Mechanical Ventilation: State of the Art

Tài Pham, MD, PhD; Laurent J. Brochard, MD; and Arthur S. Slutsky, MD

Abstract

Mechanical ventilation is the most used short-term life support technique worldwide and is applied daily for a diverse spectrum of indications, from scheduled surgical procedures to acute organ failure. This state-of-the-art review provides an update on the basic physiology of respiratory mechanics, the working principles, and the main ventilatory settings, as well as the potential complications of mechanical ventilation. Specific ventilatory approaches in particular situations such as acute respiratory distress syndrome and chronic obstructive pulmonary disease are detailed along with protective ventilation in patients with normal lungs. We also highlight recent data on patient-ventilator dyssynchrony, humidified high-flow oxygen through nasal cannula, extracorporeal life support, and the weaning phase. Finally, we discuss the future of mechanical ventilation, addressing avenues for improvement.

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From the Interdepartmental Division of Critical Care Medicine, University of Toronto, Toronto, Canada; and Keenan Research Centre for Biomedical Science, Li Ka Shing Knowledge Institute, St. Michael's Hospital, Toronto, Canada.

In the 16th century, Andreas Vesalius provided what can be considered one of the first descriptions of endotracheal intubation and artificial ventilation, describing the insertion of a tube of reed into an animal's trachea and blowing air into the lungs to keep the animal alive.[1,2] Four centuries later, the iron lung[3] was the first negative-pressure ventilator successfully used in clinical practice. However, care of the patient was difficult using the iron lung because the patient's body was entirely enclosed in a metal tank. Hence, techniques that were remarkably similar to what Vesalius used were employed during the golden era of mechanical ventilation (MV), which was inaugurated during the poliomyelitis epidemics of the early 1950s. In Blegdams Hospital, Copenhagen, Denmark, Bjørn Ibsen, an anesthesiologist trained in Boston, Massachusetts, recommended tracheostomy and positive-pressure ventilation to treat patients with paralytic poliomyelitis.[4] Virtually overnight, mortality for these patients decreased from 87% to 40%.[5] Approximately 1500 medical students provided manual ventilation by squeezing rubber bags connected to endotracheal tubes for an estimated 165,000 hours.[5] For logistical reasons, these patients all received care in the same ward, essentially the first intensive care unit (ICU).

The difficulties with manual ventilation highlighted the need for mechanical devices, and both Claus Bang, a Danish physician, and Carl-Gunnar Engström, a Swedish anesthesiologist, developed the first efficient mechanical ventilators.[6] The first arterial blood gas analyzers were built shortly thereafter. The next major step in the evolution of MV was the use of positive end-expiratory pressure (PEEP), mainly encouraged by the identification of the adult (acute) respiratory distress syndrome (ARDS) by Ashbaugh et al.[7] The Servo 900A (Siemens-Eléma) released in 1972 was the first mechanical ventilator with PEEP, and the servo valves controlling flow allowed the introduction of new modes of ventilation such as pressure-controlled ventilation and pressure support ventilation (PSV).[8] Ventilators became progressively more compact, user-friendly, and electronically based than pneumatic-based ventilators and incorporated a host of modes of ventilation and advanced monitoring capabilities.[9]

A recent epidemiological study estimated that in the United States, approximately 310 persons per 100,000 adult population undergo invasive ventilation for nonsurgical indications.[10] Despite this extensive use of MV, no precise recommendations exist summarizing when to initiate MV for acute respiratory failure. The main indications are (1) airway protection for a patient with a decreased level of consciousness (eg, head trauma, stroke, drug overdose, anesthesia), (2) hypercapnic respiratory failure due to airway, chest wall, or respiratory muscle diseases, (3) hypoxemic respiratory failure, or (4) circulatory failure, in which sedation and MV can decrease the oxygen cost of breathing.

In this review, we provide an update on the principles underlying the management of MV for critically ill adult patients. We summarize the physiologic basis of MV, the interaction with the patient's physiology, and its major adverse effects and complications. We describe ventilation for specific patient groups such as those with ARDS[11] and chronic obstructive pulmonary disease (COPD), followed by an overview of the weaning phase. Finally, we briefly address the future of MV.

ARTICLE HIGHLIGHTS

- Mechanical ventilation is "a necessary evil": a lifesaving technique but with important potential complications.
- Decades of physiologic and clinical research have led to the concept of "protective ventilation" to minimize ventilation-induced lung injury but also minimize oxygen toxicity and optimize hemodynamics.
- Patient-ventilator dyssynchronies are frequent and associated with worse outcomes, but it is not clear whether they cause the poor outcomes or are a marker of severity of the underlying condition.
- Mechanical ventilation is part of a global strategy ("bundle") and not a stand-alone treatment: sedation management, etiologic treatment, physiotherapy, and prevention of muscle loss are all important considerations in the ventilated patient.
- Minimizing the length of mechanical ventilation is the best way to minimize complications: as soon as mechanical ventilation is initiated, clinicians should consider how and when to discontinue its use; and throughout its course, decide which weaning strategy is most appropriate.

BASIC PHYSIOLOGY

Understanding of the basic physiology of respiratory mechanics is necessary to optimally apply MV. Much of our progress in understanding and managing acute respiratory diseases comes from this understanding. The physiologic measurements obtained in the ventilated patient can be considered to be detailed pulmonary function testing and are available on a breath-to-breath basis.[12]

The forces at play during ventilation at any point in time are described by the equation of motion of the respiratory system. Pressure, volume, and flow changes during inspiration and expiration can be described by the simplified equation of motion of the respiratory system (Figure 1): $P_{aw} = P_0 + (R \times \text{flow}) + (Vt \times E_{RS})$, where P_{aw} = airway pressure (at the airway opening), P_0 = initial alveolar pressure, R = resistance to flow, Vt = tidal volume, and E_{RS} = elastance of the respiratory system. Each term of this equation impacts the pressure applied to the airways.

P_0 is the alveolar pressure at the beginning of inspiration, which can be atmospheric pressure (termed *zero*) or greater than atmospheric (called *positive*). In patients with airway obstruction (eg, COPD), the expiratory time may be too short to allow the respiratory system to return to its relaxation volume. This aspect of airway obstruction can lead to intrinsic PEEP or auto-PEEP, a situation in which the alveolar pressure at the end of expiration is higher than the set PEEP. The airway pressure, measured by an end-expiratory occlusion (in a passive patients), is referred to as total PEEP.

E_{RS} reflects the elastic characteristics of the respiratory system and is the inverse of compliance of the respiratory system (C_{RS}): $E_{RS} = 1/C_{RS}$. The airway pressure measured during an end-inspiratory occlusion is referred to as the plateau pressure (Pplat) and is a measure of the alveolar pressure, since the pressure drop due to airway resistance is zero at zero flow. Based on the equation of motion in the absence of flow (inspiratory pause), $C_{RS} = Vt/(Pplat - P_0)$.

Resistance (R) represents the pressure difference required to generate a given flow. The resistance can be calculated in situations of constant (square) inspiratory flow as the difference between the peak inspiratory pressure and Pplat, divided by the flow (R = [peak pressure − Pplat]/flow). The major part of the inspiratory resistance is often dominated by the resistance of the endotracheal tube.

Two simple maneuvers (end-inspiratory and end-expiratory occlusions) allow determination of the major physiological abnormalities of the respiratory system, which are characterized by high resistance (R) and elevated total PEEP in COPD (or asthma), or high E_{RS} (low C_{RS}) in ARDS (Figure 2).