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PERSPECTIVE

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Pressure support, patient effort and tidal volume: a conceptual model for a non linear interaction

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Abstract

Pressure support ventilation (PSV) is a form of assisted ventilation which has become frequently used, with the aim of partially unloading the patient's inspiratory muscles. Both under- and over-assistance should be avoided to target a lung- and diaphragm- protective ventilation. Herein, we propose a conceptual model, supported by actual data, to describe how patient and ventilator share the generation of tidal volume (Vt) in PSV and how respiratory system compliance (Crs) affects this interaction. We describe the presence of a patient-specific range of PSV levels, within which the inspiratory effort (Pmus) is modulated, keeping Vt relatively steady on a desired value (Vt_{target}). This range of assistance may be considered the "adequate PSV assistance" required by the patient, while higher and lower levels may result in over- and under-assistance respectively. As we also show, the determinants of over- and under-assistance borders depend on the combination of Crs and the inspiratory effort which the patient is able to sustain over a period of time. These concepts can be applied at the bedside to understand if the level of assistance is adequate to patient's demand, focusing on the variation of relevant parameters (Vt, Pmus and pressure-muscle-index) as patient reaction to a change in the level of assistance.

Keywords Acute respiratory failure, Invasive mechanical ventilation, Pressure support ventilation, Respiratory mechanics, Inspiratory effort

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Background

Pressure support ventilation (PSV) is a form of partially assisted ventilation which has become frequently used in the acute phase of critical illness [1]. In PSV, patient and ventilator share the generation of pressure leading to tidal volume (Vt), which, multiplied by respiratory rate (RR), results in minute ventilation (MV).

Pressure support (PS) level is often set with the aim of partially unloading the patient's inspiratory muscles, and data from literature suggest that both under- and over-assistance can occur and should be avoided. In patients with acute respiratory failure, under-assistance could result in vigorous inspiratory efforts, which may induce negative alveolar pressure [2], patient self-inflicted lung injury (P-SILI), high oxygen consumption by the respiratory muscles and diaphragm myotrauma [3]. Conversely, over-assistance will result in low respiratory drive and minimal inspiratory effort, facilitating the development of diaphragm atrophy, thus increasing the duration of mechanical ventilation [4]. Over-assistance is also associated with ineffective efforts, as well as resulting in apneas and impaired sleep [5, 6]. Additionally, over-assistance can lead to high Vt and driving pressure (ΔP) of the respiratory system—i.e. the distending pressure during each breath, measured as the difference between plateau pressure during an inspiratory occlusion (Pplat) and positive end-expiratory pressure (PEEP)—which is associated with worse outcome in patients with acute respiratory distress syndrome [7].

Recently, in a physiological study, we have shown that starting from a clinical setting, there is a range of assistance level within which the patient reacts to a decrease in PS by increasing inspiratory effort thus keeping Vt and ΔP relatively steady on what seems to be a desired value by the patient, limiting the clinician's ability to modulate it [8]. This happened while RR and, hence MV remained rather constant. Interestingly, the behaviour of the patient is different when PS is increased above a certain level and over-assistance occurs. These results have been described during proportional modes of ventilation over wider range of settings [9] and PSV has been criticized for putting the patient at higher risk of asynchrony [10]. Both neurally adjusted ventilator assistance (NAVA) and proportional assist ventilation (PAV+) ensure negligible changes in Vt and RR across wide levels of ventilatory assistance [10–13]. These findings, taken together, suggest that in PSV it is also possible to find a range of assistance allowing a patient's individual intrinsic ventilatory pattern with desired values of Vt (Vt_{target}) and RR to keep a certain MV (regulated, in turn by a target PaCO2 and pH).

In this editorial we propose a conceptual model, supported by data, to describe how the patient and the ventilator share the generation of Vt in PSV and how respiratory system compliance (Crs) affects this interaction. Understanding this behaviour may help clinicians to focus on relevant monitoring parameters and to better adjust PSV.

How do patient and ventilator share the generation of tidal volume in pressure support ventilation?

Figure 1 schematically represents a conceptual model describing the generation of Vt as a function of PS assuming a patient's desired ventilatory pattern including what we will refer to as a Vt_{target} [8]. For simplicity, we assume airway resistance as constant and within normal rage

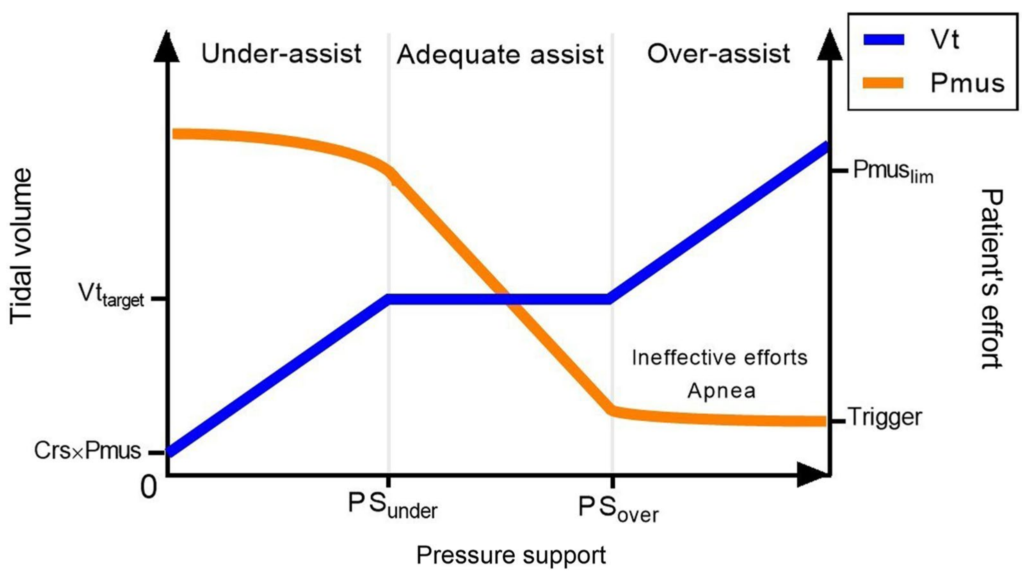

Fig. 1 A conceptual model describing the generation of tidal volume (Vt) as a function of assistance in pressure support ventilation. As shown, the pattern of interaction comprises three phases—under-assistance, adequate assistance and over-assistance—which may or may not all be evident in a specific patient, depending on the range of PS applied and her/his capability of producing inspiratory effort (Pmus). The latter is proportionally modulated by the patient in the range of adequate assistance from the ventilator–included in between the thresholds of under-assistance (PS_{under}) and over-assistance (PS_{over}) to achieve a target Vt (Vt_{target}). The patient will compensate any change in the level of assistance by an opposite change of Pmus: under-assistance (incapability of keeping Vt_{target}) will happen whenever the patient is required to exert a Pmus greater than what is sustainable over time ($Pmus_{lim}$). When PS is zeroed Vt will depend on the product of Crs and Pmus; on the contrary when PS_{over} is overcome and inspiratory effort almost zeroed except from the trigger activity (i.e. over-assistance), Vt depends solely on PS and Crs

(< 10 cmH2O/L/sec) [14]. As shown, the pattern of interaction comprises three phases: under-assistance, adequate assistance and over-assistance. In a specific patient not all three phases may be present, depending on her/his capability of producing muscle pressure (Pmus, i.e. strength and endurance), respiratory mechanics and the range of PS applied.

Adequate PSV assistance

In this range of assistance, included between the thresholds of under-assistance (PS_{under}) and over-assistance (PS_{over}), the patient can modulate her/his own Pmus, adapting to the PS set on the mechanical ventilator to achieve a desired Vt_{target}. Patient-ventilator interaction will resemble what happens in proportional modes of ventilation: the patient will compensate any change in the level of assistance by an opposite change of Pmus. Vt (and hence static ΔP) will remain constant, while only the relative contribution of patient and ventilator will vary.

Over-assistance

When the level of assistance is increased above PS_{over}, Pmus decreases and becomes minimal, (just sufficient to trigger the ventilator) and the patient becomes "quasi-passive" for most of the insufflation time (i.e. over-assisted) [8, 9]. Meanwhile, the respiratory drive is low, patient's inspiratory time is short [9] and patient's RR decreases, frequently below 18 breaths/minute in the attempt to keep MV (and hence CO_2 level) under control [15]. Under this setting, the patient's respiratory mechanics becomes the only determinant of Vt, which increases linearly with PS. This phase is characterized by the fact that pressure from the ventilator alone (PS level) is sufficient, without any contribution from Pmus, to generate the Vt_{target} and above: hence PS_{over} will be proportional to the ratio of Vt_{target} to the compliance of the respiratory system (Crs). The slope of the Vt increase in the segment of over-assistance will be directly proportional to patient's Crs, as it would happen in a classical pressure-controlled ventilation. The pressure-muscle-index (PMI) – an index measuring the elastic effort to generate Vt, can easily be obtained through an end-inspiratory occlusion [16, 17]. The over-assistance phase is characterized by a value of PMI equal-to or lower-than zero.

Under-assistance

On the other end of the "adequate assistance", the patient might not be able to generate enough Pmus to cope with the reduction in assistance below PS_{under}, and Vt progressively decreases while RR increases. The level of PS at which under-assistance occurs depends on the degree of imbalance between patient's ventilatory demand and capacity. Among the determinants of patient's ventilatory demand, are respiratory mechanics (i.e., Crs and airway resistance), intrinsic positive end-expiratory pressure, dead space and ventilation-perfusion mismatch (i.e. amount of shunt) and metabolic rate. On the other hand, patient's ventilatory capacity may be defined – using a combination of ventilatory strength and endurance—as the limit of effort which the patient is able to sustain over time under "operative" conditions before fatigue occurs ($Pmus_{lim}$). This value is classically described as the 40% of the maximal inspiratory pressure (or negative inspiratory force) [18]. Interestingly, Crs plays a key role in the development of under-assistance, since, for the same ventilatory capacity ($Pmus_{lim}$) a patient with a preserved Crs will develop under-assistance at lower levels of PS than a patient with a lower Crs who will require higher PS to be adequately assisted.

Typical scenarios of under-assistance would be weaning failure in which impaired Crs and muscle weakness concur [19] or pure muscle weakness from other neuromuscular disease or residual paralysis.

Recognizing the patterns of interaction at the bedside

Not every patient in PSV manifests all these patterns of interaction with the ventilator, according to the demand/capacity balance and to the range of PS tested. However, these patterns may be unveiled by decreasing (or increasing) the level of assistance and observing the evolution of the patient's ventilatory pattern, which normally occurs within a few minutes, as also noticed in the rapid changes of Rapid Shallow Breathing Index during weaning trials [20]. A nearly stable Vt over a certain range of PS likely indicates that the patient is adequately assisted and can modulate Pmus to achieve the Vt_{target}. Of note the patient will compensate for a decrease or increase in PS with a change in Pmus so that total static ΔP (i.e. the difference between plateau pressure and positive end-expiratory pressure, measurable during an inspiratory hold in PSV) remains constant. It might also be possible to describe the relative contribution of patient and ventilator to the generation of the Vt_{target} (and the correspondent static ΔP) by opportunely modifying a work shifting index [21] as the ratio of the elastic pressure by patient (PMI) and ventilator (PS). Both in the under- and over-assistance segment a decrease of PS will lead to a decrease of Vt. The two conditions are easily distinguishable based on the absence of PMI (over-assistance phase) and other clinical signs of under-assistance (e.g. a rise in RR and P0.1 on the ventilator screen, recruitment of accessory inspiratory muscles, CO_2 retention and diaphoresis). Currently it is unknown which level of PSV, within the "adequate" window, would be more effective to promoting lung and diaphragm protection and healing. It appears that in

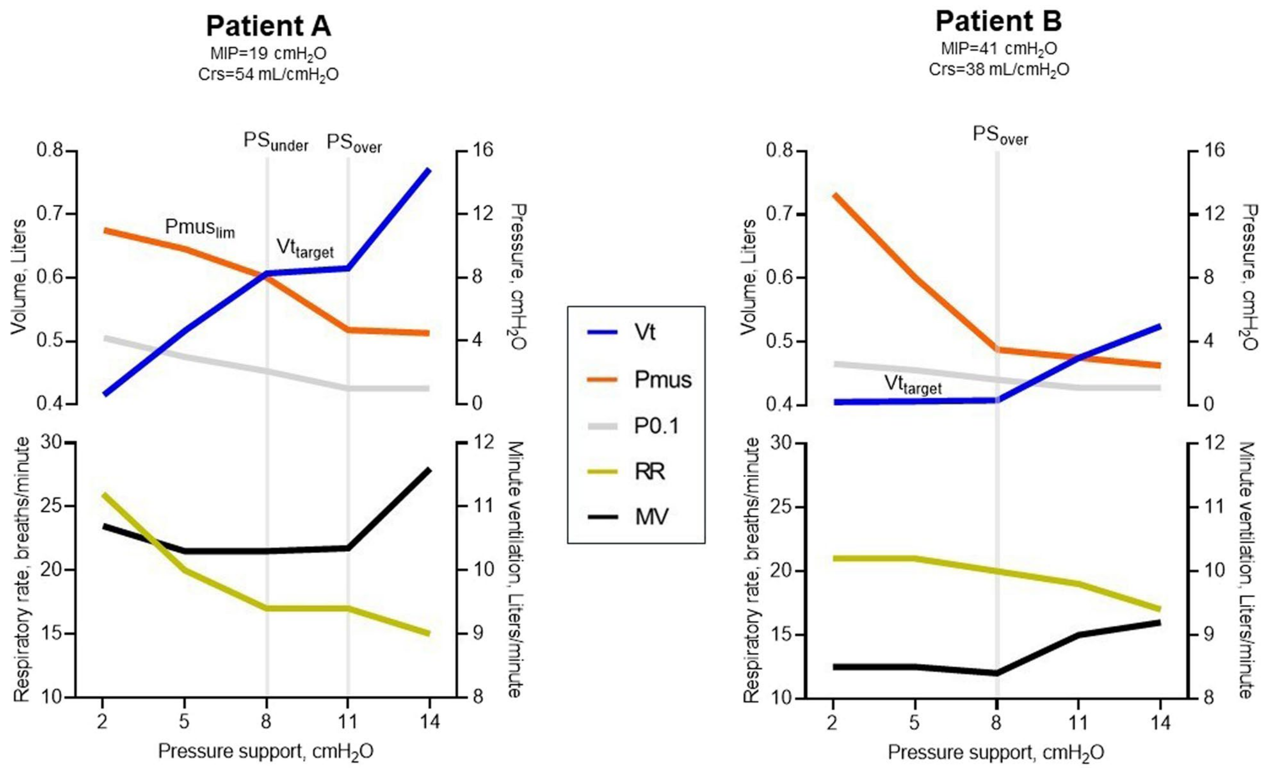

Fig. 2 Two representative patients recovering from acute hypoxemic respiratory failure tested over a range of pressure support equal to 12 cmH_2O, from a recent study [8]. Patient A (left) gets under-assisted (incapable of keeping Vt_{target}) when required to exert a Pmus greater than what is sustainable over time ($Pmus_{lim}$) (i.e. greater than 40% of the maximal inspiratory pressure, MIP). Accordingly, P0.1 and respiratory rate (RR) increase keeping minute ventilation (MV). Conversely, patient B (right), whose strength and endurance of the respiratory muscles are preserved, can keep Vt_{target} over time (i.e. Pmus less than 40% of MIP with P0.1 and RR constant) even when PS is nearly zeroed. Both patients are at risk for over-assistance whenever PS is raised above the level needed to get Vt_{target} given their Crs (PS_{over}); however, the increase of Vt over Vt_{target} is limited by lower Crs (Patient B). In this condition, even decreasing RR, MV raises and both patients get hyperventilated. Blood gas analysis at baseline: Patient A (pH 7.47, $PaCO_2$ 39 mmHg, HCO_3- 28 mmol/L, PaO_2 77 mmHg, FiO_2 0.5); Patient B (pH 7.51, $PaCO_2$ 45 mmHg, HCO_3- 35 mmol/L, PaO_2 116 mmHg, FiO_2 0.4)

the adequate window, while Vt and ΔP may be safe, no data are available regarding the ideal amount of patient effort which would lead to optimal lung and diaphragm protection.

Figure 2 shows how specific values of Crs and $Pmus_{lim}$ modulate Vt in actual patients recovering from acute hypoxemic respiratory failure tested over a wide range of assistance (12 cmH_2O, with PS ranging from 2 to 14 cmH_2O) from a recent study [8].

This proposed conceptual model has limitations. First, the reasoning applies only to PSV (and possibly Pressure Assist-Control Ventilation with spontaneous breathing), which is anyway a most frequently used mode. Second, the role of airway resistance is not considered into the conceptual model proposed due to the complex interaction with the expiratory cycling criterion. However, significant variations over time or extreme values of airway resistance are less common in clinical practice than alterations in Crs. Third, the determinants of this patient's specific Vt_{target} remain unknown. Further research is needed to address the impact of changes in the metabolic hyperbola or in conditions of neuromuscular uncoupling, when actual ventilation cannot cope the brain demand [22].

In summary, we present a conceptual model for a non-linear behaviour of the interaction between patient and ventilator during PSV, which might be applied at the bedside to understand if the level of assistance is adequate to patient's demand.

Abbreviations

Crs	Respiratory system compliance
ΔP	Static driving pressure of the respiratory system
MIP	Maximal inspiartory pressure
MV	Minute ventilation
PMI	Pressure-muscle-index
Pmus	Inspiratory effort
$Pmus_{lim}$	Limit of effort which the patient is able to sustain over time
PS_{over}	Pressure support threshold for over-assistance
PS_{under}	Pressure support threshold for under-assistance
PSV	Pressure support ventilation

RR	Respiratory rate
Vt	Tidal volume
Vt_{target}	Patient's desired tidal volume

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Author contributions
G.B. conceived the study and figures and drafted the manuscript. M.D. drafted the manuscript text, conceived and prepared the figures. L.B. and G.F. substantively revised the manuscript with critical inputs.

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Availability of data and materials
Data is provided within the manuscript.

Declarations

Ethics approval and consent to participate
For data shown from [8], the institutional ethics committee (Azienda Socio Sanitaria Territoriale Monza, Italy) approved the study on 11/05/2020 (number 3269) according to the ethical principles of the Declaration of Helsinki and to the good clinical practice of the Ministero della Sanità (15/07/1997).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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