Classification of Ventilator Modes:
Update and Proposal for Implementation

Robert L Chatburn RRT-NPS FAARC

Ventilator manufacturers and the respiratory care academic community have not yet adopted a standardized system for classifying and describing ventilation modes. As a result, there is enough confusion that potential sales, education, and patient care are all put at risk. This proposal summarizes a ventilator-mode classification scheme and complete lexicon that has been extensively published over the last 15 years. Specifically, the classification system has 3 components: (1) a description of the breathing pattern and control variables within breaths, (2) a description of control type used within and between breaths, (3) a detailed description of adjunctive operational algorithms. This 3-level specification provides scalability of detail to make the mode description appropriate for the particular need. At the bedside we need only refer to a mode briefly using the first component. To distinguish between similar modes and brand names we would need to use at least the first and second components. For a complete and unique mode specification (as in an operator's manual) we would use all 3 components. The classification system proposed in this article uses the equation of motion for the respiratory system as the underlying theoretical framework. All terms relevant to describing ventilation modes are defined in an extensive glossary. *Key words: mode, control, mechanical ventilation, mechanical ventilator, feedback control, mandatory, spontaneous, equation of motion, breathing pattern, adaptive control, trigger, cycle, limit, definitions.* [Respir Care 2007;52(3):301–323. © 2007 Daedalus Enterprises]

Introduction

The publication *Health Devices* "has repeatedly stressed the need for users to understand the operation and features of ventilators, regardless of whether they will be used to ventilate neonatal/pediatric or adult patients. The fact that ventilators are such an established technology by no means guarantees that these issues are clearly understood. . . . We continue to receive reports of hospital staff misusing ventilators because they're unaware of the device's particular operational considerations."[1]

In a recent meeting of a ventilator subcommittee of the International Organization for Standardization, Beier, Weismann, and Roelleke[2] introduced a proposal for standardizing mechanical ventilator-mode classification. However, by their own admission, there are uncertainties in the proposal. Because they have specifically referenced me and my work in their white paper, I feel it appropriate to support their intent while providing a more developed and practical solution. I have been the leading author on this subject for more than 15 years, and what I will present in this proposal is a summary of a large inventory of previous publications.[3–17]

The Problem

After studying both the engineering and clinical aspects of mechanical ventilator modes and devoting considerable resources to training clinicians, I have reached some conclusions that might be considered fundamental axioms:

1. *Current nomenclature relevant to ventilator modes is hopelessly confused and outdated.* The confusion is evident in some published books and manuscripts. Perhaps more disturbingly, the confusion is seen in literature promulgated by ventilator manufacturers and organizations

Robert L Chatburn RRT-NPS FAARC is affiliated with the Section of Respiratory Therapy, The Cleveland Clinic, Cleveland, Ohio.

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Correspondence: Robert L Chatburn RRT-NPS FAARC, Respiratory Therapy, M-56, Cleveland Clinic, 9500 Euclid Avenue, Cleveland OH 44195. E-mail: chatbur@ccf.org.

such as ECRI (formerly known as the Emergency Care Research Institute)[18] and the International Electrotechnical Commission/International Organization for Standardization.[19] This is important because most of the training for ventilator use is conducted by ventilator manufacturers, each with its own natural bias, and without regard for any uniform presentation of an underlying theoretical framework.

2. *Confusion about nomenclature leads to confusion about clinical application, which adversely affects patient care.* My personal experience, as well as that of many of my colleagues who write and teach about this subject, suggests that there is indeed a knowledge gap on the part of clinicians, based on inaccurate paradigms of ventilator functionality. This gap is widening as the pace of technological evolution has quickened. I believe that on any given day you could walk into an intensive care unit anywhere in the world and observe a patient who is panic stricken and struggling to breathe even though connected to a state-of-the-art intensive-care ventilator, because some clinician has failed to understand the capability of the machine and has an incomplete or inaccurate paradigm of ventilator mode functionality. The confusion is not limited to clinicians; manufacturers' representatives are often uninformed about competitors' products and also unable to fully articulate the specifics of their own product's functionality. Giving product specialists efficient tools for communicating with clients should be just as important as training end users. Inability to communicate puts sales at risk as much as patient care.

3. *The solution to this problem must be scalable and universally applicable.* Any standard for naming and/or describing ventilation modes must be readily applicable to a variety of uses on a continuum of complexity. At one extreme is the very simple need for clinicians to communicate at the bedside and write basic patient-care orders that are easily understood and implemented without ambiguity. At the other extreme is the need for a complete operational description suitable for a ventilator operator's manual or manufacturing design specification. Somewhere in the middle is the engineer's need to create efficient ventilator-operator interfaces. A ventilator-mode-classification system that meets these needs must also be applicable to any ventilator that ever existed and hopefully to any future design.

4. *All terminology proposed for a standard classification system must be explicitly defined.* Perhaps this is the most important issue of all. As a technological field matures, its lexicon inevitably becomes fragmented and chaotic. When this process gets to the point where practical application suffers, it is time to purge the vocabulary of dross and seek a unifying theoretical framework. Toward that end, I have supplied a glossary, at the end of this proposal, that defines the key terms used throughout the text.

Key Concepts for a Ventilator Mode Classification System

To develop a standard nomenclature based on a valid theoretical model, we must first agree on a few key concepts and terms. These are usually left undefined by writers and educators, because their meanings seem obvious enough in common usage. However, *it is not possible to create an internally consistent classification system based on peoples' intuitive understandings.* The general concepts are described below and specific definitions are provided in the glossary below.

Mandatory Versus Spontaneous Breath

Every ventilator operator's manual uses the terms "mandatory" and "spontaneous" in describing modes, but none of them give adequate (if any) definitions. While there are any number of rational definitions for these terms, there is only one set that allows for a consistent classification of all current and any conceivable future ventilation modes. This is critical because these definitions are the very foundation of any mode description.

Control

The meaning and importance of the word "control" have evolved radically, as have ventilators themselves. The problem is that the focus of the meaning has shifted subtly from patient physiology to machine function (a concept proposed to me by noted author Richard Branson). A prime example is the use of the word "control" in the phrases "assist/control" versus "volume control of inspiration." The term "assist/control" focuses on the patient's neurological control of breathing and refers to a mode in which the ventilator may either "control" the breathing pattern by triggering inspiration as a substitute for the patient's own neurological control, or "assist" the patient's inspiratory effort after the patient triggers inspiration. These definitions date back over 30 years,[20] to a time when ventilator capabilities were primitive by today's standards. In contrast, the phrase "volume control of inspiration" focuses on the ventilator's mechanical operation and refers to how the ventilator shapes the breath, regardless of how the breath is triggered. Ventilators have evolved over 5 generations[21] in the span of a single human generation. As a result, many people who have been in the field a long time still cling to the older, patient-centric view of the word "control" and thus fail to appreciate the implications and utility of the machine-centric view. Manufacturers feel compelled to perpetuate this inertia, because many of these same people

make the purchasing decisions. The result is that the term "assist/control" continues to be associated with mode selection on new ventilators, even though the meaning of the term has changed from its historical roots to the point of virtual uselessness. Originally, "assist/control" meant volume-controlled continuous mandatory ventilation (CMV). Now it can also refer to pressure control as well. In fact, the term "assist/control" only means that a breath may be either machine-triggered or patient-triggered and thus technically does not distinguish continuous mandatory ventilation from intermittent mandatory ventilation (IMV). The term could apply to any of numerous new modes, and thus offers little of its former descriptive utility. The most practical uses for the word "control" are to describe how the ventilator manages pressure, volume, and flow delivery within a breath or to describe how the ventilator manages the sequence of mandatory and spontaneous breaths to create specific breathing patterns.

Equation of Motion

The interaction between the patient and ventilator during inspiration (and expiration) in terms of pressure, volume, flow, and the time course of these variables is complex. Yet these variables can be adequately represented by a mathematical model called the equation of motion for the respiratory system.[22–25] The simplest version of this model assumes that the complicated respiratory system can be modeled as a single resistance (R, representing the artificial airway and natural airways) connected in series with a single elastance (E, representing lung and chest wall elastance). A force balance equation for this model relating the pressure generated by the ventilator at the airway opening (P_{vent}), the pressure generated by the ventilatory muscles (P_{mus}), the elastic load (P_E) and the resistive load (P_R) can be written as:

$$P_{vent} + P_{mus} = P_E + P_R$$

(see the Glossary entry for Equation of motion for a more precise version of this equation relating the variables pressure, volume, and flow, along with the parameters elastance and resistance).

This model has 2 main functions in mechanical ventilation: (1) to calculate the lung mechanics parameters of resistance and compliance given information about pressure, volume, and flow, and (2) to predict pressure, volume, and flow given values for resistance and compliance. The first application is widely implemented on newer ventilators to monitor the patient's course during changing pathology or in response to treatment. The second application is the very basis of ventilator-control theory and thus a key component of the proposed mode-classification

system. Indeed, *the equation shows that for any mode, only one variable (ie, pressure, volume, or flow) can be controlled at a time, which greatly simplifies our understanding of ventilator operation.* We can simplify matters even more by recognizing that volume and flow are inverse functions (ie, flow is the derivative of volume as a function of time, and volume is the integral of flow), such that we only need to speak about pressure control versus volume control. It is quite possible to have a very good clinical understanding of patient-ventilator interaction with nothing more than a conceptual (ie, nonmathematical) appreciation of this model. Of course, it would be ideal to understand that the model is a linear differential equation and all that this implies.

Mode

Perhaps no other word in the mechanical ventilation lexicon is more used and less understood than "mode." Intuitively, a ventilation mode must refer to a predefined pattern of interaction between the patient and the ventilator. To be specific, the pattern of interaction is the breathing pattern. Even more specifically, the breathing pattern refers to the sequence of mandatory and spontaneous breaths. Thus, a mode description reduces to a specification of how the ventilator controls pressure, volume, and flow within a breath, along with a description of how the breaths are sequenced. Indeed, as Beier et al have suggested,[2] a complete mode description should have 3 components: (1) a description of the breathing sequence and control variables within breaths, (2) a description of control type used within and between breaths, (3) a detailed description of adjunctive control algorithms. This 3-level mode specification provides the scalability mentioned above. At the bedside we need only refer to a mode briefly, using the first component. To distinguish among similar modes and brand names we would need to use at least the first and second components. For a complete and unique mode specification we would use all 3 components.

The Proposal

This proposal describes a system for specifying ventilation modes primarily for educational purposes. Ventilator manufacturers will probably not adopt this system for creating names for new or existing modes, nor would it be very practical to do so. But manufacturers would find it helpful to use this system (ie, achieve consensus) to explain their products' capabilities in a way that is consistent across the field, thereby improving understanding not only on the part of customers but also among their own staffs.

The outline in Table 1 defines the proposed classification scheme for ventilation modes. The terms used in the outline are defined in the glossary, which appears after the

Table 1. A 3-Level Ventilator-Mode Classification Scheme*

1. Breathing pattern
    a. Primary breath-control variable
        i. Volume
        ii. Pressure
        iii. Dual
    b. Breath sequence
        i. Continuous mandatory ventilation (CMV)
        ii. Intermittent mandatory ventilation (IMV)
        iii. Continuous spontaneous ventilation (CSV)
2. Control type
    a. Tactical control (within breaths)
        i. Set point
        ii. Auto-set-point
        iii. Servo
    b. Strategic control (between breaths)
        i. Adaptive
        ii. Optimal
    c. Intelligent control (between patients)
        i. Knowledge-based
        ii. Artificial neural network
3. Operational algorithms
    a. Phase variables
        i. Trigger
        ii. Limit
        iii. Cycle
        iv. Baseline
    b. Conditional variables
    c. Computational logic

*These elements can be used to characterize modes of ventilator operation. The specification of a mode should begin with, and may just be limited to, a description of the mandatory breaths. However, a complete specification includes descriptions of both mandatory and spontaneous breaths.

Table 2. All Ventilation Modes Can Be Identified By One of These 8 Breathing Patterns

Breath-Control Variable	Breath Sequence	Acronym
Volume	Continuous mandatory ventilation	VC-CMV
	Intermittent mandatory ventilation	VC-IMV
Pressure	Continuous mandatory ventilation	PC-CMV
	Intermittent mandatory ventilation	PC-IMV
	Continuous spontaneous ventilation	PC-CSV
Dual	Continuous mandatory ventilation	DC-CMV
	Intermittent mandatory ventilation	DC-IMV
	Continuous spontaneous ventilation	DC-CSV

turer should specify the control variable for each mode. For simple set-point control (see the section on control type, below), the control variable can be identified as follows: If the peak inspiratory pressure remains constant as the load experienced by the ventilator changes, then the control variable is pressure. If the peak pressure changes as the load changes but V_T remains constant, then the control variable is volume. Volume control implies flow control and vice versa, but it is possible to distinguish the two on the basis of which signal is used for feedback control. Some primitive ventilators cannot maintain either constant peak pressure or V_T and thus control only inspiratory and expiratory times (ie, they may be called time controllers). The control variable should not be confused with the manipulated variable.[7] For example, a ventilator manipulates flow to control pressure based on a pressure feedback signal.

As mentioned above, the ventilator may control pressure or volume during inspiration, but not both. However, it may switch from one control variable to the other during a single inspiration, which leads to the designation of dual control. I first coined the term "dual control" while writing a chapter in the second edition of *Respiratory Care Equipment*.[8] At the time it seemed appropriate to consider control types that automatically adjust the pressure limit to meet a target tidal volume as a form of dual control. However, in practice this may be confusing. The control variable designation is based on the equation of motion, which describes the events within a breath. Adjusting the pressure limit to meet a target tidal volume is something (at least at present) that occurs between breaths and is a function of the control type. Thus, the term dual control, as part of a level 1 description, should be restricted to situations in which inspiration starts out as volume control and then switches to pressure control before the end of the breath (or vice versa). However, it would still be convenient to have a general term that describes automatic adjustment of the pressure limit over several breaths to meet a target tidal volume as implemented with adaptive, optimal and knowledge based control types. The term "volume targeted pres-

Summary section below. As mentioned above, the scheme is scalable, in that a mode can be describe in increasing detail using 1, 2, or all 3 levels, as appropriate for the situation. The following are some specific guidelines for implementation:

1. Breathing Pattern

Given 3 possible control variables (volume, pressure, dual control) and 3 breath sequences (CMV, IMV, and continuous spontaneous ventilation [CSV]), there are 8 possible breathing patterns (Table 2). (Note that VC-CSV is not possible, because the definition of volume control would conflict with the definition of a spontaneous breath. Volume control implies that the ventilator determines the tidal volume [V_T], whereas in a spontaneous breath the patient determines the V_T.)

1a. *Control variable.* The control variable is the variable that the ventilator uses as a feedback signal to control inspiration (ie, pressure, volume, or flow). *The manufac-*

sure control" has been used to describe these schemes. In other words, pressure is the control variable during inspiration. The term "target" is appropriate because the ventilator may miss the volume goal for several reasons, whereas the pressure is always controlled to the specific setpoint during normal operating conditions. A simpler and more general term for any control scheme that allows automatic adjustment of setpoints would be "self-adjusting mode."

1b. *Breath sequence*. The acronym "CMV" has been used to mean a variety of things by ventilator manufacturers. The most logical usage in this classification system is "continuous mandatory ventilation," as part of a continuum from full ventilatory support to unassisted breathing. The acronym "IMV" has a long history of consistent use to mean intermittent mandatory ventilation (ie, a combination of mandatory and spontaneous breaths). However, the development of the "active exhalation valve" and other innovations has made it possible for the patient to breathe spontaneously *during* a mandatory breath. This is primarily a feature to help ensure synchrony between the ventilator and patient in the event that the mandatory breath parameters (eg, preset inspiratory time, pressure, volume, or flow) do not match the patient's inspiratory demands. This blurs the historical distinction between CMV and IMV. The key difference now between CMV and IMV is that with CMV the clinical intent is to make every inspiration a mandatory breath, whereas with IMV the clinical intent is to partition ventilatory support between mandatory and spontaneous breaths. This means that during CMV, if the patient makes an inspiratory effort after a mandatory breath cycles off, another mandatory breath is triggered. Thus, if the operator decreases the ventilatory rate (often considered to be a safety "backup" rate in the event of apnea), the level of ventilatory support is unaffected so long as the patient continues triggering mandatory breaths at the same rate (ie, each breath is assisted to the same degree). With IMV, the rate setting directly affects the number of mandatory breaths and hence the level of ventilatory support, assuming that spontaneous breaths are not assisted to the same degree as mandatory breaths (originally spontaneous breaths could not be assisted during IMV). CMV is normally considered a method of full ventilatory support, whereas IMV is usually viewed as a method of partial ventilatory support (eg, for weaning). *Thus, for classification purposes, if spontaneous breaths are not allowed between mandatory breaths, the breath sequence is CMV; otherwise the sequence is IMV* (Fig. 1). Given that almost every ventilator may be patient-triggered, it is no longer necessary to add the letter S (as in SIMV) to designate "synchronized" IMV (ie, the patient may trigger mandatory breaths). Such usage was important in the early days of mechanical ventilation but is an anachronism now.
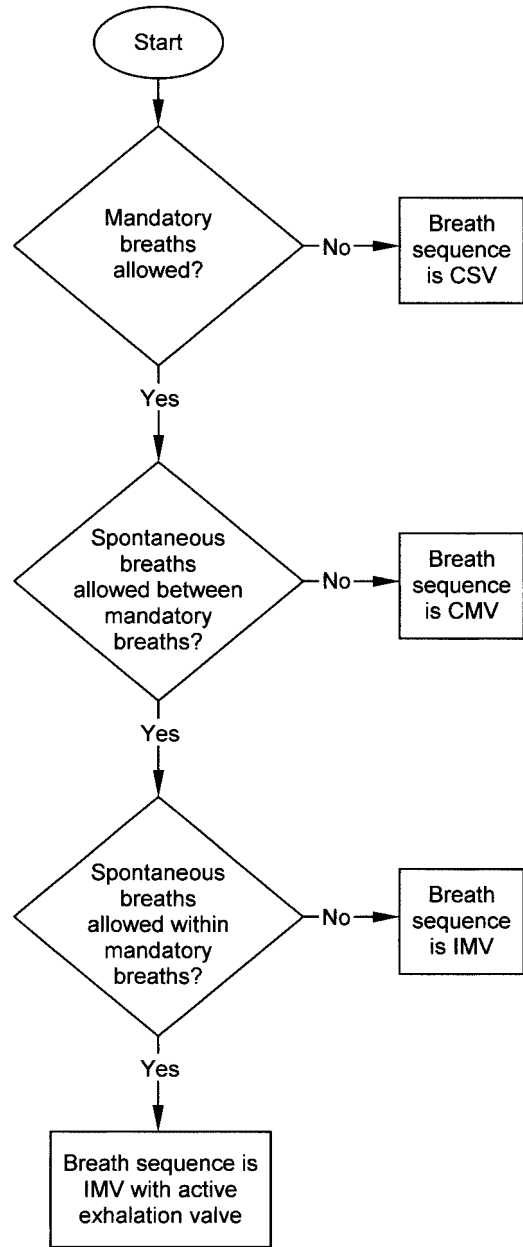

Fig. 1. Algorithm to distinguish among the 3 types of breath sequence: continuous mandatory ventilation (CMV), intermittent mandatory ventilation (IMV), and continuous spontaneous ventilation (CSV).

Patient triggering can be specified in the level-3 description, under phase variables.

There has been no consistent acronym to signify a breathing pattern composed of *all spontaneous breaths*. The logical progression would be from CMV to IMV to CSV (continuous spontaneous ventilation).

Note that the definitions for assisted breath and spontaneous breath are independent. That is, an assisted breath may be spontaneous or mandatory. A spontaneous breath

may be assisted or unassisted (a mandatory breath is assisted by definition). Understanding the difference between assisted and unassisted breaths is important clinically. For example, when making measurements for the calculation of the rapid-shallow breathing index, the breaths must be both spontaneous and unassisted. There is a common misconception, evident in the way some people talk about modes, that when the patient triggers an inspiration, he somehow "assists" the ventilator. On the contrary, it is always the ventilator that assists the patient.

2. Control Type

The control type is a categorization of the feedback control function of the ventilator. As shown in Table 1, at least 7 different control types have evolved to date. All but one (artificial neural network control) are commercially available at this time. These control types have been described in detail elsewhere[7] and are defined again in the glossary below, and in Table 3. Ventilator control types display a definite hierarchy of evolutionary complexity. At the most basic level, control is focused on what happens within a breath. We can call this *tactical control*, and there is a very direct need for operator input of static set points (eg, pressure and flow limits, V_T, timing). The next level up is what may be called *strategic control*. With strategic control, the ventilator takes over some of the tactical control normally managed by the human operator. In strategic control, the set points are dynamic in that they may be automatically adjusted by the ventilator over the course of many breaths, according to some model of desired performance. The operator is somewhat removed in that inputs are entered at the level of the model, and they take effect over several breaths, instead of at the level of individual breath control.

Finally, the highest level so far is what might be considered *intelligent control*, in which the operator can (in theory) be eliminated altogether by artificial intelligence programs that take over strategic and/or tactical control. Not only dynamic set points but dynamic models of desired performance are permitted (eg, one model for patients with neurological disorders and another for patients with chronic obstructive pulmonary disease). The artificial intelligence programmed into the computer condenses the experience of experts who have dealt with many patients, and there is the possibility of the model learning from its own experience so that the control actually spans between patients. These ideas are summarized in Figure 2.

Specifying the control type in a level-2 description allows us to easily distinguish between modes that look nearly identical on a graphics monitor but that present conceptual/verbal problems when trying to differentiate them. For example, it might be difficult to appreciate the difference between pressure support and volume support

on a Maquet Servo-i ventilator. Ask any knowledgeable person you know to describe the differences and see if you can get an accurate, coherent explanation. Then consider these simple descriptions: pressure support is PC-CSV with set-point control of inspiratory pressure; volume support is PC-CSV with adaptive control of inspiratory pressure. If you know the definitions of those terms (and they are explicitly defined in the glossary below), you can immediately understand how different the modes are. Your attention would also be directed to the clinical implications for the patient (eg, what settings are required). A level-2 description also allows the clinician to see that a ventilator function such as Dräger's AutoFlow feature is not just a "supplement" or "extra setting," as the operator's manual would have you believe, but indeed creates a whole different mode. For example, operating the Dräger Evita 4 in "CMV" yields VC-CMV with set-point control of inspiratory volume and flow. However, activating AutoFlow when CMV is set (ie, CMV + AutoFlow) yields PC-CMV with adaptive control of inspiratory pressure—and vastly different clinical ramifications for the patient! Indeed, these 2 modes are about as different as any 2 modes can be. I have many times seen clinicians befuddled simply because the nomenclature and description of AutoFlow in the operator's manual and sales literature is so misleading.

It is important to note that if the breath sequence is IMV, then a complete level-2 description of the mode will include both mandatory and spontaneous breaths. For example, on the Puritan Bennett 840 ventilator, the mode called Synchronized Intermittent Mandatory Ventilation would be described as VC-IMV with set-point control of volume for mandatory breaths and set-point control of pressure for spontaneous breaths.

3. Operational Algorithms

At the highest level of detail, the mode description must describe the explicit instructions used by the ventilator's control circuit to generate the breathing pattern. Such a description should include a listing of phase variables, conditional variables, and any special artificial intelligence programs used.

3a. *Phase variables*. There are some modes that are so similar that a level-2 description will not suffice to distinguish them. The most common example might be discerning VC-IMV with and without pressure support. In either case, a level-2 description would be the same: VC-IMV with set-point control of volume for mandatory breaths and set-point control of pressure for spontaneous breaths. Even using a level-3 description, both modes may have the same trigger, limit, and cycle variables for mandatory and spontaneous breaths. The difference is that with VC-IMV plus pressure support, the limit variable for spontaneous breaths is pressure *with a setting above baseline pressure.*

Table 3. Basic Types of Control Used in Current Mechanical Ventilators

| Control Type	Characteristics	Description of Example Mode	Example Mode	Example Ventilator
Set point	The output of the ventilator automatically matches a constant operator preset input value. Multiple set points are possible.	Mandatory breaths are pressure-limited and time-cycled, according to the operator-set values for peak inspiratory pressure and frequency.	Pressure-control intermittent mandatory ventilation (PC-IMV)	Bird VIP
Auto set point	The ventilator selects which operator-adjusted set points are enforced at the moment.	Inspiration starts in pressure-control and switches to volume-control.	Volume-assured pressure support	Bird 84000ST
		Inspiration starts in volume-control and switches to pressure-control.	CMV + pressure limited ventilation	Dräger Evita 4
Servo	The ventilator output automatically follows a varying input.	The instantaneous value of pressure is proportional to the instantaneous volume and/or flow generated by the patient.	Proportional assist	Puritan Bennett 840
			Automatic tube compensation	Dräger Evita 4
Adaptive	One ventilator set point is automatically adjusted to achieve another set point as the patient's condition changes.	Mandatory breaths are pressure-limited, and the pressure limit is automatically adjusted between breaths to achieve the preset tidal volume.	Pressure-regulated volume-control	Maquet Servo-i
			AutoFlow	Dräger Evita 4
		Inspiratory time is adjusted to maintain an inspiration-expiration ratio of 1:2 as the patient's breathing frequency changes.	Adaptive I-time	VersaMed iVent
Optimal	One ventilator set point is automatically adjusted to optimize another set point according to some model of system behavior, whose output can be maximized or minimized dynamically.	Each breath is pressure-limited, and the pressure limit is automatically adjusted between breaths (using ventilatory mechanics measurements) to minimize work of breathing.	Adaptive support ventilation	Hamilton Galileo
Knowledge-based	Set points are automatically adjusted according to a rule-based expert system.	The pressure-support level for spontaneous breaths is automatically adjusted to maintain appropriate breathing frequency, tidal volume, and end-tidal CO_2, depending on the type of patient.	SmartCare	Dräger Evita XL
Artificial neural network	Set points are automatically adjusted by an artificial neural network. The actual rules are generally unknown. The relation between inputs and outputs is determined by weighting factors at neural nodes that change with learning.	The network inputs are the current ventilator settings and partial pressures of arterial blood gases and pH. Network outputs are the most appropriate ventilator settings projected to maintain blood gases within an acceptable range.	Experimental	Not available

(Adapted from Reference 7.)

This indicates that spontaneous breaths are *assisted* (ie, the definition of an assisted breath is that airway pressure rises above baseline during inspiration). There are various ways to assist spontaneous breaths with a PC-CSV breathing pattern. For example:

- Pressure support: spontaneous breaths assisted with set-point control

- Volume assist: spontaneous breaths assisted with adaptive pressure control

- Automatic tube compensation: spontaneous breaths assisted with servo control

- Proportional assist ventilation: spontaneous breaths assisted with servo control

Tactical Control (within breaths)
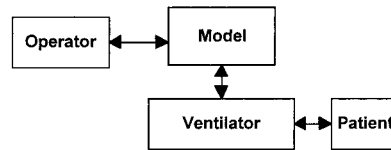*Static set points*
- set point
- auto set point
- servo
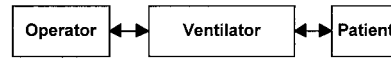
Stategic Control (between breaths)
Dynamic set points
Static models
- adaptive
- optimal

Intelligent Control (between patients)
Dynamic set points
Dynamic models
Artificial intelligence programs
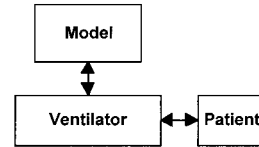- knowledge based
- artificial neural networks

Fig. 2. Summary of ventilator control types. For tactical control types, the operator is needed to adjust specific, static set points such as inspiratory pressure limit, tidal volume and inspiratory flow. With strategic control types, set points such as inspiratory pressure limit, and ventilatory frequency may change to accommodate changes in the patient's condition (eg, respiratory-system resistance and compliance). With strategic control, the operator adjusts the parameters of a static mathematical model. The model then adjusts the set points to shape the breath. With intelligent control, not only are the set points dynamic (ie, machine adjusted) according to a model, but the model itself may change from one form to another from a list of different models (eg, rule-based expert systems) or it may change by learning (eg, with an artificial neural network).

- SmartCare: spontaneous breaths assisted with knowledge-based control

One subject of confusion caused by manufacturers has to do with pressure limits. For mandatory breaths, the pressure limit on some ventilators is set relative to atmospheric pressure. But for spontaneous breaths (eg, pressure support mode), the pressure limit is set relative to the positive end-expiratory pressure (PEEP). Setting the pressure limit relative to PEEP is more useful, because it is the *change in pressure* relative to baseline (ie, PEEP) during inspiration that determines the V_T. Thus, a pressure setting relative to PEEP carries more information than a pressure setting relative to atmospheric pressure, because the clinician must know PEEP to be confident of the implications of the level of ventilation. For example, if PEEP is increased, the V_T will decrease for the same peak inspiratory pressure setting during PC-IMV on many ventilators. On the other hand, PEEP changes do not affect V_T with PC-CSV on those same ventilators (Fig. 3).

When talking about modes, it is sometimes more convenient to say that a breath is either machine-triggered or patient-triggered rather than describe the exact trigger variable. Similarly, we can use the terms machine-cycled or patient-cycled. Distinguishing between machine and patient triggering is fairly easy, but cycling can be confusing. For the breath to be patient-cycled, the patient must be able to change the inspiratory time by making either inspiratory or expiratory efforts. If this is not possible, then the breath is, by definition, machine-cycled. For example, with pressure cycling, the patient can make the inspiratory time longer by making an inspiratory effort. Because the patient is breathing in, it takes longer for the ventilator to generate the set pressure. (From the ventilator's point of view, it looks like the patient's compliance has increased.) The patient can shorten the inspiratory time by making an expiratory effort, forcing the pressure to rise more rapidly. Another example of patient cycling is the pressure support mode, in which inspiration ends when flow decays to some preset value (ie, flow cycling). Just as with pressure cycling, the patient can either prolong or shorten the time required to reach the threshold flow. If the ventilator is time-cycled, it is by definition machine-cycled, as the patient cannot do anything to change the inspiratory time aside from getting out of bed and turning a knob. Volume cycling is usually a form of machine cycling, because most ventilators today deliver the preset volume at a preset flow, and this determines the inspiratory time (inspiratory time = volume/flow). If a ventilator were designed to allow the patient to draw as much flow as needed but still cycle when the preset volume was delivered, then this type of volume cycling would be patient cycling, because the patient could shorten inspiratory time by making an in-
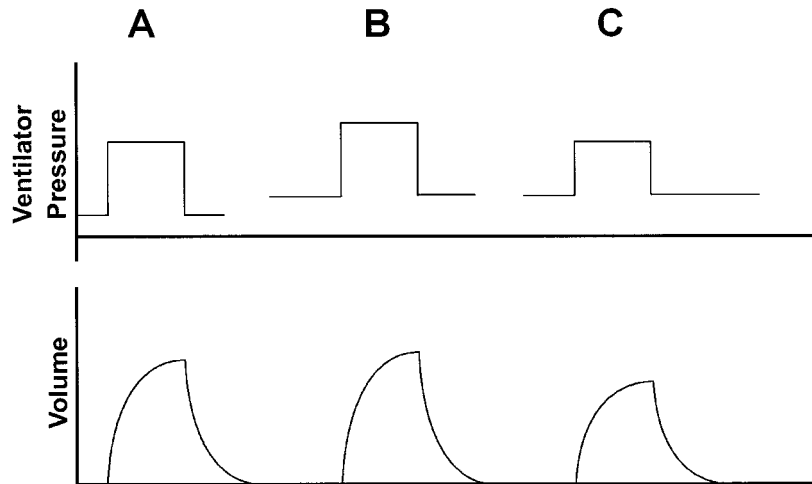
Fig. 3. The difference between setting the pressure limit relative to the positive end-expiratory pressure (PEEP) versus relative to atmospheric pressure. A: Initial pressure limit and PEEP. B: Pressure limit set relative to PEEP with an increased PEEP. C: Pressure limit set relative to atmospheric pressure with an increased PEEP. Note that the tidal volume is unchanged in B but decreased in C.

spiratory effort. This, however, would not make much sense from a patient-ventilator-synchrony point of view. The engineering design response to this situation may be to start the breath in volume control with a preset inspiratory flow and V_T-cycling threshold, then, if the patient demands more flow, switch inspiration to pressure control with a flow-cycling threshold (eg, as with the Respironics Flow-Trak feature, a type of dual-control IMV).

As mentioned above, a pressure support breath is cycled off when the flow decays to a preset value. This is a form of patient cycling, even if the patient is paralyzed (eg, inspiratory time shortens if compliance and/or resistance decreases). It is also possible that the patient may *trigger* the ventilator without using muscle pressure. For example, the Vortran Automatic Resuscitator terminates expiration (ie, inspiration is triggered on) when the pressure due to expiratory flow against the valve falls below the force from the spring acting on the other side of the valve. It would also be possible to build a device that measures expiratory flow and triggers inspiration when a preset threshold was met (ie, the reverse of flow cycling on pressure support). The key to understanding these examples of passive cycling and triggering is to realize that it is the patient's respiratory-system time constant that is responsible for the action. The patient (rather than the machine) triggers and cycles in these examples, because he can change his time constant (actively by invoking muscles) or passively (by disease).

In summary, time triggering is referred to as "machine triggering." Pressure-triggering, volume-triggering, and flow-triggering (along with rare mechanisms such as chest-wall motion, transthoracic impedance, and diaphragm electrical activity) may be called "patient triggering." Time cycling and volume cycling are examples of "machine cycling." Pressure and flow cycling are types of "patient cycling."

3b. *Conditional variables*. The more complex the mode, the more necessary it is to distinguish it on the basis of the computer logic that manages the events during the different phases of the breathing pattern. One way to do this is by specifying *conditional variables* that are used in programs that determine, for example, *if* spontaneous minute ventilation falls below a preset threshold, *then* deliver enough mandatory breaths to raise minute ventilation above the threshold. It takes this level of detail to explain, for example, the differences between one form of pressure support breath-ending criteria (eg, with a Newport ventilator) from corresponding criteria on another brand (eg, with a Siemens ventilator). This level of detail also allows the operator to distinguish a feature such as FlowBy on the Puritan Bennett ventilator as a setting for phase variables (ie, the trigger variable and threshold) rather than being a mode in and of itself. Of course, *any unique combination of breathing pattern, control type, and operational algorithms is technically a mode*, yet it may not be very practical to give it a unique name.

3c. *Computational logic*. As shown in Figure 2, advanced control types employ models that specify fairly complex interactions between ventilator and patient. The computational logic is a description of the relationship between the inputs (eg, settings), feedback signals, and outputs (eg, breathing pattern), adding detail about how the mode operates that is not given in the other components of the mode specification. For example, the adaptive support ventilation mode on the Hamilton Galileo uses work of breathing as the performance function, and it is

Table 4. Specifications for Some of the Modes Found on the Dräger Evita 4 Ventilator*

Dräger Mode Name	Breathing Pattern	Mandatory Breaths†				Spontaneous Breaths			
		Control Type	Trigger‡	Limit§	Cycle	Control Type	Trigger	Limit	Cycle
CMV	VC-CMV	Set point	Time	Flow, Volume	Time	NA	NA	NA	NA
		Computational logic: Every breath is volume-controlled and mandatory. Every breath is machine-triggered and cycled.							
CMV+AutoFlow	PC-CMV	Adaptive	Time, Flow	Pressure	Time	NA	NA	NA	NA
		Computational logic: Mandatory breaths are pressure-controlled, but the patient may trigger a breath. If the target tidal volume is not met, the pressure limit is automatically adjusted.							
CMV+pressure-limited ventilation	DC-CMV	Auto-set-point	Time, Flow	Flow, Volume, Pressure	Time	NA	NA	NA	NA
		Computational logic: Mandatory breath starts out in volume-control but switches to pressure-control if the airway pressure reaches the set maximum pressure (P_{max}).							
SIMV	VC-IMV	Set point	Time, Flow	Flow, Volume	Time	Set point	Pressure	Pressure	Pressure
		Computational logic: Mandatory breaths are volume-controlled. Spontaneous breaths may occur within the window determined by the set rate and are not assisted (ie, inspiratory pressure stays at baseline).							
PC+	PC-IMV	Set point	Time, Flow	Pressure	Time	Set point	Pressure	Pressure	Pressure
		Computational logic: Mandatory breaths are pressure-controlled. Spontaneous breaths may occur within the window determined by the set rate and are not assisted (ie, inspiratory pressure stays at baseline).							
SIMV+AutoFlow	PC-IMV	Adaptive	Time, Flow	Pressure	Time	Set point	Pressure	Pressure	Pressure
		Computational logic: Mandatory breaths are pressure-controlled and the pressure limit is automatically adjusted if the target tidal volume is not met. Spontaneous breaths may occur, within the window determined by the set rate, and are not assisted (ie, inspiratory pressure stays at baseline).							
CPAP	PC-CSV	NA	NA	NA	NA	Set point	Pressure	Pressure	Pressure
		Computational logic: Spontaneous breaths are unassisted.							
Pressure support	PC-CSV	NA	NA	NA	NA	Set point	Flow	Pressure	Flow
		Computational logic: Spontaneous breaths are assisted (ie, inspiratory pressure rises above baseline).							

*Figures 4 through 11 illustrate the corresponding pressure, volume, and flow waveforms.
†The patient can take spontaneous breaths during mandatory breaths with PC and AutoFlow, but not with pressure-limited ventilation.
‡Flow-triggering may be turned off. When off, mandatory breaths cannot be triggered, but spontaneous breaths are automatically pressure-triggered with factory-set sensitivity.
§Volume limit occurs if inspiratory time is set longer than (tidal volume/flow). Volume limit may occur for any volume-controlled breath.
NA = not available. CMV = continuous mandatory ventilation (all breaths are mandatory). VC = volume-controlled. PC = pressure-controlled. DC = dual-controlled. SIMV = spontaneous intermittent mandatory ventilation (spontaneous breaths between mandatory breaths). CPAP = continuous positive airway pressure. CSV = continuous spontaneous ventilation (all breaths are spontaneous).

related to lung mechanics, alveolar ventilation, dead-space volume, and breathing frequency.[26] As lung mechanics change, the ventilator finds the optimum frequency (to minimize work) and then sets the V_T to meet the minute ventilation requirement. This mode also employs a number of rules that ensure a lung-protective strategy. These rules would be part of the computational logic description. The SmartCare mode on the Dräger Evita XL uses a rule-based expert system to keep the patient in a "comfort zone," based on ventilatory rate, V_T, and end-tidal carbon dioxide level.[27] However, the use of "fuzzy logic" and artificial neural networks in ventilator control systems may eliminate the possibility of generating explicit decision rules and may thus improve care while making it less understandable.[28]
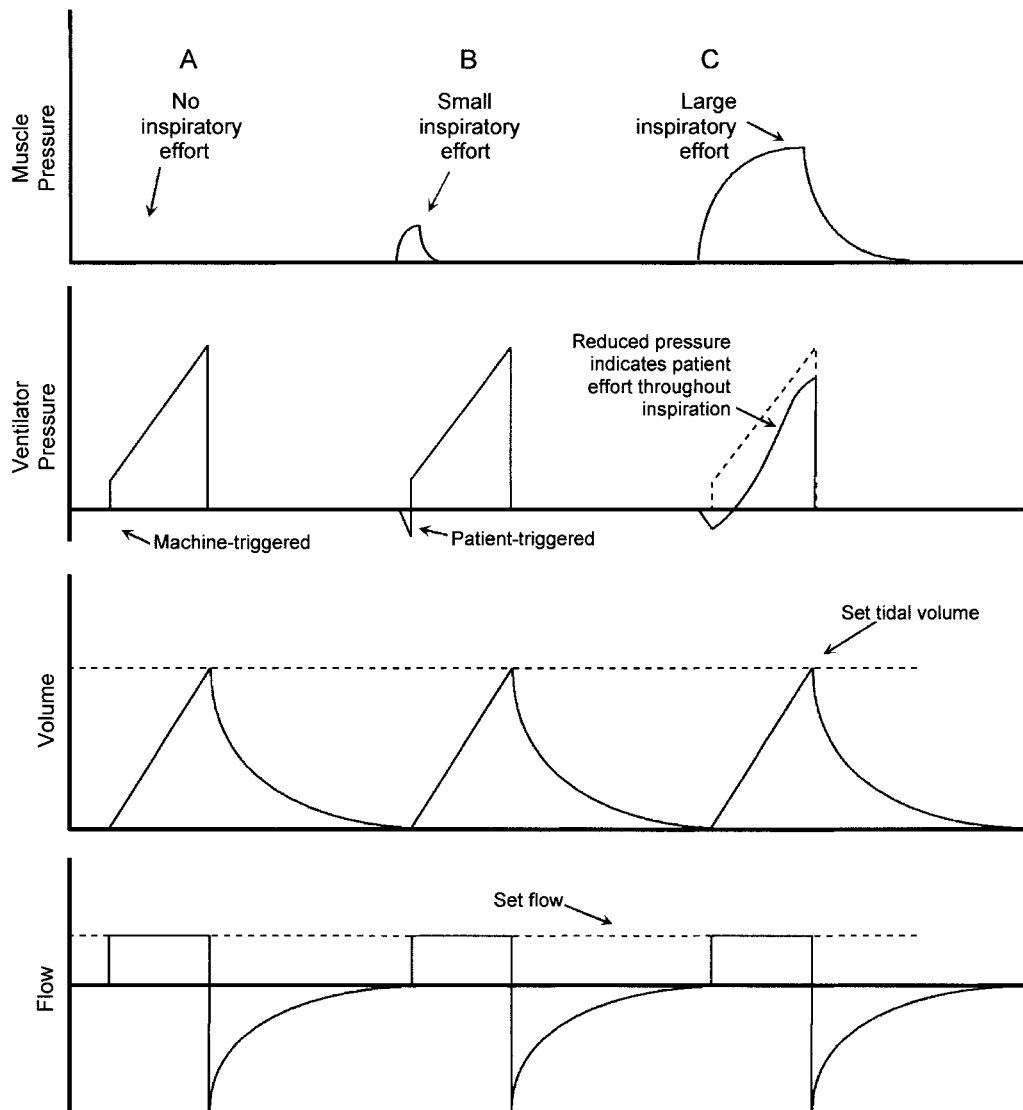
Fig. 4. Dräger Evita 4 mode called CMV, which is a volume-controlled continuous mandatory ventilation mode (VC-CMV) with set-point control (see Table 4). Breaths during VC-CMV can be machine triggered (A) or patient-triggered (B). Although VC-CMV is often chosen to rest the patient, patient effort does not necessarily stop. When airway pressure drops below baseline, the patient is doing work on the ventilator. When the airway pressure is above baseline, the ventilator is doing work on the patient. The difference in the areas between passive inspiration (A) and active inspiration (C) indicates that the patient does work during inspiration. (From Reference 9, with permission.)

Summary

Ventilator manufacturers and the respiratory care academic community have not yet adopted a standardized system for classifying and describing ventilation modes. As a result, there is much confusion among their customers, as well as their own staff, with the result that potential sales, education, and patient care are all put at risk. This proposal summarizes a ventilator-mode classification scheme and complete lexicon that has been extensively published over the last 15 years. In addition, I have presented practical considerations for implementing the scheme as the primary means of identifying ventilation modes in operator's manuals and educational materials. An example of the utility of this scheme is illustrated in Table 4, which gives detailed specifications for a sample of modes available on the Dräger Evita 4 ventilator. Graphic representations of these modes are given in Figures 4–11. A good example of how the classification scheme can also be applied to design efficient user interfaces is shown in Figure 12.

Glossary

Adaptive control. One set point (eg, the pressure limit) of the ventilator is automatically adjusted over several
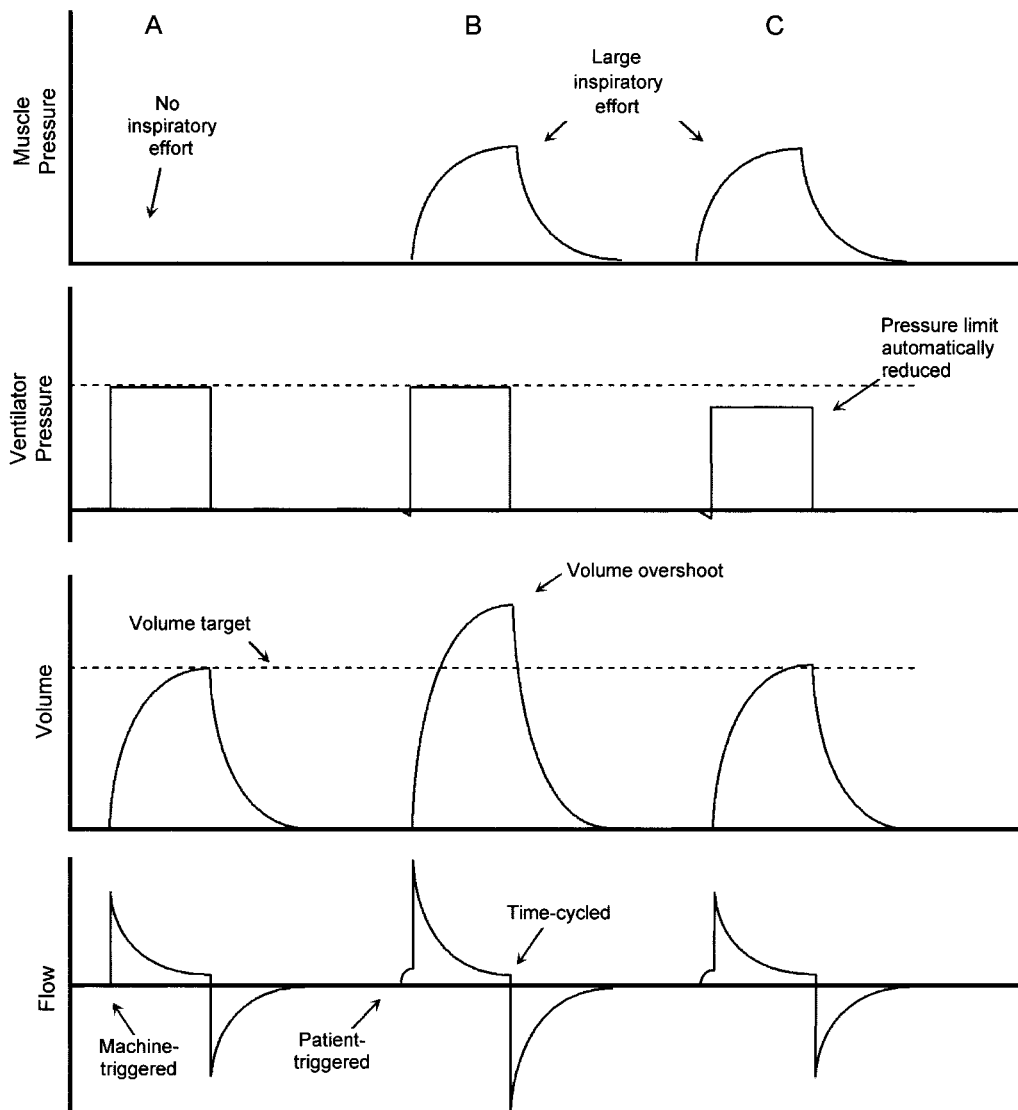
Fig. 5. Dräger Evita 4 mode called CMV + AutoFlow, which is a pressure-controlled continuous mandatory ventilation mode (PC-CMV) with adaptive control (see Table 4). During steady state, the pressure limit is just high enough to achieve the set tidal volume (A). If the patient suddenly makes a large inspiratory effort, muscle pressure adds to ventilator pressure and the resultant tidal volume is larger than the set tidal volume (B). The ventilator compensates by lowering the pressure limit (C). (From Reference 9, with permission.)

breaths to maintain another set point (eg, the target V_T) as the patient's condition changes (eg, pressure-regulated volume control mode on the Maquet Servo-i ventilator). Thus, the ventilator adapts to the need for a changing set point.

Assisted breath. A breath during which all or part of inspiratory (or expiratory) flow is generated by the ventilator doing work on the patient. In simple terms, if the airway pressure rises above end-expiratory pressure during inspiration, the breath is assisted (as in pressure support mode). It is also possible to assist expiration by dropping airway pressure below end-expiratory pressure (such

as the exhalation assist feature on the Venturi ventilator or automatic tube compensation on the Dräger Evita 4 ventilator). In contrast, spontaneous breaths during continuous positive airway pressure (CPAP) are unassisted, because the ventilator attempts to maintain a constant airway pressure during inspiration.

Automatic set-point control. The ventilator automatically selects the set point enforced at the moment. For example, the ventilator's output is automatically adjusted during the breath to maintain the set V_T, using either the set pressure limit or the set inspiratory flow. The breath can start out as pressure-controlled and automatically switch
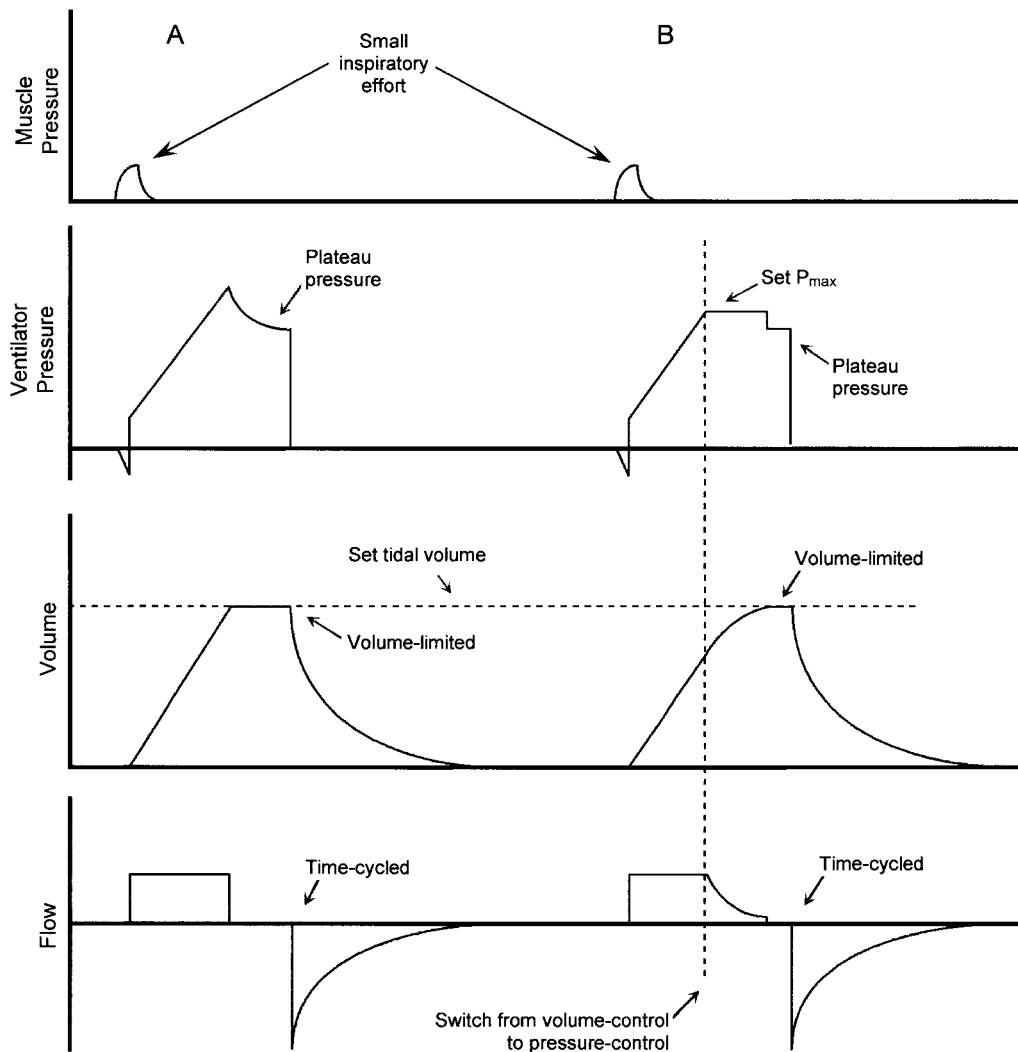
Fig. 6. A: Volume-controlled continuous mandatory ventilation (VC-CMV) versus (B) the Dräger Evita 4 mode called CMV + pressure limited ventilation, which is a dual-control CMV. Using automatic set-point control, the breath in B starts out in volume control but switches to pressure control when airway pressure reaches the set maximum (P_{max}). Flow stops when the set tidal volume is met. An inspiratory hold ensues until the set inspiratory time is met and the breath is cycled off. Notice that the inspiratory flow time is increased while the inspiratory pause time is decreased, compared to breath in A, to assure tidal volume delivery within the set inspiratory time. P_{max} results in a lower peak pressure at the airway opening but the same pressure in the lungs, because of the same tidal volume as the breath in A. (From Reference 9, with permission.)

to volume-controlled (eg, the Bird VAPS [volume-assured pressure support] mode) or vice versa (eg, the Dräger pressure-limited ventilation mode).

Automatic tube compensation. A feature that allows the operator to enter the size of the patient's endotracheal tube and have the ventilator calculate the tube's resistance and then generate just enough pressure (in proportion to inspiratory or expiratory flow) to compensate for the added resistive load. See *servo control*.

AutoPEEP. The positive difference between end-expiratory alveolar pressure and the end-expiratory pressure

(PEEP) set by the clinician. AutoPEEP is the pressure associated with the trapped gas when dynamic hyperinflation occurs. See *dynamic hyperinflation*.

Auto-trigger. (Sometimes mistakenly called "auto-cycling.") A condition in which the ventilator repeatedly triggers itself because the sensitivity is set too high. For pressure triggering, the ventilator may auto-trigger due to a leak in the system that drops airway pressure below the pressure-trigger threshold. When sensitivity is set too high, even the heartbeat can cause inadvertent triggering.
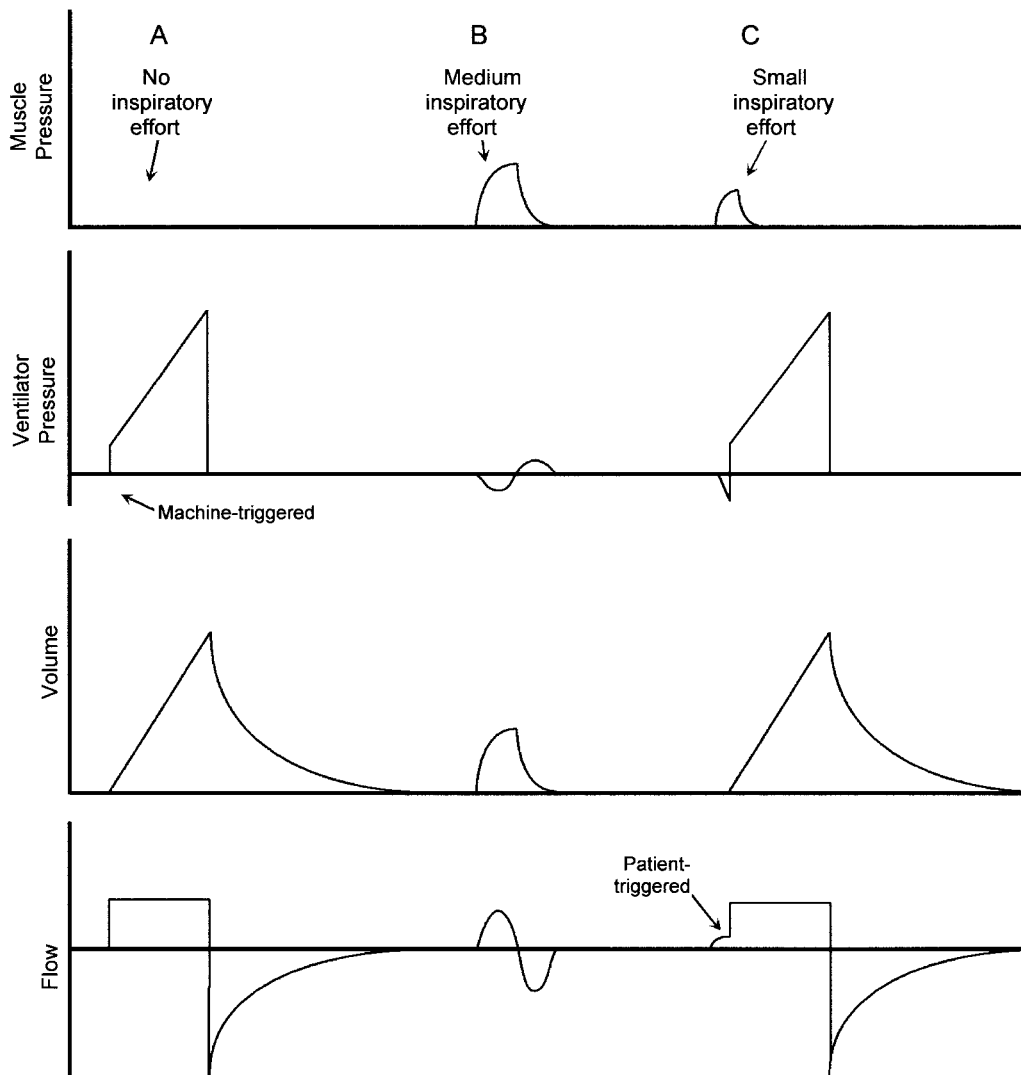
Fig. 7. Dräger Evita 4 mode called SIMV, which is a volume-controlled intermittent mandatory ventilation (VC-IMV) mode with set-point control. Mandatory breaths may be machine-triggered (A) or patient-triggered (C). When patient triggering is allowed, this mode is often referred to as synchronized IMV (SIMV). Unassisted spontaneous breaths may occur between mandatory breaths (B). The small fluctuation in airway pressure during spontaneous breaths is due to the resistance of the expiratory limb of the patient circuit and/or the opening delay in the demand flow valve. (From Reference 9, with permission.)

Breath. A positive change in airway flow (inspiration) paired with a negative change in airway flow (expiration), associated with ventilation of the lungs. This definition excludes flow changes caused by hiccups or cardiogenic oscillations. However, it allows the superimposition of, for example, a spontaneous breath on a mandatory breath or vice versa.

Breathing pattern. A sequence of breaths (CMV, IMV, or CSV) with a designated control variable (volume, pressure, or dual control) for the mandatory breaths (or the spontaneous breaths in CSV).

CMV. Continuous mandatory ventilation, in which all breaths are mandatory, unless there is a provision for spontaneous breaths during mandatory breaths (ie, using a so-called active exhalation valve). The defining characteristic is that spontaneous breaths are not permitted between mandatory breaths, because inspiratory efforts after a mandatory breath always trigger another mandatory breath.

Conditional variable. A variable used by a ventilator's operational logic system to make decisions on how to manage control and phase variables. Conditional variables can be described in terms of "if-then" statements. For
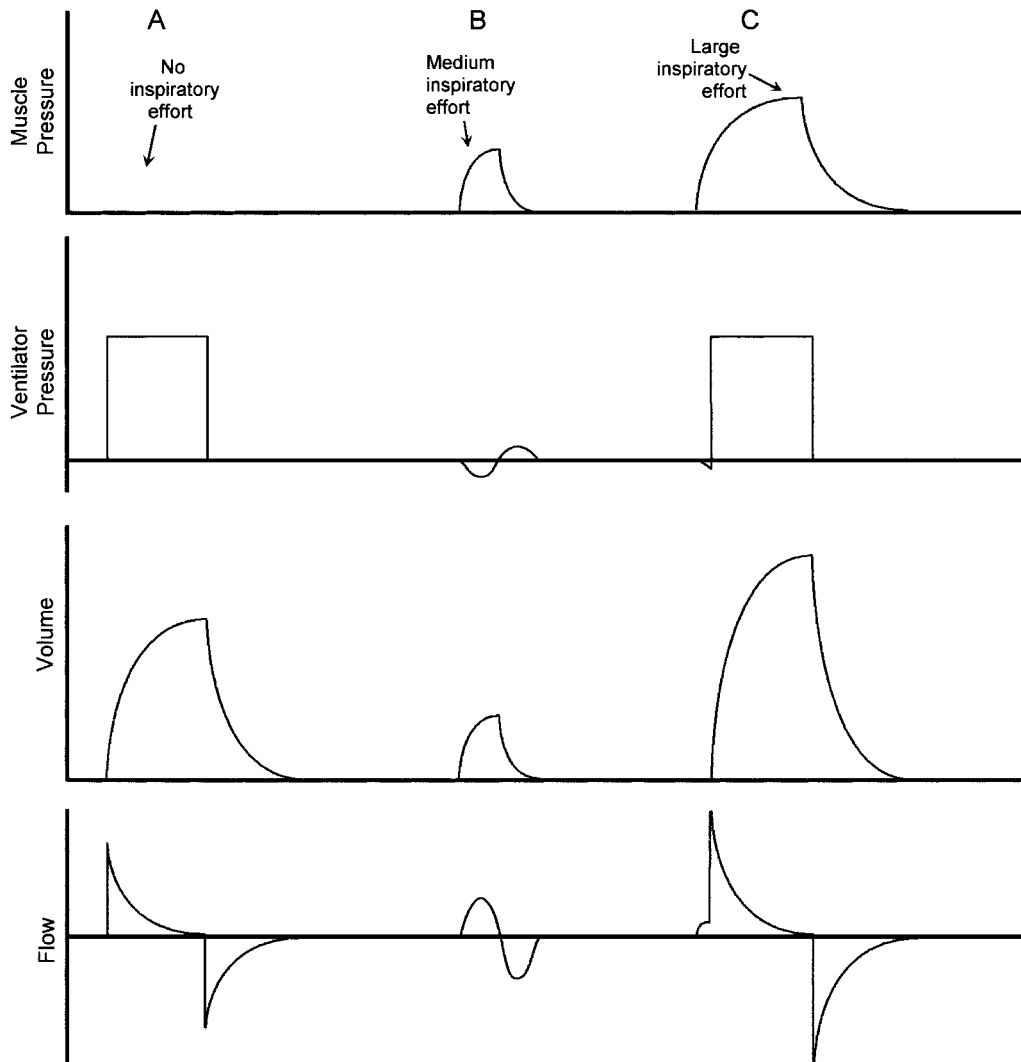
Fig. 8. Dräger Evita 4 mode called PC+, which is a pressure-controlled intermittent mandatory ventilation (PC-IMV) mode with set-point control. Mandatory breaths may be machine-triggered (A) or patient-triggered (C). When patient triggering is allowed, this mode is often referred to as synchronized IMV (SIMV). Unassisted spontaneous breaths may occur between mandatory breaths (B). The small fluctuation in airway pressure during spontaneous breaths is due to the resistance of the expiratory limb of the patient circuit and/or the opening delay in the demand flow valve. (From Reference 9, with permission.)

example, *if* minute ventilation is below the set threshold, *then* deliver a mandatory breath.

Control type. The control type is a categorization of the ventilator's feedback control function.

Control variable. The control variable is the variable that the ventilator uses as a feedback signal to control inspiration (ie, pressure, volume, or flow). For simple set-point control (see *control type*), the control variable can be identified as follows: If the peak inspiratory pressure remains constant as the load experienced by the ventilator changes, then the control variable is pressure. If the peak pressure changes as the load changes but tidal volume remains constant, then the control variable is volume. Volume control implies flow control and vice versa, but it is possible to distinguish the 2 on the basis of which signal is used for feedback control. Some primitive ventilators cannot maintain either constant peak pressure or tidal volume, and thus control only inspiratory and expiratory times (ie, they may be called time controllers).

Conventional ventilator. A ventilator that produces breathing patterns that mimic the way humans normally breathe, at rates and tidal volumes our bodies produce during our usual living activities: 12–25 breaths/min for children and adults, 30–40 breaths/min for infants.
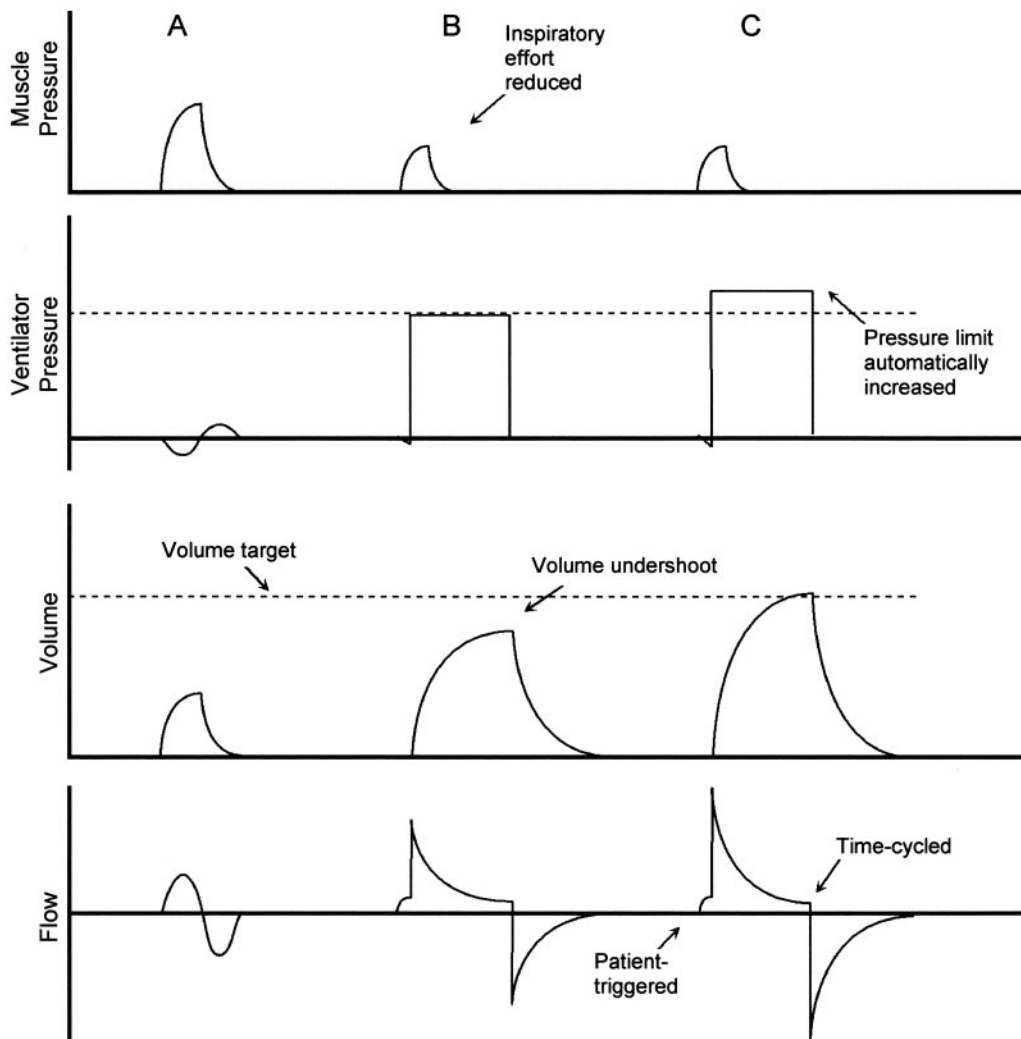
Fig. 9. Dräger Evita 4 mode called SIMV + AutoFlow, which is a pressure-controlled intermittent mandatory ventilation (PC-IMV) mode with adaptive control. Spontaneous breaths are allowed between mandatory breaths (A). The small fluctuation in airway pressure during spontaneous breaths is due to the resistance of the expiratory limb of the patient circuit and/or the opening delay in the demand flow valve. If inspiratory effort decreases, the next mandatory breath (B) will result in a reduced tidal volume. Using adaptive control, the ventilator automatically increases the pressure limit to achieve the set tidal volume (C). (From Reference 9, with permission.)

CPAP. Continuous positive airway pressure, which is a constant pressure maintained at the airway opening throughout the breathing cycle. CPAP is usually associated with unassisted breathing.

CSV. Continuous spontaneous ventilation, in which all breaths are spontaneous.

Cycle. *Verb*: To end the inspiratory time (and begin expiratory flow). *Noun*: A breath (inspiration and expiration).

Cycle variable. The variable (usually pressure, volume, flow, or time) that is measured and used to end inspiration (and begin expiratory flow).

DC-CMV. Dual-controlled continuous mandatory ventilation.

DC-CSV. Dual-controlled continuous spontaneous ventilation.

DC-IMV. Dual-controlled intermittent mandatory ventilation.

Dual control. The control variable switches between pressure and volume within a breath. Control can switch from volume to pressure (eg, pressure-limited ventilation mode on the Dräger Evita 4) or from pressure to volume (eg, volume-assured pressure support mode on the Bird 8400).
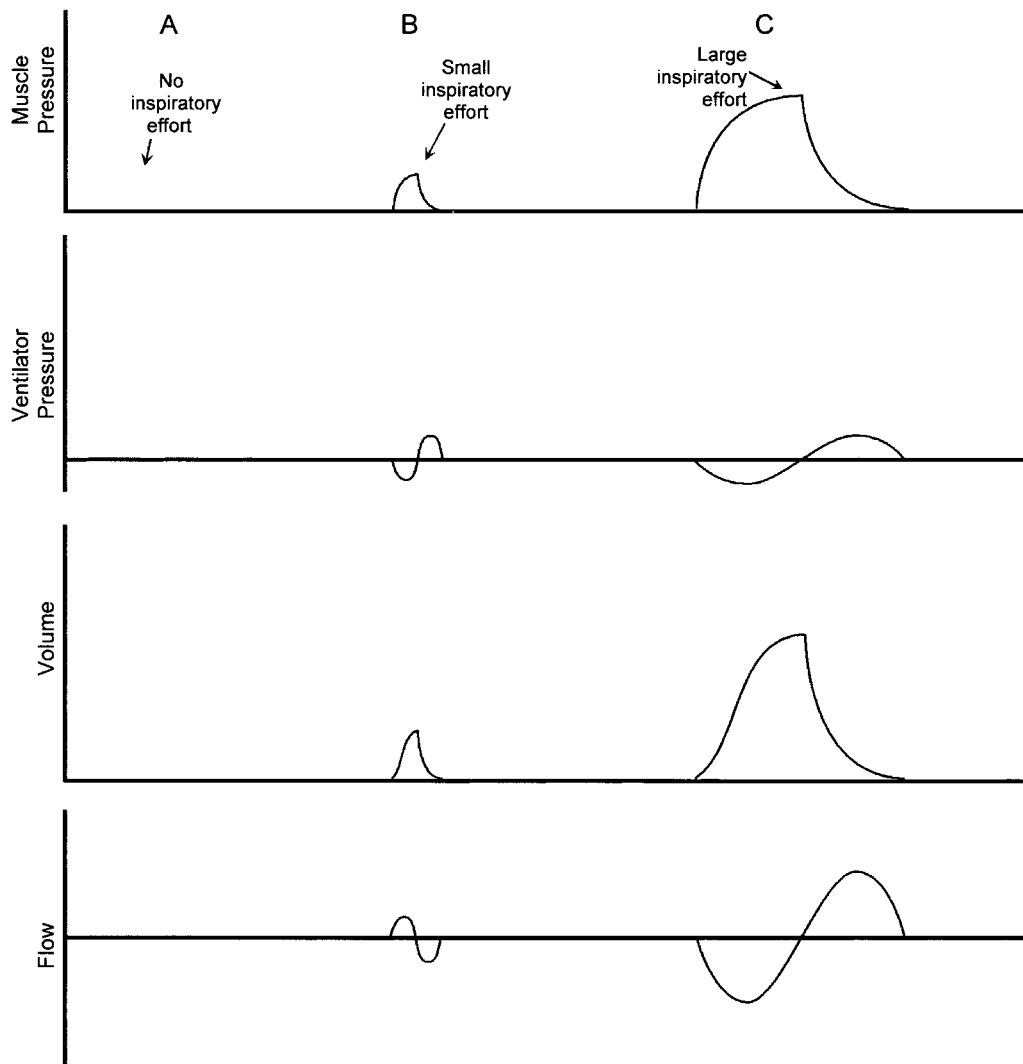
Fig. 10. Dräger Evita 4 mode called CPAP, which is a pressure-controlled continuous spontaneous ventilation (PC-CSV) mode (unassisted). Continuous positive airway pressure (CPAP) allows the patient to breathe spontaneously at a near constant pressure above atmospheric pressure. Because this is a CSV mode, if there is an apnea the patient will not be ventilated (A). Any changes in airway pressure are due to the fact that ventilators are not perfect pressure controllers. A drop in pressure during inspiration and a rise in pressure during expiration indicate that the patient is doing work on the ventilator, due to resistance of the exhalation valve and/or the opening delay of the inspiratory flow demand valve. A good pressure controller will keep the airway pressure fluctuations at a minimum regardless of the patient effort. (From Reference 9, with permission.)

Dynamic compliance. The slope of the pressure-volume curve drawn between 2 points of zero flow (eg, at the start and end of inspiration).

Dynamic hyperinflation. The increase in lung volume that occurs whenever insufficient exhalation time prevents the respiratory system from returning to its normal resting end-expiratory equilibrium volume between breath cycles.

Elastic load. The pressure difference applied across a system (eg, a container) that sustains the system's volume relative to some reference volume, and/or the amount of its compressible contents relative to some reference amount. For a linear system it is elastance $\times$ volume, or, volume/compliance. For a container, the overall effective elastance (compliance) includes the elastances (compliances) of its structural components and the compressibility of the fluid (gas or liquid) within it.

Equation of motion for the respiratory system. A relationship among pressure difference, volume, and flow, that describes the mechanics of the respiratory system. The simplest and most useful form is a differential equation with constant coefficients that describes the respiratory
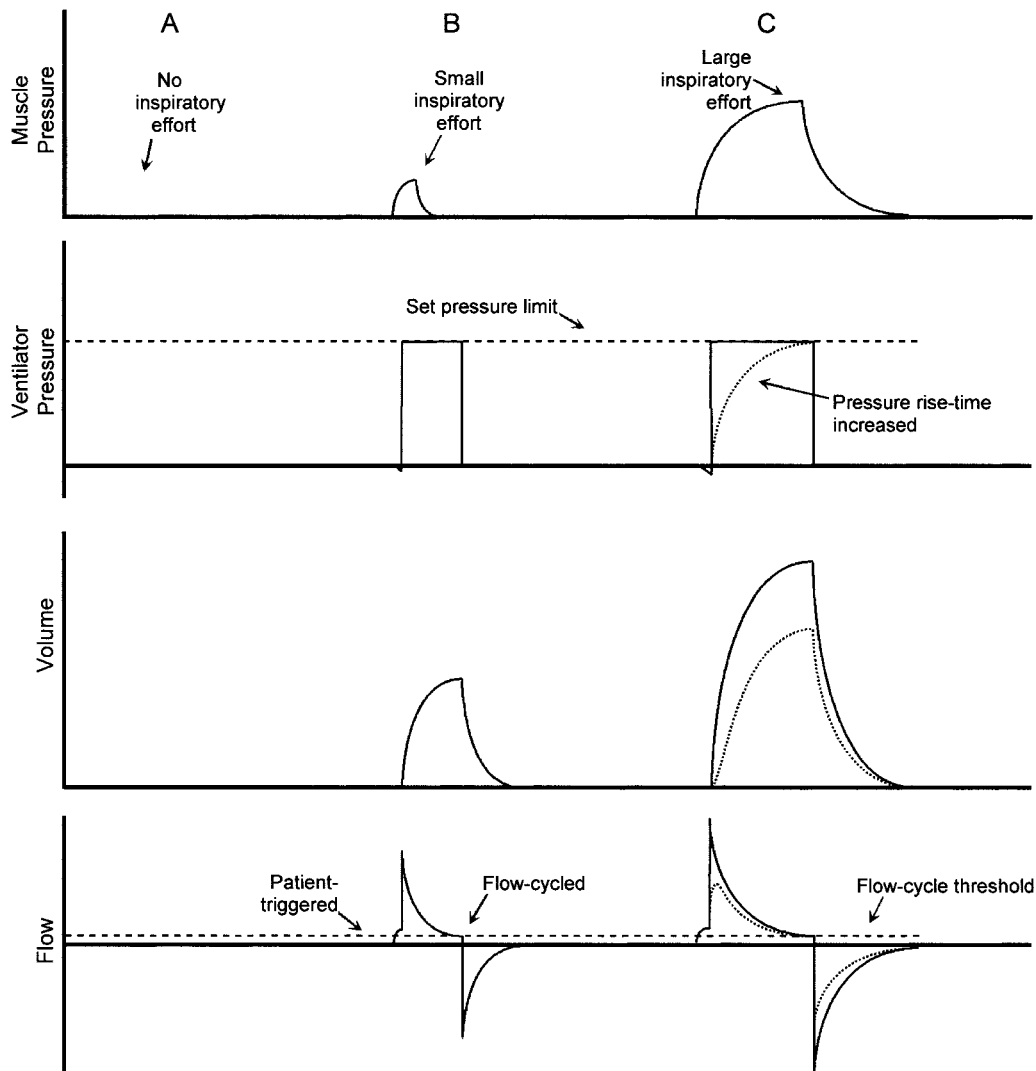
Fig. 11. Dräger Evita 4 mode called Pressure Support, which is a pressure-controlled continuous spontaneous ventilation (PC-CSV) mode (assisted). Because this is a CSV mode, if there is an apnea the patient will not be ventilated (A). Pressure support breaths are typically pressure-triggered or flow-triggered, pressure-limited (above the positive end-expiratory pressure) and flow-cycled. A relatively small inspiratory effort results in a relatively short inspiratory time (B vs C). Usually the flow cycle threshold is preset by the manufacturer as a percentage of peak flow or as an absolute flow setting. Some ventilators allow the operator to set the flow cycle threshold and the pressure rise time (the time required for airway pressure to reach the set pressure limit), to improve ventilator-patient synchrony. Rise time affects the shape of the pressure waveform and hence the volume and flow waveforms. A short rise time gives a more rectangular shape, whereas a long rise time produces a more triangular shape (C) (From Reference 9, with permission.).

system as a single deformable compartment that includes the lungs and chest wall. The version shown below, is often simplified by ignoring the inertia term ($I\ddot{v}$):

$$\Delta p_{TR} \; + \; \Delta p_{mus} \; = \; Ev \; + \; R\dot{v} \; + \; I\ddot{v}$$

where

Δp_{TR} = the change in transrespiratory pressure difference (ie, airway opening pressure minus body surface pressure), measured relative to end ex-

piratory pressure. This is the pressure generated by a ventilator (Δp_{vent}) during an assisted breath.

Δp_{mus} = ventilatory muscle pressure difference; the theoretical chestwall transmural pressure difference that would produce movements identical to those produced by the ventilatory muscles during breathing maneuvers (positive during inspiratory effort, negative during expiratory effort).
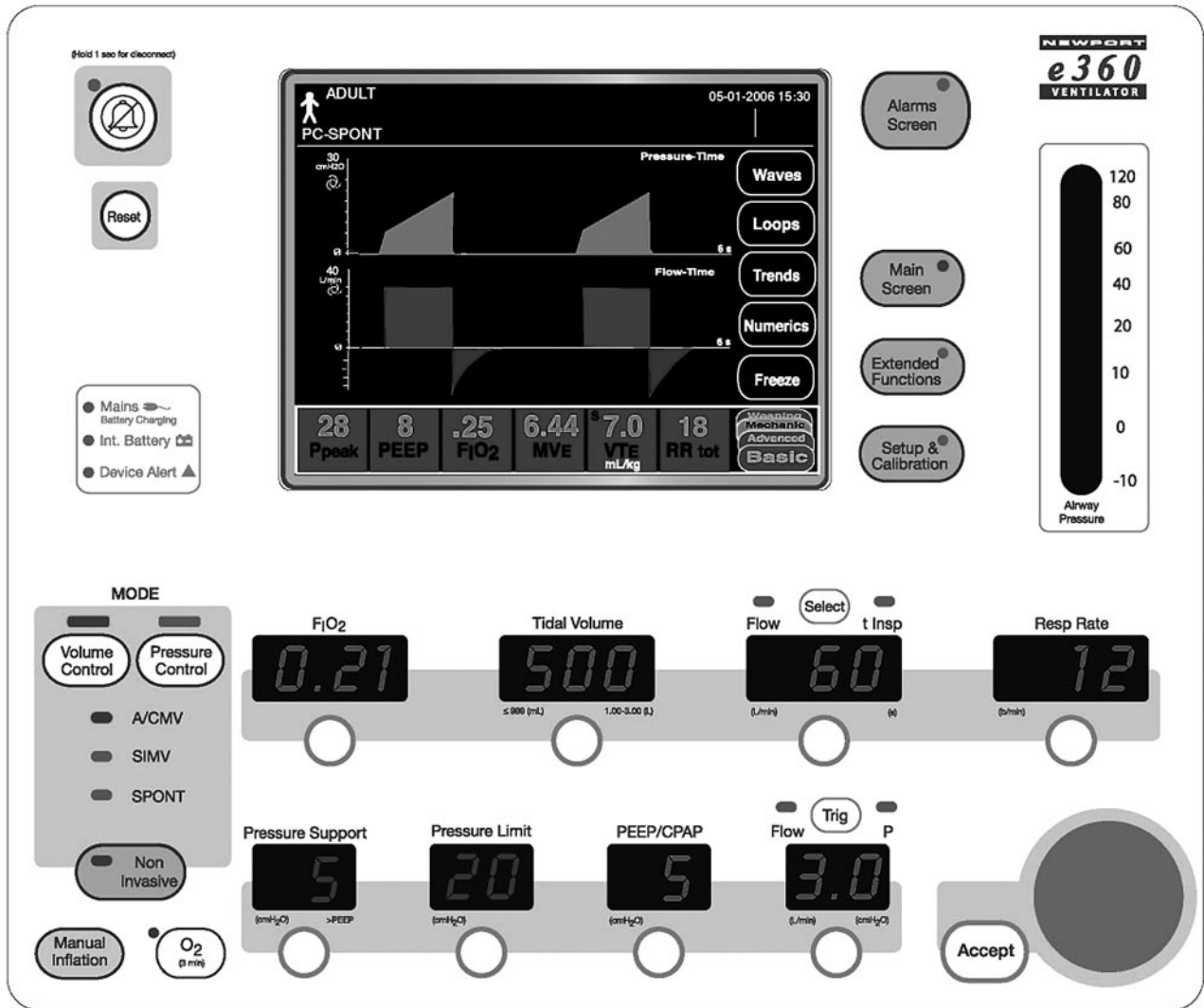
Fig. 12. Front panel of the Newport e360 ventilator. Note the convenient placement of controls to select the breathing pattern (ie, control variable and breath sequence) in the MODE area. The operator may adjust details of the operational algorithms (eg, phase variables and thresholds) to the right of the MODE area.

v = volume change relative to functional residual capacity.

$\dot{v}$ = flow, which is the first derivative of volume with respect to time, measured relative to the end-expiratory flow (usually zero).

$\ddot{v}$ = the second derivative of volume with respect to time.

$\mathbf{E}$ = elastance (inverse of compliance $\mathbf{E} = 1/\mathbf{C}$).

$\mathbf{R}$ = resistance.

$\mathbf{I}$ = inertance.

For mechanical ventilation the equation is often expressed as:

$$\Delta p_{vent} + \Delta p_{mus} = \mathbf{E}v + \mathbf{R}\dot{v}$$

where

Δp_{vent} = the transrespiratory pressure generated by the ventilator during an assisted breath.

Expiratory flow time. The period from the start of expiratory flow to the instant when expiratory flow stops.

Expiratory hold. Occlusion of the airway at the moment when the next inspiration would start; usually implemented to measure intrinsic positive end-expiratory pressure (autoPEEP).

Expiratory pause time. The period from cessation of expiratory flow to the start of inspiratory flow.

Expiratory time. The period from the start of expiratory flow to the start of inspiratory flow. Expiratory time equals expiratory flow time plus expiratory pause time.

Feedback control. Closed-loop control accomplished by using the output as a signal that is fed back (compared) to the operator-set input. The difference between the 2 is used to drive the system toward the desired output (ie, negative feedback control). For example, pressure-controlled modes use airway pressure as the feedback signal to manipulate gas flow from the ventilator to maintain an inspiratory pressure set point.

Flow control. Maintenance of an invariant inspiratory flow waveform despite changing respiratory-system mechanics.

Flow cycle. Inspiration ends and expiratory flow starts when inspiratory flow reaches a preset threshold.

Flow limit. Inspiratory flow reaches a preset value that may be maintained before inspiration cycles off.

Flow trigger. Assisted inspiration starts when inspiratory flow due to patient inspiratory effort reaches a preset threshold.

High-frequency jet ventilation. Ventilation by means of a high-frequency low-volume pulsed jet of gas into the trachea.

High-frequency oscillatory ventilation. Ventilation by means of a piston arrangement (or other mechanism) that moves gas back and forth rapidly in the patient's breathing circuit and airways, causing pressure to oscillate above and below baseline pressure.

High-frequency ventilator. Ventilator that produces breathing patterns at frequencies much higher than can be voluntarily produced (150–900 cycles per minute).

IMV. Intermittent mandatory ventilation, in which spontaneous breaths are permitted between mandatory breaths. When the mandatory breath is patient-triggered, it is commonly referred to as synchronized IMV (or SIMV).

Inspiratory flow time. The period from the start of inspiratory flow to the cessation of inspiratory flow.

Inspiratory pause time. The period from when inspiratory flow stops to the start of expiratory flow.

Inspiratory time. The period from the start of inspiratory flow to the start of expiratory flow. Inspiratory time equals inspiratory flow time plus inspiratory pause time.

Intelligent control. A class of ventilator control types that implement strategic control and/or tactical control, using artificial intelligence programs.

Knowledge-based control. A type of ventilator control that attempts to capture the experience of human experts. It may use various artificial intelligence systems, such as branching logic algorithms, lookup tables, or fuzzy logic.

Leak. The steady-state difference between the inspired V_T produced by the ventilator and the expired volume produced by the patient.

Limit. To restrict the magnitude of a variable (pressure, volume, or flow) to some preset value.

Limit variable. A variable that can reach and be maintained at a preset level *before* inspiration ends but does not end inspiration. Pressure, flow, or volume can be the limit variable.

Load. The pressure required to generate inspiration. See *elastic load* and *resistive load*.

Loop display. A graphic display of one variable against another, such as flow on the vertical axis and volume on the horizontal axis.

Mandatory breath. A breath in which the timing *and/or* size of the breath is controlled by the ventilator. That is, the machine triggers and/or cycles the breath.

Mandatory minute ventilation. A mode in which the ventilator monitors the exhaled minute ventilation as a conditional variable. As long as the patient either triggers mandatory breaths or generates his own spontaneous breath often enough to maintain a preset minute ventilation, the ventilator does not interfere. However, if the exhaled minute ventilation falls below the operator-set value, the ventilator will trigger mandatory breaths or increase the pressure limit until the target is reached.

Mean airway pressure. The average pressure at the airway opening; the mean airway pressure is the area under the pressure-time curve for one breathing cycle divided by the total breathing-cycle time (ie, inspiratory time plus expiratory time).

Mechanical ventilator. An automatic machine designed to provide all or part of the work required to move gas into and out of the lungs to satisfy the body's respiratory needs.

Minute ventilation. The average volume of gas entering, or leaving, the lungs per minute.

Mode of ventilation. A specific combination of breathing pattern, control type, and operational algorithms.

Neural network control. A ventilator control type that uses data modeling tools called artificial neural networks to capture and represent complex input-output relationships. A neural network learns by experience, the same way a human brain does, by storing knowledge in the strengths of inter-node connections.

Operational algorithms. The explicit instructions used by the ventilator's control circuit to generate the breathing pattern. These include a specification of phase variables, conditional variables, embedded system models and control logic, and/or artificial intelligence programs.

Optimum control. A type of ventilator control that uses automatic adjustment of set points to optimize other variables as patient needs change. The term "optimum" implies that some measure of system performance is maximized or minimized. For example, each breath may be pressure-limited and the pressure limit automatically adjusted between breaths. However, this adjustment is not just to hit a preset target such as V_T (as in adaptive control). Rather the adjustment is made in such a way that the work of breathing (which is calculated and updated dynamically) is minimized and a preset minute ventilation is maintained (eg, adaptive support ventilation mode on the Hamilton Galileo ventilator).

Parallel connection. In a pneumatic circuit, an arrangement in which 2 or more pathways share the same pressure drop but possibly different flows (eg, the right and left lungs).

Partial ventilatory support. The ventilator and the respiratory muscles each provide some of the work of breathing. During partial ventilatory support, muscle pressure adds to ventilator pressure in the equation of motion.

PC-CMV. Pressure-controlled continuous mandatory ventilation.

PC-CSV. Pressure-controlled continuous spontaneous ventilation.

PC-IMV. Pressure-controlled intermittent mandatory ventilation.

PEEP. Positive end-expiratory pressure, which is a positive pressure (relative to atmospheric pressure) maintained during expiration; usually associated with assisted ventilation. See *CPAP*.

Phase. One of 4 important events that occur during a ventilatory cycle: (1) the change from expiration to inspiration, (2) inspiration, (3) the change from inspiration to expiration, and (4) expiration.

Phase variable. A variable that is measured and used by the ventilator to initiate some phase of the breath cycle. See *trigger*, *limit*, and *cycle variable*.

Plateau pressure. The static transrespiratory pressure at end inspiration during an inspiratory hold for an assisted breath.

Pressure control. Maintenance of an invariant transrespiratory pressure waveform despite changing respiratory-system mechanics. In pressure-control ventilation, pressure is the independent variable in the equation of motion.

Pressure cycle. Inspiration ends (ie, expiratory flow starts) when airway pressure reaches a preset threshold.

Pressure limit. Inspiratory pressure reaches a preset value and is maintained before inspiration cycles off.

Pressure support. Pressure support is a mode in which all breaths are pressure-triggered or flow-triggered, pressure-limited, and flow-cycled.

Pressure trigger. Inspiration starts when airway pressure reaches a preset threshold.

Proportional assist. A mode in which each breath is patient-triggered, pressure-limited, and flow-cycled, similar to pressure support. However, the pressure limit is not set at some constant, arbitrary value. Rather, it is automatically adjusted by the ventilator to be proportional to the patient's effort. The idea of this mode is to allow the ventilator to support, and essentially cancel, the specific effects of pulmonary pathology. That is, the ventilator can be set to support either the extra elastic load or the extra resistive load (or both) caused by lung disease.

Resistive load. The pressure difference applied across a system (eg, a container) that is related to a rate of change of the system's volume and/or the flow of fluid within or through the system. For a linear system, it is resis-

tance $\times$ flow, or resistance $\times$ rate of change of volume. For a container, the effective resistance includes the mechanical (usually viscous) resistances of its structural components and the flow resistance of the fluid (gas or liquid) within it.

Sensitivity. The sensitivity setting of the ventilator is a threshold value for the trigger variable that, when met, starts inspiration.

Series connection. In a series connection, 2 or more components share the same flow but each may have a different pressure drop (the pressure difference between inlet and outlet) (eg, an endotracheal tube in series with the main bronchus).

Servo control. The output of the ventilator automatically follows a varying input. For example, the automatic tube compensation feature on the Dräger Evita 4 ventilator tracks flow and forces pressure to be equal to flow squared multiplied by a constant (which represents endotracheal tube resistance).

Set point. A value of a ventilator output (eg, pressure limit, tidal volume, flow limit, timing) that is input as a goal for each breath by the operator or a surrogate for the operator (ie, a mathematical model or an artificial intelligence program).

Set-point control. An algorithm that matches the output of the ventilator to a constant operator-preset input (eg, pressure limit, flow limit, V_T).

Spontaneous breath. A breath in which *both* the timing *and* size are controlled by the patient. That is, the patient both triggers and cycles the breath.

Strategic control. A class of ventilator control types that allows the ventilator to make tactical changes (ie, automatically adjusted set points) in response to changes in patient condition, based on a long-term strategy.

Synchronized IMV. IMV in which mandatory breaths may be triggered by the patient.

Tactical control. A class of ventilator control types that require the operator to adjust set points (eg, pressure limit, tidal volume, flow limit, and timing).

Tidal volume (V_T). The volume of gas, either inhaled or exhaled, during a breath.

Time constant. The time at which an exponential function attains 63% of its steady state value in response to a step input; the time necessary for inflated lungs to passively empty by 63%; the time necessary for the lungs to passively fill 63% during pressure-controlled ventilation with a rectangular pressure waveform. The time constant for a passive mechanical system is calculated as the product of resistance and compliance, and has units of time (usually expressed in seconds).

Total cycle time. Same as "ventilatory period," which is the sum of inspiratory time and expiratory time.

Total PEEP. The sum of autoPEEP and intentionally applied PEEP or CPAP.

Total ventilatory support. The ventilator provides all the work of breathing. In total ventilatory support, muscle pressure in the equation of motion is zero.

Transairway pressure difference. Pressure at the airway opening minus pressure in the lungs (ie, alveolar pressure).

Transalveolar pressure difference. Pressure in the lungs minus pressure in the pleural space. Equal to transpulmonary pressure difference only under static conditions.

Trans-chest-wall pressure difference. Pressure in the pleural space minus pressure on the body surface.

Transpulmonary pressure difference. Pressure at the airway opening minus pressure in the pleural space.

Transrespiratory pressure difference. Pressure at the airway opening minus pressure on the body surface.

Transthoracic pressure. Pressure in the lungs minus pressure on the body surface.

Trigger. *Verb*: To start inspiration.

VC-CMV. Volume-controlled continuous mandatory ventilation.

VC-IMV. Volume-controlled intermittent mandatory ventilation.

Ventilatory period. The ventilatory period (also called total cycle time or total breath cycle) is the time from the start of inspiratory flow of one breath to the start of inspiratory flow of the next breath; inspiratory time

plus expiratory time; it is the reciprocal of ventilatory frequency.

Volume control. Maintenance of an invariant inspiratory volume waveform despite changing respiratory-system mechanics, using feedback control with the volume signal.

Volume cycle. Inspiration ends (ie, expiratory flow starts) when inspiratory volume (ie, V_T) reaches a preset threshold (ie, tidal volume).

Volume limit. A preset value (ie, tidal volume) that the ventilator is set to attain before inspiration cycles off.

Volume trigger. Assisted inspiration starts when inspiratory volume (ie, small initial volume due to patient inspiratory effort) reaches a preset threshold.

Waveform display. A graphic display of pressure, volume, or flow on the vertical axis and time on the horizontal axis.

Work of breathing. The general definition of work of breathing is the integral of pressure with respect to volume. There are 2 general components of work related to mechanical ventilation. One is the work performed by the ventilator on the patient, which is reflected by a positive change in airway pressure above baseline during inspiration. The second component is the work the patient does on the ventilator to trigger inspiration.

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