A Rational Framework for Selecting Modes of Ventilation

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Mechanical ventilation is a life-saving intervention for respiratory failure and thus has become the cornerstone of the practice of critical care medicine. A mechanical ventilation mode describes the predetermined pattern of patient-ventilator interaction. In recent years there has been a dizzying proliferation of mechanical ventilation modes, driven by technological advances and market pressures, rather than clinical data. The comparison of these modes is hampered by the sheer number of combinations that need to be tested against one another, as well as the lack of a coherent, logical nomenclature that accurately describes a mode. In this paper we propose a logical nomenclature for mechanical ventilation modes, akin to biological taxonomy. Accordingly, the control variable, breath sequence, and targeting schemes for the primary and secondary breaths represent the *order, family, genus*, and *species*, respectively, for the described mode. To distinguish unique operational algorithms, a fifth level of distinction, termed *variety*, is utilized. We posit that such coherent ordering would facilitate comparison and understanding of modes. Next we suggest that the clinical goals of mechanical ventilation may be simplified into 3 broad categories: provision of safe gas exchange; provision of comfort; and promotion of liberation from mechanical ventilation. Safety is achieved via optimization of ventilation-perfusion matching and pressure-volume relationship of the lungs. Comfort is provided by fostering patient-ventilator synchrony. Liberation is promoted by optimization of the weaning experience. Then we follow a paradigm that matches the technological capacity of a particular mode to achieving a specific clinical goal. Finally, we provide the reader with a comparison of existing modes based on these principles. The status quo in mechanical ventilation mode nomenclature impedes communication and comparison of existing mechanical ventilation modes. The proposed model, utilizing a systematic nomenclature, provides a useful framework to address this unmet need.

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Introduction

Patients are buffeted between 2 major socioeconomic forces (Fig. 1). One of these forces is medical research, which produces data at a currently unmanageable rate. The second force is medical industry, which produces an unending supply of products and services used as treatments in healthcare. The process relating patients to their healthcare data is *diagnosis*. The process relating patients with available treatments is *innovation*. The most critical process in a complex healthcare environment is the *planning* that relates diagnostic data to appropriate treatment options. Effective and efficient healthcare can occur only if appropriate mapping can be accomplished between relevant data and appropriate treatments. The socioeconomic force supporting the appropriate matching between patient needs and treatments is the emerging field of medical informatics.

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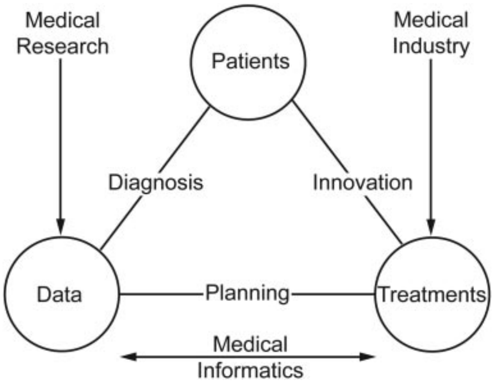

Fig. 1. Model illustrating the relations among patients, diagnostic data, and clinical treatments. As it applies to mechanical ventilation, the data are those that identify the patient's needs in the areas of safety, comfort, and liberation. The treatments are the modes of ventilation serving these needs.

Applying this conceptual model to mechanical ventilation, patient needs can be expressed in terms of the basic goals of ventilation, that is, safety, comfort, and liberation from the ventilator.[1] The treatment options are the modes of ventilation. This model suggests that to master the art and science of mechanical ventilation we need to first develop a strategy for identifying which goals of ventilation most represent the immediate patient needs (diagnosis). Next we have to understand the capabilities of the dozens of modes available on current ventilators (innovation). Finally, we need a logical system for selecting the mode that meets the patient's current needs (planning). This paper is the first attempt we are aware of to outline a rational foundation for the last process, that of selecting the most appropriate mode.

Why Compare Modes?

We need to compare modes because there are more than one and they differ enough in technological capability that they cannot possibly all offer the same benefits to the patient. Hence the need for comparison and choice. Indeed, clinicians make such comparisons and choices countless times each day all over the world. The issue is whether the comparisons are based on logic and information or on personal bias.[2] Most of our assumptions about mechanical ventilation come from mathematical models, physiology models, and scant clinical data. Considering the number of ventilators and ventilator modes from which to choose, the available animal and clinical data are very few.[3,4] We tend to use mechanical ventilation based on tradition and the immediately available technology, rather than on evidence-based medicine.[5] In fact, after decades of clinical research, the only thing we seem to know is that smaller tidal volumes (V_T) are better than larger ones.[6]

Which Modes Should Be Compared?

The first respiratory care equipment book published in the United States named only 3 modes (control, assist, and assist/control).[7] The 8th edition of this book lists 174 unique names for modes of ventilation.[8] As an example, Table 1 shows 47 unique mode names found on 4 common ICU ventilators. Thus, we are immediately impeded by 2 obstacles: first, there are too many modes. Faced with perhaps a dozen modes on a single ventilator, even a small set of selection criteria imposes a formidable challenge. The human capacity to store and process information is limited to about 4 variables at a time.[9] Second, the names of modes obscure their similarities and differences, making comparison impractical. This problem must be dealt with before any further analysis is possible.

As with any technology of sufficient complexity, the ability to compare and contrast objects requires a shift of focus away from names, to tags, using a formal classification system or taxonomy The foundations of such a taxonomy have been described previously[10–12] and incorporated in leading textbooks.[13,14] We will use it here without extensive elaboration. This system is illustrated in Table 2.

Briefly, all modes can be divided into 2 broad *orders*: volume control (VC) and pressure control (PC). Within these *orders* are *families* based on the breath sequences (ie, possible combinations of mandatory and spontaneous breaths). The definitions of "mandatory" and "spontaneous" are critical. A spontaneous breath is a breath for which the start and end of inspiration may be determined by the patient, independent of any machine settings for inspiratory time and expiratory time. That is, the patient both triggers and cycles the breath. A mandatory breath is a breath for which the start or end of inspiration (or both) is determined by the ventilator, independent of the patient. That is, the machine triggers and/or cycles the breath. There are only 3 possible sequences of breaths a mode can generate: all spontaneous breaths, called continuous spontaneous ventilation (CSV); mandatory breaths with the possibility of spontaneous breaths between them, called intermittent mandatory ventilation (IMV); and mandatory breaths with no possibility of spontaneous breaths between them, called continuous mandatory ventilation (CMV). There are nuances to these definitions, but they are beyond the scope of this paper.

Within the *families* are *genus* and *species*, identified by the targeting schemes[1] used for primary breaths (for CMV and CSV) and secondary breaths (for IMV). A targeting scheme is a model of the relationship between operator inputs and ventilator outputs to achieve a specific ventilatory pattern. Targeting schemes can be described in terms of feedback control loops.[1] There are currently only

Table 1. Unique Names of Modes Found on 4 Common ICU Ventilators (ie, Redundant Names Have Been Eliminated)

	Manufacturer	Model	Manufacturer's Mode Name
1	Covidien	PB 840	BiLevel
2	Covidien	PB 840	Pressure Control Assist Control
3	Covidien	PB 840	Pressure Control Synchronized Intermittent Mandatory Ventilation
4	Covidien	PB 840	Pressure Support
5	Covidien	PB 840	Proportional Assist Ventilation Plus
6	Covidien	PB 840	Spontaneous
7	Covidien	PB 840	Tube Compensation
8	Covidien	PB 840	Volume Control Synchronized Intermittent Mandatory Ventilation
9	Covidien	PB 840	Volume Control Assist/Control
10	Covidien	PB 840	Volume Control Plus Assist/Control
11	Covidien	PB 840	Volume Control Plus Synchronized Intermittent Mandatory Ventilation
12	Covidien	PB 840	Volume Ventilation Plus Synchronized Intermittent Mandatory Ventilation
13	Dräger	Evita XL	Airway Pressure Release Ventilation
14	Dräger	Evita XL	Automatic Tube Compensation
15	Dräger	Evita XL	Continuous Mandatory Ventilation
16	Dräger	Evita XL	Continuous Mandatory Ventilation with AutoFlow
17	Dräger	Evita XL	Continuous Mandatory Ventilation with Pressure Limited Ventilation
18	Dräger	Evita XL	Continuous Positive Airway Pressure/Pressure Support
19	Dräger	Evita XL	Mandatory Minute Volume Ventilation
20	Dräger	Evita XL	Mandatory Minute Volume with AutoFlow
21	Dräger	Evita XL	Mandatory Minute Volume with Pressure Limited Ventilation
22	Dräger	Evita XL	Pressure Controlled Ventilation Plus Assisted
23	Dräger	Evita XL	Pressure Controlled Ventilation Plus Pressure Support
24	Dräger	Evita XL	SmartCare/PS
25	Dräger	Evita XL	Synchronized Intermittent Mandatory Ventilation
26	Dräger	Evita XL	Synchronized Intermittent Mandatory Ventilation with AutoFlow
27	Dräger	Evita XL	Synchronized Intermittent Mandatory Ventilation with Pressure Limited Ventilation
28	Hamilton	G5	Adaptive Pressure Ventilation Controlled Mandatory Ventilation
29	Hamilton	G5	Adaptive Pressure Ventilation Synchronized Intermittent Mandatory Ventilation
30	Hamilton	G5	Adaptive Support Ventilation
31	Hamilton	G5	Duo Positive Airway Pressure
32	Hamilton	G5	Noninvasive Ventilation
33	Hamilton	G5	Pressure Controlled Mandatory Ventilation
34	Hamilton	G5	Pressure Synchronized Intermittent Mandatory Ventilation
35	Hamilton	G5	Synchronized Controlled Mandatory Ventilation
36	Maquet	Servo-i	Automode (Pressure Control to Pressure Support)
37	Maquet	Servo-i	Automode (Pressure Regulated Volume Control to Volume Support)
38	Maquet	Servo-i	Automode (Volume Control to Volume Support)
39	Maquet	Servo-i	Bi-Vent
40	Maquet	Servo-i	Neurally Adjusted Ventilatory Assist
41	Maquet	Servo-i	Pressure Control
42	Maquet	Servo-i	Pressure Regulated Volume Control
43	Maquet	Servo-i	Synchronized Intermittent Mandatory Ventilation (Pressure Control)
44	Maquet	Servo-i	Synchronized Intermittent Mandatory Ventilation (Pressure Regulated Volume Control)
45	Maquet	Servo-i	Synchronized Intermittent Mandatory Ventilation (Volume Control)
46	Maquet	Servo-i	Volume Control
47	Maquet	Servo-i	Volume Support

Table 2. Simplified Taxonomic Hierarchy for Classifying Modes*

Order	Family	Genus	Species			
Control Variable	Breath Sequence	Primary Breath Targeting Scheme	Secondary Breath Targeting Scheme	Example Mode Names	Abbreviation	Variety† Operational Differences
Volume	CMV	Set-point	NA	Volume Control Assist/Control	VC-CMV$_{S}$	
		Dual	NA	Continuous Mandatory Ventilation with Pressure Limited	VC-CMV$_{D}$	
	IMV	Set-point	Set-point	Volume Control Synchronized Intermittent Mandatory Ventilation	VC-IMV$_{S,S}$	
		Dual	Set-point	Synchronized Intermittent Mandatory Ventilation (Volume Control Servo-i ventilator)	VC-IMV$_{D,S}$	
		Dual/Adaptive	Set-point	Mandatory Minute Volume with Pressure Limited Ventilation	VC-IMV$_{DA,S}$	
		Dual	Adaptive	Automode (Volume Control to Volume Support)	VC-IMV$_{D,A}$	
		Adaptive	Set-point	Mandatory Minute Volume Ventilation	VC-IMV$_{A,S}$	
Pressure	CMV	Set-point	NA	Pressure Control Assist Control	PC-CMV$_{S}$	
		Adaptive	NA	Pressure Regulated Volume Control	PC-CMV$_{A}$	
	IMV	Set-point	Set-point	Airway Pressure Release Ventilation	PC-IMV$_{S,S}$	
		Set-point	NA	High frequency Oscillatory Ventilation	PC-IMV$_{S,S}$	Frequency above 150 cycles/min, negative airway pressure possible
		Adaptive	Set-point	Adaptive Pressure Ventilation Synchronized Intermittent Mandatory Ventilation	PC-IMV$_{A,S}$	
		Adaptive	Adaptive	Automode (Pressure Regulated Volume Control to Volume Support)	PC-IMV$_{A,A}$	
		Optimal	Optimal	Adaptive Support Ventilation	PC-IMV$_{O,O}$	
		Optimal/Intelligent	Optimal/Intelligent	IntelliVent-ASV	PC-IMV$_{OI,OI}$	
	CSV	Set-point	NA	Pressure Support	PC-CSV$_{S}$	Set-point constant
		Biovariable	NA	Variable Pressure Support	PC-CSV$_{B}$	Set-point automatically adjusted at random
		Servo	NA	Proportional Assist Ventilation	PC-CSV$_{R}$	Pressure proportional to volume and flow signals
		Servo	NA	Neurally Adjusted Ventilatory Support	PC-CSV$_{R}$	Pressure proportional to diaphragmatic electromyogram
		Adaptive	NA	Volume Support	PC-CSV$_{A}$	Pressure adjusted to achieve tidal volume target
		Adaptive	NA	Mandatory Rate Ventilation	PC-CSV$_{A}$	Pressure adjusted to achieve rate target
		Intelligent	NA	SmartCare/PS	PC-CSV$_{I}$	

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* Included in this table are all the unique modes listed in Table 1.

† The Variety level of description may be needed to differentiated between modes that have same order, family, genus, and species.

CMV = continuous mandatory ventilation

NA = not applicable

VC = volume control

Subscripts: S = set-point. D = dual. A = adaptive. O = optimal. I = intelligent. R = servo. B = biovariable.

IMV = intermittent mandatory ventilation

PC = pressure control

CSV = continuous spontaneous ventilation

Table 3. Targeting Schemes

Name	Description	Advantage	Disadvantage	Example Mode Name
Set-point	The operator sets all parameters of the pressure waveform (pressure control modes) or volume and flow waveforms (volume control modes).	Simplicity	Changing patient condition may make settings inappropriate.	Assist/Control
Dual	The ventilator can automatically switch between volume control and pressure control during a single inspiration.	Can adjust to changing patient condition and assure either a preset tidal volume or peak inspiratory pressure: whichever is deemed most important	Complicated to set correctly and needs constant readjustment	Volume Assured Pressure Support
Servo	The output of the ventilator (pressure/volume/flow) automatically follows a varying input.	Support by the ventilator is proportional to inspiratory effort.	Requires estimates of artificial airway and/or respiratory system mechanical properties	Proportional Assist Ventilation Plus
Biovariable	The ventilator automatically adjusts the inspiratory pressure or tidal volume randomly.	Simulates the variability observed during normal breathing and may improve oxygenation or mechanics	Manually set range of variability may be inappropriate to achieve goals.	Variable Pressure Support
Adaptive	The ventilator automatically sets a target(s) between breaths, in response to varying patient conditions.	Can adjust to changing patient condition	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology.	Pressure Regulated Volume Control
Optimal	The ventilator automatically adjusts the targets of the ventilatory pattern to either minimize or maximize some overall performance characteristic.	Can adjust to changing patient condition	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology.	Adaptive Support Ventilation
Intelligent	Targeting scheme that uses artificial intelligence programs such as fuzzy logic, rule based expert systems, and artificial neural networks	Can adjust to changing patient condition	Automatic adjustment may be inappropriate if algorithm assumptions are violated or they do not match physiology.	SmartCare/PS

7 basic targeting schemes used to create dozens of modes of ventilation.[1] These targeting schemes are described in Table 3. Because there are 2 fundamental classes of breaths (spontaneous and mandatory), we need to specify the targeting scheme for each (which may be the same). For CMV and CSV breath sequences there is only one type of breath, but it is mandatory for one and spontaneous for the other. Thus, we specify a "primary breath" targeting scheme. For IMV, where we have both mandatory and spontaneous breaths, we add a "secondary breath" targeting scheme to refer to the spontaneous breaths.

As targeting schemes have evolved, they have become more complicated and more automated. However, any targeting scheme can yield less than beneficial patient results if the underlying assumptions of the scheme design are violated. For example, set-point targeting assumes constant respiratory system mechanics, and it may be at a disadvantage if they change, making either peak airway pressure or V_T uncertain. Dual targeting assumes that mechanics may change but depends on careful setting of the criteria for switching between volume and pressure control breaths. Servo control assumes a priori values for respiratory system mechanical properties, such as resistance and elastance, which may in fact be incorrect. Some forms of adaptive targeting assume that changes in respiratory system mechanics are related only to compliance. Patient inspiratory effort is not distinguishable from change in compliance by the ventilator and may fool the targeting scheme into decreasing support when the patient needs it most.[15] Optimal targeting assumes that the patient can be represented by mathematical models (eg, the relations among work of breathing, lung mechanics, frequency, and V_T). When the models do not match the actual physiology of the patient, they may instruct the ventilator to do inappropriate things (eg, hyper/hypoventilate the patient or increase risk of ventilator-induced lung damage).

Intelligent targeting systems are based on abstract representations of the patient, such as expert rules in the form of “if the patient does this, the ventilator should do this.” These systems are still in their infancy and are based on a very limited set of “sensory” data to create the representations. Hence, the assumptions upon which the artificial intelligence system are based may easily be violated by the actual conditions of the patient. For example, the targeting scheme might assume that the patient can be aggressively weaned when in fact the patient is not ready. The point of the above discussion is that, in order to compare modes, we must consider the best case scenario, in which they are functioning under conditions that do not violate their underlying design assumptions. *We thus take for granted that the clinician has appropriately diagnosed the patient’s condition, assessed the needs, and has ruled out any mode features that may be inappropriate.* Of course, the whole point of our analysis is to provide the conceptual tools that would allow the clinician to do this.

Minor differences in *genus* or *species* (such as unique operational algorithms) can be accommodated by adding a fifth *variety* level. As an example, there are 3 varieties of PC-CSV using servo targeting. One makes inspiratory pressure proportional to the square of inspiratory flow (Automatic Tube Compensation), one makes it proportional to the electrical signal from the diaphragm (Neurally Adjusted Ventilatory Support), and one makes it proportional to the patient’s spontaneous volume and flow (Proportional Assist Ventilation). The first can support only the resistive load of breathing, while the other 2 can support both the elastic and resistive loads.

Two major benefits accrue from using this classification system. It allows us to start with a relatively large set of unique mode *names* on common ICU ventilators, and to greatly reduce it to a more manageable set of mode *tags* (classifications). In that set, redundancies are easily recognized and eliminated, leaving only unique mode tags (at least to 4 or 5 levels of discrimination) that are amenable to comparison. To demonstrate these benefits and provide an answer to which modes to compare, we consider 4 state-of-the-art ventilators used in ICUs around the world: PB840 (Covidien), Evita XL (Dräger Medical), G5 (Hamilton Medical), and Servo-i (Maquet). These 4 ventilators offer a total of 52 mode *names*, of which 47 are unique (see Table 1). After classification (using 4 levels of the taxonomy) only 17 unique *tags* are left. We add 5 more modes that have unique targeting system variations. The first 2 of these variations are not available in the United States: Mandatory Rate Ventilation (Taema-Horus ventilator made by Air Liquide), IntelliVent-ASV (Hamilton Medical), Neurally Adjusted Ventilatory Support (Maquet), High Frequency Oscillatory Ventilation (CareFusion), and Variable Pressure Support (Dräger). This set of 22 unique modes is shown in Table 2.

How Can Modes Be Compared?

There are 3 levels at which a mode of mechanical ventilation (or any other medical intervention) can be evaluated:

- The *theoretical* level refers to the knowledge we obtain from basic research and fundamentals. It is subject to evolution of knowledge, and generated with systematic scientific analysis of our current experiences.
- The *performance* level refers to how each device behaves when applied to the same circumstance (ie, 2 different ventilators applying the same mode to the same model). At this level the evaluation depends mainly on technological development, design, and equipment used.
- The clinical *outcome* level refers to the application of the mode of ventilation to a specific population and condition, and to analyzing its outcome (ie, physiology or survival).

A tenet of medical care is to have evidence regarding the therapies we apply. We hold the patient outcome as the ultimate manifestation of benefit of any given intervention. This is where the chasm develops when talking about modes of mechanical ventilation. Despite the fact that a wide variety of modes are available, only the simplest set-point targeting schemes[5] (mainly volume control CMV) are used most of the time in daily practice.[5,16–18] We could argue that such practice is justified by their simple reliability and the lack of evidence that any other mode is superior in terms of major clinical outcomes.[3,19,20] Yet we could also argue that “lack of evidence is not evidence of lack.”

There are several challenges in interpreting the extant data. The *performance* of a mode is dependent on the ventilator used (even within the same brand),[15,21–23] who uses it, what population is selected,[24,25] and what variable is evaluated.[4] The heterogeneity of the patients and interventions used in the critical care setting only add to the difficulty of drawing conclusions,[26,27] leaving the results of many trials uninterpretable or not generalizable.[24,28,29] On the *clinical outcom*e level, it takes little effort to understand *why* there will never be enough clinical evidence to appropriately compare modes. Consider, for example, that randomized controlled trials of 22 modes (approximately the number of unique modes currently available) would require 231 head-to-head comparisons. Using the ARDS Network experience to estimate the resource cost per study of about 4 years and 38 million dollars, gathering evidence would take over 900 labor years and almost 9 billion United States dollars! Thus, the clinical evidence required to compare all modes of ventilation does not exist, and probably never will.

Thus, to rationally compare the relative merits of various modes, we must resort to deductive reasoning from first principles at the *theoretical level*. We posit that a mode of mechanical ventilation has certain design features that implement a general *technological capability*. Each technological capability serves a *clinical aim*. Each clinical aim, in turn, serves specific *objectives* and general *goals* of mechanical ventilation based on the clinician's assessment of the patient. The utility of this hierarchical approach is that we can start on familiar ground (the general goals of mechanical ventilation) and progress deductively to a linkage with specific ventilator capabilities and features, some of which might seem questionable without such a line of reasoning to justify their existence. *More to the point, the capabilities form the basis for comparing the relative benefits of modes to guide appropriate selection for a given patient at a given time.* The capabilities as described here are, by definition, beneficial (with the caveats noted above). It follows that the more capabilities a mode has, the better it serves the specific goals of mechanical ventilation that are judged to be most important in any given clinical situation.

Note that this approach explicitly ignores the issue of *how* modes are used. This conceptual distinction is essential because of the huge variation in outcomes that can be attributed to the different knowledge base and skill levels of clinicians. Few would argue that, given current technology, a highly skilled clinician using a technologically simple mode would likely achieve better results than, for example, a naïve clinician using a complex mode. Our thesis is that once the patient's needs are diagnosed, the appropriate modes can be rationally selected by focusing solely on the technological capabilities that serve those needs. We are, in effect, comparing and contrasting the tools in the toolbox, independently of how they might be or have been used to produce the desired outcomes. We believe this is a unique and potentially important paradigm shift in the application of mechanical ventilation. What follows is such an analysis.

The Three Goals of Mechanical Ventilation

Any number of indications for mechanical ventilation may be found in the literature, but they can all be condensed into 3 goals: to provide gas exchange safely (primum non nocere), to provide comfort, and to promote liberation of the patient from the ventilator.[1]

The first goal, safety, has 3 basic features: providing an appropriate level of gas exchange, avoiding ventilator-induced lung injury (VILI), and warning of unsafe conditions (ie, provide optimum alarms). In physiological terms, we might say that the objectives of the first goal of safety are to optimize the ventilation-perfusion ratio of the lungs and to optimize the cyclic pressure/volume relation of the lungs (ie, operating on the steep portion of the compliance curve and thereby avoiding both shear force trauma from reopening atelectatic areas and trauma from overdistention). The second goal, to provide comfort, would have the objective of optimizing patient-ventilator synchrony. The third goal, to promote liberation, would have the objective of optimizing the weaning experience. That is, evaluating readiness for spontaneous breathing, recognizing successful spontaneous breathing trials, and advising on liberation, while minimizing the occurrence of adverse events. Table 4 shows an outline structure that we will use to relate the goals of mechanical ventilation to mode features. In the next section we provide a detailed expansion of Table 4, using specific examples of modes. The 3 goals of ventilation are explained in terms of general physiologic objectives, specific aims of clinical treatment, general capabilities of current ventilator technology, and, finally, features of specific modes that are intended to serve the aims, objectives, and goals.

Table 4. Outline of the Goals of Mechanical Ventilation With Subheading for Objectives, Clinical Aims, General Technological Capabilities of Ventilators, and Specific Mode Features

- Goals of Mechanical Ventilation
  - Objectives Serving Goals
    - Aims of Clinical Management
      - Capabilities of Ventilators
        - Features of Specific Modes

Goal: Promote Safety

Objective: To Optimize Ventilation-Perfusion of the Lungs

To optimize the ventilation-perfusion ratio means not only to ensure gas exchange, but to achieve the greatest alveolar ventilation for the least cost in terms of intrathoracic pressure increase that could degrade local pulmonary perfusion and overall cardiac output. In engineering terms, to "optimize" means to maximize or minimize some objective function. For example, an efficient pattern of mechanical ventilation might strive to minimize the work of breathing or maximize alveolar ventilation. This, of course, does not mean that the function is at the most extreme level physiologically possible, just that its maximum or minimum value is matched to the available range of ventilator settings and clinical aims. With the *objective* of optimizing the ventilation-perfusion of the lungs, the 2 basic *clinical aims* are to maximize alveolar ventilation (consistent with acceptable P_{aCO_2} levels) and to minimize intrapulmonary shunt (consistent with acceptable P_{aO_2} levels). We will now describe the currently available *techno-*

logical capabilities of ventilators and specific mode *features* grouped by clinical aim.

Aim: To Maximize Alveolar Ventilation. The main goal of mechanical ventilation is to provide adequate delivery of oxygen and elimination of carbon dioxide. Indeed, assuring alveolar ventilation has been the basic tenet of mechanical support of breathing since its inception. Current ventilator mode capabilities offer a variety of options, including both manual and automatic adjustment of minute ventilation ($\dot{V}_E$) parameters.

Capability: Automatic Adjustment of $\dot{V}_E$ Target. $\dot{V}_E$ is the product of V_T and ventilatory frequency. It is the sum of both alveolar and dead-space ventilation. Thus, a mode targeting scheme that simply manages $\dot{V}_E$ parameters (and is thus ignorant of dead space) would be less accurate in managing P_{aCO_2} than one that adjusts estimated minute *alveolar* ventilation or one that actually used CO_2 as a feedback signal.

- **Feature: Ventilator Set $\dot{V}_E$ or CO_2 Target.** In clinical practice, the level of alveolar ventilation is monitored using the P_{aCO_2}. A surrogate for that is end-tidal carbon dioxide tension (P_{ETCO_2}). Thus, a mode that uses this variable in a targeting scheme would serve the goal of attempting to optimize ventilation-perfusion. The 2 examples are SmartCare/PS (Dräger, Evita XL) and IntelliVent-ASV (Hamilton). An alternative is to monitor the $\dot{V}_E$ and then to maintain the ventilation at that level. The S9 VPAP Adapt (ResMed) automatically calculates a target ventilation (90% of the patient's recent average ventilation) and adjusts the pressure support to achieve it.

Capability: Automatic Adjustment of Support in Response to Changing Respiratory System Mechanics. If the operator elects to set the $\dot{V}_E$ target, the ventilator may still be given the authority to select the V_T or inspiratory pressure. Thus, in the face of changing respiratory characteristics, the V_T or pressure may be changed to maintain the target V_T or $\dot{V}_E$.

- **Feature: Ventilator Set Inspiratory Pressure to Achieve Target $\dot{V}_E$.** A currently available alternative is Automode (Servo-i) with Pressure Regulated Volume Control (for mandatory breaths) plus Volume Support (for spontaneous breaths). This mode adjusts the inspiratory pressure to maintain the target V_T, and if the breathing frequency fails to maintain $\dot{V}_E$, then mandatory breaths are delivered to meet the target $\dot{V}_E$. Because this mode uses an adaptive pressure targeting scheme, the inspiratory pressure will be automatically adjusted in the presence of changing respiratory system mechanics to meet the target V_T.

Even without a preset $\dot{V}_E$ target, the ventilator may automatically adjust inspiratory pressure to achieve an operator set V_T target. An example is Pressure Regulated Volume Control (Servo-i). The ventilator monitors V_T and automatically adjusts inspiratory pressure between breaths to achieve an average exhaled V_T equal to the set target. This kind of adaptive pressure targeting scheme compensates for changes in respiratory system mechanics (ie, resistance, compliance, and inspiratory effort), as opposed to a simpler set-point pressure targeting scheme where V_T changes with mechanics.

Capability: Manual Adjustment of $\dot{V}_E$ Parameters

- **Feature: Clinician Set V_T and Frequency.** The V_T and frequency set by the operator provide a minimum amount of $\dot{V}_E$ (ie, preset V_T and frequency). This simple and direct approach to safety is perhaps the reason why modes like Volume Control Assist/Control (PB840) are the most popular in worldwide intensive care use.[5]

Aim: To Maximize Oxygenation. We have discussed the ventilation part of the objective: to optimize the overall ventilation-perfusion ratio of the lungs. The oxygenation part involves not only the delivery of appropriate levels of F_{IO_2}, but also includes measures to minimize intrapulmonary shunting. Most ventilators provide this technology in the ubiquitous form of manually adjusted F_{IO_2} and PEEP. Of more interest in comparing modes are the automatic capabilities now available.

Capability: Automatic Adjustment of Oxygen Delivery. Until recently, ventilator delivered oxygen has been the result of manual adjustment of an air-oxygen blender, based on clinical variables such as arterial blood gas analysis or pulse oximeter readings. Unfortunately, relying on manual adjustments may lead to sub- or supra-optimal oxygen delivery.[30] Automatic adjustment by the ventilator may improve clinical outcomes.

- **Feature: Ventilator Set F_{IO_2}.** Hamilton Medical has incorporated the ARDS Network PEEP table into the IntelliVent-ASV mode, allowing the ventilator to adjust F_{IO_2} automatically to keep S_{pO_2} within a preset target range.

Capability: Automatic Adjustment of End-Expiratory Lung Volume. PEEP is used to avoid derecruitment of the lung during expiration. There are several methods for determining "optimum PEEP."[31] Some methods are intended to maximize lung mechanics (eg, compliance) and others to maximize oxygen delivery to the tissues (ie, the product of cardiac output and arterial oxygen content). Although there are several strategies, there is no consensus on the best algorithm. A commonly used approach is to use the ARDS Network table that associates PEEP and F_{IO_2}, as this a simple, practical, and effective approach.[6]

- **Feature: Ventilator Set PEEP.** Hamilton Medical has incorporated the ARDS Network F_{IO_2}/PEEP table into the IntelliVent-ASV mode, allowing the ventilator to adjust PEEP automatically to keep S_{pO_2} within a preset target range.

Objective: To Optimize Pressure/Volume Curve

As knowledge has evolved, we have come to appreciate that achieving "normal" values of gas exchange or a fixed respiratory pattern is not necessarily appropriate.[32,33] Our goals have shifted,[34,35] and now we think of gas exchange in the context of prevention of VILI. From an engineering standpoint, we try to optimize the ventilation-perfusion ratio (ensure ventilation) while we optimize the cyclic pressure/volume relation of the lungs (maximize compliance while avoiding atelectrauma and volutrauma).[36,37] Optimizing the pressure/volume relationship means essentially to ventilate on the steep portion of the pressure/volume curve (ie, optimal mean lung volume yielding the highest compliance with a minimal V_T and optimal PEEP) with the aim to minimize the stress and strain of the lungs.[36]

Aim: To Minimize Risk of Volutrauma. Volutrauma is the ventilator-induced injury to the lungs due to volumetric distention beyond the lung's elastic limits. In patients with acute lung injury and the ARDS, mechanical ventilation with a lower V_T than is traditionally used results in decreased mortality and increases the number of days without ventilator use.[6]

Capability: Automatic Adjustment of Lung-Protective Limits. The prudent clinician avoids setting the V_T too high (avoiding volutrauma) or too low (assuring adequate gas exchange and avoiding derecruitment). Likewise, one attempts to avoid setting inspiratory frequency too high (avoiding too much dead-space ventilation) or too low (avoiding excessive V_T to achieve the target $\dot{V}_E$). Some ventilators provide these safety considerations automatically.

- **Feature: Ventilator Set Safety Limits on Ventilation Parameters.** For Adaptive Support Ventilation (Hamilton G5 ventilator) the clinician inputs patient weight and percent-of-predicted $\dot{V}_E$ to support. The ventilator sets appropriate minimum and maximum values for V_T, mandatory breath frequency, inspiratory pressure, and inspiratory/expiratory times based on monitored values for respiratory system mechanics.

Capability: Automatic Adjustment of V_T. Despite over a decade of emphasis on the use of low V_T to prevent VILI, many clinicians are slow to adopt the new standards. Perceived barriers and knowledge deficits regarding the use of low V_T ventilation for ARDS are common and vary by caregiver type and experience.[38] Algorithms that are built into the ventilator would serve to assure delivery of safe V_T at all times.

- **Feature: Ventilator Set V_T and Frequency.** A ventilator can automatically select V_T and frequency (of mandatory breaths), based on the respiratory system characteristics and/or expert rules. Ideally, V_T delivery is kept within a boundary where VILI is minimized.[36,37,39] An example of a current mode that fulfills this goal is Adaptive Support Ventilation (G5), where the clinician inputs patient weight and percent-of-predicted $\dot{V}_E$ to support, and the ventilator automatically adjusts V_T and frequency to minimize work rate according to the respiratory system resistance and compliance.

Another available option is, if the operator elects to set the $\dot{V}_E$ and V_T targets, the ventilator may still be given the authority to select the frequency of mandatory breaths. For example, a mode called Mandatory Minute Ventilation (MMV, Evita XL) uses an adaptive targeting scheme[5] to provide volume control IMV (the breathing frequency and V_T set by the operator determines the minimum $\dot{V}_E$). If the patient has spontaneous breaths (assisted or unassisted by pressure support) and if these breaths produce a $\dot{V}_E$ above the minimum, all breaths will be spontaneous. However, when the total $\dot{V}_E$ is lower than the minimum set $\dot{V}_E$, the ventilator increases the frequency of mandatory volume control breaths to maintain the target value.

Capability: To Minimize V_T. If one embraces the concept that smaller V_T is better than larger V_T in terms of avoiding VILI, then the logical extension is that we should deliver the smallest V_T possible during mechanical ventilation. Similar reasoning has led to the development of various types of high frequency ventilators. Indeed, a recent meta-analysis has shown that high frequency oscillation might improve survival and is unlikely to cause harm.[40] Indeed, high frequency ventilators may reduce direct tidal ventilation via alternative mechanisms of alveolar ventilation.[41]

- **Feature: Ventilatory Frequencies Above 150 Breaths/Min.** In the United States, conventional ventilators are limited to a maximum frequency of 150 breaths/min (2.5 Hz). To go above that requires a special device and mode, such as the Bunnell Life Pulse high frequency jet ventilator (4–11 Hz), or the Care Fusion 3100 high frequency oscillatory ventilator (3–15 Hz).

Aim: To Minimize Risk of Atelectrauma. Atelectrauma is the ventilator-induced injury to the lungs due to repetitive alveolar collapse and reopening. Maintaining an appropriate level of end-expiratory lung volume should minimize the risk of this type of injury. The clinical surrogate for end-expiratory lung volume is PEEP. Automatic adjustment of PEEP may be a technological advancement despite the lack of consensus on the best optimization algorithm. See Automatic Adjustment of End-Expiratory Lung Volume above.

Objective: To Optimize Alarm Settings

The selection of optimal ventilator alarm profiles is a subject that has not received much attention in the literature. ICU alarms, in general, often cause as many problems as they solve, but a full discussion is beyond the scope of this paper.[42] We can speculate that the clinical aims are at least to minimize the time spent in unsafe conditions and also to minimize false alarms. These aims suggest that ventilator manufacturers should develop automatic algorithms for selection of appropriate variables to monitor[43] and alarm thresholds (or trends) that will improve predictive ability.[44] Unfortunately, we are unaware of any ventilator with such capability beyond basic default values.

Goal: To Promote Comfort

Objective: To Optimize Patient-Ventilator Synchrony

Optimizing patient-ventilator synchrony has garnered increasing attention among respiratory practitioners.[1,45] Patient-ventilator asynchrony is common and is associated with adverse effects, including discomfort and longer ICU/hospital stays.[45]

Aim: To Maximize Trigger/Cycle Synchrony. To "trigger" means to start inspiration. To "cycle" means to end inspiration. Of course, trigger and cycle events may be either machine or patient initiated. A "spontaneous" breath is one that is both triggered and cycled by the patient. Any interference by the machine (ie, trigger and/or cycle) results in a "mandatory" breath. Optimum ventilator-patient synchrony implies minimal machine interference with the patient's own neural signals to start and end inspiration.

Capability: All Breaths Are Spontaneous With Sufficient Patient Trigger Effort. From the discussion in the preceding paragraph, it follows that maximum trigger and cycle synchrony will result in a breathing sequence of all spontaneous breaths (CSV) versus one with all mandatory breaths (CMV) or mixed mandatory and spontaneous breaths (IMV). Spontaneous breaths offer advantages over mandatory breaths[46] in terms of optimizing gas exchange, comfort, and preserving respiratory muscle strength and endurance.

• Feature: All Breaths Are Patient Triggered and Patient Cycled. Modes classified as CSV allow the patient to trigger and cycle the breath. These include Pressure Support, Proportional Assist Ventilation, Neurally Adjusted Ventilatory Support, and even Automatic Tube Compensation.

Capability: Trigger/Cycle Based on Signal Representing Chest Wall/Diaphragm Movement. Optimizing patient-ventilator synchrony obviously involves minimizing the effort and delay associated with triggering and cycling inspiration. A mode that immediately detects and reacts to patient demands, as close as possible to actual brain signals, should improve patient synchrony and comfort. Currently a few ventilators trigger and/or cycle based on the diaphragm/chest wall signal. Neurally Adjusted Ventilatory Assist (NAVA) uses the diaphragm electromyogram[47] for both triggering and cycling. Two pediatric ventilators have demonstrated triggering based on abdominal motion or thoracic impedance (Seachrist IV-100B SAVI) and abdominal motion (InfantStar Star Sync, now obsolete).[48]

• Feature: Trigger/Cycle Based on Diaphragm Electromyography. The only available mode that uses diaphragm signals is NAVA (Servo-i). It does this by monitoring the electrical activity of the diaphragm using an esophageal probe. The signal obtained from the probe triggers and cycles the breath at the trigger threshold set by the clinician.

Capability: Coordination of Mandatory and Spontaneous Breaths. There is evidence to suggest that preserving as much spontaneous breathing as possible during a mode with mandatory breaths is probably beneficial, which was the original idea behind IMV.[49] Furthermore, there is some evidence that allowing unrestricted spontaneous breathing throughout the ventilatory cycle, as with Airway Pressure Release Ventilation (APRV), increases comfort and decreases the need for sedation.[50] One could also argue that allowing spontaneous efforts to suppress mandatory breaths favors patient-ventilator synchrony. This latter goal is served by modes such as Mandatory Minute Ventilation (Dräger), Adaptive Support Ventilation (Hamilton), AutoMode (Maquet), and Spontaneous/Timed Ventilation (Philips/Respironics). These strategies are forms of IMV, but we do not have data to suggest that one type of IMV is better than another.

- **Feature: Spontaneous Breaths Suppress Mandatory Breaths.** The Spont/T on the Philips V200 ventilator allows the patient to breathe spontaneously as long as the frequency is above a clinician set threshold. If the spontaneous breath rate falls below the threshold, mandatory breaths are delivered to bring the total frequency to the target level.

- **Feature: Spontaneous Breaths Permitted Between Mandatory Breaths.** Conventional modes classified as IMV (or SIMV) simply allow spontaneous breaths between mandatory breaths. Whether IMV provides a higher level of comfort than CMV is debatable, due to the possibility of relatively large, highly supported mandatory breaths intermixed with relatively small, unassisted spontaneous breaths. However, this problem may be mitigated by using Pressure Support to assist the spontaneous breaths.

- **Feature: Pressure Control Mandatory Breaths With Unrestricted Inspiration and Expiration.** Since the first pressure control neonatal ventilators were developed, the patient has always been able to breathe freely during mandatory breaths. When pressure control became available on adult devices, on many ventilators (Dräger ventilators being the notable exception) the patient was restricted to free inspiration only. Expiration could only be accomplished if expiratory efforts elevated the airway pressure to the alarm/cycle threshold. The original description of APRV showed a schematic that mimicked the operation of infant ventilators (ie, a source of constant flow and a valve that diverted flow between 2 pressure-relief valves, hence the impression that APRV was a form of bi-level CPAP). Modern implementations of APRV use sophisticated feedback control mechanisms to allow unrestricted spontaneous breathing throughout the ventilatory cycle (ie, both between and during mandatory breaths).

Aim: To Minimize AutoPEEP

Capability: Automatic Limitation of AutoPEEP

- **Feature: Ventilator Set Minimum Expiratory Time.** A substantial level of autoPEEP has untoward effects on breath triggering and work of breathing.[51,52] Although it may be impossible to prevent all autoPEEP in some patients, avoiding high levels of autoPEEP would serve the goal of patient-ventilator synchrony. Adaptive Support Ventilation (G5) is the only mode so far with this feature, having a safety rule that prevents expiratory time from being shorter than 2 expiratory time constants of the respiratory system.

Aim: To Maximize Flow Synchrony. Allowing the patient the freedom of unlimited inspiratory flow and V_T obviously promotes synchrony. This goal is served with pressure control modes. High frequency oscillation also serves this goal; however, at this time its ability to provide free inspiratory flow is better for infants than for adults, due to the available technology,[53] not because high frequency oscillation would theoretically disallow it.

Capability: Unrestricted Inspiratory Flow

- **Feature: Mandatory Breaths With Unrestricted Inspiratory Flow.** During inspiration in a mandatory pressure controlled breath, the ventilator delivers flow to maintain the set inspiratory pressure setting. If a patient inhales, the pressure is kept at the set target by increasing the flow. During exhalation, the ventilator will attempt to maintain the pressure at target by decreasing flow, or the pressure may rise until it reaches an alarm threshold. Thus, all modes with pressure controlled mandatory breaths would fall in this category.

- **Feature: Ventilator Automatically Switches From Volume Control to Pressure Control.** In dual targeting modes, such as CMV with Pressure Limited Ventilation (Evita XL), Volume Control (Servo-i), or Volume Control with Flow-Trak (V200), the ventilator may automatically switch from volume control to pressure control within the breath, if required, to meet the patient's inspiratory flow demand.

Capability: Automatic Adjustment of Flow Based on Frequency. During volume control ventilation, inspiratory flow is preset, which presets inspiratory time (inspiratory time = V_T/mean inspiratory flow). Presumably, the clinician has set these parameters to match patient demand. However, if the patient's trigger frequency changes substantially (particularly when using a mode with a CMV breath sequence), inspiratory flow and time may no longer match demand, and this contributes to flow asynchrony. Automatic adjustment of inspiratory flow is one potential solution.

- **Feature: Ventilator Maintains a Constant Inspiratory/Expiratory Ratio in Volume Control Modes.** The only example of this feature is found on the Versamed iVent ventilator and is called Adaptive Flow and I-Time. In volume control modes the operator presets the V_T, but the ventilator adjusts the inspiratory flow with changing trigger frequency to maintain an inspiratory/expiratory ratio at 1:2.[1]

Aim: To Coordinate Ventilator Work Output With Patient Demand. Synchrony between patient and ventilator can be viewed not only in terms of trigger, flow, and cycle events, but also in terms of work demand versus work supply. As mentioned above, the ventilator assists breathing by supplying some portion of the work of breathing. Because inspiratory work performed by the ventilator is calculated as the integral of the change in transrespiratory system pressure (airway pressure generated by the ventilator or P_{vent}) with respect to inhaled volume, we identify an assisted breath on ventilator graphic displays as an increase in P_{vent} above baseline during inspiration. However, airway pressure is affected not only by the mechanical properties of the respiratory system (ie, elastance and resistance) but also by inspiratory effort, often expressed as "muscle pressure" (P_{mus}).[54]

For pressure control modes, if P_{mus} increases, P_{vent} remains constant but the V_T increases. If P_{mus} increases and V_T increases, then the work the patient does (the integral of P_{mus} with respect to volume) increases, but the work the ventilator does remains constant. For volume control modes with set-point targeting, or pressure control modes with adaptive targeting, as P_{mus} increases, P_{vent} decreases but V_T remains constant. Thus, there is a work shift from ventilator to patient.[15] If the clinical goal is to match the work demand of the patient with the work supplied by the ventilator, then the ventilator must supply inspiratory pressure in proportion to inspiratory effort.

Capability: Automatic Adjustment of Support to Maintain Specified Breathing Pattern. Short of actually supplying the work demanded by the patient, the ventilator may deliver support to maintain a surrogate measure of demand. One surrogate is the pattern of spontaneous breath frequency and V_T. Another is just the spontaneous breath frequency.

- **Feature: Ventilator Set Pressure Support to Keep Patient in a Predefined Ventilatory Pattern.** The mode called SmartCare/PS (Evita XL) is essentially Pressure Support guided by a rule-based artificial intelligence targeting system.[55] In this mode, the ventilator automatically adjusts the level of pressure support to keep the patient within a "zone of comfort" based on end-tidal CO_2, V_T, and frequency.

- **Feature: Ventilator Set Pressure Support to Maintain Frequency Target.** Available in Europe, Mandatory Rate Ventilation (Taema-Hours ventilator made by Air Liquide) is a mode that is similar to Pressure Support but with adaptive targeting. Unlike conventional Pressure Support, the clinician sets a target frequency and the ventilator adjusts the pressure support in proportion to the difference between the target and actual frequencies. The assumption of the targeting scheme is that when the pressure support is correctly adjusted, the patient will have a "comfortable" ventilatory frequency (eg, 15–25 breaths/min).

Capability: Automatic Adjustment of Support to Meet Patient Demand

- **Feature: Ventilator Set Inspiratory Pressure Proportional to Inspiratory Effort.** Only with Proportional Assist Ventilation[56,57] and NAVA[58] does work output of the ventilator increase as the inspiratory effort of the patient increases. For example, with Proportional Assist Ventilation Plus (PB840) the clinician sets the percent support of total work of inspiration and the ventilator delivers inspiratory pressure in proportion to both inspiratory volume and flow, according to the equation of motion for the respiratory system. Another option is Automatic Tube Compensation (Evita XL); the clinician sets percent support of resistive work of breathing based on the size of the artificial airway, and the ventilator delivers pressure in proportion to the square of the spontaneous inspiratory flow.

Goal: To Promote Liberation

From the moment of initiation of mechanical ventilation, a prime goal is liberation. One would expect that the length of time a patient spends on ventilator support is the minimum necessary; the longer the duration of ventilation, the larger the cost and the higher risk of adverse events. Until recently, liberation has always depended on operator assessment of patient status and subsequent manual reduction of support. As the targeting systems of ventilators have evolved, we are now able to program the device to test and monitor for readiness for liberation.

Objective: To Optimize the Weaning Experience

Aim: To Minimize Duration of Ventilation. There are currently 2 approaches to automatic ventilator support reduction: patient driven and ventilator driven. Pressure control modes with adaptive pressure targeting systems[1] are examples of patient driven approaches to reduction of support. The ventilator monitors V_T and automatically adjusts inspiratory pressure between breaths to achieve average exhaled V_T equal to the target set by the clinician. In response to increased patient effort the inspiratory pressure is decreased, so these modes are sometimes referred to as automatic weaning modes. However, the mode does not recognize inappropriate increases in patient effort (eg, due to pain or anxiety) that would lead to undesirable reductions in ventilatory support. Again, the clinician's assessment of patient need and matching with appropriate mode capabilities (understanding targeting schemes and their limitations) is still the most important aspect of mechanical ventilation.

Capability: Ventilator Initiated Weaning of Support

- **Feature: Ventilator Initiated Reduction of Support and Evaluation of Response.** SmartCare/PS (Evita XL) automatically reduces support intermittently and evaluates the patient response in terms of end-tidal CO_2, V_T, and frequency, similar to the way a human operator would.[59]

Capability: Ventilator Recommends Liberation

- **Feature: Ventilator Initiated Spontaneous Breathing Trial.** SmartCare/PS tests the patient's readiness for extubation by maintaining the patient at the lowest level of inspiratory pressure. The lowest level depends on the type of artificial airway (endotracheal tube vs tracheostomy tube), the type of humidifier (heat and moisture exchanger vs heated humidifier), and the use of Automatic Tube Compensation. Once the lowest level of inspiratory pressure is reached, a one hour observation period is started (ie, a spontaneous breathing trial), during which the patient's breathing frequency, V_T, and end-tidal CO_2 are monitored. Upon successful completion of this step, a message on the screen suggests that the clinician "consider separation" of the patient from the ventilator.

Capability: Automatic Reduction of Support in Response to Increased Patient Effort

- **Feature: Ventilator Reduces Inspiratory Pressure as Inspiratory Effort Increases to Maintain Preset V_T Target.** Modes like Continuous Mandatory Ventilation with AutoFlow (Evita XL), Pressure Regulated Volume Control (Servo-i), and Volume Control Plus Assist Control (PB840) are examples of adaptive pressure targeting. These modes reduce inspiratory pressure and shift the work of breathing to the patient, but without any evaluation of response. Thus, it may be an acceptable reduction in support with an appropriate patient response, or the contrary, leave the patient with an increased work of breathing in a precarious condition.

Aim: To Minimize Adverse Events

Capability: Monitor Probability of Failure. Adverse events related to modes of ventilation are essentially due to the failure to meet the safety and comfort goals. However, there are no specific guidelines for determining when these goals are met. One way ventilators could help avoid adverse events would be to relate both current and trend data for ventilator settings and physiologic signals to some estimate of risk. Risk could be defined in terms of the probability of failure to meet the goals, and the severity of the consequences. For example, the ventilator might display a warning that "this level of pulmonary stress will result in VILI within 24 hours at 90% probability," or "the patient's V_T to frequency ratio indicates an 85% probability of hypoventilation within 30 min."

Capability: Identify Adverse Event. Another way would be for the ventilator to identify when a failure occurred, such as asynchrony. Either way, the ventilator could perhaps either fix it or provide decision support to the clinician. Unfortunately, we are aware of no research along these lines for ventilator monitoring systems.

What Mode to Use?

We have described a method to evaluate modes of mechanical ventilation based on how their technological capabilities serve clinical goals. A mode that serves the most clinical aims will rank favorably in a simple tally. Yet we must again emphasize what this tally means. As explained above, there are 3 levels at which medical interventions can be evaluated (theoretical, performance, and outcome). We made the case that evaluating all the modes at the performance level is fraught with complexities and does not lead to practical knowledge. Further, evaluation at the *outcome* level is currently impossible, given the number of modes and conditions we treat. Thus, our ranking system is based on the current *theoretical* knowledge we possess in terms of mechanical ventilation. Without a doubt, as we progress in our scientific quest, we will add new aims and objectives. And we will add to the list of technological ventilator capabilities.

The procedure for identifying the mode, as we have proposed, starts with a list of unique modes identified by applying the classification system (see Table 2). Next, we construct a matrix that allows the identification of the presence or absence of the technological capabilities that fulfill a clinical goal, as described above (Tables 5–7). These matrixes are built under the assumptions that the presence of each capability is beneficial in the appropriate scenario for a clinical goal, and that all current capabilities are identified.

What is evident from using the matrix is that the modes can be distinguished based on their capabilities. For each of the goals of ventilation there are modes that may be preferred over others. For instance, modes with automatic adjustment features that assure ventilation and tailor settings to enhance lung protection (based on expert rules) may be advantageous in promoting safety (eg, PC-IMV Optimal/Intelligent, as in IntelliVent-ASV). From a comfort standpoint, modes that allow all breaths to be spontaneous while partially unloading respiratory muscles may be preferable (eg, PC-CSV with Servo targeting as in Proportional Assist Ventilation and NAVA). Finally, serving liberation from mechanical ventilation, a mode that reduces support as patient ventilatory capacity improves may

Table 5. Unique Modes of Table 2 (With a Few Variations Added) Ranked by Technological Capabilities Related to the Goal of Safety

Mode Name	Mode Classification	Automatic Adjustment of Minute Ventilation Target	Automatic Adjustment of Support in Response to Changing Respiratory Mechanics	Automatic Adjustment of Minute Ventilation Parameters (f, V_T)	Manual Adjustment of Minimum Minute Ventilation Parameters (f, V_T)	Automatic Adjustment of Oxygen Delivery	Automatic Adjustment of End-Expiratory Lung Volume	Automatic Adjustment of Ventilation Parameters Within Lung-Protective Limits	Minimize Tidal Volume	Safety Capabilities
IntelliVent-ASV	PC-IMV$_{\text{OI,OI}}$	√	√	√		√	√	√		6
Adaptive Support Ventilation	PC-IMV$_{\text{O,O}}$		√	√				√		3
Automode (Pressure Regulated Volume Control to Volume Support)	PC-IMV$_{\text{A,A}}$		√	√	√					3
Automode (Volume Control to Volume Support)	VC-IMV$_{\text{D,A}}$		√	√	√					3
Mandatory Minute Volume with Pressure Limited Ventilation*	VC-IMV$_{\text{DA,S}}$			√	√					2
Adaptive Pressure Ventilation Synchronized Intermittent Mandatory Ventilation	PC-IMV$_{\text{A,S}}$		√		√					2
Mandatory Minute Volume Ventilation	VC-IMV$_{\text{A,S}}$			√	√					2
Pressure Regulated Volume Control	PC-CMV$_{\text{A}}$		√		√					2
SmartCare/PS	PC-CSV$_{\text{I}}$			√						1
Volume Support	PC-CSV$_{\text{A}}$		√							1
Mandatory Rate Ventilation	PC-CSV$_{\text{A}}$			√						1
Synchronized Intermittent Mandatory Ventilation (Volume Control Maquet Servo-i)	VC-IMV$_{\text{D,S}}$				√					1
High Frequency Oscillatory Ventilation	PC-IMV$_{\text{S,}}$								√	1
Volume Control Synchronized Intermittent Mandatory Ventilation (Adaptive Flow & I time GE Healthcare/Versamed iVent 201)	VC-IMV$_{\text{A S}}$				√					1
Volume Control Synchronized Intermittent Mandatory Ventilation	VC-IMV$_{\text{S,S}}$				√					1
Continuous Mandatory Ventilation with Pressure Limited*	VC-CMV$_{\text{D}}$				√					1
Volume Control Assist/Control	VC-CMV$_{\text{S}}$				√					1
Neurally Adjusted Ventilatory Support	PC-CSV$_{\text{R}}$									0
Proportional Assist Ventilation	PC-CSV$_{\text{R}}$									0
Pressure Support	PC-CSV$_{\text{S}}$									0
Airway Pressure Release Ventilation	PC-IMV$_{\text{S,S}}$									0
Pressure Control Synchronized Intermittent Mandatory Ventilation	PC-IMV$_{\text{S,S}}$									0
Pressure Control Assist Control	PC-CMV$_{\text{S}}$									0

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* Unrestricted inspiratory, but not expiratory, flow after maximum pressure threshold is met.
f = breathing frequency
V_T = tidal volume
PC = pressure control
IMV = intermittent mandatory ventilation
Subscripts: S = set-point. D = dual. A = adaptive. O = optimal. I = intelligent. R = servo.
VC = volume control
CMV = continuous mandatory ventilation
CSV = continuous spontaneous ventilation

offer an advantage (eg, PC-CSV with Intelligent targeting as in SmartCare/PS).

Internationally, the 3 most common modes used for adults are Volume Assist/Control, Pressure Assist/Control, and Pressure Support.[5] Volume Assist/Control is one of the oldest and still the most widely used mode in the world.[5] This mode's popularity may be justified by the fact that our only clinical evidence for matching goals with

Table 6. Unique modes of Table 2 (With a Few Variations Added) Ranked by Technological Capabilities Related to the Goal of Comfort

Mode Name	Mode Classification	All breaths Are Spontaneous With Patient Effort	Trigger/cycle Based on Signal Representing Chest Wall/ Diaphragm Movement	Coordination of Mandatory and Spontaneous Breaths	Automatic Limitation of AutoPEEP	Unrestricted Inspiratory Flow	Automatic Adjustment of Flow Based on Frequency	Automatic Adjustment of Support to Maintain Specific Breathing Pattern	Automatic Adjustment of Support Proportional to Patient Demand	Comfort Capabilities
IntelliVent-ASV	PC-IMV$_{OI,OI}$	√		√	√	√				4
Adaptive Support Ventilation	PC-IMV$_{O,O}$	√		√	√	√				4
Neurally Adjusted Ventilatory Support	PC-CSV$_R$	√	√			√			√	4
SmartCare/PS	PC-CSV$_I$	√				√		√		3
Automode (Pressure Regulated Volume Control to Volume Support)	PC-IMV$_{A,A}$	√		√		√				3
Automode (Volume Control to Volume Support)	VC-IMV$_{D,A}$	√		√		√				3
Mandatory Minute Volume with Pressure Limited Ventilation*	VC-IMV$_{DA,S}$	√		√		√				3
Mandatory Rate Ventilation	PC-CSV$_A$	√				√		√		3
Proportional Assist Ventilation	PC-CSV$_R$	√				√			√	3
Adaptive Pressure Ventilation Synchronized Intermittent Mandatory Ventilation	PC-IMV$_{A,S}$			√		√				2
Mandatory Minute Volume Ventilation	VC-IMV$_{A,S}$	√		√						2
Volume Support	PC-CSV$_A$	√				√				2
Synchronized Intermittent Mandatory Ventilation (Volume Control Maquet Servo-i)	VC-IMV$_{D,S}$			√		√				2
High Frequency Oscillatory Ventilation	PC-IMV$_{S,}$			√		√				2
Volume Control Synchronized Intermittent Mandatory Ventilation (Adaptive Flow & I time GE Healthcare/ Versamed iVent 201)	VC-IMV$_{A\ S}$			√			√			2
Pressure Support	PC-CSV$_S$	√				√				2
Airway Pressure Release Ventilation	PC-IMV$_{S,S}$			√		√				2
Pressure Control Synchronized Intermittent Mandatory Ventilation	PC-IMV$_{S,S}$			√		√				2
Pressure Regulated Volume Control	PC-CMV$_A$					√				1
Volume Control Synchronized Intermittent Mandatory Ventilation	VC-IMV$_{S,S}$			√						1
Continuous Mandatory Ventilation with Pressure Limited*	VC-CMV$_D$					√				1
Pressure Control Assist Control	PC-CMV$_S$					√				1
Volume Control Assist/Control	VC-CMV$_S$									0

* Unrestricted inspiratory, but not expiratory, flow after maximum pressure threshold is met.
PC = pressure control
IMV = intermittent mandatory ventilation
Subscripts: S = set-point. D = dual. A = adaptive. O = optimal. I = intelligent. R = servo.
VC = volume control
CSV = continuous spontaneous ventilation
CMV = continuous mandatory ventilation

technology is that lower V_T reduces mortality.[6] Despite their popularity, the aforementioned modes have low sophistication, which may render them inferior in safety and comfort. Similarly, Pressure Assist/Control and Pressure Support are widely used. These modes allow variable flow (comfort), but $\dot{V}_E$ is dependent on the respiratory system characteristics (minimal $\dot{V}_E$ is not assured). Thus, they serve to provide comfort, yet safety goals may not be optimally met. Again, we evaluated the modes based on the theoretical level, focusing on evaluation of capabilities under specific clinical goals. Technological advancement allows us to establish repetitive tasks to be performed by

Table 7. Unique Modes of Table 2 (With a Few Variations Added) Ranked by Technological Capabilities Related to the Goal of Liberation

Mode Name	Mode Classification	Ventilator Initiated Weaning of Support	Ventilator Recommends Liberation	Automatic Reduction of Support in Response to Increased Patient Effort	Liberation Capabilities
SmartCare/PS	$PC\text{-}CSV_I$	√	√	√	3
IntelliVent-ASV	$PC\text{-}IMV_{OI,OI}$			√	1
Adaptive Support Ventilation	$PC\text{-}IMV_{O,O}$			√	1
Automode (Pressure Regulated Volume Control to Volume Support)	$PC\text{-}IMV_{A,A}$			√	1
Automode (Volume Control to Volume Support)	$VC\text{-}IMV_{D,A}$			√	1
Mandatory Minute Volume with Pressure Limited Ventilation*	$VC\text{-}IMV_{DA,S}$			√	1
Adaptive Pressure Ventilation Synchronized Intermittent Mandatory Ventilation	$PC\text{-}IMV_{A,S}$			√	1
Mandatory Minute Volume Ventilation	$VC\text{-}IMV_{A,S}$			√	1
Volume Support	$PC\text{-}CSV_A$			√	1
Pressure Regulated Volume Control	$PC\text{-}CMV_A$			√	1
Neurally Adjusted Ventilatory Support	$PC\text{-}CSV_R$				0
Mandatory Rate Ventilation	$PC\text{-}CSV_A$				0
Synchronized Intermittent Mandatory Ventilation (Volume Control) (Maquet Servo-i)	$VC\text{-}IMV_{D,S}$				0
Proportional Assist Ventilation	$PC\text{-}CSV_R$				0
High Frequency Oscillatory Ventilation	$PC\text{-}IMV_S$,				0
Volume Control Synchronized Intermittent Mandatory Ventilation (Adaptive Flow & I time GE Healthcare/Versamed iVent 201)	$VC\text{-}IMV_{A,S}$				0
Volume Control Synchronized Intermittent Mandatory Ventilation	$VC\text{-}IMV_{S,S}$				0
Pressure Support	$PC\text{-}CSV_S$				0
Airway Pressure Release Ventilation	$PC\text{-}IMV_{S,S}$				0
Pressure Control Synchronized Intermittent Mandatory Ventilation	$PC\text{-}IMV_{S,S}$				0
Continuous Mandatory Ventilation with Pressure Limited*	$VC\text{-}CMV_D$				0
Pressure Control Assist Control	$PC\text{-}CMV_S$				0
Volume Control Assist/Control	$VC\text{-}CMV_S$				0

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* Unrestricted inspiratory, but not expiratory, flow after maximum pressure threshold is met.
PC = pressure control
CSV = continuous spontaneous ventilation
Subscripts: S = set-point. D = dual. A = adaptive. O = optimal. I = intelligent. R = servo.
IMV = intermittent mandatory ventilation
VC = volume control
CMV = continuous mandatory ventilation

the device without clinician supervision. As such, more critical care ventilators have modes with control schemes that include expert or evidence-based rules. Consequently, the device performs a task following a protocol driven by our knowledge. Thus, an artificial intelligence mode could potentially perform better than, or equivalent to, an ever-present clinician at the bedside.[59,60] More importantly, the use of a protocol (applied by a human or a ventilator), simplifies comparison in outcomes, errors in process, and can always be changed.[61]

There are several limitations to our approach for mode selection. First, our system does not include all ventilator features. There are several brands of ventilator available, and we focused only on those commonly available to ICUs. We also found that a mode may have a capability that does not serve our current goals of ventilation. For example, in Variable Pressure Support (Dräger) the inspiratory pressure is randomly changed to implement biologically variable (or "noisy") ventilation. The goal is to mimic the variability seen when humans breathe naturally.

Thus, the capability is to have automatic adjustment of support to simulate biologically variable ventilation. Recent evidence suggests noisy ventilation improved arterial oxygenation and reduced mean inspiratory peak airway pressure.[33] However, we could not place noisy ventilation in the safety goal, as the improvement in oxygenation and VILI is a result of the application, not a direct goal of the capability. Nor can we place it under comfort, as this is not the goal of the variability. Perhaps as technology and knowledge advance we will eventually have to create the goal of "biocompatibility." In the same context, there are capabilities that are not available at this time. As we have mentioned, no ventilator mode focuses on minimizing lung injury. For example, a mode that focuses on minimizing stress and strain[36] of the alveoli with the aim of decreasing lung injury would be a welcome addition.

Another limitation is that a simple tally of the potentially beneficial characteristics of modes assumes that all goals have equal weight (importance). However, the relative importance of the 3 goals (safety, comfort, and liberation) change in time. For example, in the acute stage of ventilatory failure, safety (limiting volumes, assuring ventilation) has more weight than comfort, and liberation is not a concern at all. As the patient's condition stabilizes and spontaneous ventilation becomes more evident, comfort becomes more important. Yet in many situations, clinicians may face a conundrum of whether safety or comfort is more important.[62] Selecting a mode requires the clinician to select which goal is more important and then to use the mode that fulfills these goals. Whether the employment of the technological capability would lead to "best" outcomes depends on patient condition, timing of application, and the skill of the operator. As such, we can understand why clinicians tend to give a very high weight to limiting V_T with volume control over other modes. Yet there are several approaches to limiting V_T these days, which offer other benefits in the same and other goals. Furthermore, some ventilator capabilities may have higher weight than others within the goal. Differential emphasis on features that are considered during ranking results in marked changes in order of preference in other areas, such as ranking of cars or colleges.[2]

Conclusions

In conclusion, the vast array of mode names on commercially available mechanical ventilators can be objectively evaluated in terms of their inherent technological capabilities by first classifying them and then cataloging the specific features that serve the general goals and clinical aims of patient care. While there are over 170 unique names of modes available, they reduce to less than 2 dozen unique modes by our classification. This analysis serves stakeholders in at least 3 ways: clinicians now have a better understanding of the resources available for patient care, educators have a system for simplifying the teaching of mechanical ventilation principles, and manufacturers have a clear indication of what features need to be developed in future devices.

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