Patient and Ventilator Work of Breathing and Ventilatory Muscle Loads at Different Levels of Pressure Support Ventilation

Michael J. Banner, R.R.T., Ph.D.; Robert R. Kirby, M.D.; and Neil R. MacIntyre, M.D., F.C.C.P.

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\[ C_{\text{LT}} = \text{lung-thorax compliance}; \text{PSV} = \text{pressure support ventilation}; \text{Raw} = \text{airway resistance} \]

Pressure support ventilation (PSV) is used to unload the ventilatory muscles and to decrease the work of breathing of patients with decreased lung-thorax compliance (\( C_{\text{LT}} \)) and increased airways resistance (Raw). It also augments spontaneous breathing by offsetting the work imposed by the resistance of breathing circuits and smaller-than-optimal-size artificial airways. When the ventilator is patient-triggered “ON,” an abrupt rise in airway pressure to a preselected positive pressure limit results from a variable flow rate of gas from the ventilator. As long as the patient maintains an inspiratory effort, airway pressure is held constant at the preselected level. Gas flow from the ventilator ceases when the patient’s inspiratory flow rate demand decreases to a predetermined percentage of the initial peak mechanical inspiratory flow rate (eg, 25 percent). The ventilator is, thus, flow-cycled in the PSV mode. Once the preselected inspiratory pressure limit is set, the patient interacts with the pressure-assisted breath and retains control over inspiratory time and flow rate, expiratory time, frequency, tidal volume, and minute volume.

Because PSV augments every spontaneous breath, the work of breathing is less for patients with decreased \( C_{\text{LT}} \) and increased Raw. Under these conditions, the level of PSV may be set to either partially or totally unload the ventilatory muscles. Patient work is dependent on several factors: the level of PSV, total compliance, total resistance, and the patient’s ventilatory drive. Because the patient’s work is difficult to measure directly, this contribution to the overall work of breathing during PSV has not been clearly articulated.

Hypothetical pressure-volume (work) loops are used to illustrate the work performed by a patient with decreased lung compliance and a ventilator using PSV (Figs 1 and 2). Intrapleural pressure-volume loops referenced to baseline intrapleural pressure reflect work performed on the lungs by the patient. (Additional ventilatory work is required to expand the chest wall but for purposes of discussion, we will assume that chest wall compliance is infinite; thus, changes in intrapleural and airway pressures will reflect only lung inflation.) Under conditions of spontaneous ventilation and normal compliance, airway and intrapleural pressures, tidal volume, and intrapleural pressure-volume loops are shown (Fig 1, A). Note that the ventilatory muscles generate \(-5\) cm H$_2$O pressure to inflate the lungs (ie, the change in intrapleural pressure is from \(-5\) cm H$_2$O to \(-10\) cm H$_2$O). Inspiratory transpulmonary pressure (airway pressure minus intrapleural pressure) is approximately 10 cm H$_2$O.

An acute decrease in lung compliance requires a greater change in intrapleural pressure to exchange the same tidal volume; hence, increased loading of the ventilatory muscles and work results (compare pressure-volume loops and elastic work in Fig 1). Under these conditions, the inspiratory transpulmonary pressure increases to approximately 15 cm H$_2$O. Increased ventilatory muscle loading secondary to decreased lung compliance predisposes to muscle fatigue (failure of a muscle to generate adequate force for an applied stimulus). To partially unload the ventilatory muscles and, thus, decrease work, 5 cm H$_2$O of PSV is applied (Fig 2, A). After the initial decrease of intrapleural pressure, airway pressure also decreases slightly, the ventilator is patient-triggered “ON,” and airway pressure rises abruptly to 5 cm H$_2$O. The ventilator now is supplying part of the work of breathing. (Integration of airway pressure and tidal volume represents work performed by the ventilator.) The intrapleural pressure decrease from \(-5\) cm H$_2$O to \(-10\) cm H$_2$O is indicative of work performed by the patient, who, thus, interacts with the 5 cm H$_2$O positive-pressure-assisted breath to regulate tidal volume. Total work, thus, is performed in part by the ventilator and in part by the patient. At this level of PSV, the inspiratory transpulmonary pressure of approximately 15 cm H$_2$O (Fig 2, A) requires less patient work than was required previously (Fig 1, B). Patient work now is the same as it was with normal compliance (Fig 1, A). Thus, PSV, which combines power from the ventilator and the patient’s effort, is a hybrid form of ventilation that may reduce the patient’s workload to more tolerable.
SPONTANEOUS VENTILATION

![Graph showing spontaneous ventilation with normal compliance and decreased compliance]

**Figure 1.** Work exerted by the patient to inflate the lungs during spontaneous inhalation (I) and exhalation (E) under conditions of normal and decreased lung compliance (for purposes of discussion assume that chest wall compliance is infinite). In A, when compliance is normal, the flow resistive work (area circumscribed within the lower half intrapleural pressure-volume loop) and elastic work (hatched-in area) are indicated. A greater change in intrapleural pressure and work results when the same tidal volume is exchanged under conditions of decreased lung compliance as in B (compare elastic work).

levels.

Alternatively, the level of PSV may be set high enough to totally unload the ventilatory muscles, provide essentially all the work of breathing, and, thus, allow the patient to rest. High levels of PSV have been defined as that pressure sufficient to provide a tidal volume of 10 to 12 ml/kg (ie, PSV_{max}). At such levels, the ventilator performs virtually all the work of breathing. A negligible amount of work is performed by the patient to trigger the ventilator "ON." In Figure 2, B, PSV_{max} is 10 cm H₂O. After the ventilator is patient-triggered "ON," airway pressure rises abruptly to 10 cm H₂O, and intrapleural pressure stays constant at -5 cm H₂O. Thus, an inspiratory transpulmonary pressure of 15 cm H₂O is generated, producing the same tidal volume. The patient is passive, performing no work (no change in intrapleural pressure) while the ventilator actively inflates the lungs and provides all the work. Used in this manner, PSV is similar to conventional assisted positive-pressure ventilation, but with a pressure limit.

The level of PSV may be adjusted to provide an optimal muscle load. However, in clinical practice, this setting may be difficult to determine. The proper level of muscle unloading is that which encourages reconditioning and prevention of atrophy while avoiding the development of fatigue. Respiratory rate has been advocated as a method to assess ventilatory muscle load, ie, a slow rate suggests that the patient is experiencing a subfatiguing load (15 to 25 breaths/min), whereas a higher rate (>30 breaths/min) is an inference of an intolerable load on the ventilatory muscles. The breathing pattern, ie, the presence of abdominal paradox and the use of accessory muscles are also indicative of increased ventilatory muscle loading and the onset of fatigue.

In one carefully done clinical study, an optimal muscle load for patients with ventilatory failure was imposed by adjusting the levels of PSV from 10 to 20 cm H₂O. PSV was applied to spontaneously breathing patients to unload the ventilatory muscles and to prevent diaphragmatic fatigue by diminishing work of breathing and oxygen consumption. An optimal level of PSV was defined as that which maintained maximal diaphragmatic electrical activity without fatigue. Ventilatory muscle fatigue is associated with a frequency shift in the electromyographic power spectrum of the diaphragm from higher to lower frequency. Thus, the lowest PSV level at which no reduction in the high/low ratio power spectrum occurred was judged to be

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Patient and Ventilator Work of Breathing (Bannac, Kirby, MacIntyre)
Figure 2. Application of PSV under conditions of decreased lung compliance to unload the ventilatory muscles and decrease patient work. In A, a PSV level of 5 cm H_2O is applied and the work exerted by the patient to inflate the lungs is decreased (compare with Fig 1, B). Work is also provided by the ventilator as evidenced by the area of the airway pressure-volume loop (I = inhalation; E = exhalation). Under this condition, work is performed in part by the patient and in part by the ventilator. Alternatively, all work may be provided by the ventilator by increasing the level of PSV to higher levels, e.g., 10 cm H_2O as in B. At this setting, the patient is relatively passive, intrapleural pressure does not change, and essentially no work is performed by the patient (see text).

Another possible approach to provide appropriate ventilatory muscle loads is to titrate PSV while monitoring intrapleural (esophageal) pressure.* The greater the decrease in intrapleural pressure during inhalation, the more work performed by the patient. As the level of PSV is increased (ventilator work), less of a decrease in intrapleural pressure (patient work) should be seen. At PSV_{max}, intrapleural pressure may not change, or may increase, during inhalation. The ventilatory muscles are relieved of virtually all the work of lung inflation, leaving only the much smaller load associated with inflation of the chest wall.∗

Just as stroke volume of the left ventricle increases as afterload (systemic vascular resistance) decreases, the output of the ventilatory pump depends on its impedance (total compliance and total resistance) for a given level of pressure developed.10 When used appropriately, PSV represents an approach to unload the ventilatory pump and reduce the work of breathing.

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