Patient-Ventilator Interactions

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KEYWORDS

• Patient-ventilator interactions • Ventilator dys-synchrony • Interactive ventilator modes
• Proportional assist ventilation • Neutrally adjusted ventilatory assist

KEY POINTS

- Ventilator muscle fatigue is a reversible loss of the ability to generate force or velocity of contraction in response to increased imposed elastic and resistive loads.
- A goal of mechanical ventilation is to provide safe and effective ventilatory support without imposing additional loads from patient-ventilator dys-synchrony.
- Interactive breaths require that patient effort and the ventilator response be synchronous during all 3 phases of breath delivery lest dys-synchronies occur.
- The proper delivery of assisted or supported breaths considers all 3 phases of breath delivery and uses clinical data, ventilator graphics, and at times a trial-and-error approach to optimize patient-ventilator interactions.
- Two new modes of ventilation, proportional assist and neutrally adjusted ventilatory assist, are specifically designed to optimize patient-ventilator interactions.

INTRODUCTION

Mechanical ventilator support can be controlled entirely by the ventilator, as in the controlled mechanical ventilation of a passive patient, or can interact with patient's respiratory muscle efforts, as in assisted or supported ventilation of an actively breathing patient.[1] Controlled mechanical ventilation provides the benefit of a guaranteed minute ventilation with a predetermined ventilatory pattern but often at the cost of heavy sedation or even neuromuscular blockade to silence dys-synchronous ventilatory muscle activity. Unfortunately, silencing of these muscles contributes to a state of respiratory muscle weakness, also known as ventilator-induced diaphragm dysfunction, characterized by loss of their force generating capacity and earlier onset of fatigue.[2,3] Further, excessive sedation accompanying mechanical ventilation lengthens duration of mechanical ventilation, intensive care unit (ICU) stay, hospitalization, and possibly predisposes to delirium.[3–5]

Assisted or supported ventilation, if synchronous with the patient's ventilatory muscle efforts, shares the work of breathing, facilitates muscle recovery from respiratory fatigue or failure, and avoids excessive sedation.[6–8] For this ideal shared relationship to occur, synchrony must exist between the flow and pressure delivery of the ventilator and the patient's effort during all 3 phases of breath delivery: initiation, flow delivery, and termination. Failure to synchronize breath delivery with patient effort results in a counterproductive situation because additional loads are imposed on the ventilatory muscles. This phenomenon is described as patient-ventilator dys-synchrony (PVD). Subsequently, patient distress and discomfort are

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increased along with the need for additional sedation. This article first reviews ventilatory muscle physiology with particular focus on imposed loads in the setting of fatigue and respiratory failure. It then focuses on the various ways patient effort and ventilator flow delivery interact with basic and advanced features during patient-triggered breaths with a focus on synchronous interactions. Finally, it introduces 2 newer modes of mechanical ventilation: proportional assist ventilation (PAV) and neurally adjusted ventilatory assist (NAVA), both of which are intended to optimize this relationship.

VENTILATORY MUSCLES: NORMAL PHYSIOLOGY, FATIGUE, AND FAILURE

Ventilatory muscles are designed for a lifetime of continuous work. Physiologic and pathophysiologic demands must be overcome or respiratory failure and even death may ensue. The diaphragm, a musculotendinous sheet of skeletal muscle separating the thoracic and abdominal cavities is the most significant and well-studied of ventilatory muscles. Lung inflation occurs when a sufficient force is generated largely by the diaphragm to overcome the elastic and resistive loads imposed by the respiratory system and deliver gas to the alveoli.[9] The total pressure (P_{tot}) generated by the ventilatory muscles (P_{mus}), the mechanical ventilator (P_v), or both, must overcome the loads of respiratory system elastic recoil (P_{el}) and airway resistance (P_{res}) for a given flow (V') and volume change (ΔV). This can be expressed by the equation of motion in which C_{rs} is respiratory system compliance and R is airway resistance.[1,9]

$$P_{tot} = P_{el} + P_{res}$$

$$P_{tot} = (\Delta V/C_{rs}) + (R \times V')$$

Ventilatory muscle fatigue is a reversible loss of the ability to generate force or velocity of contraction in response to these loads.[10,11] Fatigue and failure are ultimately determined by an imbalance in muscle capabilities against the loads imposed. In critically ill patients, these capabilities are often significantly impaired by limitations in energy supply, oxygen extraction, metabolic derangements, inefficient weak muscles, and intrinsic positive end-expiratory pressure (PEEP), all further predisposing to fatigue.[11–14]

Increase in ventilatory muscle demands result primarily from the increased mechanical loads of abnormal respiratory mechanics (pressure loads) and increased ventilation needs (volume loads).[11,13,15] Mechanical loads can be described as the single values of work, the integral of pressure over change in volume, or pressure-time product (PTP), the integral of pressure over inspiratory time.[15] PTP with its reliance on pressure loads better correlates with muscle energetics, fatigue potential, and oxygen consumption. Thus, it is increasingly favored to measure the energy demands of ventilatory muscles. Further efforts have expanded on the PTP with a value known as the pressure time index (PTI) assessing pressure load (P_i) as a fraction of maximal pressure (Pi_{max}) generating capabilities along with the fraction of the total ventilatory duty cycle (T_{tot}) devoted to muscle contraction or inspiratory time (T_i). This is an even more reliable measure of energy expenditure and predictor of muscle fatigue.[16–18]

$$PTI = (P_i/Pi_{max})\ (T_i/T_{tot})$$

PTI values generally exceed 0.05 at rest and are rarely greater than 0.1 even with strenuous exercise. Values greater than 0.15 for the diaphragm predict a finite period before fatigue develops.[16]

All components of the PTI can change unfavorably in the setting of acute respiratory failure leading to ventilatory muscle fatigue and failure.[1] In patients challenged with high resistive loads, such as chronic obstructive pulmonary disease (COPD), asthma, or large airway obstructions; or with high elastic loads, such as interstitial lung disease, cardiogenic pulmonary edema, or acute respiratory distress syndrome (ARDS), the required ventilatory pressures (Pi) can be life-threatening. Additionally, pressure loads imposed from ventilator dys-synchrony may contribute to the Pi, impeding respiratory muscle recovery. A low Pi_{max} typical of neuromuscular disease, malnutrition, or shock further reduces ventilatory muscles reserves in the setting of a critical illness. High minute ventilation requirements typical of acute respiratory failure often increase tidal volume (Vt) and shorten the total ventilator cycle time (increase breathing rate) increasing T_i/T_{tot}. Central adaptive but potentially counterproductive mechanisms may influence this pattern, triggering the onset of rapid shallow breathing, which reduces P_i at the cost of increasing the ratio of physiologic dead space and possibly worsening hypercapnia.[19]

Optimal ventilator management minimizes ventilator-induced loads during mechanical ventilation while supporting recovery from the inciting unfavorable demands. The following sections focus on the role and management of ventilator-induced loads, their importance, and novel approaches to optimization.

INTERACTIVE VENTILATOR MODES AND PATIENT-VENTILATOR DYS-SYNCHRONY

Interactive breaths are described as assisted or supported. An assisted breath is patient-triggered and time or volume-cycled, whereas a