



Prevention of respiratory complications of the surgical patient: actionable plan for continued process improvement

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Purpose of review

Postoperative respiratory complications (PRCs) increase hospitalization time, 30-day mortality and costs by up to \$35 000. These outcomes measures have gained prominence as bundled payments have become more common.

Recent findings

Results of recent quantitative effectiveness studies and clinical trials provide a framework that helps develop center-specific treatment guidelines, tailored to minimize the risk of PRCs. The implementation of those protocols should be guided by a local, respected, and visible facilitator who leads proper implementation while inviting center-specific input from surgeons, anesthesiologists, and other perioperative stakeholders.

Summary

Preoperatively, patients should be risk-stratified for PRCs to individualize intraoperative choices and postoperative pathways. Laparoscopic compared with open surgery improves respiratory outcomes. High-risk patients should be treated by experienced providers based on locally developed bundle-interventions to optimize intraoperative treatment and ICU bed utilization. Intraoperatively, lung-protective ventilation (procedure-specific positive end-expiratory pressure utilization, and low driving pressure) and moderately restrictive fluid therapy should be used. To achieve surgical relaxation, high-dose neuromuscular blocking agents (and reversal agents) as well as high-dose opioids should be avoided; inhaled anesthetics improve surgical conditions while protecting the lungs. Patients should be extubated in reverse Trendelenburg position. Postoperatively, continuous positive airway pressure helps prevent airway collapse and protocolized, early mobilization improves cognitive and respiratory function.

Keywords

lung-protective ventilation, postoperative respiratory complications, respiratory failure, score for prediction of postoperative respiratory complications (SPORC), upper airway, ventilator-induced lung injury

INTRODUCTION

Postoperative respiratory complications (PRCs) are common, with incidence estimates of 3–7.9% in general surgery [1,2] and higher rates reported in lung surgery [3]. The most important PRCs are reintubation, acute respiratory failure, pulmonary edema, pneumonia, and atelectasis. Measures of resource utilization have gained prominence as bundled payments have become more common [4]. PRCs increase hospitalization time, mortality, and costs [5^{*},6^{*},7,8]. For instance, in patients undergoing abdominal surgery, postoperative respiratory failure is associated with approximately 10-fold increased perioperative 30-day mortality [6^{*}]. Furthermore, postoperative reintubation, pulmonary edema, and atelectasis are predictors of adverse discharge disposition – defined

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Curr Opin Anesthesiol 2017, 30:399–408

DOI:10.1097/ACO.0000000000000465

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KEY POINTS

- PRCs have a profound impact on hospital utilization, healthcare costs, and patient mortality.
- Surgical patients should undergo preoperative risk-stratification to determine their risk of PRCs, and a tailored perioperative plan should be designed on the basis of this risk.
- Specific considerations for the preoperative, intraoperative, and postoperative period are discussed in this document.
- Hospital centers should have a local, multidisciplinary team design hospital bundles and patient pathways to help implement perioperative practices that reduce PRCs.

as in-hospital mortality or discharge to a nursing home [5[¶]].

The pathological anatomy of respiratory complications can be categorized as respiratory muscle dysfunction or as disease of the airway itself. Functionally, we can subdivide PRCs into either upper airway-related [e.g., reintubation of an obstructive sleep apnea (OSA) patient, Fig. 1, upper pink box] or

pulmonary (such as pulmonary edema, Fig. 1, lower blue box) [9,10].

The upper airway is an anatomical region between the soft palate, epiglottis, genioglossus muscle, and soft tissue anterior to the spinal column (Fig. 1), and its collapse leads to desaturation, atelectasis, and respiratory failure. Competing dilating and collapsing forces determine the patency of the upper airway [11,12] (Fig. 1, upper green and yellow boxes). Dilating forces include pharyngeal dilator muscles (e.g., the genioglossus and tensor palatini muscles) and caudal traction on the airway from expansion of the lungs [improved with increased positive end-expiratory pressure (PEEP) that increases end-expiratory lung volume]. Perioperatively, many factors such as sedatives, opioids, or hypoactive delirium can decrease airway dilator muscle tone. Dilating forces also decrease when caudal traction on the trachea is decreased (e.g., with atelectasis or supine position). Collapsing forces include external pressure from surrounding soft tissue (increased with pharyngeal airway edema, excess fat, hematoma, tumors, or supine position) and negative intraluminal pressure created by respiratory pump muscles (primarily the diaphragm and

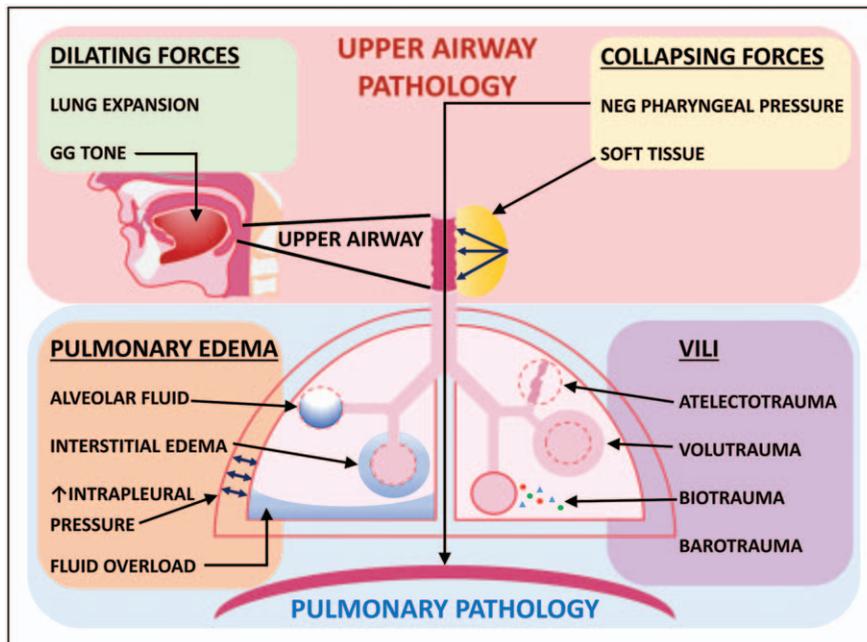


FIGURE 1. Upper airway and pulmonary disorders. Upper airway disorders are given in the pink box. Dilating forces (green box) include increased lung expansion and increased upper airway dilator muscle tone (genioglossus muscle shown). Collapsing forces (yellow box) include increased negative pharyngeal pressure generated by respiratory pump muscles (diaphragm shown), and increased soft tissue causing external mechanical load on the upper airway (yellow mass with arrows next to upper airway). Pulmonary disorders are given in the blue box. Pulmonary edema (orange box) with interstitial fluid (alveolus with surrounding fluid), alveolar fluid (blue alveolus), or both, can be caused by increased negative pulmonary pressure (blue arrows), fluid overload (blue base of lung), or multiple causes of interstitial edema. Ventilator-induced lung injury (purple box) can be due to barotrauma, atelectotrauma (deflated alveolus), biotrauma (multicolored dots), or volutrauma (distended alveolus). GG, genioglossus muscle; UA, upper airway; VILI, ventilator-induced lung injury.

intercostal muscles). Significant postoperative pulmonary edema occurs in 1–2% of surgical patients undergoing general anesthesia [5[■]]. Causes of non-cardiogenic pulmonary edema include negative pressure pulmonary edema (NPPE; likely the most frequent postoperative mechanism), fluid maldistribution secondary to overload, and less frequently, neurogenic edema (associated with acute hypertension in brain trauma/surgery patients) and anaphylaxis.

Pulmonary edema can lead to unanticipated inpatient stays, the need for ICU admission, reintubation, and increased costs [9,10]. Disturbances of pulmonary fluid homeostasis can be induced by four pathways leading to increased interstitial fluid: increased hydrostatic pressure in the pulmonary capillary bed (or decreased pressure in the interstitium), decreased osmotic pressure of plasma, increased permeability of capillary membranes, or decreased return of fluid to the circulation via lymphatics. Acute upper airway collapse or laryngo/bronchospasm can cause NPPE secondary to high negative pulmonary pressures generated against a closed airway (Fig. 1, lower orange box). Atelectasis is the most frequent mechanism of perioperative desaturation and occurs minutes after induction of general anesthesia due to reduction of regional transpulmonary pressure in dependent areas [13]. Intraoperatively, this is accentuated by inflammation triggered by surgical incision and bacterial translocation, chest wall restriction, cephalad displacement of the diaphragm by surgical retractors, and supine position. Postoperatively, a restrictive lung pattern secondary to diaphragmatic dysfunction is observed, compromising respiratory mechanics and gas exchange.

The injurious effects of perioperative atelectasis are magnified by pain, high driving pressure, and inflammation. Accordingly, the anesthetic and surgical perioperative insults can create conditions of ‘multiple-hit’ lung injury, which can be further augmented by the tissue stress induced by intraoperative mechanical ventilation [14]. Even without excessive ventilator pressures (barotrauma), ventilator-induced lung injury has multiple causes (Fig. 1, lower purple box). Decreased compliance in derecruited areas causes overinflation of aerated lung tissue in nondependent areas with larger transpulmonary pressure (volutrauma). Cyclic lung derecruitment causes low-volume lung injury (atelectotrauma). Release of local proinflammatory mediators from biophysical forces and systemic inflammation triggered by surgical incision, tissue manipulation, bacterial translocation, and endotoxemia also contribute to lung injury (biotrauma) [14]. Thus, intraoperative optimization of ventilation

with a maximally protective strategy is vital. We discuss below multilevel strategies that help maintain patency of the upper airway when it is unprotected and ventilation strategies that minimize lung trauma.

Preoperative screening and measures for prevention of postoperative respiratory complications

Preoperatively, patients should be screened to identify those at high risk for postoperative respiratory failure so that resources and management can be appropriately selected for these patients. Amongst surgical patients, many do not see an anesthesiologist prior to the day of surgery and instead are screened preoperatively via phone to generate or update the electronic healthcare record. Given the strong association between PRCs and various comorbid diseases, it may be fruitful to utilize readily available data on demographics and comorbidities to make predictions regarding respiratory complication risk. One such tool is the score for prediction of postoperative respiratory complications (SPORC), illustrated in Fig. 2 [15].

Please note that there are several risk factors not included in the SPORC, which are important but require a patient–provider interaction, such as

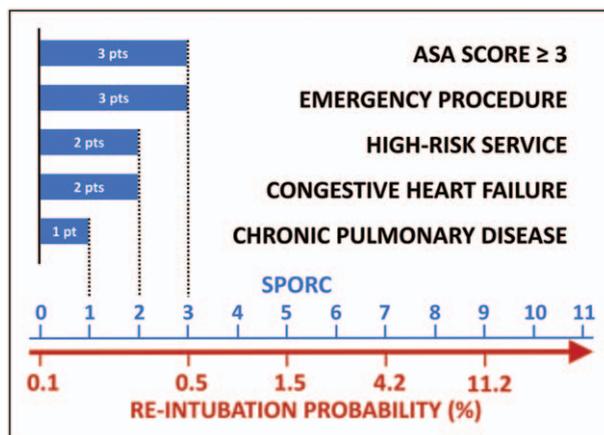


FIGURE 2. How to implement the SPORC. Point values (pts, shown as blue bars) are shown for the prediction factors: American Society of Anesthesiologists (ASA) score greater than or equal to three (three points), emergency procedure (three points), referring high-risk service (two points), history of congestive heart failure (two points), and chronic pulmonary disease (one point). The points for each risk factor are summed to reach a final SPORC score. The corresponding probability for reintubation is given on the red scale below the row of SPORC values. Reproduced with permission from [15]. SPORC, score for prediction of postoperative respiratory complications.

wheezing, and clinical signs and symptoms of fluid overload. Current smokers have increased mortality risk following major surgery [16]. Smoking cessation at least 1 year prior to surgery abolishes the higher postoperative mortality risk and decreases the respiratory event rate [17].

Sarcopenia identified early after admission is a predictor of postoperative pulmonary complications and adverse discharge disposition [18,19]. Although preoperative lung rehabilitation improved the forced expiratory volume in one second in marginal patients undergoing lung cancer resection, there was no reduction in postoperative mortality, morbidity, or length of stay [20].

Intraoperative

As OSA is an independent risk factor for difficult mask ventilation during induction of anesthesia [21], optimizing airway management with upright posture may be prudent in some patients in the preinduction stage to optimize mask ventilation, during anesthesia with an unprotected airway, post-extubation, and immediately *post partum*. A bundle intervention for intraoperative care of patients with OSA has been recommended by Dr Shiroh Isono, Chiba, Japan and others [22].

After induction of general endotracheal anesthesia (GETA), lung-protective mechanical ventilation seeks to avoid derecruitment without overdistension of alveoli by keeping transpulmonary pressures such that the lung tissue stays in the linear part of its local pressure–volume curve. This strategy has gained widespread acceptance in ICUs following large studies revealing that it decreases morbidity and mortality in the setting of acute lung injury [23,24]. Clinicians should aim to achieve low transpulmonary pressures (typically expressed as driving pressures) and should choose procedure-specific PEEP. In patients undergoing GETA, protective ventilation was associated with decreased PRCs, with PEEP at least 5 cmH₂O and a median plateau pressure of 16 cmH₂O or less having the lowest risk of PRCs [25]. Protective effects of PEEP seem to be procedure-specific, as one study found that PEEP of at least 5 cmH₂O in major abdominal surgery lowers odds of PRCs, while the same PEEP was not associated with significant effects on PRCs in craniotomy patients [26]. In addition, patients with poor chest wall compliance need higher levels of PEEP, and optimal aeration may require a recruitment maneuver [27].

Although high FiO₂ may improve tissue oxygenation, it can impair pulmonary function. High FiO₂ (mean of 0.79) compared with low FiO₂ (mean of 0.31) was associated with significant, dose-

dependent increases in rates of PRCs, and 30-day mortality [28].

Increased average minimum alveolar concentration of inhalational anesthetics (volatile anesthetics and nitrous oxide) is dose-dependently associated with a lower 30-day mortality, lower hospital cost, and lower risk of PRCs. This finding was robust to sensitivity analysis of multiple subgroups, but interestingly, was not found to be present in patients with the longest periods of hypotension (≥ 11 min with mean arterial pressure < 55 mmHg) [29].

The use of intermediate-acting nondepolarizing neuromuscular blocking agents (NMBAs) is associated with an increased risk of postoperative desaturation to SaO₂ less than 90% after extubation and reintubation requiring unplanned admission to an ICU [30]. These same outcomes are increased with the use of high-dose neostigmine, especially if neuromuscular transmission monitoring is not applied [30]. In another study, use of NMBAs and their reversal with neostigmine were also both found to dose-dependently increase the risk of respiratory complications. However, use of proper neostigmine reversal guided by neuromuscular transmission monitoring, defined as use of 60 μ g/kg or less after recovery of train-of-four count of two, was associated with elimination of increased risk of PRCs [31]. Postoperative residual paralysis, defined as train-of-four T₄/T₁ less than 0.9, is associated with increased morbidity, delayed postanesthesia care unit (PACU) discharge by 60 min, and prolonged hospital length of stay [32–34]. Sugammadex administration decreases the incidence of postoperative residual paralysis compared with neostigmine [35]. However, even with sugammadex, residual neuromuscular blockade as high as 9.4% is possible when neuromuscular monitoring is not used [36].

Fluid administration impacts the course of patients. Both liberal and the most restrictive fluid resuscitation strategies have been associated with respiratory complications (pulmonary edema or increased deadspace during hypovolemia, respectively), whereas moderately restrictive fluid volumes are consistently associated with optimal postoperative outcomes [37,38,39]. Some data suggest that very high doses of opioids administered during surgery are associated with increased 30-day readmission rate [40].

Compared with anesthesia without an epidural or spinal, neuraxial blockade may reduce postoperative morbidity and mortality in disease-entity-based subcohorts [41]. Despite the effects of local anesthetics on motor function and sympathetic innervation, epidural anesthesia improves postoperative lung function and reduces PRCs [42]. A

Table 1. Strategies to minimize postoperative respiratory complications

Intraoperative considerations					
Factor	Improved outcome	Favorable strategy	Respiratory complication	Study cohort	Reference
Ventilation					
Protective lung ventilation	Major PRC, hospital length of stay	PEEP ≥ 5 cmH ₂ O, median tidal volume ≤ 10 ml/kg of predicted body weight, median plateau pressure ≤ 30 cmH ₂ O	Pulmonary edema, respiratory failure, pneumonia, and reintubation	Noncardiac surgery with endotracheal intubation; major abdominal surgery	Ladha <i>et al.</i> [25 ^{***}], de Jong <i>et al.</i> [26 ^{***}]
Oxygen toxicity	Major PRC, mortality, and ICU admission	Low intraoperative inspiratory oxygen fraction (mean of 0.31)	Respiratory failure, reintubation, pulmonary edema, and pneumonia	Noncardiac surgery	Staeher-Rye <i>et al.</i> [28 ^{**}]
Recruitment maneuvers and PEEP titration	Lung volumes, respiratory system elastance, and oxygenation	A recruitment maneuver followed by end-expiratory pressure titration	–	Critically ill, mechanically ventilated, morbidly obese (BMI > 35) patients	Pirrone <i>et al.</i> [27 ^{**}]
Surgical factors					
Laparoscopic vs. open surgery	PRC	Laparoscopic surgical approach	Pleural effusion, respiratory insufficiency, ARDS, pulmonary infection, and pulmonary embolism	Major hepatectomy surgery	Fuks <i>et al.</i> [43 ^{***}]
Anesthetic factors					
Fluid administration	Length of stay, costs, postoperative ileus, pneumonia, major PRC, 30-day mortality and renal complications	Moderate/goal-directed fluid administration	Respiratory failure, reintubation, pulmonary edema, and pneumonia	In patients undergoing colon, rectal, hip, or knee surgery; 12 liberal fluid therapy RCTs; noncardiac surgery	Shin <i>et al.</i> [37 ^{***}]; Thacker <i>et al.</i> [39 ^{**}]; Corcoran <i>et al.</i> [38]
Dose of NMBA and neostigmine	PRC	Low-dose use of NMBA, proper neostigmine reversal (≤ 60 μ g/kg after recovery of train-of-four count of 2)	Respiratory failure, reintubation, pulmonary edema, and pneumonia	Noncardiac surgery with NMBA use	McLean <i>et al.</i> [31 ^{***}]
Use of NMBA and neostigmine	Oxygen desaturation and reintubation	No use of intermediate-acting NMBA and neostigmine	SpO ₂ < 90% with a decrease in oxygen saturation after extubation of >3%; reintubation	Noncardiac surgery	Grosse-Sundrup <i>et al.</i> [30]
Dose of inhalational anesthetics	Major PRC, mortality, hospital length of stay, costs	High-dose inhalational anesthetic	Respiratory failure, reintubation, pulmonary edema, and pneumonia	Noncardiac surgery with inhalational anesthetic use	Grabitz <i>et al.</i> [29 ^{***}]
Neuraxial anesthesia	Morbidity and mortality	Use of neuraxial blockade with epidural or spinal anesthesia	Pulmonary embolism, pneumonia, and respiratory depression	Randomized surgical cases with or without neuraxial anesthesia	Rodgers <i>et al.</i> [41]
Dose of opioids	30-day readmission	Low-dose intraoperative opioid	Respiratory failure, reintubation, pulmonary edema, and pneumonia	Noncardiac surgery	Grabitz <i>et al.</i> [40]
Postoperative considerations					
Admission to ICU	Hospital length of stay, PRC, and costs	Optimal decision of postoperative ICU vs. ward admission	Respiratory failure, reintubation, pulmonary edema, and pneumonia	Noncardiac and nontransplant surgery	Thevathasan <i>et al.</i> [44 ^{**}]

Table 1 (Continued)

Intraoperative considerations					
Factor	Improved outcome	Favorable strategy	Respiratory complication	Study cohort	Reference
Monitoring on surgical floor	Rescue events and transfers to ICU	Appropriate postoperative monitoring (e.g., pulse oximetry)	–	Orthopedic surgery	Taenzer <i>et al.</i> [45]
Postoperative analgesia	Opioid-induced respiratory depression	Opioid-sparing analgesia	Respiratory depression	Surgical patients with acute pain	Lee <i>et al.</i> [46 ^{***}]
CPAP	AHI, oxygen desaturations, mean oxygen saturation, and opioid-induced respiratory depression	CPAP treatment in postanesthesia care unit	Apnea–hypopnea index and oxygen desaturation	Bariatric surgery	Zaremba <i>et al.</i> [47 ^{***}]
Upright positioning	Pharyngeal collapsibility	Postural change from supine to sitting	–	Patients with OSA	Tagaito <i>et al.</i> [48]
Fowler's position	Apnea–hypopnea index, oxygen saturation <90%	Elevated body position	Apnea–hypopnea index, oxygen saturation <90%	OB, postdelivery	Zaremba <i>et al.</i> [49 ^{***}]
Avoid reintubation in surgical ICU patients	Reintubation	Avoid elevated blood urea nitrogen, low hemoglobin, and muscle weakness in SICU patients	Reintubation	Surgical ICU patients (noncardiac)	Piriyapatsom <i>et al.</i> [50 ^{***}], Farhan <i>et al.</i> [51]
Early mobilization in the ICU	Length of stay in the ICU, functional mobility at hospital discharge	Early, goal-directed mobilization using an interprofessional approach of closed-loop communication and SOMS algorithm	–	ICU patients, mechanically ventilated (<48 h; expected to require ≥24 h)	Schaller <i>et al.</i> [53 ^{***}]

ARDS, acute respiratory distress syndrome; CPAP, continuous positive airway pressure; NMBA, neuromuscular blocking agent; PEEP, positive end-expiratory pressure; PRC, postoperative respiratory complication; RCT, randomized controlled trial.

laparoscopic surgical approach may also have beneficial effects on postoperative respiratory outcomes compared with open surgery [43^{***}]. Different intraoperative factors that can be modulated to decrease PRCs are described in Table 1.

Postoperative

In OSA, the upper airway is more collapsible [52], and supine positioning promotes upper airway collapse and doubles the AHI index compared with lateral position [54]. Likewise, in anesthetized, paralyzed patients with OSA, sitting position significantly improves the cross-sectional area of the retro-palatal and retro-glossal airways and decreases the closing pressure (indicating a more patent airway) compared with supine position [48]. In addition, neck extension in anesthetized patients with sleep-disordered breathing increases maximal oropharyngeal airway size and decreases closing pressures of the airway (indicating a more patent airway), whereas neck flexion with bite opening has the

opposite effect [55]. Comparing sniffing position (neck flexion and upper cervical extension) with a neutral airway in anesthetized OSA patients, sniffing position increases airway cross-sectional area and decreases closing pressure (more open airway) [56].

Interestingly, sleep apnea is much more common in pregnant than nonpregnant women and persists into the early post-partum period. Post-partum airway obstruction is a major cause of anesthesia-related maternal death [57]. Consistent with findings in OSA, upper body elevation to 45 degrees increases the cross-sectional area of the upper airway as measured by acoustical pharyngometry and mitigates sleep apnea as measured by polysomnography in women 48 h after delivery [49^{***}]. It is prudent to extubate patients at risk of extubation failure in the reverse Trendelenburg position to decrease airway collapse after removal of the endotracheal tube [58].

Prolonged postoperative hypoxemia can occur during recovery from surgery [59^{***}]. Patients receiving opioids for postoperative analgesia are

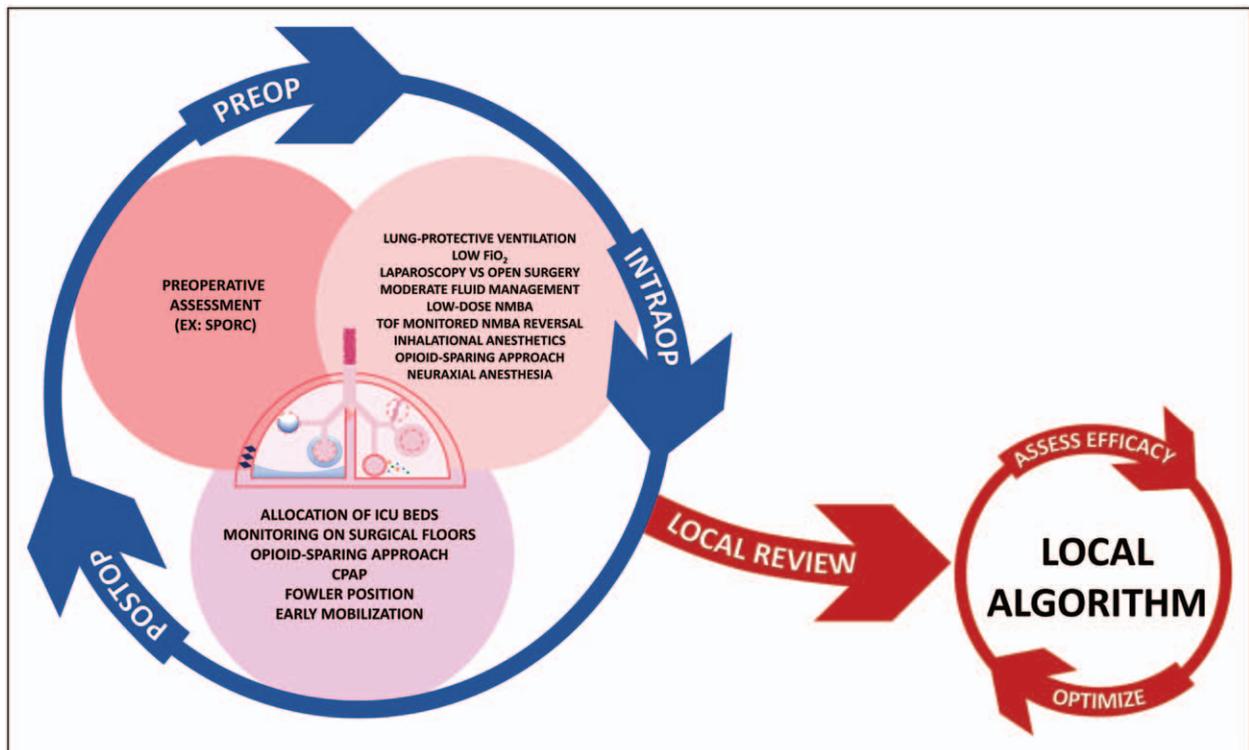


FIGURE 3. Review of literature and guidelines for creation of a locally implemented algorithm. Clinicians must think globally (blue circle with arrows) about the myriad preoperative (dark pink circle), intraoperative (light pink circle), and postoperative (light purple circle) factors that can potentially decrease postoperative respiratory complications. Review of this complex, global view by a local, respected, multidisciplinary team (red 'local review' arrow) can lead to the creation of a more easily and systematically implemented local algorithm that creates actionable hospital bundles (red circle). This local algorithm needs ongoing evaluation of efficacy, which should trigger optimization of the local algorithm (red arrows surrounding algorithm circle).

particularly at risk of experiencing desaturation due to opioid-induced respiratory depression [46²²]. A pharmacophysiologic interaction trial showed that continuous positive airway pressure compared with atmospheric pressure applied through an oronasal mask improved sleep-disordered breathing and ameliorated the respiratory-depressant effects of opioids postoperatively [47²²].

Furthermore, proper monitoring in the PACU can decrease the number of ICU transfers and improves patients' outcomes by detecting early signs of respiratory complications [45]. Of note, it is important to use objective criteria to determine whether or not a patient needs to be admitted to an ICU. A recent study demonstrates that admission to the ICU rather than ward admission is associated with adverse outcomes in healthier patients [44²²]. Admission to the ICU strains the health system by increasing resource utilization and costs of hospital care. Furthermore, patients surviving an ICU stay subsequently demonstrate a higher risk of 5-year mortality [60].

Sarcopenia, frailty, and muscle strength are independent predictors of adverse discharge

disposition and reintubation in surgical ICU patients [19²²,50²²,51]. Postoperatively, early mobilization improves functional independence. Our data demonstrate that early, goal-directed mobilization shortens patients' length of stay in the SICU and improves functional mobility at hospital discharge [53²²]. Postoperative factors that can be modulated to decrease PRCs are described in Table 1.

Act locally: development and implementation of center-specific guidelines

Guideline-driven clinical decision pathways are efficiently encapsulated by algorithms. Those algorithms and performance improvement measures developed by multidisciplinary teams on a local hospital or departmental level are likely to be the most successful [61].

In general, the following steps are followed: plans are created to implement improvement throughout the system and effectiveness is continually monitored and changes are made as needed. As clinicians, there is often divergence between what we know from reading current literature and what

we practice. This ‘knowing-doing gap’ is what implementation science seeks to overcome. We have recently shown that proper implementation of a clinical algorithm improves important patient outcomes. Of utter importance is the selection of a locally respected ‘facilitator’ who makes sure that all voices are heard and that plans made on the basis of algorithms are properly implemented [53[■]]. In this way, a nuanced subject matter can be made into algorithmic, usable hospital bundles by a local multidisciplinary team (Fig. 3).

CONCLUSION

More than a 10-fold increase in mortality risk is incurred by severe PRCs leading to reintubation and unplanned ICU admission [5[■]]. Thus, preoperative risk stratification to identify patients at increased risk of PRCs and subsequent tailoring of an anesthetic plan with respiratory optimization is warranted. Surgery type affects PRCs, and laparoscopic surgery improves respiratory outcomes. Intraoperative use of appropriately restrained fluid management, increased utilization of inhaled anesthetics (while not allowing hypotension), judicious and careful titration of NMBAs with appropriately monitored reversal, minimization of opioids, and lung-protective ventilation should be used. Postoperatively, patients at high risk of PRCs should be extubated in the reverse Trendelenburg position. Obese patients and those with OSA should be treated with an ‘OSA hospital bundle’ [22[■],52,58]. PACU discharge disposition should incorporate patient risk stratification for PRCs as a key element of respiratory safety. Local guidelines need to be developed to optimize patients’ triage. Early, goal-directed mobilization should be implemented. The creation of local algorithms and hospital bundles will facilitate implementation of these suggested evidence-based practices to improve patient outcomes.

Acknowledgements

We would like to thank Jeff and Judy Buzen for their support.

Financial support and sponsorship

The work was supported by an unrestricted grant from Jeff and Judy Buzen to Dr. Eikermann.

Conflicts of interest

Within the past 2 years, M.E. received investigator-initiated research funding from Merck and Jeff and Judy Buzen, Massachusetts, USA. He has equity stakes at Calabash Bioscience Inc. There are no other relationships or activities that could appear to have influenced the submitted work.

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