Preoperative Pulmonary Risk Assessment

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Postoperative pulmonary complications have a significant impact on perioperative morbidity and mortality and contribute substantially to health care costs. Surgical stress and anesthesia lead to changes in respiratory physiology, altering lung volumes, respiratory drive, and muscle function that can cumulatively increase the risk of postoperative pulmonary complications. Preoperative medical evaluation requires a structured approach to identify patient-, procedure-, and anesthesia-related risk factors for postoperative pulmonary complications. Validated risk prediction models can be used for risk stratification and to help tailor the preoperative investigation. Optimization of pulmonary comorbidities, smoking cessation, and correction of anemia are risk-mitigation strategies. Lung-protective ventilation, moderate PEEP application, and conservative use of neuromuscular blocking drugs are intra-operative preventive strategies. Postoperative early mobilization, chest physiotherapy, oral care, and appropriate analgesia speed up recovery. High-risk patients should receive inspiratory muscle training prior to surgery, and there should be a focus to minimize surgery time.
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Introduction

The perioperative period exposes the respiratory system to several physiological changes and challenges that, for majority of patients, do not have clinical consequences. However, in some patients, they lead to clinically important events that are known as postoperative pulmonary complications (PPC). PPCs significantly increase morbidity and mortality and can significantly prolong the hospital stay.[1] Although the literature on surgical risk stratification has traditionally focused on cardiac risk factors, PPCs occur with similar or even higher frequency compared with cardiac complications.[2] The evaluation of perioperative pulmonary risk allows targeted implementation of risk mitigation strategies that can improve patient outcomes. This review aims to describe patient-related and procedure-related (ie, surgery or anesthesia) pulmonary complications, focusing on the incidence, impact of these complications in the postoperative period, clinical and objective evaluation for risk stratification, and some strategies to reduce risk.

Epidemiology

An estimated 312 million surgeries are performed annually worldwide, of which 3–16% are complicated by major morbidity, with permanent disability or death occurring in 0.4–0.8%.[3] This translates to potentially 9 million people experiencing a morbid complication from surgery and 1.2 million people potentially being permanently disabled or dying after surgery every year. These estimates may have a wide variation according to the definitions used, country, state, hospital, time studied, and other factors, which can affect the magnitude of these calculations.[4] However, these numbers highlight the potential health care and patient impact, as well as the importance of careful risk assessment and implementation of effective mitigation strategies.

Definition and Impact of Postoperative Pulmonary Complications

PPCs were broadly defined as a complication of surgery affecting the respiratory system.[5] They ranged from self-limiting disorders such as mild atelectasis, tracheobronchitis, or bronchospasm to highly morbid complications such as postoperative pneumonia, effusion, pneumothorax, ARDS, pulmonary embolism, or respiratory failure. Recent work by different groups has sought to define PPCs, in order to establish uniformity in reporting research outcomes. The European Perioperative Clinic Outcome taskforce defined PPC as a composite outcome based on a systematic review of literature[6] and the Standardized End point for Perioperative Medicine Initiative created global standard definitions for PPC.[7] These collaboratives reduced the main PPCs to atelectasis, ARDS, pneumonia, and aspiration. Both of these definitions are currently used in practice and are summarized in Table 1 along with other commonly used definitions in different studies of PPCs. This is relevant as the incidence of PPC (and its clinical impact) will vary according to the definition, abstraction method, surgical intervention, patient population, and PPCs included. As a result, some surveys estimate rates for PPC ranging from as low as 2% to as high as 33%.[22-25] A nationwide survey of data from 414 U.S. hospitals analyzing surgical data from 1.2 million patients estimated a little more than 160,000 PPCs (13.1%).[26] If the data from this survey is extrapolated to surgeries taking place nationwide, it is estimated that $\sim$ 1 million PPCs occur annually in the United States, potentially accounting for $>$ 46,000 additional deaths and 4.8 million additional hospitalized days.[23]

PPCs contribute significantly to overall morbidity and lead to a longer hospital stay. Postoperative respiratory failure requiring unplanned re-intubation has been shown to increase the length of stay and morbidity.[22] It is estimated that patients who have $\geq$ 1 PPCs have 1.5 times the hospital stay and a 6-fold increased chance of being discharged to a rehabilitation center rather than home.[27] In another study, PPCs added 2–9 d to the hospital stay compared to those who did not experience a complication.[25]

To highlight the relevance of PPCs, studies have shown that the rates of PPCs are equal to or slightly higher than rates of cardiac complications.[28,29] In fact, PPCs seem to be more likely than cardiac complications to be associated with long-term mortality after surgery. In a cohort of subjects $>$ 70 y old who underwent noncardiac surgery, only pulmonary and renal complications predicted long-term mortality.[30,31] Khuri et al[32] reviewed the National Surgical Quality Improvement Program (NSQIP) database and observed a 30-d mortality of 21% among patients who developed PPC compared to 2% who did not. Ghaferi et al[33] studied the variation in hospital mortality due to PPCs across different hospitals, focusing on pneumonia, respiratory failure, and pulmonary embolism. They concluded that while the incidence of these PPCs were similar across all centers, any difference in perioperative mortality was contingent on early recognition and management of PPCs.[33]

The financial impact of PPCs is substantial. The diagnostic, therapeutic, and rehabilitative resources needed to rescue a patient with PPCs are not trivial. The cost of rescue is 2–3 times higher in patients who encountered a pulmonary

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Table 1. Summary of EPCO and StEP Definitions for PPC

Outcome Measure	EPCO Definition	StEP Definitions	Other Published Definition
Postoperative pneumonia	Chest radiograph with at least one of: infiltrate, consolidation, cavitation;plus at least one of: fever > 38°C with no other cause, white cell count < 4 or > 12 × 10^9 L, or > 70 y of age with altered mental status with no other cause plus at least 2 of: new purulent/changed sputum, increased secretions/suctioning, new/worse, cough/dyspnea/tachypnea, rales/bronchial breath sounds, or worsening gas exchange	Centers for Disease Control criteria*	Two or more of the following for > 48 h: new cough/sputum production, physical findings compatible with pneumonia, fever > 38°C, and new infiltrate on chest radiograph[8] New or progressive infiltrate on chest radiograph or crackles or dullness on percussion and any of: new purulent/changed sputum, positive blood cultures, isolation of pathogen from sputum[9,10]
Respiratory failure	Postoperative P_{aO_2} < 8 kPa (60 mm Hg) on room air, a P_{aO_2}/F_{IO_2} < 40 kPa (300 mm Hg), or arterial oxyhemoglobin saturation measured with pulse oximetry < 90% and requiring oxygen therapy	Same as ARDS per Berlin definition[11] OR Reinstitution of mechanical or noninvasive ventilation after extubation	Ventilator dependence for >1 postoperative day or re-intubation[2,12,13]; need for postoperative mechanical ventilation > 48 h[14,15]; unplanned re-intubation because of respiratory distress, hypoxia, hypercarbia, or respiratory acidosis within 30 d of surgery[9,14-16]; re-intubation within 3 d requiring mechanical ventilation[17]; ARDS[18,19] requiring mechanical ventilation within 7 d of surgery[20,21]; requiring NIV[22]
Pleural effusion	Chest radiograph with blunting of costophrenic angle, loss of sharp silhouette of the ipsilateral hemidiaphragm in upright position, displacement of adjacent anatomical structures, or (in supine position) hazy opacity in one hemithorax with preserved vascular shadow	Did not consider it PPC	Pleural effusion requiring thoracocentesis[2,12,13,21]
Atelectasis	Lung opacification with mediastinal shift, hilum or hemidiaphragm shift toward the affected area, with compensatory hyperinflation in adjacent non-atelectatic lung	Atelectasis detected on computed tomography or chest radiograph	Requiring bronchoscopic intervention[21]
Pneumothorax	Air in the pleural space with no vascular bed surrounding the visceral pleura	Did not consider it PPC	Pneumothorax requiring chest tube[21,22]
Bronchospasm	Newly detected expiratory wheeze treated with bronchodilators	Did not consider it PPC	Clinical diagnosis resulting in change in therapy; refractory wheeze requiring parenteral drugs in addition to preoperative regimen
Aspiration pneumonitis	Acute lung injury after inhalation of regurgitated gastric contents	Clear clinical history of aspiration and radiological evidence	
ARDS	Did not define	Per Berlin definition†	
Tracheobronchitis			Purulent sputum with normal chest radiograph, no intravenous antibiotics

* ≥ 2 serial chest radiographs with at least one of the following (1 radiograph is sufficient for patients with no underlying pulmonary or cardiac disease): new or persistent infiltrates, consolidation, or cavitation, AND at least one of the following: fever (>38°C) with no other recognized cause, leukopenia (white cell count < 4 × 10^9) or leukocytosis (white cell count > 12 × 10^9), or altered mental status with no other recognized cause for adults > 70 y old; AND at least two of the following: new onset of purulent sputum or change in character of sputum, or increased respiratory secretions, or increased suctioning requirements; new onset or worsening cough, or dyspnea, or tachypnea; rales or bronchial breath sounds; or worsening gas exchange (eg, hypoxemia, increased oxygen requirement, increased ventilator demand).

† Berlin definition of respiratory distress syndrome. Timing: within 1 week of a known clinical insult or new or worsening respiratory symptoms; AND bilateral opacities on chest imaging that are not fully explained by effusions, lobar/lung collapse, or nodules; AND origin of edema: respiratory failure not fully explained by cardiac failure or fluid overload (requires objective assessment like echocardiography to exclude hydrostatic edema), AND oxygenation: mild between 200–300 mm Hg with PEEP or CPAP 5 cm H_2O, or moderate between 100–200 mm Hg with PEEP 5 cm H_2O, or severe < 100 mm Hg with PEEP 5 cm H_2O.

EPCO = European Perioperative Clinic Outcome
StEP = Standardized Endpoint for Perioperative Medicine Initiative
PPC = postoperative pulmonary complication
NIV = noninvasive ventilation

complication compared to those who didn't develop a PPC.[34] It is estimated that PPCs contribute to a 9–25% increase in total hospitalization cost.[35,36] Taking into consideration the volume of surgeries that take place annually and that an estimated 54% of the surgical adverse events are preventable, the use of systemic strategies to reduce the incidence of PPCs carries a tremendous public health relevance. [37]

Physiological Impact of Surgical Stress and Anesthesia

Surgery poses an insult and challenge to the physiologic homeostasis, leading to systemic endocrine, inflammatory, and physiologic responses. The endocrine response involves an increase in the level of stress hormones (eg, cortisol, growth hormone, adrenocorticotrophic hormone, catecholamines, renin, and antidiuretic hormone). This shifts the body's homeostasis toward a catabolic state with consequent utilization of proteins, fats, and carbohydrates as substrates for the production of glucose and acute-phase proteins; it also promotes salt and water retention. The inflammatory response leads to cytokine release (IL-1, IL-6, TNF-α) from leukocytes and fibroblasts. The magnitude of the response is proportional to the degree of surgical injury.[37,38] The response may last 3–5 d, while inflammatory response peaks at 24 h and lasts 72 h in most cases.[37]

General and neuroaxial anesthesia leads to systemic physiological changes. The cardiovascular system effects include an increase in cardiac index and systemic vasodilation, which are known cause of cardiac morbidity.[39-41] Induction and maintenance of general anesthesia cause a loss of respiratory muscle tone, small airway closure, and alveolar collapse, which leads to ventilation/perfusion mismatch and hypoxemia.[42] Overall, anesthesia impairs respiratory effort, cough strength, and respiratory muscle function. These effects last beyond the immediate perioperative period. Meyers et al[43] reported that vital capacity, functional residual capacity, and FEV_1 decreases postoperatively, with recovery to normal levels taking up to day 5 postoperatively. Cognitive function is also affected; for example, use of general anesthesia during surgery has been associated with delirium and cognitive dysfunction that peaks at day 1 to day 3 postoperatively. Cognitive dysfunction can impair respiratory and ciliary mechanics that can lead to inability to clear airway secretions and engage in risk abatement strategies.[44] Postoperatively, impairment of respiratory muscle function can contribute to PPCs. The impairment can be caused by pain, functional disruption from incisions, and phrenic nerve involvement due to injury or reflex inhibition of phrenic motor neuron output from traction of abdominal viscera.[45,46] Postoperative pain and the strategy used for analgesia impacts dynamic pulmonary functions. Pooler et al. reported that postoperative pain results in 35% reduction of vital capacity secondary to impaired respiratory movement and patient's reluctance to cough.[47]

In summary, patients develop expected physiological changes (inflammation, fluid retention, weakness, pain and confusion) during and after surgery that create conditions which increase the risk of PPC.

Perioperative Risk Assessment

Pulmonary evaluation of surgical risk is meant to address risk assessment as well as identify risk mitigation strategies for PPC. Risk assessment requires analysis of patient-related risk factors, surgery-related risk factors, and anesthesia-related risk factors. Of particular relevance is the greater weight of surgery-related factors in the preoperative risk assessment of the patient, which differs from preoperative cardiac evaluation, where patient-related factors are more relevant than the intrinsic factors related to the surgery.[48,49]

Patient-Related Risk Factors

A comprehensive review of a patient's history and a physical evaluation are essential to identify a patient's overall fitness and comorbid conditions. Among the risk factors for PPCs are age, smoking, critical illness, and comorbid conditions such as COPD.

Advancing age, especially $\geq$ 50 y, increases the risk of surgery independently of comorbidities. As the age advances to $\geq$ 80 y, the odds of a PPC increase 5-fold.[1,50-52] Cigarette smoking also confers a modest increase in the risk of PPCs.[53-55] There had been conflicting evidence with regard to the potential increase in pulmonary complications with preoperative smoking cessation for a period < 8 weeks prior to surgery, but this concern has been refuted in light of more recent studies.[56,57] Smoking increases the odds of PPC and mortality; current smokers were more likely than ex-smokers to experience PPCs, and ex-smokers were more likely than non-smokers to experience PPCs, especially if they smoked 10 pack years.[54,58] Likewise, smoking cessation before major surgery reduced postoperative complications.[59] Preoperative tobacco cessation should be offered independent of the timing of surgery. Any opportunity to help patients stop smoking should be used. The benefits of preoperative smoking cessation in decreasing PPC risk increase proportionally with the length of cessation, especially when this timeframe is > 8 weeks.[54,57,60]

Another important predictor of PPCs is the functional and general health status. In pooled analyses, it was observed that partial and total physical dependence is associated with higher risk of postoperative respiratory failure and pneumonia (odds ratios 1.65, 2.51, respectively).[9,14] The American Society of Anesthesiologists (ASA) classification is based on the estimation of chronic illness and comorbid conditions as well as clinical acuity of the patient. An ASA class ≥ 2 is associated with an odds ratio of 4.87 for PPCs.[1,61]

Some specific comorbidities are common sources of PPC. The health of the pulmonary parenchyma is key to maintain function. The risk of developing a PPC increases with the presence of conditions that impair respiratory muscle function, increase water content in the lung, or affect lung compliance, resistance, or gas exchange. A classic example of a condition that affects all of these factors is congestive heart failure; in several studies it is one of the strongest predictors of respiratory failure postoperatively (odds ratio 2.93 vs 1.88).[14,25,62] Patients with neuromuscular weakness are also at higher risk of PPC due to increased risk for hypoventilation and impaired cough.[63] Obesity may cause restrictive physiology and is known to reduce lung volumes perioperatively. Retrospective studies and pooled analyses of small cohorts did not associate any increased risk of postsurgical complications with obesity.[64,65] Trials on larger cohorts have found a higher incidence of PPC in patients with obesity.[66,67] In fact, a recent trial evaluating higher PEEP in obese subjects undergoing noncardiac surgery reported that the incidence of PPCs was 23% independent of the PEEP strategy used.[68] Patients with obesity may also have obstructive sleep apnea (OSA), diagnosed or undiagnosed before surgery, which increases the perioperative risk for complications, including PPCs.[69,70] OSA significantly increases the risk of re-intubation after surgery and poses a higher risk for ICU transfer.[71-73] Data from the Veterans Affairs NSQIP database showed that altered sensorium (OR 1.39) and recent weight loss (≥ 10% in last 6 mo; OR 1.62) predisposes to postoperative respiratory failure and pneumonia; regarding the weight loss, it is not defined whether it is voluntary or involuntary.[1,9,14]

In terms of obstructive lung disease, it has been described that COPD doubles the risk of PPCs.[74] Physical exam is key to preoperative assessment of PPC risk from COPD. Lawrence et al[12] observed decreased breath sounds, prolonged expiration, low oxygen saturation, wheezing or rhonchi on exam are associated with a 6-fold increase in PPC. In contrast, well-controlled asthma, independent of severity, has minimal impact on the perioperative risk of PPC.[75,76] Patients on long-term steroids for asthma control might be at risk of hypothalamic-pituitary-adrenal suppression, and perioperative stress steroid doses should be considered.[77,78]

Patients with interstitial lung disease are generally at higher risk for PPCs.[79] There is a paucity of data for assessment of a patient with interstitial lung disease candidacy. Patients with low diffusing capacity of the lung for carbon monoxide (D_{LCO}) and FEV_1 or FVC ≤ 60% are considered poor candidates for surgery. Patients with interstitial lung disease who have a combined physiological index > 40 (calculated from pulmonary function tests or computed tomography scan) have a > 50% chance of developing lung injury and are high risk for PPCs when undergoing lung resection or open lung biopsy.[80,81] The utility of this index remains to be validated for general surgery. Patients with pulmonary hypertension are also at higher risk of PPC; those patients who have a 6-min walk distance < 332 m have a higher mortality rate.[82] Other ominous signs are right atrial enlargement, pericardial effusion, the amount of septal shift to the left on a transthoracic echocardiogram, and right axis deviation on echocardiogram.[81]

Preoperative anemia when untreated confers increased risk of adverse outcomes in surgical patients; it carries a prevalence of > 30% in non-cardiac surgery, with an increased prevalence in elderly patients.[83] In patients with lung cancer its prevalence has been reported to be 26%.[84] The presence of anemia along with the use of allogeneic blood transfusions are independently associated with PPCs and surgical site infections.[85] Even mild anemia (hemoglobin < 13 g/dL in males and < 12 g/dL in females) carry an increased risk of adverse perioperative outcomes.[86]

Surgery-Related Risk Factors

Procedure- and surgery-related factors pose an unmodifiable risk for PPCs. Yet we must recognize that the site of surgery (ie, proximity to the respiratory system) significantly impacts the risk of PPC development.[48,49] For example, while studying the risk of postoperative pneumonia and respiratory failure, Arozullah et al[9,14] reported that aortic and thoracic surgeries pose the highest risk, followed by upper abdominal and neurosurgical procedures. Another important determinant is the urgency level. Most preoperative guidelines recommend assessing for the level of urgency of surgical procedures, as either elective or urgent/emergent, because the latter increases the risk for complications (odds ratio 2.2).[87-89] The duration of surgery is another independent risk factor for developing PPCs, with duration ≥ 4 h doubling the risk of PPCs.[69] In summary, the increase in surgical urgency, the increase in proximity to the diaphragm, and the length of the procedure are all predisposing risk factors for a higher incidence of PPCs.

Volume administration is related to the development of pulmonary edema. It is evident that these are intra-operative therapeutic interventions, but certain strategies may lead to the administration of fluid that has no therapeutic effect and only increases salt and chloride administration. Indeed, blood and crystalloid infusions are often inevitable during emergent surgeries, yet patients who receive > 4 units of blood seem to be at increased risk of pneumonia.[9]

Anesthesia-Related Risk Factors

Anesthesia management strategies during surgery should be carefully planned as there is a causal relationship between type of anesthesia used and the development of PPCs.[9,14,90] Intraoperative use of general anesthesia is associated with higher rates of respiratory failure and postoperative pneumonia compared to neuraxial anesthesia.[9,91] Inhaled anesthesia can alter and impair surfactant function, and the altered ratio of oxygen to nitric oxide can increase the gas reabsorption; all of these mechanisms can increase the development of atelectasis.[92] Use of general anesthesia increased the risk of PPCs (odds ratio 1.83),[1,9] hence an alternative (eg, neuraxial/regional anesthesia) is preferred when possible.[93] This is highlighted by the finding that patients with COPD who undergo surgery with general anesthesia, compared with regional anesthesia, have a higher risk of developing PPCs, ventilator dependence, and unplanned postoperative intubations.[94]

The use of neuromuscular blockers also has an effect on respiratory muscle strength, which can last for several days.[95,96] Use of intermediate and long-acting neuromuscular blockers is associated with postoperative atelectasis, re-intubation, pneumonia, and pulmonary edema.[20,97,98] Investigators evaluating the effects of neuromuscular blockers in a prospective blinded study reported that postoperative pneumonia and respiratory failure are more common in patients who receive intermediate and long-acting neuromuscular blockers as part of anesthesia in a dose-dependent manner.[95,97] Unfortunately, evidence so far suggests that continuous neuromuscular monitoring intraoperatively and use of reversal agents doesn't seem to confer any protection against PPCs.[98]

Preoperative History and Physical Exam

A thorough medical history and physical exam are key to assess risk for PPCs. The history should focus on features related to overall cardiopulmonary fitness level, underlying lung disease, congestive heart failure, smoking history, and overall functional status.[99] Exercise tolerance assessed using a questionnaire during the preoperative period independently predicts improved survival and quicker recovery after major surgery.[99] Information about any recent respiratory infections or increased phlegm production must be obtained. Physical exam to assess oxygen saturation at rest, cardio-respiratory signs, and overall body habitus will help define gas exchange, inspiratory and expiratory muscle function, fluid/volume status and risk for OSA. There are 2 tests that can help outline mitigation strategies, the cough test and the STOP-Bang questionnaire. The positive cough test, in which a patient attempts deep breathing and coughs involuntarily, is a predictor of PPC.[10] As we discussed above, OSA correlates with PPCs. The STOP-Bang questionnaire is a simple and effective tool to screen for sleep apnea.[100]

Risk Stratification Tools

Preoperative risk prediction models are an attempt to provide objective assessments of risk to guide clinical decision making in the perioperative period. There are many prediction models that help stratify patient risk for pulmonary complications prior to surgery. Table 2 outlines several of these models. The use of risk stratification tools in clinical practice is variable for a number of reasons. The barriers range from poor awareness among clinicians, lack of clarity on the precision of these tools in specific populations and for specific pulmonary complications, lack of data measuring the effect of using risk stratification tools on clinical behavior, patient outcome, and resource utilization.[107] It is worth highlighting some key observations. First, each model was derived in specific populations, which will affect its performance. The ARISCAT (Assess Respiratory Risk in Surgical Patients in Catalonia Tool) was derived using a Spanish registry to predict postoperative pulmonary pneumonia.[90] A trial that externally validated the ARISCAT using a larger, European data registry indicated that the tool performed differently in different geographic populations.[69] To overcome some of these limitations, the American College of Surgeons NSQIP, which was created in 1990s to facilitate risk-adjusted outcomes reporting in Veterans' Affairs hospitals, now includes a number of private-sector hospitals. The NSQIP risk tool can predict the risk of pneumonia and respiratory failure within 30 d of surgery.[15,108] Second, the definitions used to define PPC are different. Each model evaluates different outcomes. This is not necessarily a negative, but the clinician may want to use different tools to obtain specific risks related to the patient population or procedure. Third, there is inter-observer variability among physicians in estimation of risk and outcome measures using these tools. These can be explained by lack of reliability of the nonobjective data from the patient and clinical accuracy of administrative data used for case-mix adjustment purposes in these models.[109] These models may score a patient on a scale to provide a risk category relative to the original study population (from which the score was derived), but they do not provide an individualized risk prediction of PPCs. With this in mind, an approach that combines clinical assessment, patient preference, risk stratification tools, and an anesthetist/surgeon assessment on intra-operative risk provides a more holistic approach.

Role of Preoperative Tests

It may be evident by now that studies are not an essential part of preoperative pulmonary risk assessment. There are, however, situations (outlined below) where studies have important role, and the patient's history and physical evaluation (including pulse oximetry) yield enough information to make a risk assessment.

Preoperative spirometry was once thought to be useful to predict PPCs. Lawrence et al[13] reported that physical exam was a better predictor of PPC than spirometry values. Similarly, ASA class was shown to be superior to abnormal spirometry in estimating developments of PPC.[110] Spirometry can help identify unknown obstructive disease if clinical evaluation leaves a degree of uncertainty, but there are no spirometry values below which surgery should be denied.[111,112] While there is consensus and data to support the value of routine spirometry before lung resection to estimate the predictive postoperative lung function and in evaluating for coronary artery bypass candidacy, its value for other high-risk procedures (eg, aortic, upper abdominal) remains unproven.[1,113] All patients undergoing lung resection surgery need baseline spirometry and D_{LCO} estimation. Pneumonectomy can decrease FEV_1 by 34–36%, lobectomy by 9–17%, and segmentectomy by 5%. D_{LCO} may decline by 20–28%, 4–11%, and ~ 10% with pneumonectomy, lobectomy, and segmentectomy, respectively.[113] Predictive postoperative lung function can be assessed using quantitative ventilation-perfusion scan or the segment method using a computed tomography scan if either predictive postoperative FEV_1 or D_{LCO} is between 30% and 60%.[114] If the predictive postoperative FEV_1 or D_{LCO} is $<$ 30%, the patient needs further evaluation with cardiopulmonary exercise test.[113]

Arterial blood gas analysis often doesn't change management when compared with clinical assessment alone.[22] The National Institute for Health and Care Excellence supports obtaining an arterial blood gas analysis for patients with ASA class $\geq$ III with either confirmed or suspected pulmonary disease.[115] In practice, patients with neuromuscular disease, chronic hypercapneic respiratory failure, or obesity hypoventilation may benefit from an arterial blood gas analysis to establish the baseline preoperative gas exchange or to further justify or titrate noninvasive ventilation recommendations. A ubiquitous and useful tool is assessed with a pulse oximeter. In a patient supine and breathing room air, low oxygen saturation is an independent risk factor for PPCs: $\leq$ 95% doubles the risk of PPCs, and $\leq$ 90% increases it 10-fold.[90]

Preoperative chest radiographs do not add significant value to patient history and physical exam in predicting PPCs. An abnormal chest radiograph is likely to be predictable from clinical assessment, but once an abnormal radiograph is found, it is associated with PPCs.[10,13] The Choosing Wisely initiative recommends against routine chest radiographs in ambulatory patients without specific history and physical exam signs. Obtaining a chest radiograph is reasonable if acute cardiopulmonary disease or stable cardiopulmonary disease is suspected in a patient with known cardiovascular disease.[116,117]

Strategies to Minimize Perioperative Pulmonary Risk

There are several interventions we can implement to minimize the perioperative risk. As Ghaferi et al[33] noted, postoperative morbidity and mortality depend on how complications are managed, rather than on their incidence itself. The preoperative optimization strategy targets interventions to decrease the identified risks. We divided these interventions based on known comorbidities, preoperative, operative and postoperative periods.

Preexisting Pulmonary Conditions

If allowed by the timing of the surgery, the aim is to ensure optimal the control of obstructive lung disorders. COPD and asthma should be treated with guideline-based therapy; in the case of asthma, the target is to reach 80% of the best personal peak flow.[118,119] Patients with COPD should continue all their inhaled medications until the day of surgery. Some practitioners use short periods of systemic corticosteroids (eg, 5 d) if the patient is actively wheezing, with the aim to optimize COPD prior to surgery. This strategy is considered safe and does not appear to increase the risk of pneumonia or wound complications.[77,120] Theophylline, if used chronically, should be continued.[112] Those on a recent or a prolonged course of steroids should be considered for perioperative steroid replacement.[77] On the day of surgery, anxiolytic medications may be used to avoid bronchospasm from a painful procedure prior to induction.[78] The use of albuterol may help prevent bronchospasm from airway manipulation prior to induction.[78]

A respiratory infection should be treated appropriately; postponing elective surgery, if allowed by the need for surgery, for 4–6 weeks after the onset of a respiratory infection is strongly recommended because airway reactivity persists even after pathogen elimination.[69]

Congestive heart failure should be optimized through guideline-directed medical therapy by a cardiologist.[121] Ensuring close observation of the fluid balance in the days prior to surgery can help identify patients at risk for further exacerbation of heart failure. Patients with OSA (formally diagnosed or with high index of suspicion based on a score $>$ 5 on the STOP-Bang questionnaire) undergoing elective surgery should be commenced on CPAP perioperatively, and preoperative adherence to CPAP should be assured and encouraged.[100]

The preoperative period may be a teachable moment for smoking cessation, and surgery is associated with increased likelihood of quitting smoking.[122] Smoking cessation should be encouraged in the perioperative period and supplemented with behavioral therapy and nicotine substitution.[54,123] The benefits of smoking cessation are proportional to the smoke-free period.[57]

Table 2. Summary of Perioperative Risk Assessment Tools to Predict PPC

Tools	Year	Population	Outcomes	Study Design	Variables	External Validation	Limitations
ARISCAT[69,90] Available through Medical Calculators app MDCalc (https://www.mdcalc.com/ariscat-score-postoperative-pulmonary-complications)	2010	Multi-specialty elective and emergency surgery requiring an operating theater	PPC as defined by EPCO	Prospective, multi-center, prospective	Age, respiratory infection, preoperative anemia (hemoglobin ≤ 10 g/dL), site of surgical incision, duration of surgery, emergency Status	Prospective external validation in eastern and western Europe	RF externally validated as part of secondary analysis
		Anesthesia: general, neuraxial, or plexus block		Cohort from Europe		c-statistics 0.80 (95% CI 0.78–0.82)	Obstetric and transplantation surgeries excluded
Arozullah et al[9,14] Available through Medical Calculators app MDapp (https://www.mdapp.co/arozullah-respiratory-failure-index-calculator-595/)	2000	Multi-specialty (non-cardiac), including abdominal, vascular, and thoracic	Respiratory failure (need for post-operative mechanical ventilation > 48 h)	Retrospective analysis of multi-center prospective cohort of VAMCs using NSQIP database	Type of surgery, albumin, blood urea nitrogen, functional status, age, history of COPD	Retrospective internal validation in VAMCs population	Cardiac surgeries, endoscopic procedures, dental procedures and transplantations excluded
		Anesthesia: general, spinal, and epidural				c-index = 0.843 Hosmer-Lemeshow goodness-of-fit statistic= 8.16 ($P > .41$)	
Gupta et al[15,16] Available through Medical Calculators app MDCalc (https://www.mdcalc.com/gupta-postoperative-respiratory-failure-risk	2011, 2013	Multi-specialty elective and emergency, including abdominal, vascular, cardiac, and thoracic	Respiratory failure (unplanned re-intubation because of respiratory distress, hypoxia, hypercarbia, or respiratory acidosis within 30 d of surgery)	Retrospective analysis of multi-center prospective cohort using NSQIP database	Functional status, ASA class, sepsis, emergency case, type of procedure	Retrospective internal validation in a different cohort from the same database	Obstructive sleep apnea and venous thromboembolism not evaluated as comorbidity
			Pneumonia (CDC definition)			RF c-statistic 0.897 Pneumonia c-statistic 0.855	
ThRCRI[101] Online calculator not available	2010	Lung resection surgery (lobectomy or pneumonectomy)	Cardiac complications	Prospective multi-center cohort in Europe and United States	Serum creatinine, coronary artery disease or congestive heart failure, cerebrovascular history, surgical emergency	Prospective external validation in a different cohort in the United States	Accounts for surgery pathologic stage I non-small cell lung cancer (T1 N0 and T2a N0)
						Area under the curve 0.75	
Thorascore[102] Available through Society of French Anesthesiologist Web site (https://sfar.org/scores2/thoracoscore2.php)	2007	Thoracic surgery	In-hospital mortality (30 d)	Retrospective analysis of multi-center prospective cohort (not specific to PPC) in France	Age, gender, priority of the procedure, type of procedure, Zubrod score, malignancy, ASA class, performance status, and comorbidity score	Retrospective internal validation in a different cohort from the same database	Not applicable to lung resection and esophageal surgery; does not account for FEV and neuromuscular staging
						c-statistic 0.86 (95% CI 0.83–0.89)	
NSQIP[103] Available through NSQIP Web site (https://riskcalculator.facs.org/RiskCalculator/)	2013	Multi-specialty elective and emergency, including abdominal, vascular, cardiac, and thoracic	Pneumonia, unplanned intubation, pulmonary embolism, renal failure Other non-pulmonary complications	Retrospective analysis of multi-center prospective cohort (not specific to PPC)	21 variables	Validation data for PPC not available	Failure to validate risk in colorectal, plastic, and geriatric surgery
Bahl et al[104] Available at https://venousdisease.com/dvt-risk-assessment-online/	1991	Multi-specialty elective and emergency, including abdominal, vascular, cardiac, and thoracic	Venous thromboembolism	Retrospective single-center prospective cohort	Age, sex, recent illness, known thromboembolic disease, morbidity, body mass index, COPD, inflammatory bowel disease, malignancy	Retrospective external validation	Retrospective study, does not focus on PPC
						C-statistic 0.58 (0.71 for plastic surgery)	
SLIP - 2[105]Online Calculator not available	2014	Multi-specialty elective and emergency,	ARDS	Retrospective analysis of multi-center			Excluded patients with traumatic brain injury and

(Continued)

Table 2. Continued

Tools	Year	Population	Outcomes	Study Design	Variables	External Validation	Limitations
		including abdominal, vascular, cardiac, and thoracic		prospective cohort (not specific to PPC) in the United States	Sepsis, surgical emergency and status, breathing frequency, cirrhosis,	Retrospective internal validation in a different cohort from the same database Area under the curve 0.84 (95% CI 0.81–0.88)	COPD; ARDS due to aspiration was not included due to limited cases
STOP-Bang[106] Available at website http://www.stopbang.ca/osa/screening.php	2008	Multi-specialty elective and emergency, including abdominal, vascular, cardiac, and thoracic	Obstructive sleep apnea, delirium, difficult intubation	Perioperative prospective single center	Body mass index, age, neck circumference, gender	Prospective external validation in a different cohort (Brazil)	Externally validated in elective surgery patients; small sample size for a validation study

PPC = postoperative pulmonary complications
EPCO = European Perioperative Clinic Outcome
ASA = American Society of Anesthesiologists
NSQIP = National Surgical Quality Improvement Program
VAMC = Veterans Affairs medical center
CDC = Centers for Disease Control and Prevention

Preoperative Interventions

Preoperative aerobic exercise and inspiratory muscle training reduce length of stay and PPCs in patients undergoing cardiac and abdominal surgery, but not in patients undergoing joint replacement surgery.[124,125] The rationale is that these activities strengthen all of the muscles involved in respiratory mechanics, mainly the diaphragm, intercostal muscles, serratus and subscapularis.

In patients with anemia, the use of allogeneic blood transfusion is associated with adverse outcomes including increased mortality, surgical site infection, increased length of stay, and transfusional reactions; therefore the guidelines support a parsimonious approach to blood utilization, with a threshold for transfusion when hemoglobin is < 7 g/dL (< 8 g/dL in patients with active coronary artery disease); there is also emphasis on the optimization of hematinic levels (eg, parenteral iron, B12 supplementation).[126] The optimization of anemia should be done preoperatively because enhancing the hemoglobin values will improve patient outcomes; in addition, and most importantly, optimization of anemia attempts to maintain hemoglobin levels above the transfusional threshold.[126]

Operative Interventions

Surgeons may choose different strategies when faced with higher risks for pulmonary complications, especially those that confer higher risk of disability or prolonged mechanical ventilation. If possible, avoidance of general anesthesia in favor of alternative strategies (eg, neuraxial/regional anesthesia) is preferred when possible.[93] Epidural anesthesia when used with general anesthesia helps reduce postoperative pain and can help preserve lung function. This strategy, particularly in patients with COPD, has been shown to reduce PPCs, especially pneumonia.[91,127,128] Regional anesthesia in the postoperative period can be opioid-sparing and can allow for early mobilization, deep-breathing, and clearing of respiratory secretions.

Neuromuscular blockers should be used cautiously. When neuromuscular agents are used, reversal does not decrease the rate of PPCs. In fact, reversal of neuromuscular blockers with neostigmine is associated with negative pressure pulmonary edema and re-intubation.[129] Sugamadex is another neuromuscular blockade reversal agent; however, although it has been proposed to reduce pulmonary edema, this was not proven in a recent randomized trial, and its incidence of negative pressure pulmonary edema is similar to neostigmine.[98,130]

Mechanical ventilation using a low tidal volume (6–8 mL/kg of predicted body weight) and moderate PEEP has been reported to reduce postoperative respiratory failure and length of hospital stay.[131] Conventional ventilation (tidal volume ≥ 10 mL/kg of predicted body weight, and zero to low PEEP) in anesthetized patients has been shown to increase the concentration of inflammatory cytokines in the patient's serum, predisposing them to ARDS and acute lung injury.[132] This gives physiological context to a recent meta-analysis which indicated that incidence of postoperative respiratory failure, reintubations, and PPCs increases with increases in tidal volume in a dose-dependent manner.[133] Ideal PEEP settings for mechanical ventilation is also a growing area of research in operative medicine, PEEP $\leq$ 5 cm H_2O appears to be predisposing to atelectasis and increases risk for PPC. High PEEP ($>$ 10 cm H_2O) and use of recruitment maneuvers cause intra-operative hemodynamic compromise and hypoxia and in recent trials have failed to prevent PPCs with a trend toward more harm.[67,68,134] Analysis of a large cohort undergoing noncardiac surgery indicated that zero PEEP is harmful, whereas PEEP of 5 cm H_2O with intra-operative plateau pressure $\leq$ 16 cm H_2O is associated with the lowest risk of PPCs.[135] It is also important to minimize fluid administration especially in patients who are prone to lung injury and pulmonary edema.[136] A review of evidence on liberal versus restrictive approach showed that, although the definition of liberal and restrictive varies among institutions, an intra-operative volume $\leq$ 2,700 mL of intravenous fluids appears to show a trend toward lower postoperative complications.[137,138] Higher amounts of intra-operative crystalloid infusion are a risk factor for ARDS, as the risk of ARDS significantly increases after intra-operative volume infusion exceeds 1.5L.[139] Goal-directed fluid therapy using esophageal Doppler to analyze blood flow and obtaining objective data about individual fluid responsiveness is now increasingly being used. It can measure blood flow in the descending aorta using an esophageal probe and utilizing a nomogram of biometric data to derive the value for stroke volume. A $>$ 10% increase in stroke volume in response to a fluid bolus is considered a positive fluid response.[138,140]

Postoperative Interventions

Postoperative interventions focus on returning the body back to baseline function as soon as possible and preventing the development of PPCs during periods of vulnerability. These interventions are outlined in Table 3. In general, we focus on ensuring fluid balance returns to euvolemia by instituting restrictive fluid strategies, avoidance of unnecessary crystalloid and blood transfusions, and judicious use of diuretics to maintain a negative or even fluid balance. We recommend early mobilization to the safest maximum achievable, as well as elevation of the head of the bed to at least 11 degrees, but optimally to 30 degrees. Oral hygiene will decrease the bacterial load, and thus decrease the risk of pneumonia. Incentive spirometry, or any respiratory maneuver to increase residual volumes, is also valuable, and the patient should be trained in this therapy before surgery and again postoperatively. Incentive spirometry alone has not been shown to reduce PPCs after thoracic, cardiac, or abdominal surgery, this may be associated with poor technique by the patient rather than it being an ineffective strategy.[141-143] The importance of engaging family, nursing, and the whole team in the use of these respiratory techniques is key for their effectiveness. Voluntary cough is also a technique to improve airway clearance and respiratory muscle use. Patients with ineffective cough after respiratory therapy coaching may benefit from cough assist devices while they recover back to baseline. In patients who have preexisting use of noninvasive ventilation (eg, patients with known neuromuscular weakness, hypercapneic respiratory failure), we recommend early extubation to their device or similar settings in a hospital-titratable device. Many times, these patients will not pass usual weaning criteria due to their underlying disease. In fact, on the basis of their underlying disease, they should not. Extubation to noninvasive support can be considered to avoid prolonged mechanical ventilation and further sedation. Patients on chronic inhalers for management of asthma or COPD should resume their medications immediately after surgery. This will require careful assessment by a respiratory therapist to ensure the appropriate technique and delivery of the medications.

The use of structured protocols, specifically in units that are used to dealing with specific high-risk surgeries, will lead to better care. For example, implementation of a protocol focused on postoperative early mobilization using the I COUGH protocol, which involves incentive spirometry 10 times each hour (while awake), patient in a chair and elevated head of the bed to 30 degrees, deep breathing and coughing exercise every 2 h, and oral hygiene twice a day reduces the incidence of postoperative pneumonia and respiratory failure requiring unplanned intubations by 50% in general and vascular surgery subjects.[142]

Preoperative Risk Assessment Documentation

The approach to preoperative evaluation is based on patient condition and surgery need, under the direction of the patient goals of care and preferences. Risk assessment remains a subjective endeavor, even when trying to provide numeric estimates, because a patient and a physician may view risk in very different ways. For example, the physician may see the risk of prolonged mechanical ventilation as too high, while the patient may see this as a risk worth taking on the basis of their preferences and goals. This is key for the discussion of risk. When there is discordance between the physician and the patient's assessment of risk, we recommend a joint conference meeting with the surgeon and all involved parties (including family). This helps find commonalities and align goals of care; more importantly, it helps the team devise mitigation strategies to decrease risk. Although physicians are often asked to clear a patient for surgery, this is a physician-centered view rather than a patient-centered view. We need to engage the patient (and, if requested, the family) in our discussions, and then provide recommendations based on these discussions. In addition, rather than using the term "clear," we advocate specifying that the patient was part of the risk assessment discussion for surgery and took into account their comorbidities, treatment, and personal preferences.

Clear communication via the medical record and, if needed, multidisciplinary discussion of the preoperative clinical risk assessment are essential. Although this sounds like an obvious expectation, studies of preoperative notes demonstrate a very high failure rate (~ 80%) to demonstrate organ-specific perioperative morbidity or mortality risk.[144]

There is a paucity of standardized guidelines for preoperative pulmonary risk documentation and recommendations for perioperative optimization for risk mitigation. We favor identifying the patient's risk for the development of PPCs and providing a clear outline of the risk from a clinical standpoint, and then providing a recommendation for specific interventions throughout the perioperative continuum of care to mitigate the risk of PPCs.

Among the multiple preoperative risk prediction tools for PPCs, the ARISCAT is the only one that has been externally validated. It estimates the risk of the most common PPCs, including atelectasis, aspiration pneumonitis, respiratory failure, respiratory infection, pleural effusion, and bronchospasm. Because the ARISCAT index does not include OSA, which is a strong independent risk factor for PPCs and adverse postoperative outcomes, we also recommend use of the STOP-Bang questionnaire.[100]

The ARISCAT index will yield a risk stratification of low, intermediate, and high risk of PPCs. We initially identify the risk score and stratification (Table 4). For example, the documentation for a patient with intermediate risk would be as follows: "The patient has a 13% risk of postoperative pulmonary complications (13 patients of 100) that include atelectasis, aspiration pneumonitis, respiratory failure, respiratory infection, pleural effusion, and bronchospasm." As we discussed above, adding a risk percentage may be useful from the objective standpoint, but it also may create psychological barriers in caregivers. In general, the need for the surgery changes the appraisal of risk. So, statements such as "The risk is higher than normal, yet not prohibitive for surgery" can help convey the need for preventive interventions yet guide caregivers to continue to assess best ways to provide the needed surgery.

We then use the STOP-Bang questionnaire. Depending on the value, this tool has a sensitivity to predict moderate to severe OSA. Patients with a STOP-Bang score of 0–2 are classified as low risk for moderate to severe OSA, while patients with a STOP-Bang score > 5 are classified as high risk for moderate to severe OSA. For example, the documentation for a patient with high risk would be as follows: "The patient has a STOP-Bang score of > 5, which confers a high risk for moderate to severe OSA."

Then there should be an assessment of the risk for airway abnormalities and complications; often this assessment is performed by the anesthesiologist, but when a respiratory specialist conducts this assessment, it allows for enhanced communication with the anesthesiologist for proper identification and preoperative planning for complex airway management.[145] We favor a recently validated tool called DIFFMASK, which predicts difficult mask ventilation, but its elements are also predictors for difficult intubation. A score > 6 is associated with greater difficulty achieving successful mask ventilation.[146] For example, for a patient with a score > 6, the documentation would be as follows: "The patient has a DIFFMASK score > 6, which indicates a difficult face mask ventilation and possibly difficult airway management."

Once the risk stratification is done, the next step is to outline the recommendations in the preoperative, intraoperative, and postoperative periods. This outline can be made on the basis of the assessments above and focusing on the specific areas the patient will need (eg, respiratory muscle training, mobilization).

For all patients, the recommendations are as follows:

- Early mobilization out of bed and ambulation.
- Head of the bed elevation > 30 degrees when supine.
- Good oral hygiene (to prevent risk of aspiration pneumonitis).
- Smoking cessation counseling.
- Influenza vaccination (using the preoperative consult as an opportunity).
- Postoperative lung expansion maneuvers.
- Continuation of home bronchodilators (for patients on chronic use).
- Continuation or initiation of postoperative CPAP (for formally diagnosed or suspected OSA).

For patients with high risk, caregivers can add preoperative inspiratory muscle training for at least 1 week prior to surgery.[147]

In our institution, we defer to the anesthesiology department to determine the best anesthesia strategy. Nonetheless, in patients with a high risk of PPCs and can receive neuraxial anesthesia, we favor its use over general anesthesia; this can be outlined in the recommendation along with formal conversation with the anesthesia team. Also, in patients with chronic lung disease, minimizing atelectasis and lung injury can be achieved with lung-protective ventilation, judicious use of neuromuscular blocking agents, and cautious use of opioid analgesia after the procedure.[133,148]

Table 3. Summary of Mitigation Strategies for Postoperative Pulmonary Complications

Complication	Patient-Related Risk Factors	Operative Risk Factors	Mitigation Strategy
Pneumonia	Age > 60 y Altered mental status Alcohol intake (> 2 drinks ≤ 2 weeks of surgery) COPD ASA class ≥ 2 Current smoker Poor functional status	High-risk surgical site (abdominal aortic aneurysm repair, thoracic surgery, abdominal surgery, neurosurgery) General anesthesia Neuromuscular blockade (medium to long-acting) Emergency surgery PRBC > 4 units used	Smoking cessation Postoperative CPAP use Head of bed elevation > 30° when supine Good oral hygiene Preoperative aerobic exercise and IMT I COUGH postoperative respiratory care Regional block for postoperative analgesia
Respiratory failure	Age > 60 y Altered mental status Obstructive sleep apnea Congestive heart failure ASA class ≥ 2 Poor functional status Recent weight loss ≥ 10%	High-risk surgical site (abdominal aortic aneurysm repair, thoracic surgery, abdominal surgery neurosurgery) General anesthesia Neuromuscular blockade (medium to long-acting) Emergency surgery	Smoking cessation Postextubation CPAP use Preoperative aerobic exercise and IMT I COUGH postoperative respiratory care Regional block for postoperative analgesia Restrictive fluid strategy Intermediate to high PEEP use Lung-protective ventilation
Pleural effusion	Age > 60 y Congestive heart failure ASA ≥ 2 Smoking	Surgical site: thoracic surgery Liberal fluid administration Neuromuscular blockade reversal	Postextubation CPAP use Preoperative aerobic exercise and IMT I COUGH postoperative respiratory care Regional block for postoperative analgesia Restrictive fluid strategy
Bronchospasm	COPD exacerbation Uncontrolled asthma Smoking ASA ≥ 2	Endotracheal intubation Neostigmine use	Smoking cessation Optimize COPD with short 5-d course of corticosteroids Peak flow ≥ 80% preoperatively Laryngeal mask airway use Sevoflurane or propofol for maintenance anesthesia Ketamine for anesthesia induction Postextubation CPAP useI COUGH postoperative respiratory care Regional block for postoperative analgesia
Atelectasis	Obesity (body mass index > 40 kg/m^2) Smoking (current smoker)ASA ≥ 2	Surgical site: thoracic surgery, abdominal surgery High (≥ 0.80) in anesthesia gas NGT decompression Low intraoperative PEEP (~ 5 cm H_2O) General anesthesia Neuromuscular blockade Surgical duration > 2 h	Postextubation CPAP use Preoperative aerobic exercise and IMT I COUGH postoperative respiratory care Regional block for postoperative analgesia Restrictive fluid strategy Moderate – high PEEP Minimally invasive surgery (laparoscopic)

ASA = American Society of Anesthesiologists
PRBC = packed red blood cells
IMT = inspiratory muscle training
NGT = nasogastric tube

Table 4. ARISCAT Index

Risk Stratification	Risk Score	Rate of Postoperative Pulmonary Complications
Low	< 26	1.6–3.4%
Intermediate	26–44	13–13.3%
High	> 45	38–42.1%

ARISCAT = Assess Respiratory Risk in Surgical Patients in Catalonia Tool

In summary, proper clinical assessment of the patient, supported by risk stratification tools as well as by the patient preferences, must be shared and discussed with other members of the treatment team, especially surgeons and anesthesiology; we should also consider the communication of this assessment to facilitate the expectations for medical management in the postoperative period.

Summary

Postoperative pulmonary complications are common, and they have consequences for the patient, the family, and the health care system. As respiratory practitioners, we need to focus on assessing risk in the context of the patient's goals and preferences. Our risk assessment leads to implementation of mitigation strategies to minimize those risks.

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