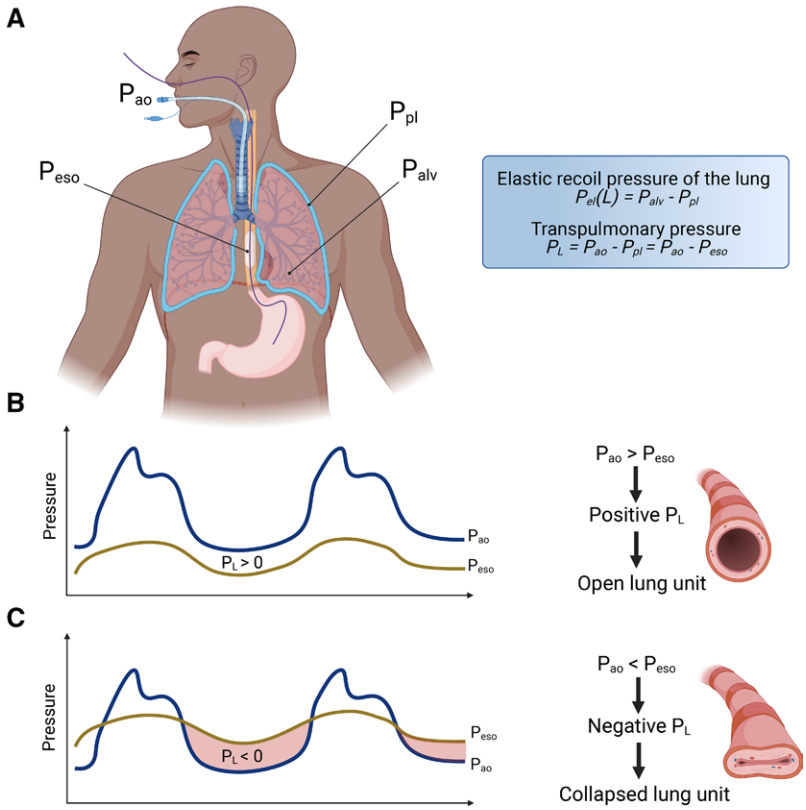

Fig. 5. Principles of esophageal manometry and the use of transpulmonary pressure. (*A*) position of the esophageal pressure balloon at the lower third of the esophagus, and relationship among the different pressures measured in the respiratory system. Transpulmonary pressure (P_L) is an approximate of the elastic recoil pressure of the lung or P_{el}(L). (*B*) Selection of positive end-expiratory pressure consistent with a positive P_L during the expiration period is expected to maintain alveoli recruited throughout the breathing cycle. (*C*) By contrast, negative P_L allows for the collapse of lung units. P_{alv}, alveolar pressure; P_{ao}, pressure at airway opening; P_{eso}, esophageal pressure; P_{pl}, pleural pressure.

reported therapeutic approaches considering the clinical period (pre-, intra-, or postoperative) and the underlying pulmonary condition (normal *vs.* inflamed lung).

Preoperative Period

Prehabilitation combining preoperative patient education, preoperative physiotherapy, smoking cessation, and nutritional optimization has been proposed to prevent postoperative pulmonary complications including pulmonary atelectasis.[170–175] In high–respiratory risk patients undergoing coronary artery bypass graft surgery, preoperative intensive inspiratory muscle training prevents postoperative pulmonary complications including atelectasis.[176] In patients undergoing upper abdominal surgery, a randomized clinical trial found that a single preoperative physiotherapy session (30 min) significantly reduced postoperative pulmonary complications (including atelectasis on chest x-ray film).[177] However, the relatively high rate of postoperative pulmonary complications in controls and the influence of regional practices should encourage the replication of these results in larger cohorts. Finally, meta-analysis findings suggested a beneficial effect of preoperative inspiratory muscle training before cardiac or major abdominal surgery for prevention of postoperative atelectasis and pneumonia. Yet results could be overestimated due to lack of adequate blinding and study size.[178]

Intraoperative Period

V_T

Supraphysiological V_T (10 to 15 ml/kg of predicted body weight) has been until recently the decades-long cornerstone of intraoperative atelectasis treatment.[1,179] Indeed, lower V_T implies the potential for poorly ventilated lung regions exposed, in the absence of PEEP, to progressive deaeration. Yet while effective to prevent atelectasis, large V_T has been associated with higher risk of postoperative pulmonary complications in meta-analyses,[180,181] registry-based studies,[182] and clinical trials in abdominal[183] and thoracic[184] surgery. The protective range of V_T in surgical patients may be broader than stricter lower tidal volume

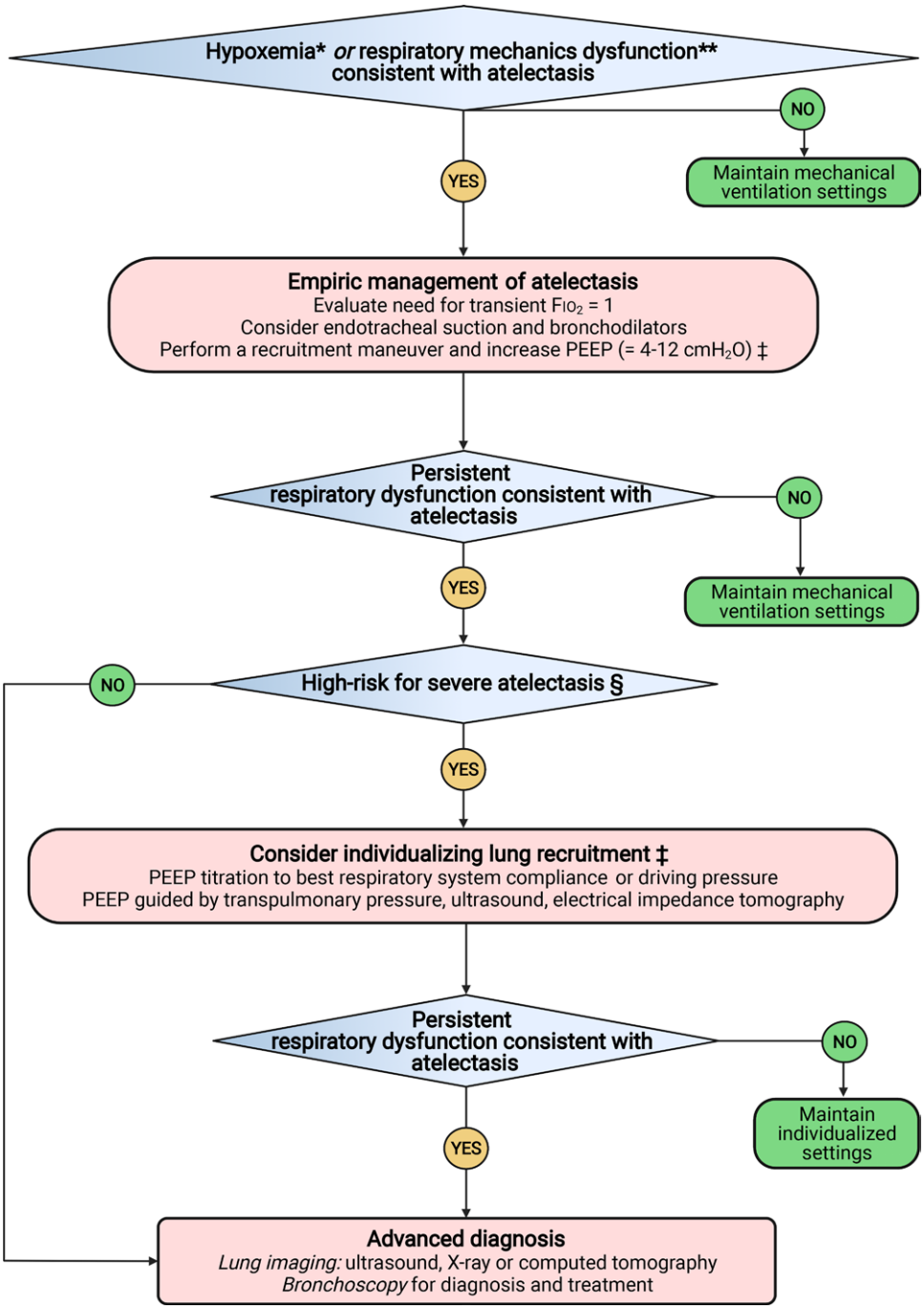

Fig. 6. Algorithm for intraoperative management of pulmonary atelectasis. A standard ventilatory strategy targeting surgical patients is implemented after anesthesia induction (positive end-expiratory pressure [PEEP] 2 to 5 cm H_2O, no recruitment maneuvers, tidal volume 6 to 10 ml/kg of predicted body weight). In patients presenting intraoperative respiratory compromise consistent with pulmonary atelectasis, fixed higher PEEP is set after a recruitment maneuver. Attention is given to basic maneuvers to eliminate additional causes, *e.g.*, secretions and bronchoconstriction, and maintain safety (transient increase in fractional inspired oxygen tension [F_{IO_2}]). If the respiratory dysfunction persists despite empiric alveolar expansion, an individualized strategy can be considered in high-risk conditions for atelectasis: PEEP titration targeting optimization of usually available (*e.g.*, compliance, driving pressure) or advanced respiratory measurements (transpulmonary pressure, ultrasound, electrical impedance tomography). If individualization of lung recruitment fails to improve lung function or in patients without specific risk for intraoperative atelectasis, a specific diagnostic approach should be implemented without delay using lung imaging or bronchoscopy. *Hypoxemia may be defined by oxygen saturation measured by pulse oximetry drop by more than 5% or F_{IO_2} increase by more than 30% to maintain oxygenation with PEEP of 5 cm H_2O (presuming other causes such as airway, ventilator, or hemodynamic issues have been excluded). **Significant respiratory mechanics change may be defined by a compliance of the respiratory system drop by more than 20%, or a driving pressure 15 cm H_2O or greater with PEEP of 5 cm H_2O and tidal volume of 6 ml/kg predicted body weight. ‡Attend to hemodynamic stability during recruitment maneuvers. §Body mass index 35 kg/m^2 or greater, pneumoperitoneum, Trendelenburg position, upper abdominal surgery with diaphragmatic surgical retractors, diaphragmatic injury, intraoperative lung injury, or pulmonary edema.

Table 2. Randomized Clinical Trials on Alveolar Expansion Strategies during General Anesthesia

	Inclusion Criteria		Groups: Intervention: Alveolar Expansion				Groups: Control				Outcomes	
			Intraoperative				Intraoperative					
Clinical Trial	Patients	Surgery	PEEP (cm H_2O)	Recruitment Maneuver	V_T (ml/kg predicted body weight)	Postoperative	PEEP (cm H_2O)	Recruitment Maneuver	V_T (ml/kg predicted body weight)	Postoperative	Primary	Secondary
IMPROVE[183] Multicenter (n = 400)	Body mass index < 35 kg/m² Risk class > 2*	Abdominal ≥ 2 h	6–8	Yes	6–8	None	0	No	10–12	None	↓Pulmonary or systemic complications	↓ Postoperative atelectasis ↓Ventilatory support ↓Hospital length of stay
PROVHILO[188] Multicenter (n = 900)	Body mass index < 40 kg/m² Intermediate–high risk†	Open abdominal	12	Yes	8	None	≤ 2	No	8	None	No effect—pulmonary complications	Postoperative atelectasis: nonsignificant ↑Hypotension ↑↑Vasoactive drugs
iPROVE[194] Multicenter (n = 1,012)	Body mass index ≤ 35 kg/m² Intermediate–high risk†	Abdominal ≥ 2 h	I: Titrated (C_{dyn}): 10 ± 3	Yes	8	3 h of continuous positive airway pressure (if Spo_2 ≤ 96% on room air)	5	No	8	Supplemental oxygen (Venturi mask)	No effect—pulmonary or systemic complications	Group I: ↓Pulmonary atelectasis and complications ↓ ICU length of stay
			II: Titrated (C_{dyn}): 10 ± 3	Yes	8	3 h of continuous positive airway pressure						
			III: 5	No	8	3 h of continuous positive airway pressure						
PROBESE[189] Multicenter (n = 2,013)	Body mass index ≥ 35 kg/m² Intermediate–high risk†	90% abdominal ≥ 2 h	12	Yes	7	None	4	No	7	None	No effect—pulmonary complications	Postoperative atelectasis: nonsignificant ↑Hypotension ↑Bradycardia ↑Vasoactive drugs ↓Intraoperative hypoxemia
Karalapillai *et al.*[185] Single center (n = 1,236)	> 40 yr old Invasive arterial pressure	56% abdominal ≥ 2 h	5	No	10	None	5	No	6	None	No effect—pulmonary complications	Postoperative atelectasis: nonsignificant ↓Acidosis ↓Hypercapnia Similar Pao_2/Fio_2
PROVECS[102] Multicenter (n = 494)	Body mass index < 35 kg/m²	On-pump cardiac	8	Yes	6–8	Before extubation: recruitment maneuver 30 cm H_2O PEEP 8 cm H_2O After extubation: none	2	No	6–8	Before extubation: PEEP 2 cm H_2O After extubation: none	No effect—pulmonary complications	Postoperative atelectasis: nonsignificant ↓Intraoperative hypoxemia

(*Continued*)

Table 2. (Continued)

	Inclusion Criteria		Groups: Intervention: Alveolar Expansion				Control				Outcomes	
			Intraoperative				Intraoperative					
Clinical Trial	Patients	Surgery	PEEP ($cm H_2O$)	Recruitment Maneuver	V_T (ml/kg predicted body weight)	Postoperative	PEEP ($cm H_2O$)	Recruitment Maneuver	V_T (ml/kg predicted body weight)	Postoperative	Primary	Secondary
Leme *et al.*[201] Single center (n = 320)	Body mass index < 40 kg/m^2 Pao_2/Fio_2 < 250 mmHg at ICU arrival	On- or off-pump cardiac	—	—	—	Before extubation: recruitment maneuver 45 $cm H_2O$ PEEP 13 $cm H_2O$ After extubation: continuous positive airway pressure if Spo_2 < 90% on oxygen	—	—	—	Before extubation: recruitment maneuver 20 $cm H_2O$ PEEP 8 $cm H_2O$ After extubation: continuous positive airway pressure if Spo_2 < 90% on oxygen	↓Pulmonary complications including atelectasis	↓ICU length of stay ↓Hospital length of stay
PPV[184] Multicenter (n = 346; premature interruption)	Lung cancer	Thoracic (one-lung ventilation)	Two-lung: 5–8 One-lung: 5–8	Yes	5 5	None	Two-lung: 0 One-lung: 0	Yes Yes	10 10	None	↓Pulmonary complications including atelectasis	↓Systemic complications ↓Ventilatory support ↓Hospital length of stay
Park *et al.*[155] Single center (n = 312)	Lung or esophageal cancer	Thoracic (one-lung ventilation)	Two-lung: 5 One-lung: Titrated (driving pressure of the respiratory system): 3 [2–5]	Yes	6–8 6	Daily deep breathing exercises and incentive spirometry	Two-lung: 5 One-lung: 5	Yes Yes	6–8 6	Daily deep breathing exercises and incentive spirometry	↓Pulmonary complications including atelectasis	No effect—ICU or hospital length of stay

All listed trials were randomized, were adequately powered to assess postoperative pulmonary outcomes, and included pulmonary atelectasis based on lung imaging at least as a component of the primary endpoint. Values shown as mean ± SD or median [interquartile range].

*Pulmonary risk quantified by Arozullah *et al.*[114] †By ARISCAT.[292]

C_{dyn}, dynamic compliance; Fio_2, fractional inspired oxygen tension; ICU, intensive care unit; IMPROVE, Intraoperative PROtective VEntilation trial; iPROVE, Individualized Perioperative Open-lung Ventilatory Strategy; PEEP, positive end-expiratory pressure; PPV, Pulmonary Surgery with Protective Ventilation; PROBESE, PRotective Ventilation with Higher versus Lower PEEP during General Anesthesia for Surgery in OBESE Patients; PROVECS, PROtective VEntilation in Cardiac Surgery; PROVHILO, PROtective Ventilation using HIgh versus LOw positive end-expiratory pressure; Spo_2, oxygen saturation measured by pulse oximetry; V_T, tidal volume.

ranges utilized in critical care. A recent clinical trial found that V_T of 6 *versus* 10 ml/kg of predicted body weight with PEEP of 5 cm H_2O resulted in similar outcomes after major surgery (table 2),[185] in line with a previous large registry-based study.[157] The presence of PEEP of 5 cm H_2O in these cases may be essential for equivalent outcomes, as absence of PEEP in association with low V_T may be deleterious.[5] Such a finding underscores a limitation of previous studies addressing V_T using bundle interventions of V_T and PEEP settings,[183,184] which prevent the individual assessment of V_T and PEEP to outcomes. Overall, current evidence supports a V_T range of 6 to 10 ml/kg of predicted body weight for two-lung ventilation of surgical patients with noninflamed lungs.

Of note, current data suggest that the protective effect may not derive from lower V_T by itself but from its role in limiting lung strain, defined as change in lung volume divided by the initial lung volume, and clinically estimated from driving pressures. Indeed, registry-based studies in surgical patients undergoing noncardiothoracic[157] and cardiac surgery[158] and studies in acute respiratory distress syndrome (ARDS)[186] have indicated that improved outcomes are related primarily to driving pressures, not to V_T. While these two variables are related, driving pressure is more specifically associated with lung strain, a possible explanation of those findings. That would lead the clinician to consider ventilatory interventions when driving pressures increase, rather than merely focusing on V_T.[16]

Recruitment Maneuvers

Recruitment maneuvers correspond to the transient application of high airway pressures that translate into high transpulmonary pressures aiming at reopening collapsed lung regions. Different types of maneuvers have been used, including sustained inflation for 30 s at airway pressure 30 cm H_2O,[102,183,187] or transient increase in V_T and PEEP for three breaths to reach plateau pressure of 30 to 35 cm H_2O in normal-weight people[188] or 40 to 50 cm H_2O in the obese.[189] Recruitment maneuvers are efficacious in reducing pulmonary atelectasis volume[165] and improving intraoperative respiratory mechanics[190] and oxygenation.[91,187,191] However, this effect may be transient when high F_{IO_2} is used during the maneuvers[192] or when these are not associated with appropriate PEEP management.[14] For instance, recruitment maneuvers only lead to physiologic and radiographic improvement in obese patients or during pneumoperitoneum when associated with increased PEEP.[14,91,193] In clinical trials, periodic recruitment maneuvers failed to improve postoperative pulmonary outcomes even when combined to high PEEP after abdominal or cardiac surgery (table 2).[102,188,194,195] Accordingly, current recommendations limit the use of recruitment maneuvers to patients presenting a respiratory dysfunction suggestive of atelectasis according to an individual risk–benefit assessment and always combined with PEEP (fig. 6). Recruitment maneuvers should be performed with the ventilator instead of manually, with the lowest pressure, during the shortest effective time and with a continuous hemodynamic monitoring.[168]

PEEP

The application of PEEP aims to prevent or treat atelectasis by maintaining positive transpulmonary pressure when alveolar pressure reaches its lowest end-expiratory level. During general anesthesia, PEEP improves gas exchange and respiratory mechanics,[179] and reduces the volume of collapsed lung both in adults[3,196] and children.[197] This occurs either with mere application of PEEP to normal lungs,[3] or when PEEP follows lung recruitment maneuvers in high-risk settings for atelectasis (*e.g.*, obesity).[14,91,193]

Besides those beneficial physiologic effects, PEEP can also prevent the mechanical and biologic lung injuries associated with atelectasis[26] and, consequently, improve postoperative pulmonary outcomes. Such protection has been implied by the observation of better postoperative pulmonary outcomes with moderate PEEP (5 to 8 cm H_2O) than with lower to no or high PEEP in large registry-based studies in noncardiothoracic surgery,[157,198] and worse outcomes when PEEP of approximately 0 is associated with low V_T.[5] In multicenter randomized controlled trials, moderate PEEP bundled with low V_T leading to better outcomes than when no PEEP was combined with high V_T further supported its value (table 2).[183,184]

Application of PEEP higher than those moderate levels (*i.e.*, 8 to 12 cm H_2O) has not brought additional improvement of postoperative pulmonary outcomes, although it reduces intraoperative atelectasis. Indeed, large randomized controlled trials using high PEEP (12 cm H_2O) strategies consistently enhanced intraoperative oxygenation and respiratory mechanics, while they failed to improve postoperative pulmonary and extrapulmonary outcomes (table 2).[188,189,194] Importantly, high PEEP may expose patients to excessive alveolar pressures, as suggested by the finding of biomarkers of alveolar overdistension[103,199] and the higher incidence of arterial hypotension, bradycardia, and need for vasopressors in patients exposed to it.[188,189,200] Consequently, recent expert recommendations propose the avoidance of PEEP of 0 cm H_2O while limiting intraoperative PEEP to fixed low levels (2 to 5 cm H_2O) as the standard intraoperative approach.[168] High PEEP strategies would be restricted to clinical scenarios strongly suggestive of significant atelectasis (*e.g.*, oxygenation or respiratory mechanics compromise)[156,201] or consistent with high risk for lung collapse (*e.g.*, body mass index greater than 50; obesity *plus* pneumoperitoneum or Trendelenburg; abdominal hypertension; fig. 6).[9,70,189,202]

The considerable variability in individual PEEP requirements for optimal lung mechanics, oxygenation, or aeration depending on patients' characteristics (*e.g.*, body mass index[9,14]) or surgical factors (*e.g.*, abdominal surgery,[90,164,203] robotic-assisted laparoscopic surgeries,[9] stage of surgery,[159] one-lung ventilation[155]) has been increasingly documented.

Such variability implies the need for PEEP individualization, which can be done using respiratory mechanics including estimates of transpulmonary pressure using esophageal balloons,[9,159,194,204] pulse oximetry,[205] and bedside lung imaging (ultrasound or electrical impedance tomography).[94,152,153,202] Studies to date, mostly physiologic, indicate that these personalized interventions resulted in better transpulmonary pressures, driving pressures,[159] intraoperative lung expansion,[94,202] and postoperative lung aeration[152] than fixed PEEP strategies. Demonstration of the outcome benefits of individualized PEEP approaches will require further investigation.

Inspired Fraction of Oxygen

Partial or complete alveolar denitrogenation with oxygen promotes oxygen absorption atelectasis.[117,192] Accordingly, atelectasis area quantified by computed tomography was 20 times higher with preoxygenation with F_{IO_2} of 1.0 for intubation than with F_{IO_2} of 0.3 in nonobese patients.[120] Of note, desaturation time (*i.e.*, time to reach a S_{PO_2} less than 90%) is still 1.8 min longer after preoxygenation with F_{IO_2} of 1.0 than with F_{IO_2} of 0.8.[206] In the obese, adding continuous positive airway pressure during preoxygenation mitigates the collapsing effect of F_{IO_2} of 1.0 as it improves end-expiratory lung volume and oxygenation during and after intubation.[207] Besides the intubation period, a dose-dependent association between median intraoperative F_{IO_2} and major postoperative pulmonary complications and 30-day mortality has been reported after noncardiothoracic surgery in a large registry-based study, suggesting a protective effect of restrictive approaches.[208] Yet in large randomized clinical trials, intraoperative F_{IO_2} of 0.8 or greater *versus* 0.3 did not significantly impact postoperative atelectasis (assessed by chest x-ray film or computed tomography),[209] pulmonary complications,[210] or supplemental oxygen requirements[211] after abdominal surgery in mostly nonobese patients. Accordingly, intraoperative F_{IO_2} should target normoxic and not hyperoxic conditions. High F_{IO_2} should be particularly directed to treatment or prevention of hypoxemia (*e.g.*, preintubation and preextubation), and avoidance of F_{IO_2} of 1.0 might be most beneficial intraoperatively to patients at high risk for atelectasis.[212]

Spontaneous Ventilation

Maintaining diaphragmatic tone during general anesthesia preserves negative pleural pressure and diaphragmatic shape, favoring alveolar ventilation distribution[213] and aeration of the dorso-caudal lung in small clinical studies.[3,214] Adding high-flow oxygen in nonintubated spontaneously breathing anesthetized children further improved lung aeration.[135]

Lung Recruitment during Perioperative Lung Inflammation

Either in complex surgical cases or in the surgical ICU, anesthesiologists frequently manage critically ill patients with respiratory dysfunction due to or associated with significant acute inflammatory lung injury, *e.g.*, systemic inflammatory response, sepsis, postcardiopulmonary bypass, transplant surgery, extrapulmonary surgical complications, lung trauma, transfusion-related acute lung injury, and lung ischemia. In such conditions, implementation of strategies for lung protection is particularly important as increased susceptibility to lung injury including mechanical lung injury is likely present, as supported by the concept of two-hit injury,[215,216] and determines an increased risk for further respiratory dysfunction, multiorgan failure, and death.[186] The frequently present alveolar instability and higher opening pressures (45 to 60 cm H_2O)[217,218] than normal lungs (30 to 40 cm H_2O)[111] set these patients at increased risk for atelectasis. For these reasons, PEEP 5 cm H_2O or greater should be used in virtually all patients presenting with acute lung inflammation. PEEP higher than that required for oxygenation (*e.g.,* higher PEEP tables from Acute Respiratory Distress Syndrome Clinical Network)[219] is likely reserved to patients fulfilling criteria for moderate and severe ARDS (P_{aO_2}/F_{IO_2} 200 mmHg or less with bilateral lung infiltrates and acute onset, and not explained by cardiac failure or fluid overload).[220,221] Individualized PEEP settings have been increasingly advanced also in this group of patients aiming at optimal respiratory mechanics (*e.g.*, respiratory system compliance,[222] driving pressure,[186] transpulmonary pressure,[163] oxygenation,[219] or imaging measures of lung expansion).[223] Such approaches have shown physiologic benefit to respiratory system mechanics and blood oxygenation,[163] while mortality benefits await confirmation. Attention to complications associated with high PEEP, *e.g*, hemodynamic instability and pneumothorax, is key for safety during severe lung injury, as major morbidity has been associated with aggressive use of "open-lung" strategies.[222] Systematic use of low V_T (6 to 8 ml/kg of predicted body weight) and associated attention to driving pressure should compose the ventilatory management.[186]

Of note, critically ill patients presenting *uninjured lungs* did not benefit from the systematic use of low V_T (6 ml/kg *vs.* 10 ml/kg of predicted body weight)[224] and PEEP higher than 5 cm H_2O.[225] Accordingly, the ventilatory management of lung recruitment in critically ill patients with normal lung function is consistent with the approach described for the surgical patient.

Large Airways Hygiene

In intubated patients, mucociliary clearance impairment, bronchial hypersecretion, ineffective coughing, and lack of gas humification could compound to produce airway obstruction as with mucus plugs, thus precipitating obstructive atelectasis. Tracheal suctioning should be performed on an as-needed basis to avoid lung derecruitment and hypoxemia.[226] In case of lobar and segmental obstructive atelectasis, fiberoptic bronchoscopy allows for confirmation of diagnosis and etiological treatment with bronchial toilet

under fiberoptic guidance and restoration of lung aeration.[227] Routine nebulization of N-acetylcysteine and salbutamol (every 6 h) is not advantageous as no reduction of ventilator-free days was observed in intubated ICU patients ventilated for more than 24 h as compared to on-demand treatment.[228]

Nonventilatory Preventive Strategies

Nonventilatory intraoperative interventions contribute to prevention of postoperative atelectasis. Opioids are associated with ventilatory depression and a large registry-based study on a wide range of adult noncardiac surgeries under general anesthesia showed that indeed, a lower dose of intraoperative fentanyl (approximately 60 to 120 mcg for a 70-kg patient) was associated with lower rate of pulmonary complications including atelectasis than higher doses (approximately 4 mcg/kg) and interestingly also than no fentanyl.[47] Lower doses of neuromuscular blocking agents in a similar population also related to fewer major postoperative pulmonary complications. These are also reduced by accurate reversal of neuromuscular blocking agents with associated appropriate monitoring of neuromuscular function.[48,229] The combination of rocuronium-sugammadex, compared to neostigmine, may reduce certain postoperative pulmonary complications but the benefit on atelectasis has not been definitely demonstrated.[230,231] Optimized fluid administration through perioperative monitoring of stroke volume (*e.g.*, esophageal Doppler) and goal-directed hemodynamic therapy during major surgery prevent fluid overload and reduce postoperative pulmonary complications in randomized clinical trials.[169,232,233] Large observational studies in cardiac[234] and noncardiac[235] surgery further suggest that optimized patient blood management to limit blood product transfusion may help in preventing postoperative pulmonary complications.

Emergence from Anesthesia and Extubation

Emergence from anesthesia and extubation may hasten alveolar derecruitment.[94,103,147,153,236] Specifically, high pre-extubation F_{IO_2} has been associated with absorption atelectasis.[237,238] Yet the clinical impact on postoperative outcomes is unknown, and safety issues related to shortening desaturation time with F_{IO_2} less than 1.0, such as for difficult extubations, should be considered.[239,240]

In mostly nonobese patients undergoing emergence from anesthesia with F_{IO_2} of 1.0 at the end of noncardiothoracic surgery, neither weaning PEEP to 0 cm H_2O[236] nor performing recruitment maneuvers and adding PEEP 10 cm H_2O[241] before extubation significantly affected postoperative atelectasis formation or gas exchange.

In contrast, an intensive alveolar recruitment strategy (PEEP 13 to 30 cm H_2O) performed before extubation in selected patients presenting hypoxemia (Pa_{O_2}/F_{IO_2} less than 250 mmHg) at the end of cardiac surgery improved lung aeration and significantly reduced the incidence of postoperative pulmonary complications and hospital length of stay.[201] Limiting tracheal suction and applying positive airway pressure during cuff deflation before extubation to prevent postoperative atelectasis appear safe and have been suggested to prevent early postoperative atelectasis. However, the systematic use of this approach requires further validation.[242] Importantly, extubation should be performed in patients who have recovered from neuromuscular blockade (train-of-four greater than 0.9).[50,243]

Postoperative Period

Intraoperative lung recruitment may not consistently translate into higher postoperative lung aeration.[103,147,152,153] Accordingly, strategies aiming to maintain lung recruitment in the postanesthesia care unit, ICU, or surgical ward may independently improve postoperative outcomes and be at least as valuable as intraoperative lung expansion interventions. Multimodal bundle strategies[244,245] aiming at reducing postoperative alveolar collapse have been advanced, but clinical trials are still required to produce high-level evidence.[169,172,246]

Noninvasive Ventilatory Support

Noninvasive positive pressure ventilation after extubation may prevent pulmonary atelectasis and compensate for the postoperative reduction of FRC.[246,247] Continuous positive airway pressure and noninvasive ventilation increase the pressure at airway opening and improve gas exchange.[248,249] While mechanisms underlying the benefits of noninvasive positive pressure support have not been entirely defined, improvement in lung aeration through alveolar recruitment is likely the most relevant followed by the potential reduction in work of breathing, and improved cardiac function with reduction of pulmonary edema.[247] Recently, high-flow nasal cannula has been used to noninvasively increase pressure at the airway opening. In adults, at flow rates approximately 60 l/min, with closed mouth, mean airway pressure is approximately 5 cm H_2O,[250] which is satisfactory in many cases but may be inadequate in settings requiring higher airway pressures (*e.g.,* obesity). In children up to 6 yr of age, a flow rate of 2 $l \cdot kg^{-1} \cdot min^{-1}$ had a significant effect on lung expansion.[135] Clinical studies have explored noninvasive ventilatory support to *treat* postoperative respiratory failure or to *prevent* postoperative pulmonary atelectasis and complications

Curative Use. In selected patients already presenting postoperative hypoxemia, the curative use of noninvasive ventilatory support substantially improved postoperative outcomes as compared to conventional oxygen therapy and should be considered as a standard of care. Recent European guidelines[251] propose the immediate use of noninvasive ventilation or continuous positive airway pressure rather than conventional oxygen therapy for hypoxemic patients after abdominal, cardiac, or thoracic surgery to reduce atelectasis and prevent further respiratory failure.[251]

In hypoxemic patients after major abdominal surgery (*e.g.,* room air Spo_2 96% or less for 5 min[194]), postoperative continuous positive airway pressure (5 to 10 cm H_2O) was effective in preventing postoperative pulmonary complications[194] and reintubation,[252] and noninvasive ventilation (inspiratory pressure support 5 to 15 cm H_2O; PEEP 5 to 10 cm H_2O) reduced 90-day mortality as compared to standard oxygen therapy.[253] Noninvasive ventilation prevented postoperative reintubation in patients presenting acute respiratory failure after cardiothoracic surgery, also reducing ICU length of stay,[254–256] and after solid organ transplantation, also reducing ICU mortality.[257] In patients presenting with hypoxemia after cardiothoracic surgery (approximately 32% with obesity), high-flow nasal oxygen therapy (flow 50 l/min; F_{IO_2} 50%) was noninferior to noninvasive ventilation to prevent reintubation.[258]

Preventive Use. High-risk patients, *e.g.*, the obese, may particularly benefit from extended postoperative noninvasive ventilatory support.[259] After bariatric surgery, preventive continuous positive airway pressure or noninvasive ventilation improved blood oxygenation[260] and postextubation lung volumes,[261] while early application of high-flow nasal cannula decreased postoperative hypoxemia and prevented postoperative pulmonary atelectasis.[262] Similarly, in mostly nonobese patients who had undergone elective cardiac surgery, preventive nasal continuous positive airway pressure (10 cm H_2O, 6 h or greater) reduced the rate of postoperative complications and reintubation but had no significant effect on ICU or hospital length of stay.[263] Despite these results, recent randomized clinical trials assessing the preventive use of postoperative noninvasive ventilatory support did not demonstrate efficacy of continuous positive airway pressure or high-flow nasal cannula after abdominal surgery in mostly nonobese patients at intermediate-to-high pulmonary risk,[194,264] noninvasive ventilation after thoracic surgery in chronic obstructive pulmonary disease patients,[265] or high-flow nasal cannula after cardiac surgery in overweight to obese patients.[266,267] These results emphasize the need for better treatment stratification (*e.g.*, super-obese, significant intraoperative atelectasis) and identification of the optimal interface, time of initiation, and dose of preventive ventilatory support.

Early Mobilization

Early mobilization, as part of enhanced recovery after surgery,[268] has been suggested to improve postoperative FRC.[269] In clinical trials, early mobilization relieved lung atelectasis after video-assisted thoracoscopic surgery[270] and coronary artery bypass graft surgery,[271] but the effect on pulmonary complications was not significant after colorectal surgery.[272,273]

Respiratory Physiotherapy Targeting Lung Expansion

Deep-breathing exercises and incentive spirometry have been associated with improved FRC and atelectasis reduction after abdominal[274,275] and cardiothoracic surgeries.[276,277] A reminder system may improve outcomes and the adherence to postoperative physiotherapy.[276] Nonetheless, while presumably beneficial, the widespread use of incentive spirometry has been questioned, and appropriate matching of indications, techniques, and doses needs to be established due to low quality of evidence.[278–280]

Analgesia

When compared to systemic opioid-based analgesia, postoperative epidural analgesia is associated with a preventive effect on pulmonary atelectasis.[281,282] The potential mechanisms are the improvement of cough by greater expiratory muscle strength,[283] deep breathing with higher diaphragmatic inspiratory velocities,[284] and earlier mobilization by enhanced analgesia,[285] while avoiding the respiratory depression produced by systemic opioids. After thoracotomy, paravertebral block is an alternative to epidural analgesia to prevent pneumonia and need for ventilatory support.[286]

Oxygen Therapy

In spite of scarce evidence during routine oxygenotherapy,[287] humidification of inspired gas may improve bronchial drainage and prevent mucus plug responsible for airway obstruction.[288] Room air trials should be regularly performed in patients receiving oxygen in order to reevaluate the indication for oxygen therapy and, importantly, identify patients at risk for pulmonary complications, as these could benefit from additional noninvasive respiratory support.[166,194]

Mucolytics

Prophylactic intravenous ambroxol may prevent postoperative atelectasis in at-risk patients, but the quality of evidence is low.[289] N-acetyl cysteine failed to prevent postoperative atelectasis after elective upper laparotomy.[290]

Relief of Extrinsic Compression

Along with lung expansion techniques, relieving severe extrinsic compression due to pleural effusion (*e.g.,* thoracocentesis) or abdominal hypertension (*e.g.,* paracentesis, medical treatment of ileus, laparostomy) as well as significant pneumothorax may be necessary to improve lung aeration. Gastric decompression should be strictly selective (*e.g.*, severe postoperative gastric distension). Routine use of a nasogastric tube significantly increased the incidence of postoperative atelectasis and pneumonia in a meta-analysis of clinical trials.[291]

Interventions described in this section compose most of the current clinical tools to approach perioperative atelectasis. As can be derived from the presentation, the evidence on interventions specifically addressing atelectasis is dispersed in sources varying from clinical trials, in combination with other pulmonary outcomes, to individual studies or meta-analyses

addressing subsets of patients, single interventions, and particular outcomes. Formal systematic analyses are needed to advance quantitative and specific understanding in the field.

Conclusions

Pulmonary atelectasis is a prominent perioperative clinical entity. Hypoxemia and lowered respiratory system compliance are classical presentations of atelectasis in the operating room, but specific and quantitative diagnosis always requires lung imaging. While patient- and surgery-related risk factors are well known, the direct impact of intraoperative pulmonary atelectasis on postoperative outcomes is still unclear. Mechanical ventilation strategies aiming to maximize alveolar recruitment in all-comers during surgery did reduce undesirable gas exchange and respiratory mechanics dysfunction and are, consequently, effective in improving physiologic dysfunction. Yet they did not affect mid- or long-term postoperative pulmonary or composite outcomes. To date, the generalizability of those results remains controversial, as shown by the limited clinical guidelines. Future directions for anesthesiologists and investigators should primarily address the stratification of patients' risk for severe pulmonary atelectasis, the use of titrated physiology-based strategies, and the extension of lung recruitment from the pre- to the postoperative period.

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Competing Interests

Dr. Fernandez-Bustamante reports financial relationships with Merck Sharp & Dohme Corp. (Kenilworth, New Jersey) and the U.S. Department of Defense (Arlington, Virginia). The other authors declare no competing interests.

Correspondence

Address correspondence to Dr. Vidal Melo: Department of Anesthesia, Critical Care and Pain Medicine, Massachusetts General Hospital, 55 Fruit St., Boston, Massachusetts 02114. vidalmelo.marcos@mgh.harvard.edu.

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