Design Features of Modern Mechanical Ventilators

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KEYWORDS

• Mechanical ventilation • Modes of ventilation • Patient–ventilator interactions
• Ventilator-induced lung injury • Closed-loop control

KEY POINTS

- Mechanical ventilator design features can be challenging to understand because of imprecise and confusing terminology.
- Mechanical ventilator design features have evolved, reflecting new awareness of ventilator-induced lung injury and patient–ventilator synchrony.
- As newer designs are introduced, clinical adoption will require outcome data to support their use.

INTRODUCTION

Positive pressure mechanical ventilators have evolved over the last several decades from simple high pressure gas regulators to sophisticated microprocessor systems controlling many aspects of breath delivery, inspiratory/expiratory timing, and expiratory pressure.[1] Terminology describing these operations has also evolved and often has become confusing. Some of this confusion is a consequence of manufacturer's trade names describing a common design feature in multiple proprietary terms. Another problem has been that simple older terminology is unable to fully describe many of the advances that have occurred. Two examples are the mandatory versus spontaneous breath classification and the concepts underlying controlled versus assisted ventilation. The terms mandatory versus spontaneous originally meant machine alone versus patient alone. Today things are blurred as patients can trigger breaths (spontaneous feature) with substantial ventilator support supplied (mandatory feature). The term control originally meant parameters that the ventilator manipulated (volume or pressure controlled). Now the term is often used to distinguish a machine-triggered breath from a patient-triggered breath (assist control). This article will generally avoid the mandatory/spontaneous terminology and use the terms assist and control to mean a patient- and machine-triggered breath.

BASIC CONCEPTS

Breath Delivery Algorithms

Although the engineering principles underlying positive pressure breath delivery can be complicated,[2,3] from a clinical perspective, a mechanical breath can be classified in terms of what initiates the breath (trigger variable), what controls gas delivery during the breath (target or limit variable), and what terminates the breath (cycle variable).[4]

In general, breaths can be initiated (triggered) by patient effort (assisted breaths) or by the machine timer (controlled breaths). Effort sensors are generally either pressure or flow sensors and are defined by their sensitivity/responsiveness. Target or limit variables are generally either a set flow or a set inspiratory pressure. With flow

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targeting, the ventilator adjusts pressure to maintain a clinician-determined flow magnitude and pattern (sine, square, accelerating, decelerating); with pressure targeting, the ventilator adjusts flow to maintain a clinician-determined inspiratory pressure. Modern systems also usually allow adjustment of the rate of pressure rise in pressure targeting. Cycle variables are generally a set volume, a set inspiratory time, or a set reduction in inspiratory flow as the lung fills. This flow-cycling criterion is manufacturer-specific (eg, 25%–35% of peak flow), or it can be clinician-adjusted on many newer machines. A secondary cycling mechanism may be present on some devices if inspiratory time exceeds a certain fraction (eg, 80%) of a set total cycle time. Breaths can also be cycled off if pressure limits are exceeded.

With this approach, breath delivery algorithms from modern mechanical ventilators can be broken into 5 basic breaths: volume control (VC), volume assist (VA), pressure control (PC), pressure assist (PA), and pressure support (PS) (**Fig. 1**).[4]

Basic Modes of Ventilatory Support

The availability and delivery logic of different breath types define the mode of mechanical ventilatory support. The mode controller is an electronic, pneumatic, or microprocessor-based system designed to provide the proper combination of breaths according to set algorithms and feedback data (conditional variables). The 5 most common modes are volume assist control (VACV), pressure assist control (PACV), volume synchronized intermittent mandatory ventilation (V-SIMV), pressure synchronized intermittent mandatory ventilation (P-SIMV), and stand-alone pressure support ventilation (PSV) (**Table 1**).[4] Examples of proprietary names for these basic modes are given in **Table 2**. Depending upon the set control breath rate, VACV and PACV can range from totally machine controlled to totally patient assisted. V-SIMV and P-SIMV can provide VA and VC or PA and PC breaths respectively interspersed with either unsupported or pressure supported (PS) breaths. Data from international surveys[5] indicate that the most commonly used mode worldwide is volume assist control, with pressure assist control a distant second. IMV modes have been steadily decreasing in use, while stand-alone PSV modes have been increasing in use.

Choice of mode depends upon the clinical goals and an understanding of ventilator breath design features.[4] Mandatory breath rates are set

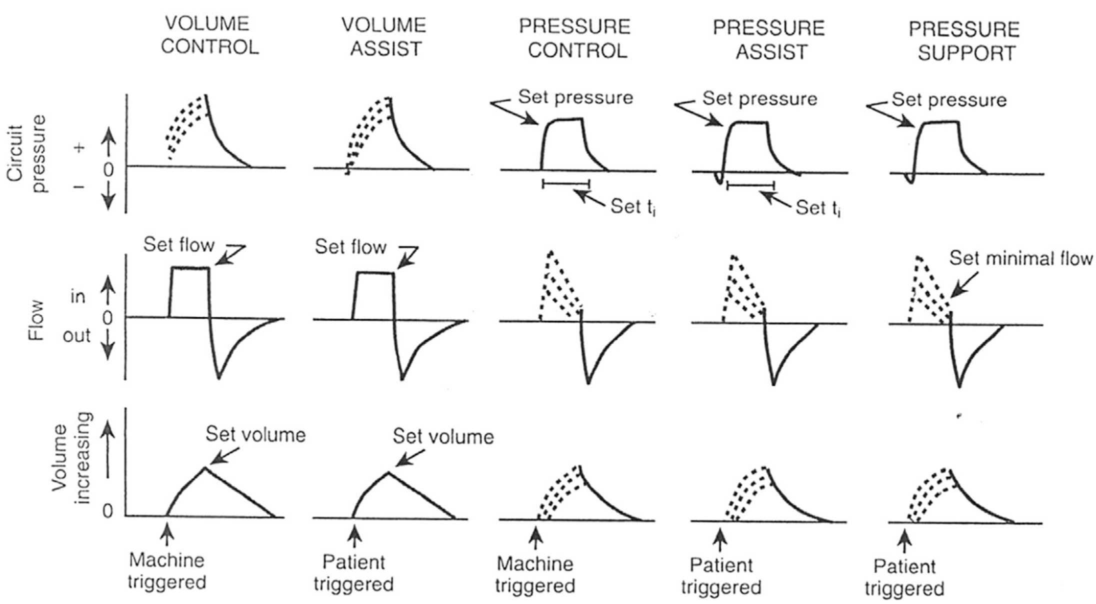

Fig. 1. The 5 basic breaths defined by trigger, target, and cycle variables. Depicted are airway pressure, flow, and volume tracings over time. Solid lines reflect set changes; dotted lines reflect variable changes from effort or mechanics changes. The five basic breaths. Volume control is machine triggered, flow targeted, and volume cycled. Volume assist is patient triggered, flow targeted, and volume cycled. Pressure control is machine triggered, pressure targeted, and time cycled. Pressure assist is patient triggered, pressure targeted, and time cycled. Pressure support is patient triggered, pressure targeted, and flow cycled. (*From* MacIntyre NR. Principles of mechanical ventilation. In: Broaddus VC, editor. Murray and Nadel's textbook of respiratory medicine, 6th edition. New York: Elsevier; 2016. p. 1762; with permission.)

Table 1
The 5 basic modes defined by the breaths available

Mode	VC	VA	PC	PA	PS	Sp
	Breath Types Available					
Volume assist control	X	X	–	–	–	–
Pressure assist control	–	–	X	X	–	–
Volume SIMV	X	X	–	–	X	X
Pressure SIMV	–	–	X	X	X	X
Pressure support	–	–	–	–	X	–

The breaths are the 5 breaths depicted in Fig. 1 plus an unassisted spontaneous breath (Sp). Note that the clinician-set breath rate can result in VACV and PACV being totally controlled ventilation (high set rate), virtually totally assisted ventilation (very low or absent set rate), or assist control ventilation (intermediate set rate).

Abbreviations: PA, pressure assist; PC, pressure control; PS, pressure support; VA, volume assist; VC, volume control.

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depending upon the reliability of the patient's effort to supply an appropriate number of breaths. Pressure versus flow/volume targeting balances the synchrony enhancement of pressure targeting against the volume guarantee of flow/volume targeting.[6] When using patient-triggered pressure-targeted breaths, cycling on time (PA breaths) versus flow (PS breaths) depends on patient comfort/synchrony.

Airway pressure release ventilation (APRV) is often touted as a new mode but in fact is simply a variant of P-SIMV, in which the inspiratory time is set longer than the expiratory time. Patient efforts thus occur during the inflation phase and can produce additional unassisted or PS breaths. A point of confusion exists in setting up APRV in that dedicated APRV modes on most devices have the set inspiratory pressure referenced to atmospheric pressure rather than the set expiratory pressure. Proponents of APRV argue that the long I:E ratio raises mean Paw without additional set positive end expiratory pressure (PEEP) or tidal volume (VT) and that the spontaneous efforts during the inflation phase enhance gas mixing and cardiac filling.[7,8] Examples of proprietary names are given in Table 2.

Positive End Expiratory Pressure

PEEP can be generated in 2 basic ways: applied or intrinsic. Applied PEEP is clinician set and is usually provided by valving systems in the expiratory limb. Modern ventilators also can adjust circuit flow during exhalation to assure PEEP maintenance in the setting of circuit leaks. Intrinsic PEEP develops in the setting of high minute ventilation, short expiratory times, and high airway resistance/high compliance lung units. Importantly, applied PEEP distributes evenly throughout the lung while intrinsic PEEP is highest in high resistance/high compliance lung units and lowest in low compliance/low resistance units.[9] Conventional approaches to PEEP generally rely on set PEEP and avoidance of intrinsic PEEP. However, proponents of APRV argue for the use of intrinsic PEEP to maximize expiratory flow and minimize expiratory time.

FEEDBACK CONTROL FEATURES

As mechanical ventilators have evolved, so has the capability for microprocessor-based systems to monitor conditional variables and use this information to automatically adjust timing, flow, pressure, and even Fio_2 (feedback control). An early example was the use of a patient effort sensor (conditional variable) to adjust the number of mechanical

Table 2
Examples of proprietary names for the 5 basic modes and 2 feedback features

	PB840	Avea/Vela	Servo I	G5	Evita V500
VACV	A/C (VC)	VAC	VC	(S) CMV	VC-AC
PACV	A/C (PC)	PAC	PC	P-CMV	PC-AC
VSIMV	SIMV (VC)	VSIMV	SIMV (VC)	SIMV	VC-SIMV
PSIMV	SIMV (PC)	PSIMV	SIMV (PC)	P-SIMV	PC-SIMV
PSV	SPONT (PS)	CPAP/PSV	PS/CPAP	SPONT	PC-PSV
PRVC	VC+	PRVC	PRVC	APV	VC-AC (Autoflow) PC-AC (VG)
APRV	BiLevel	BiPhasic	Bi-Vent	APRV	PC-APRV

Courtesy of Medtronics PB840, Carlsbad (CA); CareFusion Avea/Vela, Yorba Linda (CA); Maquet Servo I, Solna, Sweden; Hamilton G5, Reno (NV); Draeger Evita, Telford (PA).

breaths provided during either assist control modes or SIMV.[10] A variation on this breath rate feedback mechanism was mandatory (or minimum) minute ventilation, which used minute ventilation to adjust the number of positive pressure breaths delivered.[11] Currently available systems to partially close the loop will be described.[12,13]

Inspiratory Pressure and Flow Adjustments Based on Artificial Airway Geometry

The endotracheal tube (ETT) imposes a significant inspiratory resistance on a spontaneously breathing patient.[14] This imposed load can have an impact on flow synchrony during interactive assisted/supported breaths and can make it difficult to assess potential for ventilator withdrawal during periods of unassisted/unsupported breathing.

Low-level (eg, 5–8 cmH_2O) PS has been proposed as a way of eliminating the ETT resistive load.[15] However, the PS algorithm supplies a constant inspiratory pressure, which, because of the high fixed resistance of the ETT, tends to undercompensate the load at the beginning of the breath. Patient muscle unloading thus is uneven and may be suboptimal.

To better address this loading pattern, many ventilators have the capability to calculate the ETT resistance properties based on clinician input of ETT length and diameter. The ventilator incorporates this calculation with measurements of instantaneous flow to apply pressure proportional to resistance throughout the total respiratory cycle.[16,17] It must be recognized that the ETT compensation strategy is based on the input geometry of the artificial airway and cannot account for changes in tube characteristics induced by kinks or partial occlusions or the relationship of the tube opening against the tracheal wall.

Feedback Control of Combination Pressure- and Flow-Targeted Breaths

Over the last 2 decades, several engineering innovations have attempted to combine the flow synchrony advantages of pressure-targeted breaths with the volume guarantee features of flow/volume targeted breaths. The most common approach uses standard pressure-targeted breaths with the ventilator adjusting the pressure target according to a clinician-set V_T.[18] When these breaths are exclusively supplied with time cycling, the mode is commonly referred to as pressure-regulated volume control (PRVC) but has a number of proprietary names (see **Table 2**). When these breaths are supplied exclusively with flow cycling, the mode is commonly referred to as volume support (VS). Some ventilators will switch between these 2 breath types depending on the number of patient efforts. The maximum pressure change from breath to breath on most systems generally is limited to a few centimeters of water to prevent large swings in pressure and volume.

These modes have been assessed clinically in 2 settings. First, in severe parenchymal lung injury (eg, ARDS [acute respiratory distress syndrome]), PRVC has been used as a way to provide more synchronous pressure-targeted breaths while assuring that safe tidal volume delivery is maintained. One study demonstrated that this was possible, although a minority of patients had significant periods of time with excess VT.[19] Second, VS has been touted as a means to automatically wean patients, the theory being that as patients recover, they will make stronger inspiratory efforts, and VS will automatically reduce inspiratory pressure. Conversely, inspiratory pressure would increase if patient effort diminished or respiratory system mechanics worsened. Whether this approach is superior to routine spontaneous breathing trials (SBTs) is unclear.

One must also be cautious in using VS in this weaning setting, because if the clinician set volume is excessive for patient demand, a patient may not attempt to take over the work of breathing for that volume, and thus support reduction and weaning may not progress. In addition, if the pressure level increases in an attempt to maintain an inappropriately high set tidal volume in the patient with airflow obstruction, intrinsic PEEP (PEEPi) may result. VS may also inappropriately lower inspiratory pressure in a patient with excessive flow demands induced by pain, anxiety, or acidosis.[20]

Enhanced Feedback Control of Combination Pressure- and Flow-Targeted Breaths

Airway occlusion pressure ($P_{0.1}$),[21] oxygen saturation (Sp_{O_2}),[22] and end-tidal CO_2 concentrations[23,24] have been incorporated into the pressure flow/volume hybrid breaths described. The one system that is commercially available uses end-tidal CO_2 and respiratory rate along with the tidal volume to adjust the applied inspiratory pressure (SmartCare, Dragerwerk AG, Lubeck, Germany).[24] The system attempts to find an inspiratory pressure that maintains the respiratory rate and tidal volume in a clinician-set comfort zone. The end-tidal CO_2 serves as a backup signal to assure adequate ventilation is occurring. Inspiratory pressure is reduced to as low a level as possible within these boundaries; then the clinician should be alerted to perform an SBT when this pressure reaches 9 cm H_2O. Although clinical trials have failed to consistently show an advantage to this approach,[25,26] an automated system that is just as good as clinicians could have applications in settings with rapidly recovering patients or low availability of clinicians to make frequent assessments.

Feedback Control of Ventilator Breath Delivery Based on Respiratory System Mechanics

A novel approach to automated feedback control of ventilator support controls a pressure-targeted breath using a V_T, frequency and inspiratory-to-expiratory (I:E) ratio algorithm based on respiratory system mechanics. Known as adaptive lung ventilation or adaptive support ventilation (ASV),[27–30] the system calculates respiratory system mechanics using several controlled test breaths. It then uses a minimal work calculation[31] to set the frequency–tidal volume pattern that minimizes the combined resistance and compliance components of work. The ASV algorithm then attempts to minimize intrinsic PEEP by measuring the expiratory time constants (RCe = resistance × compliance) and providing an expiratory time of at least 3 RCe.

With ASV, clinicians must set the desired minute ventilation and the proportion of that minute ventilation that the machine is to supply. Ideal body weight also can be used to calculate the desired minute ventilation based on metabolic demands and predicted dead space. Clinicians also must set the PEEP and FI_{O_2} in the United States (described later in this article). When spontaneous efforts occur with ASV, the algorithm responds with fewer mandatory breaths and adjusts inspiratory pressure according to the minimal work tidal volume considerations listed previously. ASV has been shown to perform as designed, although in healthier lungs, tidal volumes may exceed lung-protective guidelines.[30] Meaningful outcome studies do not exist.

Feedback Systems Controlling Positive End-Expiratory Pressure and FIO_2

On a mechanical ventilator, an FIO_2 controller conceptually could be coupled to a feedback controller of PEEP to meet oxygenation and mechanical goals (ie, PaO_2 or SpO_2 targets balanced against lung compliance or plateau pressure). One system approved outside the United States incorporates the PEEP-FiO_2 table used by the National Institutes of Health (NIH) ARDS Network study.[32] With this algorithm, PEEP and FIO_2 combinations are guided by a PaO_2 target range of 55 to 80 mm Hg and a plateau pressure limit of 30 to 35 cm H_2O. Although this table proved safe and effective in ARDS Network trials, whether an automated system using it will improve outcomes has yet to be demonstrated.

MODES DRIVEN BY NOVEL SENSORS OF PATIENT EFFORT

Two new modes have been introduced over the last 2 decades that use unique feedback control based on patient effort to control positive pressure breath delivery.[13,33] The first is proportional assist ventilation (PAV), an approach that applies a clinician set pressure and flow gain on patient-generated flow and volume.[34] PAV uses intermittent controlled test breaths to calculate resistance and compliance. It can then use measured flow and volume to calculate both resistive and elastic work. The clinician is required to set a desired proportion of the total work that should be performed by the ventilator. The ventilator then measures the patient flow and volume demand with each breath and adds both pressure and flow to provide the selected proportion of the breathing work. PAV has been compared with power steering on an automobile, an analogy that has much truth. Like PAV, power steering reduces the work to turn the wheels but does not automatically steer the car; the driver must control the car's ultimate direction just as the patient ultimately must control the magnitude of the breath and the timing of the breathing pattern.

Because PAV requires sensors in the ventilator circuitry to measure patient effort, it is susceptible to the same sensor performance and intrinsic PEEP issues that affect breath triggering in other assisted modes.[24] Also like conventional assisted modes, the clinician must set PEEP and FIO_2. Finally, breath termination (cycling) is much like pressure support and is determined by a clinician-adjustable percentage of maximal inspiratory flow.

PAV has been shown in multiple studies to perform as designed.[35,36] However, whether PAV improves meaningful clinical outcomes (eg, sedation needs, shorter needs for mechanical ventilation) remains to be determined.

A second novel mode is neurally adjusted ventilatory assistance (NAVA), which utilizes a diaphragmatic electromyogram (EMG) signal to trigger, govern flow, and cycle ventilatory assistance.[37] The EMG sensor is an array of electrodes mounted on an esophageal catheter that is positioned in the esophagus at the level of the diaphragm. Ventilator breath triggering is thus virtually simultaneous with the onset of phrenic nerve excitation of the inspiratory muscles, and breath cycling is tightly linked to the cessation of inspiratory muscle contraction. Flow delivery is driven by the intensity of the EMG signal (electrical activity of the diaphragm or EADi), and the clinician sets a mL/mV gain factor.

Like PAV, NAVA depends exclusively on patient effort for timing, intensity, and duration of the breath. Thus, like PAV, clinicians must set appropriate alarms and backup positive pressure ventilation, especially for patients with unreliable respiratory drives. Also like PAV, clinicians must set PEEP and FiO_2.

NAVA has been shown to perform as designed,[13,37–39] and conceptually, NAVA should provide excellent patient–ventilator synchrony. However, data demonstrating improved outcomes (eg, duration of mechanical ventilation, sedation needs) are lacking. Another concern with NAVA is the expense associated with the EMG sensor.

REFERENCES

1. MacIntyre NR. Evolution of the modern mechanical ventilator. In: Hill N, Levy M, editors. Ventilator management strategies for critical care. New York: Marcel Dekker; 2000. p. 37–52.
2. Chatburn RL, El-Khatib M, Mireles-Cabodevila E. A taxonomy for mechanical ventilation: 10 fundamental maxims. Respir Care 2014 Nov;59(11): 1747–63.
3. Branson RD, Chatburn RL. Technical description and classification of modes of ventilator operation. Respir Care 1992;37:1026–44.
4. MacIntyre NR. Principles of mechanical ventilation. In: Broaddus VC, editor. Murray and Nadel's textbook of respiratory medicine. 6th edition. New York: Elsevier; 2016. p. 1761–77.
5. Esteban A, Ferguson ND, Meade MO, et al. Evolution of mechanical ventilation in response to clinical research. Am J Respir Crit Care Med 2008;177: 170–7.
6. MacIntyre NR, McConnell R, Cheng KC, et al. Patient-ventilator flow dyssynchrony: flow-limited versus pressure-limited breaths. Crit Care Med 1997;25:1671–7.
7. Habashi NM. Other approaches to open-lung ventilation: airway pressure release ventilation. Crit Care Med 2005;33(Suppl 3):S228–40.
8. Myers T, MacIntyre NR. Does airway pressure release ventilation offer important new advantages in mechanical ventilatory support? Respir Care 2007;52:452–60.
9. Kacmarek RM, Kirmse M, Nishimura M, et al. The effects of applied vs auto-PEEP on local lung unit pressure and volume in a four-unit lung model. Chest 1995;108:1073–9.
10. Weisman IM, Rinaldo JE, Rogers RM, et al. Intermittent mandatory ventilation. Am Rev Respir Dis 1983; 127:641–7.
11. Hewlett AM, Platt AS, Terry VG. Mandatory minute volume: a new concept in weaning from mechanical ventilation. Anaesthesia 1977;32:163–9.
12. MacIntyre NR, Branson RD. Feedback enhancements on conventional ventilator breaths. In: Tobin MJ, editor. Mechanical ventilation, principles and practice. 3rd edition. Philadelphia: McGraw Hill; 2011. p. 403–14.
13. Lellouche F, Brochard L. Advanced closed loops during mechanical ventilation (PAV, NAVA, ASV, SmartCare). Best Pract Res Clin Anaesthesiol 2009;23:81–93.
14. Bersten AD, Rutten AJ, Vedig AE, et al. Additional work of breathing imposed by endotracheal tubes, breathing circuits, and intensive care ventilators. Crit Care Med 1989;17:671–80.
15. Bersten AD, Rutten AJ, Vedig AE. Efficacy of pressure support in compensating for apparatus work. Anaesth Intensive Care 1993;21:67–71.
16. Guttmann J, Bernhard H, Mols G, et al. Respiratory comfort of automatic tube compensation and inspiratory pressure support in conscious humans. Intensive Care Med 1997;23:1119–23.
17. Fabry B, Haberthur G, Zappe D, et al. Breathing pattern and additional work of breathing in spontaneously breathing patients with different ventilatory demands during inspiratory pressure support and automatic tube compensation. Intensive Care Med 1997;23:545–50.
18. Branson RD, MacIntyre NR. Dual control modes of mechanical ventilation. Respir Care 1996;41: 294–305.
19. Kallet RH, Campbell AR, Dicker RA, et al. Work of breathing during lung-protective ventilation in patients with acute lung injury and acute respiratory distress syndrome: a comparison between volume and pressure-regulated breathing modes. Respir Care 2005;50:1623–31.
20. Jaber S, Delay JM, Matecki S, et al. Volume-guaranteed pressure-support ventilation facing acute changes in ventilatory demand. Intensive Care Med 2005;31:1181–8.
21. Iotti GA, Braschi A. Closed loop support of ventilator workload: the P0.1 controller. Respir Care Clin N Am 2001;7:441–51.
22. Strickland JH, Hasson JH. A computer-controlled ventilator weaning system: a clinical trial. Chest 1993;103:1220–6.
23. Dojat M, Harf A, Touchard D, et al. Evaluation of a knowledge-based system providing ventilatory management and decision for extubation. Am J Respir Crit Care Med 1996;153:997–1004.
24. Dojat M, Harf A, Touchard D, et al. Clinical evaluation of a computer-controlled pressure support mode. Am J Respir Crit Care Med 2000;161: 1161–6.
25. Lellouche F, Mancebo J, Jolliet P, et al. A multicenter randomized trial of computer-driven protocolized weaning from mechanical ventilation. Am J Respir Crit Care Med 2006;174:894–900.

26. Rose L, Presneill J, Johnston L, et al. A randomised, controlled trial of conventional versus automated weaning from mechanical ventilation using SmartCare/PS. Intensive Care Med 2008;34:1788.
27. Laubscher TP, Heinrichs W, Weiler N, et al. An adaptive lung ventilation controller. IEEE Trans Biomed Eng 1995;41:51–9.
28. Iotti GA, Polito A, Belliato M, et al. Adaptive support versus conventional ventilation for total ventilator support in acute respiratory failure. Intensive Care Med 2010;36:1371–9.
29. Weiler N, Eberle B, Latorre F, et al. Adaptive lung ventilation. Anaesthesist 1996;45:950–6.
30. Dongelmans DA, Paulus F, Veelo DP, et al. Adaptive support ventilation may deliver unwanted respiratory rate–tidal volume combinations in patients with acute lung injury ventilated according to an open lung strategy. Anesthesiology 2011;114(5):1138–43.
31. Otis AB. The work of breathing. Physiol Rev 1954;34(3):449–58.
32. NIH ARDS Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000;342:1301–8.
33. Sinderby C, Beck J. Proportional assist ventilation and neurally adjusted ventilatory assist–better approaches to patient ventilatory synchrony? Clin Chest Med 2008;29(2):329–42.
34. Younes M. Proportional assist ventilation, a new approach to ventilatory support. Am Rev Respir Dis 1992;145:114–20.
35. Bosma K, Ferreyra G, Ambrogio C, et al. Patient-ventilator interaction and sleep in mechanically ventilated patients; pressure support versus proportional assist ventilation. Crit Care Med 2007;35(4):1048–54.
36. Grasso S, Puntillo F, Mascia L, et al. Compensation for increase in respiratory workload during mechanical ventilation. Pressure-support versus proportional-assist ventilation. Am J Respir Crit Care Med 2000;161(3 Pt 1):819–26.
37. Sinderby C. Neurally adjusted ventilatory assist (NAVA). Minerva Anestesiol 2002;68:378–80.
38. Brander L, Leong-Poi H, Beck J, et al. Titration and implementation of neurally adjusted ventilatory assist in critically ill patients. Chest 2009;135(3):695–703.
39. Spahija J, de Marchie M, Albert M, et al. Patient-ventilator interaction during pressure support ventilation and neurally adjusted ventilatory assist. Crit Care Med 2010;38(2):518–26.