Documentation Issues for Mechanical Ventilation in Pressure-Control Modes

Robert L Chatburn MHHS RRT-NPS FAARC and Teresa A Volsko MHHS RRT FAARC

As hospitals begin to implement electronic medical records, the inadequacies of legacy paper charting systems will become more evident. One area of particular concern for respiratory therapists is the charting of mechanical ventilator settings. Our profession's lack of a standardized and generally accepted taxonomy for mechanical ventilation leaves us with a confusing array of terms related to ventilator settings. Such confusion makes database design impossible for information technology professionals and is a risk-management concern for clinicians. Of particular note is the complexity related to set airway pressures when using modes whose primary control variable is pressure (versus volume). We review the clinically relevant issues surrounding documentation of the patient-ventilator interactions related to airway pressure and provide suggestions for a standardized vocabulary. *Key words: mechanical ventilation; terminology; medical record; charting; simulation; ventilator design; information technology; medical informatics; taxonomy.* [Respir Care 2010; 55(12):1705–1716. © 2010 Daedalus Enterprises]

Introduction

Technological advances in ventilator design provide clinicians with a variety of options to support the work of the respiratory system and improve gas exchange. To safely and effectively initiate and manage mechanical ventilation, the clinician must have a good understanding of the ventilator design and mode capability to appropriately match the ventilator's output with the patient's physiologic demand. Ventilators have substantially evolved over the last 3 decades.[1] What was once a simple machine has been transformed into a complex computer with sophisticated software. Unfortunately, the advances in ventilator technology and innovative marketing strategies have outstripped our system of nomenclature for mechanical ventilation. Confused terminology can create problems, especially when very similar or identical names are applied to different ventilation modes, or different names are applied to the same mode.

Inconsistencies of this nature can be found in the literature and contribute to misinterpretation of findings and inaccurate reporting. In a comparison of the use of volume-control and pressure-control ventilation to treat respiratory failure in patients with chronic obstructive pulmonary disease, Karakurt et al used the acronym "IMV" to mean both invasive mechanical ventilation and intermittent mandatory ventilation.[2] Carvalho et al vaguely describe bi-level and pressure-support ventilation (PSV) modes as "frequently used modes of spontaneous breathing" in a report that compared the effect of bi-level ventilation and PSV on oxygenation and pulmonary blood flow.[3] They confounded the concept of a "mode" with the concept of "spontaneous breathing," and the definitions of both were left to the reader's imagination.

Inaccurate descriptions of ventilator modes occur frequently. For example, in a systematic review of 50 published reports, Rose and Hawkins highlighted the inconsistencies that occurred when authors described biphasic positive airway pressure (BIPAP) ventilation and airway pressure-release ventilation (APRV).[4] Such inconsistencies are more than just a nuisance; from an educator's

Robert L Chatburn MHHS RRT-NPS FAARC is affiliated with the Respiratory Institute, The Cleveland Clinic, and with Lerner College of Medicine, Case Western Reserve University, Cleveland, Ohio. Teresa A Volsko MHHS RRT FAARC is affiliated with the Respiratory Therapy Program, Department of Health Professions, Youngstown State University, Youngstown, Ohio.

Mr Chatburn has disclosed relationships with IngMar, Hamilton, Covidien, and Dräger. Ms Volsko has disclosed no conflicts of interest.

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

perspective, they create barriers to the learning process, which may prevent the clinician from completely understanding how to properly operate the ventilator.

The lack of a generally accepted and standardized vocabulary for mechanical ventilation complicates the assessment process. Educational and competency assessment tools focus on specific knowledge components or technical skills. If terms are not accurately or consistently defined, educators have difficulty developing the content matrices and test items needed to assess work-based training,[5] as well as initial and ongoing competency assessment instruments.[6] Lack of consistency with terminology may compromise the reliability and validity of the testing instrument. These implications also affect the accuracy from which quality monitoring tools are developed and data are gathered. Lack of a well developed quality-assessment tool may create a barrier to the discovery of procedural and documentation errors. Documentation errors in the medical record increase the risk of medical decision errors and adverse patient outcomes.[7,8]

A study by Vawdrey and colleagues concluded that even at institutions where manual charting of ventilator settings is performed well, automatic data collection should be used to eliminate delays, improve charting efficiency, and reduce errors caused by incorrect data transcription.[9] Yet an incomplete or conflicted lexicon prevents the design of even a simple data-acquisition system to allow efficient data mining; you cannot measure what you cannot describe. Inconsistent terminology makes database normalization impossible. Normalization is the process of creating database tables according to specific rules in order to eliminate redundant or duplicate data and to avoid problems with inserting, updating, or deleting data.[10] For example, a database for an electronic medical record that contains a single field called "pressure support" could result in a violation of what is called the "first normal form" for a relational database, because (as we will show below) "pressure support" has multiple meanings, which creates the need to store multiple different values for the same record, which would lead to ambiguous search results if only one data field is available.

Specific Problems With Documenting Pressure-Control Modes

The general issues of documentation have been at the forefront of discussions during the work-flow design for electronic charting in the intensive care units (ICUs) at the Cleveland Clinic. This task, recently engaged by the respiratory therapy department, was a component of a larger project to expand the use of electronic charting throughout the hospital. The conversion to an electronic medical record has cast a spotlight on some issues related to documentation of ventilator settings, particularly with pressure-control modes, which have previously been "hiding in the shadows" with paper charting. Note that in this paper we use the term "pressure-control" in a generic sense, referring to any mode in which the pressure waveform is preset, in contrast to a mode in which the volume waveform is preset (ie, volume control). The basic problems we are experiencing stem from the evolution of ventilator technology and the lack of progress towards a standardized vocabulary and associated documentation procedures. The problems are in 2 main categories: documenting the inspiratory pressure of mandatory breaths and documenting the pressure support of spontaneous breaths.

Mandatory Breaths

Mandatory breaths are defined as those for which inspiration is machine-triggered (initiated) *and/or* machine-cycled (terminated). Historically, pressure control of mandatory breaths was initially available only on infant ventilators. On these devices the convention is to indicate the peak inspiratory pressure (PIP) as gauge pressure (ie, relative to atmospheric pressure). When pressure control became available on adult ventilators, the convention switched to indicating PIP as relative to the set end-expiratory pressure (PEEP). Later, when "bi-level" modes such as BIPAP and APRV became features on adult ventilators, the convention for these modes switched back again to indicating PIP as gauge pressure in those modes. Indeed, both conventions are sometimes used on the same ventilator, depending on whether the pressure-control mode is "conventional" or "bi-level." Bi-level modes are distinguished by the use of an "active exhalation valve" that allows unrestricted spontaneous breathing (either assisted or unassisted) at any time, including during a mandatory breath with an extended inspiratory time (so called "PEEP high" at "T high").

Table 1 gives a sample of the actual definitions found in the operator's manuals of some common ventilators used in the United States. Figure 1 illustrates the conventions shown in Table 1. Aside from the inconsistency in the abbreviations and the definitions themselves, there is a much more important and fundamental problem: we believe that "inspiratory pressure" is universally understood to mean a change in airway pressure during a breath assisted by a ventilator. However, the baseline reference pressure may be either the atmospheric pressure (Patm) or the PEEP, depending on the ventilator. And some ventilators, such as the Covidien Puritan Bennett 840 and the Maquet Servo-i, use Patm or PEEP, depending on the mode.

Spontaneous Breaths

Spontaneous breaths are defined as those for which inspiration is *both* patient-triggered (initiated) and patient-

Table 1. Definitions From Ventilator Manuals

Manufacturer	Ventilator	Ventilating Pressures: Term	Ventilating Pressures: Manufacturer's Definition	Baseline Reference Pressure
Dräger	EvitaLX	Phigh	Set value of the upper pressure level in airway pressure-release ventilation (APRV)	PEEP
		Pinsp	Set value of the upper pressure level in the EvitaLX's PCV+ mode	PEEP
		Plow	Set value of the lower pressure level in APRV	Patm
		Pmax	Set value for pressure-limited ventilation	Patm
		Pmean	Mean airway pressure	Patm
		Pmin	Minimum airway pressure	Patm
		Ppeak	Peak pressure	Patm
		Pplat	End-inspiratory airway pressure	Patm
		Psupp	Set value of pressure support	PEEP
		ΔPsupp	Setting for Psupp relative to PEEP	PEEP
Hamilton	G5	Pcontrol	Pressure control: a control setting in the G5's PC-CMV and P-SIMV modes: pressure (additional to PEEP/CPAP) applied during the inspiratory phase	PEEP
		P high	High positive airway pressure: a control setting	Patm
		Pinsp	Inspiratory pressure: the target pressure (additional to PEEP/CPAP) applied during the inspiratory phase in the G5's adaptive support ventilation (ASV) mode	PEEP
		PIP	Positive inspiratory pressure from glossary	Unknown
		P low	Low positive airway pressure level: a control setting	Patm
		Ppeak	Peak airway pressure: a monitored parameter	Patm
		Pplateau	Plateau airway pressure: a monitored parameter	Patm
		Pmean	Mean airway pressure: a monitored parameter	Patm
		Psupport	Inspiratory pressure support: a control setting valid during SPONT (spontaneous) breaths. Psupport is pressure (additional to PEEP/CPAP) applied during the inspiratory phase	PEEP
Maquet	Servo-i	PC	Pressure control	PEEP
		Paw	Airway pressure	Patm
		Ppeak	Max inspiratory pressure	Patm
		Phigh	High pressure level	Patm
		Pmean	Mean airway pressure	Patm
		Pplat	Pressure during end-inspiratory pause	Patm
		PS	Pressure support	PEEP
		PS above Phigh	Inspiratory pressure support level for breaths triggered during the T_{high} period in the Servo-i's BiVent mode	Phigh
		PS above PEEP	Inspiratory pressure support level for breaths triggered during the T_{PEEP} period in the Servo-i's BiVent mode	PEEP
Covidien	Puritan Bennett 840	$PEEP_H$	High level of positive airway pressure in Puritan Bennett 840's BiLevel mode	Patm
		$PEEP_L$	Low level of positive airway pressure in Puritan Bennett 840's BiLevel mode	Patm
		P_{MEAN}	Mean circuit pressure: a calculation of the measured average patient circuit pressure over an entire respiratory cycle	Patm
		P_I	Inspiratory pressure: the operator-set inspiratory pressure at the patient Y-piece (above PEEP) during a pressure-control mandatory breath	PEEP
		$P_{I\ END}$	End inspiratory pressure: the pressure at the end of the inspiration phase of the current breath. If plateau is active, the displayed value reflects the level of end-plateau pressure.	Patm

(continued)

Table 1. Definitions From Ventilator Manuals (continued)

Manufacturer	Ventilator	Ventilating Pressures: Term	Ventilating Pressures: Manufacturer's Definition	Baseline Reference Pressure
		P_{PEAK}	Maximum circuit pressure: the maximum pressure during the inspiratory phase of a breath	Patm
		P_{SUPP}	Pressure support: a setting of the level of inspiratory assist pressure (above PEEP) at the patient Y-piece during a spontaneous breath	PEEP
Pulmonetics	LTV 950	MAP	Mean airway pressure	Patm
		PIP	Peak inspiratory pressure: the maximum circuit pressure during the inspiration and first 300 ms of the exhalation phase. PIP is measured at the patient Y-piece.	Patm
		Pressure Control	The target pressure above 0 cm H_2O for pressure-control breaths	Patm
		Pressure Support	The target pressure above 0 cm H_2O for pressure-support patient breaths	Patm
CareFusion	Avea	Insp Pres	During a mandatory pressure breath the ventilator controls the inspiratory pressure in the circuit. For pressure and time cycled pressure limited breaths, the pressure achieved is a combination of the preset inspiratory pressure plus PEEP.	PEEP
		Pressure Support	The pressure level during inspiration is a preset pressure support ventilation level plus PEEP.	PEEP
CareFusion	VIP Bird	High Pressure Limit	A control parameter in the VIP Bird's Time Cycle mode (ie, IMV/CPAP) that establishes the peak inspiratory pressure for mandatory breaths. This is an alarm parameter in the VIP Bird's Volume Cycled modes (ie, Assist/Control and SIMV/CPAP).	Patm
		Pressure support	Sets the inspiratory pressure above PEEP/CPAP	PEEP
Dräger	Babylog 8000	Pinsp	Inspiratory pressure: a control parameter that sets the maximum airway pressure	Patm
		Peak	The measured maximum value of airway pressure during a breath	Patm

cycled (terminated). The introduction of pressure support (PS) to assist spontaneous breaths added complexity. Historically, we have documented a single setting for PS, defined as an assisted breath that is patient-triggered, pressure targeted to a preset value, and patient-cycled. There has always been some ambiguity with this practice because the target inspiratory pressure (ie, "pressure support level") is set relative to atmospheric pressure in some ventilators (eg, LTV 950 home-care/transport ventilator, see Table 1) but is set relative to PEEP in others (eg, most ICU ventilators, see Table 1). Interestingly, when infant ventilators evolved to the point of offering pressure support, a dichotomy was introduced, in that the breath type determined the baseline pressure to which inspiratory pressure was referenced. Inspiratory pressure for spontaneous breaths was referenced to PEEP, as in adult ventilators, whereas inspiratory pressure for mandatory breaths continued to be referenced to Patm (see Bird VIP in Table 1). This ambiguity has simply been ignored, with the idea that operators with sufficient training will recognize the difference. Nevertheless, errors have occurred when operators have charted and set the same value on different ventilators.

With the development of the "active exhalation valve," unrestricted spontaneous breathing became possible during mandatory pressure-control breaths. This feature is particularly prominent in modes such as APRV[11] and BIPAP.[12,13] Some ventilator manufacturers now allow spontaneous breaths during mandatory breaths to be assisted with pressure support. Unfortunately, there is no standardization among manufacturers, and 2 conventions have emerged from 2 of the major vendors:

1. Covidien (Puritan Bennett 840 ventilator): PS is set as a single value and is always relative to PEEP (and is labeled PS above PEEP on the display). As a consequence, the level of assistance is always lower for spontaneous breaths occurring during the mandatory breaths (ie, during "$PEEP_H$"), because the level of assistance (proportional to

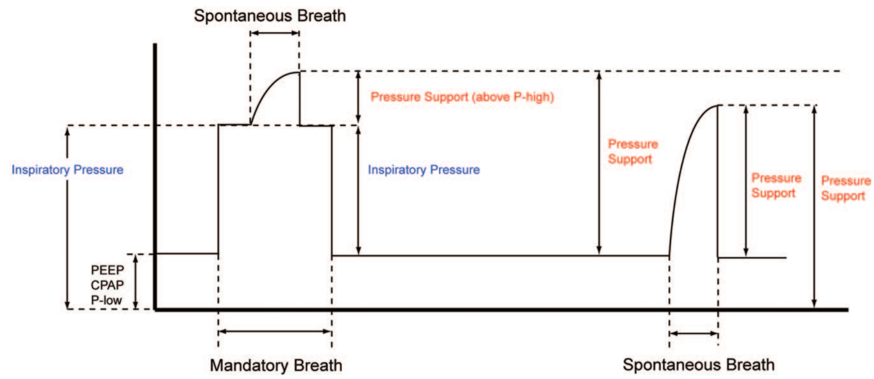

Fig. 1. Idealized airway pressure waveform, showing various conventions used for pressure parameters (see Table 1). Note that there are 2 ways to define the inspiratory pressure (blue) of a mandatory breath, and 4 ways to define the pressure support of a spontaneous breath (red). PEEP = positive end-expiratory pressure. CPAP = continuous positive airway pressure. P-low = low pressure.

ΔP) at "$PEEP_H$" is PS − $PEEP_H$, whereas the level of assistance at "$PEEP_L$" is PS − $PEEP_L$.

2. Maquet (Servo-i ventilator): PS is set as 2 values, labeled "PS above P-high" and "PS above PEEP." As a consequence, the level of assistance for spontaneous breaths occurring during the mandatory breaths may be lower than, the same as, or higher than the assistance for spontaneous breaths occurring between mandatory breaths, depending on the relative values of "PS above P-high" and "PS above PEEP."

Ramifications of Inconsistent Terminology

Mathematical models have been described that allow generalizations based on hypothetical ventilation scenarios.[14-16] These models indicate that during pressure-control ventilation, the delivered tidal volume is a function of the pressure change relative to the start of the breath (ie, ΔP). Therefore, defining the operator-set inspiratory pressure as having a baseline reference of PEEP makes physiologic and mathematical sense. On the other hand, defining set inspiratory pressure as having a baseline reference of Patm has the appeal of being equivalent to measured peak airway pressure and thus indicating something about the potential risk of over-distention of the lungs.

The problem is that when a patient is changed from one ventilator (or mode) using one convention to another ventilator (or mode) with the other convention, the risk of inadvertently setting the wrong inspiratory pressure increases and could lead to adverse events. For example, imagine a ventilated patient with respiratory system resistance of 10 cm H_2O/L/s and compliance of 0.035 L/cm H_2O. This patient is transported on a ventilator with set inspiratory pressure of 25 cm H_2O (relative to Patm), PEEP of 10 cm H_2O, and inspiratory time of 1.0 s. Under the assumption of no intrinsic PEEP, the measured peak airway pressured with this particular ventilator is 25 cm H_2O, the ΔP is 25 –10 = 15 cm H_2O, and the tidal volume would be 495 mL (note that this value is derived from a model of exponential volume increase in response to a step change in inspiratory pressure[14]). On arrival to the ICU, pressure-control ventilation is initiated with a ventilator in which inspiratory pressure is set relative to PEEP. If the same settings were used (inspiratory pressure 25 cm H_2O and PEEP 10 cm H_2O), the new peak airway pressure would be 25 + 10 = 35 cm H_2O, ΔP would be 25 cm H_2O, and the tidal volume would be 825 mL!

In this example the patient is put at risk of ventilator-induced lung injury and cardiac compromise because of the inadvertent increase in ΔP and mean airway pressure. If the transport had been in the opposite direction, the patient would have been at risk of hypoventilation due to a lower ΔP and loss of oxygenation due to decreased mean airway pressure. You could argue that a knowledgeable clinician would not make such a mistake, because of familiarity with the 2 ventilators. But what if the patient was being manually ventilated during intra-hospital transport to the ICU and the only data available were the inspiratory pressure and PEEP? Clearly, the risk of confusion, if not actual harm, is inherent in the way we document ventilator settings, due to lack of standardization.

The rest of this discussion will focus on potential solutions regarding the definitions and charting of airway pressures during pressure-control ventilation modes. Figure 1 illustrates the most complicated scenario, in which a patient is ventilated with a "bi-level" mode. The term bi-level, as used here, means pressure-control intermittent mandatory ventilation with unrestricted spontaneous breaths permitted throughout the ventilatory cycle (ie, both during and between mandatory breaths). Note in particular that there 2 possible definitions (in blue) for the inspiratory pressure of a mandatory breath, and 4 possible definitions (in red) for pressure support.

Proposed Solutions for Documenting Pressure-Control Modes

Basic Concepts

The first step in simplifying this issue is to recognize that certain terms are relatively unambiguous, including peak airway pressure, mean airway pressure, plateau pressure, and PEEP. Because these are parameters (characteristics) of the airway pressure waveform, which is universally represented relative to atmospheric pressure, and these parameters are widely understood to be measured relative to atmospheric pressure as the baseline, they need no further explanation. When comparing 2 pressures, both need to be referenced to the same value: either absolute pressure (measured relative to a vacuum), or gauge pressure (measured relative to atmospheric pressure), to maintain dimensional consistency. By convention, all ventilator pressures are displayed as gauge pressure (hence "atmospheric" gauge pressure equals zero).

The pressure associated with tidal volume delivery is a different matter. It has been called many things, including inspiratory pressure, peak inspiratory pressure, pressure control, pressure limit, P high, and ΔP. As stated above in the section on Ramifications of Inconsistent Terminology, an explicit knowledge of the baseline value for calculating the change in pressure (ΔP) has clinical importance. But which baseline should we use: Patm or PEEP? We can gain some clarity on terminology by referring to the equation of motion for the respiratory system[17]:

$$P = EV + R\dot{V} \tag{1}$$

where P is transrespiratory system pressure (ie, pressure at the airway opening minus pressure on the body surface), E is respiratory-system elastance, V is volume, R is respiratory system resistance, and $\dot{V}$ is flow. This equation relates pressure, volume, and flow as variable functions of time, where the change in each is relative to its value at end-expiration (ie, the value at the start of inspiration). Thus, we have a theoretical precedent for referencing PEEP as the relevant baseline for defining inspiratory pressure. As an aside, the term EV is the pressure associated with the volume expansion of the elastic compartment (ie, lungs and chest wall), or transthoracic pressure (ie, pressure in the lungs minus pressure on the body surface). Given that the change in V during inspiration, ΔV, is called "tidal volume," the associated change in transthoracic pressure (ΔEV) during inspiration may be identified as "tidal pressure."

The next step is to make unambiguous distinctions between mandatory and spontaneous breaths. These definitions have been reported in the literature[18] and described in several textbooks,[14,19-22] but we will repeat them here:

A spontaneous breath is one for which the patient can substantially influence the timing of the breath (ie, both frequency and inspiratory time), either by active ventilatory effort or passively through lung mechanics. This implies that the patient initiates and terminates inspiration. In other words, inspiration is both patient-triggered and patient-cycled. Note that this definition of spontaneous does not require that a ventilator be involved and is thus consistent with the more common yet less rigorous usage of the word to mean unassisted breathing. During normal breathing, inspiration is triggered and cycled by the natural neurological controls of the nervous system. Thus, a spontaneous breath may or may not be assisted with a ventilator: the definition of "assisted" being entirely unrelated to the definition of "spontaneous." An assisted breath is one for which the ventilator performs some portion of the work of breathing.

A mandatory breath is one for which the patient has lost a substantial degree of control of the timing of the breath (ie, frequency and/or inspiratory time). This occurs when the ventilator initiates and/or terminates inspiration. In other words, inspiration is machine-triggered and/or machine-cycled. Thus mandatory breaths are either machine-triggered and machine-cycled, machine-triggered and patient-cycled, or patient-triggered and machine-cycled. Mandatory breaths may also be synchronized with the patient's inspiratory and/or expiratory efforts (Figure 2).

A short digression is required here to examine the concepts of triggering and cycling in more detail, because the complexities of some modes require that the definitions be applied thoughtfully. Trigger and cycle criteria can be grouped into 2 categories: machine-initiated and patient-initiated. Machine-initiated criteria are those that determine the start and/or end of the inspiratory phase independent of a signal from the patient to begin inspiration. This means that the ventilator determines the inspiratory time and/or expiratory time, or, alternatively, the inspiratory time and/or frequency independent of the patient's natural ventilatory control mechanisms. Machine-triggering criteria include (but are not limited to) frequency, expiratory time, percent of peak expiratory flow, and minimum spontaneous minute ventilation. Machine-cycling criteria include (but are not limited to) inspiratory time and tidal volume.

Patient-initiated criteria are those that affect the start and end of the inspiratory phase relatively independent of machine settings. This means that the patient may substantially affect the inspiratory time and frequency. Patient-triggering criteria include (but are not limited to) transrespiratory system pressure, inspiratory volume, inspiratory flow, diaphragmatic electromyogram (EMG) signal, and transthoracic electrical impedance. Patient-cycling criteria include (but are not limited to) transrespiratory system,

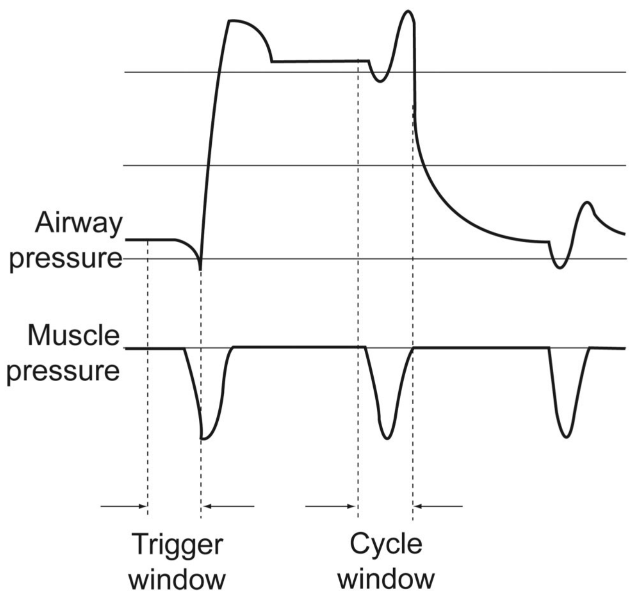

Fig. 2. Airway pressure and simulated muscle pressure waveforms, illustrating synchronization of a mandatory breath in a bi-level mode. Detection of a patient signal (eg, flow or pressure change) within the trigger window initiates a trigger event to synchronize the mandatory inspiration with the patient's inspiratory effort. Similarly, detection of an expiratory signal within the cycle window initiates a cycle event to synchronize the mandatory expiration with the patient's expiration. This figure was made with a lung simulator (ASL 5000, IngMar Medical, Pittsburgh, Pennsylvania) connected to a ventilator (Avea, ViaSys/CareFusion, San Diego, California) set to deliver airway-pressure-release ventilation (pressure support = 0) with the Avea's "TI sync" and "TE sync" features activated.

pressure, percent of peak inspiratory flow, diaphragmatic EMG signal, and transthoracic electrical impedance.

Simplified Definitions for Documentation

The terms and abbreviations proposed below are a compromise between specificity and simplicity. We have attempted to provide enough letters in abbreviations to properly identify the parameters of interest, while keeping them simple enough (particularly for compound parameters) to be easily implemented in electronic medical record displays that may not, for example, support subscripts.

Inspiratory Pressure for Mandatory Breaths

We propose to standardize the term "inspiratory pressure," symbolized IP, for mandatory breaths. There appears to be a trend among adult intensive-care ventilator manufacturers to define the setting of inspiratory pressure in pressure-control modes as relative to PEEP, which is consistent with the discussion above regarding the equation of motion. However, for accurate documentation purposes we need to accommodate ventilators with which the operator cannot directly set IP relative to PEEP. Therefore, we need to define 2 specific cases of IP, according to the baseline pressure reference. We suggest IP for inspiratory pressure set relative to (ie, above) PEEP, and PIP for "peak inspiratory pressure" set relative to atmospheric pressure. Using PIP for a *set* target value for inspiratory pressure is analogous to using peak airway pressure (PAP or Ppeak) for the *measured* maximum value for inspiratory pressure, and should therefore be easy to remember. Also, infant ventilators have historically used this convention. A less satisfactory alternative might be PIP-Patm which would lead to the unwieldy term PS-PIP-Patm to designate pressure support above the target inspiratory pressure for a mandatory breath.

Some examples will illustrate usage of these terms. If PEEP = 5 cm H_2O, then an IP setting of 20 cm H_2O would yield a peak airway pressure of 25 cm H_2O, whereas a PIP setting of 20 cm H_2O would yield a peak airway pressure of 20 cm H_2O. Expressed mathematically:

$$\text{Ppeak} = \text{IP} + \text{PEEP} = \text{PIP}$$
$$\text{Ppeak} = 20 + 5 = 25$$
$$\text{IP} = \text{Ppeak} - \text{PEEP} = 25 - 5 = 20$$

where Ppeak is the *measured* peak airway pressure relative to atmospheric pressure (Patm), IP is the *set* inspiratory pressure relative to the set positive end-expiratory airway pressure (PEEP), and PIP is the *set* inspiratory pressure relative to Patm.

Inspiratory Pressure for Assisted Spontaneous Breaths: Pressure Support

The set inspiratory pressure for spontaneous breaths has been so long identified with "pressure support" as to constitute a de facto standard. Therefore we suggest continuing to use PS to indicate the IP of an assisted spontaneous breath. However, in order to accurately document PS settings on all ventilators in a universal electronic medical record, PS must have unique field descriptions in the database that correspond to clinical usage. (A database field is a single named variable or category of information, such as "mean airway pressure"). We have 3 options:

1. Define a field called PS and associate it with a field representing the name of the ventilator. This solution would address all ventilators for which only one PS value is set, and would allow decoding of the pressure baseline (ie, Patm or PEEP) for other devices by using the name of the ventilator as a reference along with a look-up table. However, this solution would not allow distinction between the 2 PS settings for the Maquet ventilators or any subsequent ventilators that are introduced with the same feature. Fur-

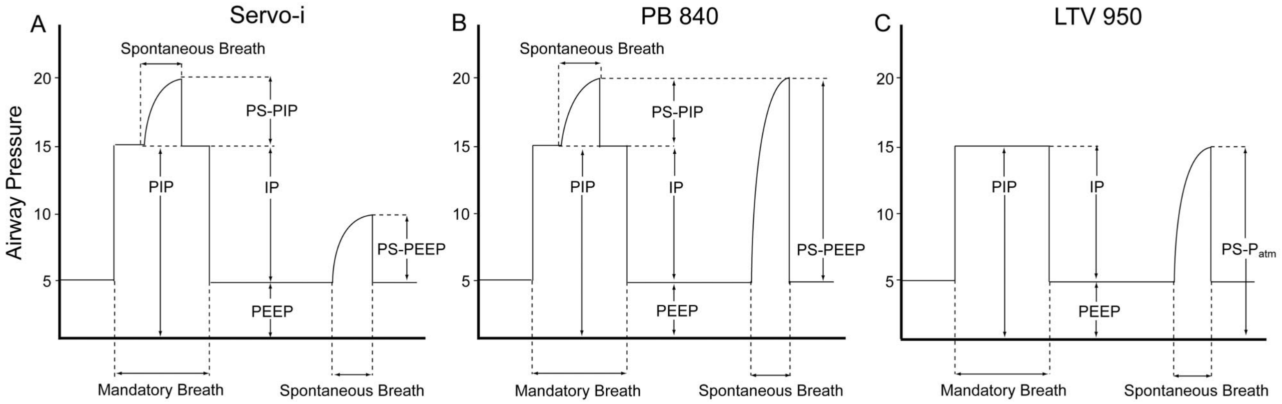

Fig. 3. Our proposal for how set pressures should be defined for pressure-control ventilation modes on 3 of the ventilators mentioned in Table 1. PB = Puritan Bennett. PS = pressure support. PIP = peak inspiratory pressure. PEEP = positive end-expiratory pressure. IP = inspiratory pressure. Patm = atmospheric pressure.

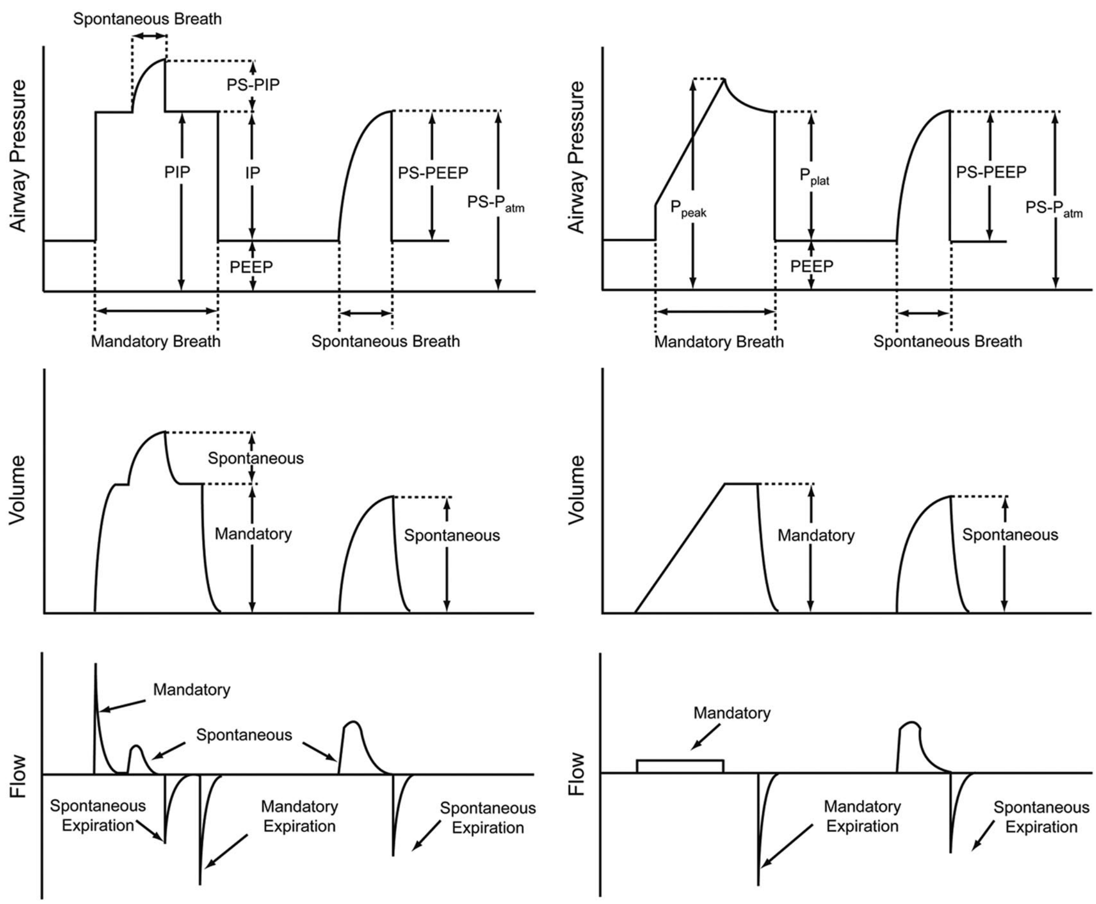

Fig. 4. Idealized pressure, volume, and flow waveforms for pressure-control and volume-control ventilation, illustrating the use of our proposed conventions for the set and measured airway pressures. PS = pressure support. PIP = peak inspiratory pressure. IP = inspiratory pressure. PEEP = positive end-expiratory pressure. Patm = atmospheric pressure. Ppeak = peak airway pressure measured relative to atmospheric pressure (zero). Pplat = plateau pressure, or static pressure at the end of an inspiratory hold, measured relative to atmospheric pressure (zero).

thermore, using the ventilator name as a reference requires information outside the database (ie, ventilator operator's manuals or personal experience) to interpret the PS data in the database, which is a major weakness. Most importantly, this solution would not work if the ventilator name field was left blank.

2. Define 2 fields, PS-PIP and PS-PEEP, as generic descriptors of the PS level during mandatory and between mandatory breaths, respectively. This overcomes the limitation of option 1 and allows documentation of PS nearly independent of the ventilator brand. These specific labels are shorter and more informative than, for example, "PS above P-high" and are not tied to a particular manufacturer's terminology. PS-PIP would require no extra calculations for the Maquet ventilators but would require a separate calculation for the Covidien Puritan Bennett 840 ventilator (which uses PS-PEEP). This calculation (applicable only in the bi-level mode on this ventilator) would be:

$$\text{PS-PIP} = \text{PS-PEEP} + \text{PEEP} - \text{PIP} = \text{PS-Patm} - \text{PIP} \quad (2)$$

This equation converts pressure support relative to PEEP to pressure support relative to atmospheric pressure, so that we can then subtract PIP, which is also relative to atmospheric pressure. For example, consider the Covidien Puritan Bennett 840 in bi-level mode, with $PEEP_L = 5$, $PEEP_H = 15$ and $PS = 20$. Note that $PEEP_H = PIP$, $PEEP_L = PEEP$, and PS = PS-PEEP in the above equation. Then:

$$\text{PS-PIP} = 20 + 5 - 15 = 10 \quad (3)$$

Note that peak airway pressure for spontaneous pressure-supported breaths during mandatory breaths is PS-PEEP + PEEP or, in this example, 20 + 5 = 25. PS-PIP values > 0 indicate inspiratory assist of spontaneous breaths during mandatory breaths (ie, during $PEEP_H$), whereas PS-PIP values ≤ 0 indicate no support of these types of breaths and are ignored. The calculation could in theory be performed by the database, but in practice it would require a reference to a ventilator name field and it would not work if that field was blank. Of more concern, this option leaves no way to document PS-Patm.

3. Define 3 fields: PS-PIP, PS-PEEP, and PS-Patm. Addition of the field PS-Patm would remove all ambiguity from PS documentation, making it completely independent of ventilator brand. If the PS is set relative to Patm, the value is entered directly into the PS-Patm field. Otherwise, PS-Patm could be automatically calculated from the directly entered PS-PEEP and PEEP fields, requiring no extra work by the operator. If PS-Patm is entered directly instead of being calculated, PS-PEEP is automatically calculated. (There is a precedent for this. On the Respironics Vision ventilator the operator sets "inspiratory positive airway pressure [IPAP]" and "expiratory positive airway pressure [EPAP]" and the ventilator calculates and displays the resultant PS relative to PEEP [EPAP].) Inspiratory pressure is entered as either IP or PIP; if one is directly entered (depending on the ventilator), the other is calculated. If PS-PIP is null, meaning it does not have an entered value (including an entered value of 0 if PS is not available during mandatory breaths) *and* if PS-PEEP is entered directly instead of calculated from a PS-Patm entry, then PS-PIP is calculated automatically from the inspiratory pressure setting (to accommodate the Puritan Bennett 840 ventilator). This option is the only one that requires no manual calculations by the operator.

Table 2. Suggested Terminology for Pressure-Control Ventilation Modes

Term	Definition
Set Values	
IP	Inspiratory pressure above set PEEP
PIP	Peak inspiratory pressure above atmospheric pressure (zero)
PEEP	Positive end-expiratory pressure
PS-PEEP	Pressure support level above set PEEP
PS-Patm	Pressure support level above atmospheric pressure (zero)
PS-PIP	Pressure support level above set PIP during a mandatory breath in pressure-controlled intermittent mandatory ventilation (IMV) mode (eg, airway pressure-release ventilation [APRV])
Measured Values	
Ppeak	Peak airway pressure measured relative to atmospheric pressure (zero)
Pmean	Mean airway pressure measured relative to atmospheric pressure (zero)
Pplat	Plateau pressure, or static pressure at the end of an inspiratory hold measured relative to atmospheric pressure (zero)
PEEP	Positive end-expiratory pressure measured relative to atmospheric pressure (zero)

Selection of the optimal solution from the above options is relatively straightforward. If complete documentation is required, then only option 3 is acceptable. Option 3 offers a complete and automatic (therefore more easily implemented) solution, assuming that the programming requirements can be met in the available electronic medical record software.

Figure 3 shows how set pressures are defined with option 3 for pressure-control ventilation on three of the ventilators mentioned in Table 1. Figure 4 shows the idealized pressure, volume, and flow waveforms for volume-control and pressure-control, illustrating the use of our suggested conventions for both set and measured airway pressures.

Figure 4 illustrates the fact that there are potentially 3 tidal volumes that could be charted: a mandatory tidal volume; a spontaneous tidal volume taken during a mandatory breath; and a spontaneous tidal volume taken be-

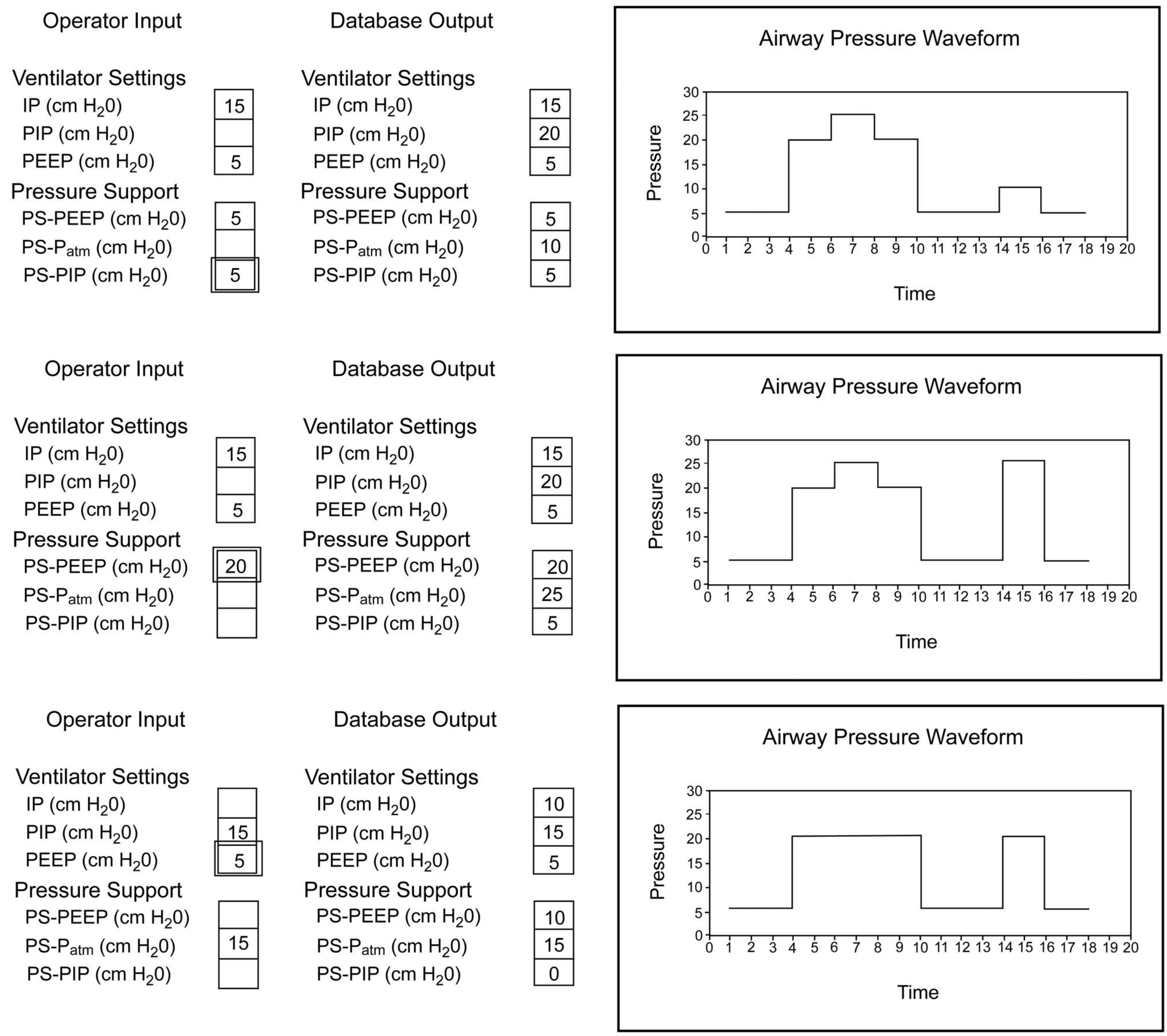

Fig. 5. Examples of charting simulator output for representative ventilators in the bi-level ventilation mode mentioned in Figure 3. Top: Servo-i. Middle: Puritan Bennett 840. Bottom: LTV 950. IP = inspiratory pressure. PIP = peak inspiratory pressure. PEEP = positive end-expiratory pressure. PS = pressure support. Patm = atmospheric pressure. Ppeak = peak airway pressure measured relative to atmospheric pressure (zero).

tween breaths. One could argue that to monitor the implementation of lung-protective strategies, all three of these tidal volumes should be named and charted. On the other hand, one could argue that calling attention to the pressure support level is sufficient surveillance and that there is more practical value in simply monitoring mandatory versus spontaneous minute ventilation in bi-level modes. We will defer this discussion until we have more experience and feedback on our current proposal.

Incidentally, we believe that the use of terms such as "PEEP high" represents a common misunderstanding among some authors and manufacturers: that bi-level modes are not a form of pressure-controlled intermittent mandatory ventilation, but simply 2 levels of shifting baseline pressure. The concept of a bi-level mode as just 2 alternating levels of PEEP has been promulgated by authors[23] and manufacturers alike, and has even dictated the layout of ventilators' user interfaces. This view was presented in the original description of APRV[11] and probably reflects those authors' desire to distinguish the new mode from other modes available on adult ventilators of the era, which did not allow unrestricted spontaneous breathing (they ignored infant ventilators that did have this capability and were also often used with inverse inspiratory-expiratory ratios). However, in our experience in teaching and using ventilation modes, people who view bi-level ventilation in

Table 3. Simulator Equations

Cell Reference	Name	Equation
E25	IP (cm H_2O)	Input data
E26	PIP (cm H_2O)	Input data
E27	PEEP (cm H_2O)	Input data
E29	PS-PEEP (cm H_2O)	Input data
E30	PS-Patm (cm H_2O)	Input data
E31	PS-PIP (cm H_2O)	Input data
H25	IP (cm H_2O)	= IF(AND(COUNTA(E25:E26) = 2,E25<>E26-E27),″?″,IF(AND(E25 = ″″,E26 = ″″),″″,IF(E27 = ″″,″″,IF(E25<>″″,E25,E26-E27))))
H26	PIP (cm H_2O)	= IF(AND(COUNTA(E25:E26) = 2,E25<>E26-E27),″?″,IF(AND(E25 = ″″,E26 = ″″),″″,IF(E27 = ″″,″″,IF(E26<>″″,E26,IF(E27 = ″″,E25 + 0,E25+E27)))))
H27	PEEP (cm H_2O)	= IF(E27 = ″″,″″,E27)
H29	PS-PEEP (cm H_2O)	= IF(AND(COUNTA(E29:E30) = 2,E29<>E30-E27),″?″,IF(AND(E29 = ″″,E30 = ″″),″″,IF(E29<>″″,E29,IF(E27 = ″″,″″,IF((E30-E27)<0,0,E30-E27)))))
H30	PS-Patm (cm H_2O)	= IF(AND(COUNTA(E29:E30) = 2,E29<>E30-E27),″?″,IF(AND(E29 = ″″,E30 = ″″),″″,IF(AND(E29 = ″0″,E30 = ″″),0,IF(E30<>″″,E30,IF(E27 = ″″,″″,E27+E29)))))
H31	PS-PIP (cm H_2O)	= IF(ISERROR(IF(AND(E31 = ″″,H29>H25),H29-H25,IF(E31 > 0,E31,0))),″″,(IF(AND(E31 = ″″,H29>H25),H29-H25,IF(E31 > 0,E31,0))))

this way have difficulty recognizing that time-triggered and time-cycled changes in airway pressure are not only mandatory pressure-control breaths by definition, but are associated with substantial, sometimes alarmingly large tidal volumes.

Implementation

Table 2 summarizes the terms and definitions we propose for standardizing documentation of ventilator settings for pressure-control modes. While our proposal is modest in scope, implementation of any change regarding hospital culture is a challenge. Therefore, we have created a training tool that serves 2 purposes:

- Define the calculations that a database might use to minimize operator data-entry effort
- Simulate actual ventilator-setting entry into an electronic medical record to allow staff to become familiar with the new conventions before actual implementation

Figure 5 shows screen shots of the simulation (programmed in a spreadsheet program [Excel, Microsoft, Redmond, Washington]) corresponding to the examples in Figure 3. The spreadsheet simulation calculates the desired report parameters based on the input ventilator settings, and illustrates the corresponding idealized airway pressure waveforms to help the learner visualize the definitions. Table 3 gives the simulation spreadsheet equations (not including the code for the waveform graphic). Note that the equations are considerably more complex than is suggested by Table 2, because of added error-trapping features. Table 4 gives the instructions for using the simulation. A fully programmed simulation is available for free download at http://www.mediafire.com/?nzzudzzejyy.

Conclusions

To our knowledge, this is the first time the issue of standardized documentation of ventilator pressures has been given a formal analysis in a peer-reviewed medical journal or medical textbook, although the ECRI Institute has formally recognized the problem.[24] Our treatment of the subject may seem overly complicated, but we argue that the complexity is already there and we are just exposing it. Paper charting of ventilator settings, particularly when such charts do not become an official component of the patient's medical record, allows a multitude of "sins." We might even argue that ambiguous charting is the norm rather than the exception, because paper forms are often poorly designed, outdated, and therapists can easily compensate for missing or erroneous data by simply looking at the ventilator. But such compensation is impossible when remotely viewing an electronic medical record.

Our only options are to ignore the complexity described here, as in the past, and not record the information, or to accept the complexity and apply a standardized vocabulary. Failure to come to terms with these issues constitutes

Table 4. Instructions for the Documentation Simulator

Mandatory Breaths
Enter the set inspiratory pressure according to how the ventilator displays it
The database report calculates whichever value you leave blank
A database output of ? means that both PIP and IP were entered but IP does not equal PIP minus PEEP
Spontaneous Breaths
Spontaneous breaths between mandatory breaths (eg, during P-low in airway pressure-release ventilation [APRV]*)*
Enter set pressure support level according to how the ventilator displays it (ie, if relative to PEEP, use PS-PEEP; if relative to atmospheric pressure, use PS-Patm)
A database output of ? means both PS-PEEP and PS-Patm were entered and PS-PEEP does not equal PS-Patm minus PEEP
Spontaneous breaths during mandatory breaths (eg, during P-high in APRV)
For Servo-i enter 0 if not used. Otherwise enter the P-high setting for PS-PIP
For Puritan Bennett 840 the ventilator allows PS-PIP but it is set indirectly by setting PS-PEEP. Do not enter a value for PS-PIP: the database will calculate it.
If ventilator allows setting of PS-PEEP and automatically makes PS-PIP the same, then enter the same value for both settings.
For all other ventilators enter 0 for PS-IP.

both a failure of risk-management and inadequate planning for conversion to electronic medical charting of mechanical ventilation. In addition, our students expect us to provide them with adequately explicit terminology for them to understand the current technology. We realize that this proposed standard constitutes a "consensus of two" but hope that it will stimulate further discussion on this important topic.

Documentation of ventilator settings in electronic medical records requires explicit definitions of terms. However, the current terminology supplied by ventilator manufacturers lacks the standardization necessary for accurate documentation of ventilator settings of pressure-control modes. Our proposal for standardization is based on a distinction between mandatory and spontaneous breaths, for which we have provided detailed definitions. For mandatory breaths, inspiratory pressure should be documented as peak inspiratory pressure (PIP) if it is set relative to atmospheric pressure, or just inspiratory pressure (IP) if it is set relative to PEEP. For spontaneous breaths, 3 different parameters need to be determined: pressure support set relative to PEEP (PS-PEEP); pressure support set relative to atmospheric pressure (PS-Patm); and pressure support set relative to the inspiratory pressure of a mandatory breath (PS-PIP).

REFERENCES

1. Colice GL. Historical perspective on the development of mechanical ventilation. In: Tobin MJ. Principles and practice of mechanical ventilation, 2nd edition. New York: McGraw-Hill; 2006;1-36.
2. Karakurt Z, Yarkin T, Altinöz H, Güngör A, Adigüzel N, Güngör G, et al. Pressure vs. volume control in COPD patients intubated due to ARF: a case-control study. Tüberk Toraks 2009;57(2):145-154.
3. Carvalho AR, Spieth PM, Beda A, Lopes AJ, Nevkove B, Heller AR, et al. Pressure support ventilation nd biphasic positive airway pressure improve oxygenation by redistribution of pulmonary blood flow. Anesth Analg 2009;109(3):856-865.
4. Rose L, Hawkins M. Airway pressure release ventilation and biphasic positive airway pressure: a systematic review of definitional criteria. Intensive Care Med 2008;34(10):1766-1773.
5. Norcini J, Burch V. Workplace-based assessment as an educational tool: AMEE Guide No. 31. Med Teach 2007;29(9):855-871.
6. Johnston JM, Leung GM, Fielding R, Tin KY, Ho LM. The development and validation of a knowledge, attitude and behaviour questionnaire to assess undergraduate evidence-based practice teaching and learning. Med Educ 2003;37(11):992-1000.
7. Calligaris L, Panzera A, Arnoldo L, Londero C, Quattrin R, Trincon MG, Brusaferro S. Errors and omissions in hospital prescriptions: a survey of prescription writing in a hospital. BMC Clin Pharmacol 2009;9(9):1-6.
8. Häyrinen K, Saranto K, Nyänen P. Definition, structure, content, use and impacts of electronic health records; a review of the research literature. Int J Med Inform 2008;77(5):291-304.
9. Vawdrey DK, Gardner RM, Evans S, Orme JF, Clemmer TP, Greenway L, Drews FA. Assessing data quality in manual entry of ventilator settings. J Am Med Inform Assoc 2007;14(3):295-303.
10. Hernandez MJ. Database design for mere mortals. Reading, PA: Addison-Wesley; 1997:21-32.
11. Stock MC, Downs JB, Frolicher DA. Airway pressure release ventilation. Crit Care Med 1987;15(5):462-466.
12. Baum M, Benzer H, Putensen C, Koller W, Putz G. Biphasic positive airway pressure (BIPAP)–a new form of augmented ventilation. Anaesthesist 1989;38(9):452-458. *Article in German.*
13. Hörmann C, Baum M, Putensen C, Mutz NJ, Benzer H. Biphasic positive airway pressure (BIPAP): a new mode of ventilatory support. Eur J Anaesthesiol 1994;11(1):37-42.
14. Marini JJ, Crooke PS 3rd, Truwit JD. Determinants and limits of pressure-preset ventilation: a mathematical model of pressure control. J Appl Physiol 1989;67(3):1081-1092.
15. Marini JJ, Crooke PS 3rd. A general mathematical model for respiratory dynamics relevant to the clinical setting. Am Rev Respir Dis 1993;147(1):14-24.
16. Crooke PS, Head JD, Marini JJ, Hotchkiss JR. Patient-ventilator interaction: a general model for nonpassive mechanical ventilation. IMA J Math Appl Med Biol 1998;15(4):321-337.
17. Chatburn RL. Classification of mechanical ventilators. In: Tobin MJ. Principles and practice of mechanical ventilation. 2nd edition. New York: McGraw-Hill; 2006:37-52.
18. Chatburn RL. Classification of ventilator modes: update and proposal for implementation. Respir Care 2007;52(3):301-323.
19. Chatburn RL, Volsko TA. Mechanical ventilators. In: Wilkins RL, Stoller JK, Kacmarek RM. Egan's fundamentals of respiratory care, 9th edition. St. Louis: Mosby Elsevier; 2009:965-999.
20. Chatburn RL, Branson RD. Classification of mechanical ventilators. In: MacIntyre NR, Branson RD. Mechanical ventilation, 2nd edition. Philadelphia: W.B. Saunders; 2008:1-48.
21. Pilbeam SP, Cairo JM. Mechanical ventilation: physiological and clinical applications, 4th edition. St. Louis: Mosby Elsevier; 2009:45-62.
22. Cairo JM, Pilbeam SP. Mosby's respiratory care equipment, 8th edition. St Louis: Mosby Elsevier; 2009:345-408.
23. Habashi NM. Other approaches to open-lung ventilation: airway pressure release ventilation. Crit Care Med 2005;33(3 Suppl):S228-S240.
24. ECRI Institute. Unfamiliarity with differences in the way ventilators set pressure-control values may lead to lung injuries [hazard report]. Health Devices 2010;39(6):206-207.