Prevention of Postoperative Pulmonary Problems Starts Intraoperatively

J. Poelaert, L. Szegedi, and S. Blot

Introduction

Pulmonary complications are a burden for the postoperative patient [1]. Atelectasis and pneumonia have been recognized as the most frequent pulmonary problems in critically ill surgical intensive care unit (ICU) patients [2]. However, it is sometimes difficult to differentiate clinically between atelectasis and pulmonary infection. About a century ago, collapse of the lung, related to insufficient inspiratory power was reported [3, 4]. Altered gas exchange was characteristic in these patients [5], and Bendixen et al. used the term “atelectasis” for the very first time in 1963 [6]. Atelectasis occurs with progressive loss of compliance, not least as a consequence of loss of laryngeal muscle tone and disappearance of intrinsic positive end-expiratory pressure (PEEP), after induction of anesthesia, paralysis and bypassing the oropharynx [7]. Atelectasis resolves only with some deep inflations of the lung (recruitment), adequate pain relief, physiotherapy and early mobilization of the patient.

Pulmonary infections are another problem, in particular for high-risk surgical patients [8]. Although preventive measures against ventilator-associated pneumonia (VAP) have a relatively high adherence rate of 72%, there is consider-
able variability among countries [9] and disciplines. Moreover, knowledge of these preventive measures is not widespread among non-ICU physicians. Once present, VAP and postoperative pneumonia necessitate antibiotic therapy, sometimes in association with prolonged need for mechanical ventilatory support. Both entities, atelectasis and pulmonary infections, increase considerably the length of stay in the hospital and thus costs. Adequate prevention could lead to a significant reduction in cost both at health care and social-economical levels.

In this review, these two clinical entities are critically examined, in particular in the light of preventive measures that could be undertaken in daily practice. We deliberately do not discuss states of acute lung injury (ALI), which can also be present in postoperative patients, often with detrimental consequences. Although some preventive measures can already be initiated intraoperatively, others can be pursued in the ICU setting.

**Incidence of Postoperative Pulmonary Complications**

The incidence of atelectasis is hard to assess and difficult to calculate. Only imaging can provide a hint of occurrence rates: In patients with normal lungs, 90% of patients developed atelectatic regions in the most dependent segments, which were still present 1 h after intubation [7, 10]. In 50% of patients these atelectasis regions remained present until 24 h after intubation. Moreover, they are related to constitutional characteristics [11].

In contrast, postoperative pneumonia and VAP have been studied extensively both in the general ICU and in postoperative cardiac surgical patients. The incidence of VAP after cardiac surgery encompasses 6.3 episodes per 1,000 days of mechanical ventilation [12]. In a meta-analysis, Smetana et al. assessed the risk factors for postoperative pneumonia in non-cardiothoracic surgical patients [13]; congestive heart failure, age, American Society of Anesthesiologists (ASA)-class >2, and chronic obstructive pulmonary disease (COPD) appeared to be the most important risk factors. Box 1 shows the most important and relevant risk factors for postoperative pulmonary infection. Postoperative pneumonia was associated with a significant 30-day mortality of 21% in patients undergoing non-cardiac surgery [14], and in a general surgical cohort, 30-day mortality was higher in patients with a postoperative pulmonary complication (19.5%; 95% confidence interval (CI), 12.5–26.5%) than in those without (0.5%; 95% CI, 0.2–0.8%) [2]. Postoperative pneumonia is also associated with larger hospital costs and longer lengths of stay compared with uncomplicated surgery [15]. Patients especially at risk of postoperative pneumonia and VAP are those undergoing high-risk surgery in the presence of extensive co-morbidities, those undergoing cardiac and cardiovascular surgery [16], open thoracic or thoracoplasty surgery [17], and major upper abdominal procedures and prolonged procedures [2].
knowledge of these ians. Once present, sometimes in asso-
ciation with other factors, atelectasis may be difficult to treat, especially in the intensive care unit. It affects many patients and can lead to prolonged hospitalization and increased mortality.

### Box 1

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<tr>
<th>Major and Complicated Surgery</th>
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<tr>
<td>Cardiac surgery</td>
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<tr>
<td>Major vascular surgery</td>
<td>ASA-class &gt; 2</td>
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<tr>
<td>Major upper abdominal procedure</td>
<td>Chronic obstructive pulmonary disease</td>
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<tr>
<td>Other high-risk surgeries</td>
<td></td>
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<tr>
<td>Extensive co-morbidities</td>
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ASA: American Society of Anesthesiologists

### Atelectasis

#### Pathophysiology

Atelectasis is the result of general anesthesia, ventilation and patient-related factors. In large series of postoperative patients (n = 24,000), 0.9% developed hypoxemia, not resolving with only supplemental oxygen [18]. Intraoperatively, atelectasis is responsible for a large part of hypoxemia. Upon administration of a hypotonic, opioid or neuromuscular blocker, muscular tone is abolished within the first few minutes [1]; during endotracheal suctioning, again, atelectasis may be induced through induction of negative intra-thoracic pressure [19]. Surgical manipulation causing compression and/or traction may be aggravated by type and length of intervention, age and body habitus, bleeding, etc. Cephalic displacement of the diaphragm during general anesthesia in the dorsal decubitus position, sometimes with increased intra-abdominal pressures, as well as the Trendelenburg position, intensifies hypoventilation and compression of the most dorsal lung segments (Box 2). Furthermore, loss of muscle tone and the cardiac weight itself may induce further pulmonary compression or inadequate expansion. Rapidly, the dependent lung segments fill up with fluid, hampering any rapid recruitment [20]. In addition to impaired oxygenation and compliance, microvascular leakage occurs as a witness of damaged endothelial function in anesthetized rats when atelectasis is present [21].

Atelectasis can be classified into three groups: Compression atelectasis occurs during general anesthesia and is caused by chest geometry and diaphragm position and motion [22]; in the case of absorption atelectasis, the greater the inspired oxygen fraction after induction, the faster the collapse of the lung regions [23]; loss-of-surfactant atelectasis collapse occurs within 5 min after a vital capacity maneuver at an inspired oxygen fraction (FiO₂) of 1.0 or immediately after removal of PEEP at FiO₂ of 0.5. Atelectasis in turn impedes surfactant function, making the lung more prone to collapse again after reopening [24].
Box 2
Factors predisposing to atelectasis
- Type and length of surgery
- Age
- Body habitus
- Bleeding
- Loss of muscle tone and cephalic displacement of the diaphragm during general anesthesia
- Increased intra-abdominal pressure
- Cardiac weight
- Increased FiO₂ and low alveolar ventilation
- Intra-tracheal suctioning
- Impaired surfactant

Absorption atelectasis is induced by increased FiO₂ and low alveolar ventilation; in addition, impaired surfactant will also provoke atelectasis (Box 2). In addition to hypoxemia, a fall in functional residual capacity (FRC) and decreased lung compliance, a significant increase in pulmonary resistance may occur, mainly by hypoxic pulmonary vasoconstriction, potentially hampering ejection by the right ventricle.

Diagnosis

Atelectasis is clinically suspected whenever impaired oxygenation and decreased lung compliance occur in a situation that could be related to atelectasis. This clinical diagnosis is particularly important intraoperatively, when active diagnosis is difficult. In situations where imaging is possible, bedside chest radiography appears the first choice.

Typically, signs of volume loss characterize the presence of atelectasis:
- displacement of thoracic structures: Interlobar fissure, hemidiaphragm, shift of mediastinal organs
- compensatory hyperinflation of certain lung segments
- typical triangular shape of collapsed lung segment
- obliteration of a lung segment may opacify adjoining parts of the mediastinum.

A more sensitive and specific diagnosis of atelectasis can be made with computed tomography (CT) scans. Already in 1986, Strandberg et al. described with CT scan the presence of atelectasis after induction of anesthesia [7, 10]. A CT scan depicts areas of increased density [11, 25] with an abrupt decrease in FRC and a lowered inflection point on the pressure-volume relationship. The densities correlate with collapsed lung alveoli [26]. Although CT scans indeed offer a near-
ly perfect tool for evaluation of the presence of atelectasis [25], this technique is often not very useful because of the need for transportation of an often-hypoxemic patient. All these methods provide regionally specific information, but only as a snapshot in time. Magnetic resonance imaging (MRI) currently has no additional value in the diagnosis of atelectasis. In contrast, ultrasound allows detection of many deviations in lung structure, pleural fluid, etc. In the ICU, this technique has shown value in detecting alveolar collapse [27]. However, intraoperatively ultrasound is often inadequate to visualize properly collapsed lung tissue. Electrical impedance tomography (EIT) is a new technology, which permits continuous visualization of the distribution of ventilation. Data are continuously displayed in the form of images, waveforms and parameters. Measures can be taken to individually tailor ventilator settings. Determining how different lung regions respond to therapeutic interventions over time is challenging without continuous regional information. The use of EIT in ICU settings is well-established; however, intraoperatively its value still has to be demonstrated. Regional ventilation distribution and recruitment has been assessed in experimental models of direct and indirect ALI as well as in normal lungs [28]. Recently, this technology was used to evaluate the effects of PEEP during pneumoperitoneum in laparoscopic surgery. PEEP led to improved aeration of the dorsal lung parts with consequent improved oxygenation and pulmonary compliance [29].

**Prevention and Treatment**

Experimental and clinical studies suggest recruitment of collapsed alveoli needing peak inspiratory pressures of $>30$ cm H$_2$O for $>45$ s to allow slow alveoli, with a low time constant, to reopen [30]. Table 1 shows the different studies and compares outcomes after recruitment maneuvers. Additional PEEP is obligatory to keep the alveoli open but only after a recruitment maneuver has been applied [19, 25, 30].

<table>
<thead>
<tr>
<th>Author</th>
<th>Specimen</th>
<th>Method</th>
<th>Result</th>
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<tbody>
<tr>
<td>Magnusson (1998) [64]</td>
<td>Pigs</td>
<td>ECC</td>
<td>Atelectasis in control Repeat within 6 h</td>
</tr>
<tr>
<td>Murphy (2001) [65]</td>
<td>Human</td>
<td>ECC</td>
<td>Earlier extubation</td>
</tr>
<tr>
<td>Tschernko (2002) [66]</td>
<td>Human</td>
<td>ECC</td>
<td>Decreased intrapulmonary shunting</td>
</tr>
<tr>
<td>Minkovich (2007) [67]</td>
<td>Human</td>
<td>ECC</td>
<td>After ECC and in the ICU</td>
</tr>
<tr>
<td>Shim (2009) [68]</td>
<td>Human</td>
<td>Off pump</td>
<td>Earlier extubation; ICU LOS no change</td>
</tr>
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</table>

ECC: extracorporeal circulation; LOS: length of stay
In a small group of cardiac surgical patients, a recruitment maneuver induced a rapid decrease in cardiac output, concomitant with a fall in preload conditions [31]. In an animal experimental setting with lung injury, the same findings were described [32]. Furthermore, care should be taken to monitor right ventricular function because of potential overload during the maneuver [32]. Lower peak inspiratory pressures led to less impressive changes in hemodynamics, although equivalent results on oxygenation and compliance recovery [33]. Continuous perioperative monitoring of pressures, volumes and, if available, regional ventilation is necessary during general anesthesia to allow correct adjustment of ventilatory settings.

**Postoperative Pneumonia and Ventilator-Associated Pneumonia**

**Pathophysiology**

Postoperative pneumonia and VAP have been described in terms of aspiration of subglottic secretions and gastroesophageal reflux. Bacterial leakage (often $10^{10}$ bacteria/ml secretion [34]) in conjunction with impaired lung defense, results in tracheobronchial colonization and induction of ventilator-associated tracheobronchitis (VAT) and VAP. This aspiration risk is not a minor issue, as shown by Mahul et al., but can run up to volumes of 150 ml per day [34]; intraoperatively, even in the prone position, drainage from nose and mouth could be as high as 50 ml/h [35]. Risk factors for aspiration include not only the endotracheal tube (ETT), but also mechanical ventilation without PEEP, tracheal suctioning, the presence of a nasogastric tube with gastroesophageal reflux, and various patient-related factors (Box 3).

**Box 3**

Risk factors for aspiration

- Type of tracheal tube
- Mechanical ventilation without positive end-expiratory pressure
- Intra-tracheal suctioning
- Presence of the nasogastric tube
- Gastroesophageal reflux

Patients suffering from preoperative hypoxemia or a pulmonary infection less than one month before surgery show a significantly increased risk of postoperative pulmonary complications [2].

All types of mechanical ventilation are non-physiological and, in a vicious circle manner, cause further damage to the lungs, with either a biochemical injury (with loss of cytokines, complement, prostanoids, reactive oxygen species, leukotrienes, proteases), and/or a biophysical injury (shear, overdistension, cyclic stretch, increased intrathoracic pressure). Protective tools, such as barrel-shaped polyvinyl
chloride (PVC) cuffed ETTs, do not prevent aspiration as demonstrated recently in *in vitro* studies [35, 36]: with an ETT in a rigid cylinder, a dye solution poured above the barrel-shaped PVC cuff of the ETT descended along the channels formed within the PVC.

**Diagnosis**

VAP is diagnosed on the basis of several criteria. Essential clinical criteria include the presence of fever, purulent sputum and hypoxemia. In addition, a positive Gram-stain, leukocytosis and a positive chest X-ray should be present [37, 38]. The problem occurs after major surgery in patients in whom these criteria are not obvious or overt. Fabregas et al. suggested that the presence of infiltrates on the chest radiograph and two of three clinical criteria (leukocytosis, purulent secretions, fever) had a sensitivity of 69% and a specificity of 75% [39], rates that are not worse than those with the clinical pulmonary infection score.

**Preventive Measures**

Prevention is the cornerstone with respect to abolishing atelectasis and pulmonary infections induced through inadequate sealing and subsequent leakage along the cuff of the endotracheal tube (Fig. 1).

![Fig. 1 Measures to prevent post-operative pulmonary complications (see text for details)](image-url)

- **Pre-Operative Measures**
  1. Teeth brushing
  2. Antiseptic rinsing

- **Intra-Operative Measures**
  1. Adapting anesthesia to individual patient needs
  2. Maintaining cuff pressure at 20–30 cmH₂O
  3. Maintaining PEEP at 5–8 cmH₂O
  4. Aspiration of subglottic secretions with a dedicated ET tube
  5. Using an ET with a changed cuff design/material

- **Post-Operative Measures**
  1. Extubation if possible
  2. Semi-upright position (~45°)
  3. Adapting sedation levels to individual patient needs
  4. Antiseptic rinsing
  5. Teeth brushing if patient is awake
Preoperative Measures
In esophageal cancer surgery and in cardiac surgical patients, a clear decline in occurrence rate of postoperative pneumonia was observed with teeth brushing (40, 41). Rinsing of the buccal cavity with a 2% solution of chlorhexidine reduces the frequency of postoperative pneumonia considerably [42]. In a recent meta-analysis, Labeau et al. showed that use of antiseptics resulted in a significant risk reduction of VAP (RR 0.67; 95% CI 0.50–0.88; p = 0.004) [43]. Chlorhexidine application was shown to be effective (RR 0.72; 95% CI 0.55–0.94; p = 0.02), in particular in a cardiac surgical subset (RR 0.41, 95% CI 0.17–0.98).

Intraoperative Measures
The rates of VAP and of postoperative pneumonia are time-related: The longer the surgical procedure lasts, the greater the risk of aspiration and thus pulmonary infection. A surgical procedure of more than 2 h increases the risk 4-fold [44]. In this respect, comorbidities play an important role. The sooner the patient can breathe spontaneously and be weaned from the ventilator, the better. This implies that sedation levels in the ICU should be moderate and systematically adapted to the disease state of the patient; the anesthetic level also needs to be adapted in this manner. In addition to these important issues, some preventive measures can be undertaken to reduce intraoperative aspiration.

- Lubrication: In one-lung ventilated thoracic surgery patients, Sanjay et al. demonstrated that lubricated PVC cuffs of a double-lumen tube sealed the trachea nearly twice as long as non-lubricated tubes with a resultant decrease in pulmonary infection rates [45].
- Cuff pressure management: Since the introduction of the high-volume low-pressure tube, cuff pressures have been set considerably lower than with the high-pressure low-volume cuffed ETT. Tracheal damage has decreased considerably, but the risk of underinflation of the cuff has increased [46]. Even with an adequately inflated cuff, the rate of leakage must still be considered. Intervals of a cuff pressure <20 cm H₂O during the first 8 ventilation days significantly increased the risk of postoperative pneumonia (OR 4.23, CI 1.12–15.92).

  Intermittent control of cuff pressure, at least every four hours, to obtain a cuff pressure between 20 and 30 cm H₂O [47, 48], is one approach to this problem. Care should be taken to release the cuff pressure manometer from the valve of the cuff; so that minimal leakage occurs; in this way a slightly increased lower level of, e.g., 24 cm H₂O should be considered. Not controlling the cuff pressure will certainly lead to either underinflation or overinflation and to adequate cuff pressures in less than 20% of cases [49].
- PEEP: Early onset VAP, occurring less than 5 days after intubation, was significantly less frequent in non-hypoxemic patients ventilated with 5–8 cm H₂O PEEP during lung surgery [50]. Prophylactic PEEP was found to be safe and to reduce VAP-rates, including late-onset VAP [51].
- Aspiration of subglottic secretions with a dedicated ETT, with a PVC cuff, may reduce the risk of aspiration [51]. In only 31 patients after cardiac surgery,
Bouza et al. demonstrated a significant difference in VAP-rate, days on ventilator and length of stay in the ICU in those patients needing ventilator support for more than 48 h. Combined use of PEEP and subglottic aspiration reduced the risk of VAP from 48% in controls to 27% in patients intubated with this dedicated ET tube [52]. Similarly, Mahul et al. demonstrated, in a mixed medical-surgical ICU population expected to require >72 h of ventilatory support, that subglottic secretion drainage resulted in a lower frequency of VAP or a later onset [34]. Valles et al. reported a similar reduction in VAP rate without, however, any difference in outcome [53]. Other investigators have described comparable results [12, 54, 55]. Estimating the cost of VAP treatment at €4,300 and a reduction in the VAP-rate of 30% with a dedicated ETT with subglottic secretion drainage, a cost-benefit equilibrium is present.

The problems and debate associated with the single drainage lumen tube include the correct dorsal position of this lumen and the presence of an open, non-occluded lumen. Indeed, viscous secretions may occlude the sole lumen and suctioning against the tracheal wall may also occlude the lumen of the suction channel [56]. Occlusion was found in 43% of investigated patients. Introduction of an ET tube with multiple drainage suction holes above the cuff could improve the preventive function of such tubes by less frequent occlusion rates [57], but larger in vivo studies are missing.

- **Changed cuff design:** Several in vitro studies have suggested that a modified cuff design could reduce the risk of aspiration and transition of subglottic secretions into the trachea. Indeed, Bullenkopf et al. demonstrated the presence of small channels in the PVC cuff, permitting transit of secretions into the tracheal lumen; the existence of these channels has been shown both with fluoroscopy and with dye solutions [58]. In an in vitro investigation, Zanella et al. demonstrated that a tapered-shaped, cuffed ET tube clearly delayed the risk of transit of dye solution up to 12 h on the condition that PEEP (5–8 cm H2O) was present [36], in contrast to a barrel-shaped cuffed ET-tube, for which the security margin lasted only 2 and maximum 6 h. Finally, Dave et al. demonstrated in three different sized artificial tracheas that the tapered-shaped PVC cuff was more effective in preventing leakage [59]. To the best of our knowledge, published in vivo studies are not yet available.

Theoretically, it is conceivable that a tapered-shaped cuff indeed seals the tracheal lumen much better as this cuff fits perfectly into the lumen at a particular level [60]. The perfect fit is closely related to a particular level of the cuff at which no channels in the PVC are formed. Depending on the tracheal anatomy of a particular patient, this improved sealing can be at an upper or rather lower cuff level.

- **Changed cuff material:** In the past decade, ETTs with a polyurethane cuff have been developed. Because of the ultra-thin wall, polyurethane cuffs have smaller channels formed by the folds in the cuff. This characteristic has resulted in more favorable research outcomes in comparison with their PVC cuffed counterparts. In an in vitro study by Dave et al., it was demonstrated that PVC cuffs always leaked more and faster compared to polyurethane cuffs [59]. In a ran-
domized controlled trial in 134 cardiac surgical patients, it was demonstrated that use of polyurethane cuffed tubes resulted in a reduced prevalence of postoperative pneumonia. The risk of pneumonia was reduced by nearly 50%, albeit the prevalence of pneumonia in the control group was particularly high [48]. Similarly, Lucangelo et al. showed that a barrel shaped polyurethane cuffed ETT sealed the tracheal lumen better [61]. In children, Dullenkopf et al. demonstrated similar results [62].

Postoperative Measures
Intraoperative measures will certainly diminish considerably the risk of aspiration and, therefore, decrease the potential risk for initial bacterial descent towards the trachea. Preventive measures such as teeth brushing and antiseptic mouth rinsing should be restarted in the postoperative setting. Supine body position is a clear risk factor for pulmonary infections in ventilated patients; in a study comparing supine with semi-recumbent positioning in 86 intubated and mechanically ventilated patients, the rate of microbiologically confirmed pneumonia was significantly lower in the semirecumbent patients \( p = 0.018 \), and the odds ratio for development of nosocomial pneumonia was 6.8 \( (1.7-26.7) \) \( p = 0.006 \) for supine position [63]. Although the semi-recumbent position is not possible intraoperatively, whenever possible in terms of hemodynamic status, patients should be positioned in a semi-upright position (about 40\(^\circ\)) once extubated in the operating room or postoperative care setting.

Conclusion
It is obvious that prevention of (postoperative) pulmonary complications should be a main goal in every perioperative setting. Preventive strategies start already before surgery and should be initiated on the ward with systematic application of oral hygiene. Intraoperatively, anesthesiologists should start more extensive preventive action including optimal cuff pressure and PEEP administration in addition to monitored and individually titrated mechanical ventilator parameters. Using a dedicated ETT is only supported by in vitro studies and should be related to the presumed duration of postoperative ventilator support at induction of the anesthetic.

References
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42. Panchabhai TS, Dangayach NS, Krishnan A, Kothari VM, Karnad DR (2009) Oropharyngeal cleansing with 0.2 % chlorhexidine for prevention of nosocomial pneumonia in critically ill patients: an open-label randomized trial with 0.01 % potassium permanganate as control. Chest 135:1150-1156.

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