After 2 decades of military dictatorship, in 1985 a civilian president was elected in Brazil. The events surrounding the inauguration related as much to the disciplines of perioperative medicine as to diplomacy. After abdominal surgery, the elected president developed a most significant postoperative pulmonary complication: severe acute respiratory distress syndrome (ARDS). He never took office.

Pulmonary complications such as pneumonia, bronchospasm, effusion, failure to wean, and postextubation respiratory failure are leading causes of postoperative complications, second only to wound infection. Severe postoperative pulmonary complications resulting in reintubation and subsequent unplanned intensive care unit admission translate to a more than 90-fold increase in mortality risk. As a consequence, it is imperative to improve our understanding of the problem and investigate methods to minimize it.

In this issue of Anesthesiology, Severgnini et al. report on important new data implying an association between intraoperative mechanical ventilation strategy and postoperative pulmonary complications in patients undergoing moderate/large abdominal surgery. Stimulated by previous findings in intensive care and preliminary intraoperative results, the authors investigated the effect of a protective ventilatory strategy against what they called “standard ventilation” during abdominal surgery. The main conclusion is that the application of a protective ventilatory strategy with physiological tidal volumes and high positive end-expiratory pressure (PEEP) during abdominal surgery lasting more than 2h improved respiratory function and reduced a clinical pulmonary infection score in the days after surgery, even if it did not affect length of hospital stay.

How Do Anesthesia and Surgery Affect Pulmonary Function?

Atelectasis develops within minutes after the induction of general anesthesia and is a significant source of intraoperative gas exchange abnormalities. Intraoperatively, these can be 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 dysfunction secondary to diaphragmatic dysfunction is observed, which compromises respiratory mechanics and gas exchange, is magnified by pain, and presents clinically as a marked reduction in the ratio of abdominal to rib cage motion. Accordingly, the anesthetic and surgical perioperative insults can create conditions of a “multiple-hit” lung injury, which can be further augmented by the tissue stress induced by intraoperative mechanical ventilation (fig. 1). This emphasizes the need for interventions to minimize the aggregate effect of those insults.

Ventilator-induced Lung Injury

Mechanical ventilation can produce significant lung injury that translates to increased mortality in patients with ARDS. This finding changed the paradigm of mechanical ventilation...
settings from one of adjustments exclusively aiming at optimizing gas exchange to that of optimizing gas exchange while minimizing lung injury. In the absence of excessive ventilatory pressures that could produce barotrauma, the causes of ventilator-induced lung injury can be characterized as overinflation of aerated lung areas (volutrauma), cyclic lung derecruitment (atelectrauma), and increase in local proinflammatory mediators resulting from biophysical forces in the absence of gross ultrastructural damage (biotrauma). Through the process of mechanotransduction, cells lining the capillaries, airways, and alveoli transform the mechanical forces into injurious chemical signals that interact with reparative pathways to produce lung injury.\textsuperscript{6} In low-volume lung areas, injurious mechanical forces can derive from concentration of stress in the interface between atelectatic and expanded areas,\textsuperscript{7} propagation of air/fluid interfaces in the airway producing injury on the bronchiolar epithelium,\textsuperscript{8} and energy released in the rupture of liquid bridges during airway reopening.\textsuperscript{9}

**Protective Ventilation**

Minimization of these injurious mechanical factors can be accomplished by ventilator strategies that help avoid lung derecruitment without undue overdistension. The ensuing principles of “protective” mechanical ventilation are, accordingly, aimed at keeping all lung regions in the linear portion of their local pressure-volume curve. An essential concept is that of transpulmonary pressure, the difference between the alveolar and intrapleural pressures, and an essential determinant of lung inflation. Better than the plateau pressure, the transpulmonary pressure describes the expanding forces applied to the lung. The optimal transpulmonary pressures limit the risks of overdistension and barotrauma, whereas avoiding lung derecruitment. Clinical strategies to

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**Fig. 1.** (A) Intraoperative anesthetic and surgical insults creating conditions for a “multiple-hit” lung injury during abdominal surgery. Lung derecruitment occurs soon after induction of anesthesia in dependent poorly expanded areas resulting from reduction of the regional transpulmonary pressure (block arrows, low-volume lung injury panel). This is exacerbated by paralysis of the diaphragm and application of surgical retractors. During mechanical ventilation, those dependent regions are at risk for low-volume lung injury, with cyclic derecruitment of terminal airways and alveoli, concentration of mechanical forces, shear stress and tangential forces (dotted arrows) conducive to cellular membrane stress failure, and bronchiolar epithelial cell injury due to pressure gradients during airway opening (thin arrows). Reduced compliance in these derecruited regions also facilitate hyperinflation in nondependent areas of larger transpulmonary pressures (block arrows, hyperinflation panel). Systemic inflammation triggered by surgical incision, tissue manipulation, bacterial translocation, and endotoxemia can additionally contribute to lung injury. (B) Spontaneously breathing awake patient with less heterogeneity in regional lung aeration and more caudal position of diaphragm. SIRS = systemic inflammatory response syndrome.
achieve protective mechanical ventilation include the use of low-tidal volumes, plateau pressure limitation, PEEP, and recruitment maneuvers. The approach had remarkable success in reducing mortality in ARDS patients with use of physiological tidal volumes (6 ml/kg of predicted body weight) and limitation of end-inspiratory plateau pressures. Instead, the precise approach for the application of PEEP and recruitment strategies during ARDS is still not established. Although high PEEP is likely beneficial in severe ARDS, it may be deleterious to outcomes of patients with mild and moderate ARDS. Interestingly, the subset of less severe ARDS patients in the famous ARDS network study, that is, patients at the highest quartile of compliance (best respiratory mechanics) did not appear to show a survival benefit of low-tidal volumes.

The definition of protective ventilation for the large majority of anesthetized patients undergoing surgery does not exist—most of them do not present with ARDS. Remarkably, considering the large number of patients receiving general anesthesia with mechanical ventilation, the literature provides only limited information related to the pathophysiology of surgery-associated lung injury, its prevention, and treatment.

What Does Severgnini et al. Add to the Existing Literature?

The results by Severgnini et al. suggest that a protective ventilatory strategy composed of PEEP, recruitment maneuvers, and physiological tidal volumes can improve several aspects of respiratory function for at least 5 days after surgery including oxygenation, spirometry, and chest x-ray findings. The clinical pulmonary infection score, based on oxygenation and chest x-ray findings, in addition to temperature, leukocyte count, and volume of tracheal secretions, was also favorably affected by protective ventilation.

We speculate, based on the presented data, that the prevention of lung derecruitment rather than the lower tidal volumes might have been the predominant factor associated with those beneficial findings. Indeed, tidal volumes in each group were similar (7.7 vs. 9.5 ml/kg predicted body weight), whereas the PEEP values (10 vs. 0 cm H₂O) were meaningfully different. That PEEP was effective in recruiting lung regions in this group of patients is supported by the fact that plateau pressures were similar (18 and 16 cm H₂O) across studied groups whereas PEEP values differed by 10 cm H₂O.

Application of PEEP to the normal lungs has been recently shown to produce not only expansion of large lung regions, but also homogeneity in lung volume and ventilation distribution in small probably microscopic lung regions. It is possible that lung expansion in the protective ventilation group induced by PEEP and recruitment maneuvers could have altered the pulmonary micromechanics, reducing the magnitude of injurious physical forces, and ultimately producing better outcomes. This detectable effect of PEEP in 28 patients undergoing abdominal surgery without initial lung disease contrasts with the futility of applying high PEEP in 276 patients with ARDS studied in the National Institutes of Health-supported ALVEOLI study.

Of note, the effects of the ventilatory strategy persisted for 5 days after surgery, when resumed spontaneous breathing would be expected to provide equivalent levels of lung inflation in both groups of patients managed otherwise similarly in terms of pain control. This suggests that the ventilation strategy-associated injury during abdominal surgery would not only be characterized as loss of lung aeration but represent persistent structural changes. Possible pathological processes include small airway injury and surfactant dysfunction, which could create regional lung inflammation and injury during mechanical ventilation. Such factors could be critical for outcome in patients with comorbidities or intraoperative complications.

Limitations

As a small study focused on most clinically obtained measurements, the work by Severgnini et al. has several limitations. The magnitude of the effect observed in the study is notable and at odds with some previous observations. Treschan et al. compared the pulmonary effects of low- versus high-tidal volume mechanical ventilation in patients undergoing major abdominal surgery. They found only small adverse effects of high-tidal volume (12 cc/kg) on postoperative pulmonary function testing that occurred as late as 5 days after surgery, even though a two-fold higher sample size was included. It could be argued, based on Ariscat scores, percentage of smokers, duration of anesthesia, and end-tidal PCO₂ values provided, that the protective ventilation group in Severgnini et al. trial was composed of individuals with lower risk of postoperative respiratory failure. In addition, their technique used for pulmonary function testing is prone to bias related to insufficient blinding of the assessor. Future large outcome studies are needed to establish the impact of those factors in face of different ventilatory strategies, and pathophysiological studies are also required to better understand the mechanisms of the perioperative lung injury.

In summary, the hypothesis-generating study of Severgnini et al. calls our attention to the fact that a protective mechanical ventilation strategy during abdominal surgery may reduce postoperative respiratory morbidity. Intraoperative mechanical ventilation is entirely under the control of the anesthesiologist. We are, thus, encouraged to advance our understanding of the topic to provide a pathophysiologic-oriented mechanical ventilation customized to specific patient subsets and to ultimately improve anesthetic and surgical outcomes.

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