

Which Ventilators and Modes Can Be Used to Deliver Noninvasive Ventilation?

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A wide variety of ventilators and modes can be used to deliver noninvasive ventilation (NIV). To navigate successfully through the many options, the clinician must first have a clear understanding of the goals of mechanical ventilation: namely, safety, comfort, and timely liberation. Examining the specific objectives associated with these goals, we can distinguish priorities for NIV. This paper reviews the methods of achieving those objectives by reviewing the characteristics of ventilation modes and how those characteristics are measured in performance-evaluation studies. This review provides the basis for a simple procedure for selecting the most appropriate NIV technology for the patient and the environment of care. Key words: mechanical ventilation, ventilator, ventilation mode, noninvasive ventilation, NIV, bi-level, proportional-assist ventilation, pressure support, lung model. [Respir Care 2009;54(1):85–99. © 2009 Daedalus Enterprises]

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WHICH VENTILATORS AND MODES CAN BE USED TO DELIVER NONINVASIVE VENTILATION?

Table 1. Criteria for Considering Noninvasive Ventilation

Disease processes and situations that definitely indicate NIV (strong evidence ^{1,2})
COPD exacerbation
Facilitation of weaning/extubation in patients with COPD
Acute cardiogenic pulmonary edema
Immunocompromised (hematologic malignancy, bone marrow or solid-organ transplant, AIDS)
Inclusion criteria (at least 2 should be present)
Use of accessory muscles
Paradoxical breathing
Respiratory rate ≥ 25 breaths/min
Dyspnea (moderate-to-severe or increased in COPD)
$P_{aCO_2} > 45$ mm Hg with pH < 7.35
$P_{aO_2}/F_{IO_2} < 200$ mm Hg
Exclusion criteria
Apnea
Hemodynamic or cardiac instability
Uncooperative patient
Facial burn or trauma
High risk of aspiration
Copious secretions
Anatomic abnormalities that interfere with gas delivery

COPD = chronic obstructive pulmonary disease
AIDS = acquired immune deficiency syndrome
 F_{IO_2} = fraction of inspired oxygen

Introduction

You have assessed the patient. He seems to meet many of the standard textbook criteria^{1,2} for considering noninvasive ventilation (NIV) (Table 1). But now you face a bewildering array of technological decisions. The selection of patient-ventilator interface is not too difficult (ie, nasal mask, nasal pillows, oronasal mask, full-face mask, or helmet), except that manufacturers called oronasal masks “full face” until someone invented a real full-face (“total face”) mask³ and now there is a nomenclature issue. But what about the ventilator? Which ventilator do you use, and which mode do you select? And how do you even know which mode is which when the literature is full of confusing terms and acronyms, such as volume-cycled, pressure-cycled, volume-limited, control mode, assist-control (A/C) mode, pressure-control ventilation (PCV), intermittent positive-pressure ventilation (IPPV), bi-level positive airway pressure (BiPAP), spontaneous/timed (S/T) mode, volume-assist/control, pressure-assist/control, pressure-support ventilation (PSV), and proportional-assist ventilation (PAV)?

In this paper I will take a step-by-step approach to this problem, by first reviewing the general goals of mechanical ventilation and how they might be emphasized differently in NIV versus invasive ventilation (ie, intubated pa-

Table 2. Goals and Objectives of Mechanical Ventilation

<u>Do no harm (minimize risks and maximize safety)</u>
Provide adequate gas exchange by optimizing the ventilation-perfusion ratio
Acceptable blood gas values
Minimal dead space
Adequate cardiac output and blood pressure
Avoid ventilator-induced lung injury by optimizing the lung volume/pressure ratio (optimize mechanics)
Optimal PEEP
Optimal tidal volume
Minimize risk of ventilator-associated pneumonia
<u>Promote patient comfort</u>
Avoid patient-ventilator asynchrony by optimizing the ratio of ventilator work output to patient work output, ie, ventilatory demand
Optimal trigger and cycle sensitivities (spontaneous breaths)
Optimal inspiratory time and peak inspiratory flow (mandatory breaths)
<u>Liberate patient from ventilator as soon as possible</u>
Minimize duration of mechanical ventilation
Optimal criteria for weaning screen, spontaneous breathing trial, and extubation
Optimal adherence to protocols and avoidance of delays

PEEP = positive end-expiratory pressure

tients). Next I will review the basic nomenclature and classification scheme for ventilation modes, to dispel some of the confusion about jargon. Having identified which modes best meet the goals of NIV, I will then discuss which ventilators best provide the modes. Finally, I will conclude with a simplified algorithm for selecting the most appropriate ventilator and mode for NIV in a given situation.

Goals and Objectives of Ventilation: Invasive Versus Noninvasive

The goals of mechanical ventilation, in the most basic terms, can be thought of as (1) do no harm, (2) promote patient comfort, and (3) liberate the patient from mechanical ventilation as soon as possible (Table 2). No doubt these goals are the same whether treating the patient invasively or noninvasively. However, if we look at the specific objectives associated with these goals, perhaps we can distinguish priorities for the 2 approaches to ventilation. For example, intubated patients are usually more critically ill, so safety objectives (eg, following blood gas values to assure adequate ventilation and using a lung-protective ventilation strategy) tend to predominate over comfort objectives (eg, intubated patients are often sedated). Table 3 lists some criteria to determine if safety should be the priority. If none of those

Table 3. Criteria to Determine if a Noninvasive Ventilation Candidate's Condition Warrants Safety as a Priority

Apnea risk	
Central apnea	
Failure to trigger due to intermittent leaks	
Hypoventilation Risk	
Severe COPD exacerbation	
Failed extubation	
Hypoxemia Risk	
High F_{IO_2} requirement	
High PEEP requirement	
COPD = chronic obstructive pulmonary disease	
F_{IO_2} = fraction of inspired oxygen	
PEEP = positive end-expiratory pressure	

criteria are met, and there are no other countervailing circumstances, the priority should be comfort. Comfort objectives tend to predominate with patients treated with NIV, because these patients are usually awake, alert, and desire to interact with the world in as normal a fashion as possible, particularly if the NIV is for a chronic or permanent condition. If this distinction between invasive ventilation and NIV is valid, then it should guide our selection of ventilation modes.

For a brief overview of how ventilation modes are described and classified, see the Appendix, which provides the basic concepts and terminology for the rest of this paper.

Which Modes Best Meet the Goals of NIV?

Having defined a “mode” as a basic ventilatory pattern (for the simplified purposes of this paper), we can now review the literature with minimum confusion regarding terminology. In other words, I will translate the various names used in the cited articles into the standardized terms for ventilatory patterns (with the exception that I will also refer to continuous positive airway pressure [CPAP], PSV, and PAV).

But, before evaluating the merits of various modes, we need to review the laboratory evaluation of ventilator performance in general. The key difference between invasive ventilation and NIV is that NIV typically involves air leaks, because NIV uses a mask instead of an endotracheal tube. NIV air leaks can be large enough to affect the ventilator's triggering and cycling functions and the rate of inspiratory pressure rise. Thus, the standard laboratory setup for assessing ventilator performance under NIV conditions is to connect the ventilator to a simulated load (ie, lung model with variable resistance and compliance) with a circuit that has a variable (ie, controllable) leak.

Evaluating Ventilator Performance

Lung Models

The most common lung model for this type of experimental setup is a double-bellows model, such as the Training and Test Lung (Michigan Instruments, Grand Rapids, Michigan).⁴ With this device, one bellows is connected to a “driving” ventilator set to simulate the patient's ventilatory muscle actions. The other bellows is connected to the ventilator being evaluated. The connection to the test ventilator is often via a simulated patient head fitted with a mask. The connection between the mask and the test ventilator includes a variable leak (eg, a valve that opens to the atmosphere). Flow transducers are placed in the circuit between the mask and the test ventilator and between the lung simulator and the mask. Pressure, volume, and flow signals are then digitally recorded and analyzed with a computer. Figure 1 shows a typical setup.⁵

The problem with the above-mentioned setup is that the lung simulator mechanical properties (ie, resistance and compliance) are limited to a finite number of discrete spring-tension settings or calibrated flow resistors. In addition, researchers often have to create their own data-analysis algorithms (eg, to calculate trigger delay). Fortunately, there is a better test lung commercially available. In my opinion, the best available lung simulator is the ASL 5000 (IngMar Medical, Pittsburgh, Pennsylvania).⁶ It is based on a computer-controlled piston that moves inside a cylinder. Volume (V) as a function of time (t) is measured directly as piston displacement. Flow (\dot{V}) is the derivative of volume with respect to time (dV/dt). Airway pressure (P) is governed by the equation of motion for the respiratory system:

$$P = (1/C)V(t) + R(dV/dt) - P_{mus}(t)$$

where C is compliance, R is resistance, and $P_{mus}(t)$ is ventilatory muscle pressure as a function of time, which is either set to zero (ie, passive inflation and deflation) or is defined by the operator to simulate active breathing. The simulator can be programmed as a single-compartment or double-compartment model (ie, 1 or 2 lungs). Compliance is simulated by moving the piston according to $dV = (C)(dP)$. The relationship between pressure and volume can be made nonlinear to better approximate the model to the S-shaped pressure/volume response curve of a real patient. Resistance is defined by $dP = (R)(dV/dt)$, so the piston is moved at a speed of $dV/dt = dP/R$. Different values for resistance can be selected for flows in the direction of inspiration and expiration, and the resistor settings can be linear or parabolic. Parabolic resistors have been the choice for most physical resistors, because implementations of linear resistors demand linear flow over

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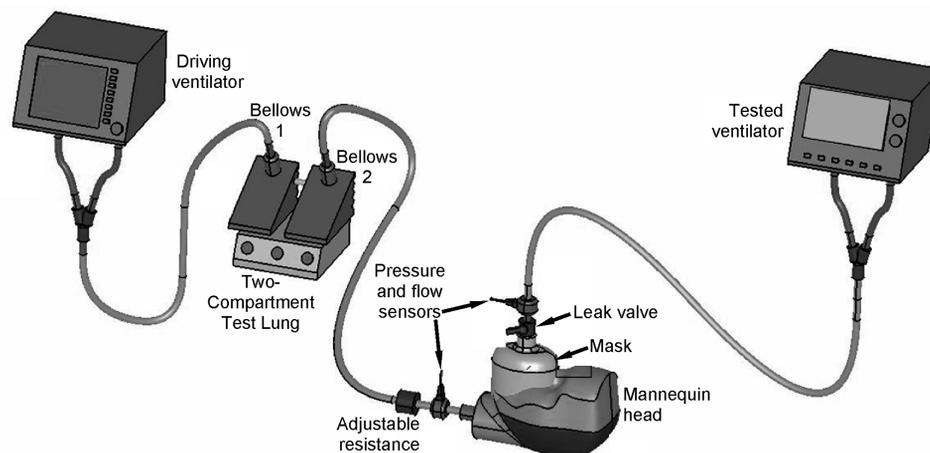


Fig. 1. Bellows lung simulator setup to evaluate ventilator performance during noninvasive ventilation. (Adapted from Reference 5, with permission.)

the whole expected flow range. The ASL 5000 simulator avoids those difficulties and provides a response that represents both types.

Spontaneous breathing effort is simulated by specifying a P_{mus} function. The operator can set the frequency, amplitude, and various parameters of the waveform. An optional device, the Simulator Bypass and Leak Valve Module (IngMar Medical, Pittsburgh, Pennsylvania), provides 3 levels of simulated leak (Fig. 2), to provide the reproducible leaks required for ventilator-performance testing with simulated NIV scenarios. Figure 3 shows a typical experimental setup.⁷ The ASL 5000 comes with software specifically designed to test ventilator performance, so it has a wide variety of waveform-analysis features and calculated variables.

In this article I report results obtained with an ASL 5000, programmed with the settings shown in Table 4.

Performance Variables

Patient-ventilator asynchrony during NIV can be classified according to the 4 breath phases: the switch from expiration to inspiration; inspiration; the switch from inspiration to expiration; expiration.

Leaks in the delivery system cause problems in Phase 1, such as delayed triggering, decreased sensitivity (missed trigger efforts), or increased sensitivity (auto-triggering). Phase 2 effects include a decreased rate of inspiratory pressure rise. Phase 3 effects occur if the leak is large enough to prevent inspiratory flow decay to the cycle threshold. In Phase 4, leaks may cause loss of positive end-expiratory pressure (PEEP).

Some of the variables that have been defined (eg, by the ASL 5000) to evaluate ventilator performance (Fig. 4) include:

Drop to P_{min} : The change in airway pressure from PEEP to the minimum airway pressure (ie, pressure below baseline before inspiratory flow starts going in the positive direction) caused by a patient inspiratory effort. Some authors have referred to this as “trigger pressure.” However, the precise meaning of trigger pressure is the pressure threshold the ventilator uses to start inspiratory flow. The P_{min} recorded at the airway opening during the trigger phase of a breath is the result of several factors, including the inspiratory effort, the patient circuit compliance, and the ventilator’s gas-flow delivery characteristics, so the airway pressure typically continues downward even though the ventilator has started inspiratory flow. Thus, P_{min} may be less than the true trigger pressure. Indeed, “trigger pressure” is not even relevant when inspiration is flow-triggered.

Inspiratory time (T_I): The time from the start of inspiratory effort (ie, P_{mus} beginning to go below zero) to the start of expiratory flow (or to maximum volume of the ASL 5000).

Time to P_{min} : The time from the start of inspiratory effort (ie, P_{mus} beginning to go below zero) to the minimum airway pressure.

Time from P_{min} to baseline (PEEP): The time it takes for airway pressure to go from minimum airway pressure to baseline (PEEP).

Trigger response time: The time from the start of inspiratory effort to the point where airway pressure reaches baseline (PEEP) (ie, the sum of *Time to P_{min}* and *Time from P_{min} to baseline*).

Patient trigger work: The integral of P_{mus} with respect to volume from the start of inspiratory effort to the point where airway pressure returns to PEEP after P_{min} .

Pressure-time product: The integral of airway pressure (relative to PEEP) with respect to time from the start of

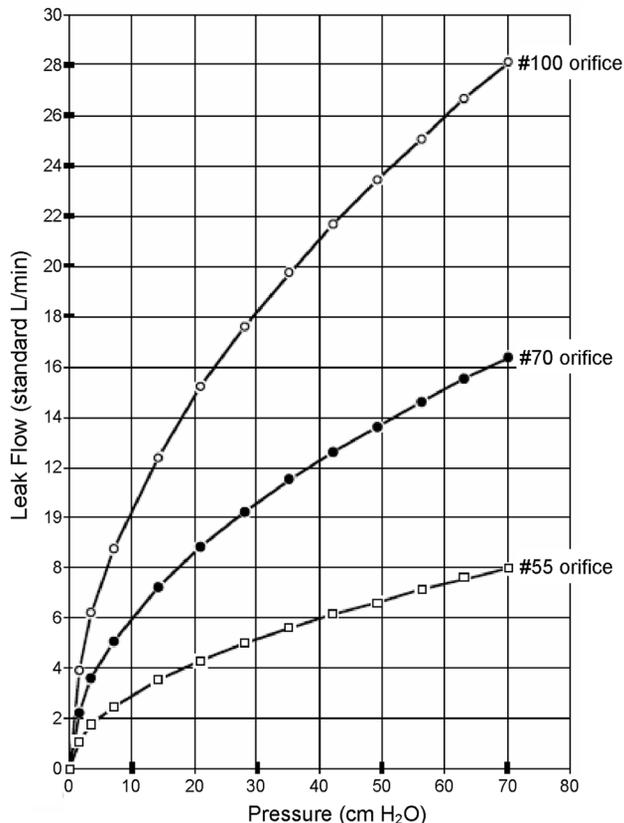


Fig. 2. Pressure versus flow characteristics of the Simulator Bypass and Leak Valve Module used with the Ingmar ASL 5000 lung simulator. (Courtesy of Ingmar Medical.)

inspiratory effort to the point where airway pressure returns to PEEP after P_{\min} .

Inspiratory T_{90} : Time for airway pressure to rise to 90% of the steady-state value. This is an index of pressure-waveform distortion due to a leak. A lower value indicates that pressure rises slower because of flow loss from the leak.

Cycling delay: T_I minus inspiratory effort time (ie, the time that P_{mus} is below zero). A positive number means inspiratory flow from the ventilator ended after the effort ended (delayed cycling), and a negative number means that inspiratory flow ended before the effort ended (premature cycling).

Volume Control Versus Pressure Control

The first consideration in evaluating modes is whether there is a difference between volume control (VC) and pressure control (PC) when trying to ventilate in the presence of large and possibly unstable leaks. Rather than try to guess or infer the answer from experimental data, we can much more reliably model the situation mathematically. For this purpose we borrow a schematic and analy-

ses from electrical engineering. Figure 5 shows the respiratory system represented as an electrical resistance connected in series with a capacitance. The leak is modeled as a resistance in parallel with the respiratory system. Pressure control is modeled as a step change in voltage applied across the model, and volume control is modeled as a step change in electrical current. The mathematical model that corresponds to this electrical model is analogous to the equation of motion. The equation is solved for volume (as a function of time) using the Laplace Transform (Fig. 6).⁸ In Figure 6 the intersection of the 2 solid lines represents the target tidal volume (V_T) delivered with a preset T_I and the no-leak condition. The shape of the 2 sets of curves show that pressure control delivers more of the target V_T for any time less than the target T_I than does volume control. However, the difference in leak between the 2 modes (ie, the vertical distance between “leak off” and “leak on” in Fig. 6) becomes clinically unimportant as T_I decreases (eg, as breathing frequency increases). The theoretical waveforms in Figure 6 show that a leak causes lung volume to rise exponentially rather than linearly in volume control. In effect, volume control has been changed to pressure control, because the pressure drop across the leak acts like a pressure-limiting valve. What I conclude from this analysis is that, theoretically, pressure control is better than volume control.

Another theoretical advantage of pressure control is that, for the same V_T , pressure control results in a lower peak inspiratory pressure⁹ (provided that the T_I is longer than about 3 time constants of the respiratory system). This is true when volume control is achieved with a constant flow. A lower peak inspiratory pressure may allow less mask tightness and better patient comfort. However, some ventilators (eg, the Aequitron LP-10, Aequitron Medical/Mallinckrodt, Plymouth, Minnesota) deliver volume-controlled breaths with a descending-ramp flow waveform that approximates the shape of the flow waveform during pressure control, so the peak inspiratory pressure is similar (Fig. 7).

But are the differences important in the real world of NIV? To answer that question I compared VC-CMV to PC-CMV with an Aequitron LP-10 ventilator. I achieved pressure control by setting the V_T to 1.0 L and using the mechanical pressure-limit knob to adjust peak inspiratory pressure. I connected the ventilator to the ASL 5000 lung simulator, as described above, and set the ventilator to deliver a V_T of about 480 mL. I recorded delivered V_T at baseline (no leak) and at leak settings of 1, 2, and 3 on the Simulator Bypass and Leak Valve Module. Figure 8 shows the results. The V_T with volume control dropped 32% (at leak setting 3), compared to only 6% with pressure control. This confirms not only that the theoretical results are valid but also that the effect may be clinically important. The take-home message is that pressure control should

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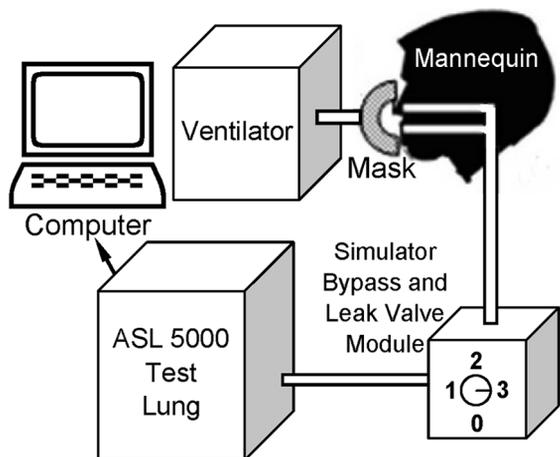


Fig. 3. Experimental setup to evaluate ventilator performance during noninvasive ventilation with the Ingmar ASL 5000 test lung and Simulator Bypass and Leak Valve Module. (Courtesy Robert L Kacmarek PhD RRT FAARC.)

Table 4. Settings Used With the Ingmar ASL 5000 Lung Simulator

Single-compartment model to simulate a patient with COPD
Mechanical Variables

- Uncompensated residual volume: 0.5 L
- Inspiratory resistance: 10 cmH₂O/L/s
- Expiratory resistance: 10 cmH₂O/L/s
- Compliance: 80 mL/cmH₂O

P_{mus} Variables

- Frequency: 15 breaths/min
- Amplitude: 5 cmH₂O
- Inspiration: 5% (of ventilatory period)
- Hold: 3%
- Release: 15%
- P_{mus} modified by airway pressure (backing off): 50%
- Baseline mask leak: 4 L/min at mean airway pressure of 8 cmH₂O

provide a more stable ventilatory support than volume control if there is a large and variable leak.

There are, however, advantages to volume control. Piston-driven portable volume-control ventilators can provide higher ventilating pressure, which may be required in patients with high respiratory-system impedance (eg, due to obesity). These ventilators can operate considerably longer on battery power than blower-driven pressure control devices. Finally, patients using volume-control ventilators can be taught to “stack” (ie, double-trigger) breaths to attain a high inspired lung volume to increase cough flow.²

Some studies have compared pressure control to volume control in terms of physiologic variables. Two studies^{10,11} found no difference in oxygenation or ventilation between the two. Girault et al¹² found that volume control had lower inspiratory work load than did pressure control. Vitacca et al¹³ found no difference in NIV success rate be-

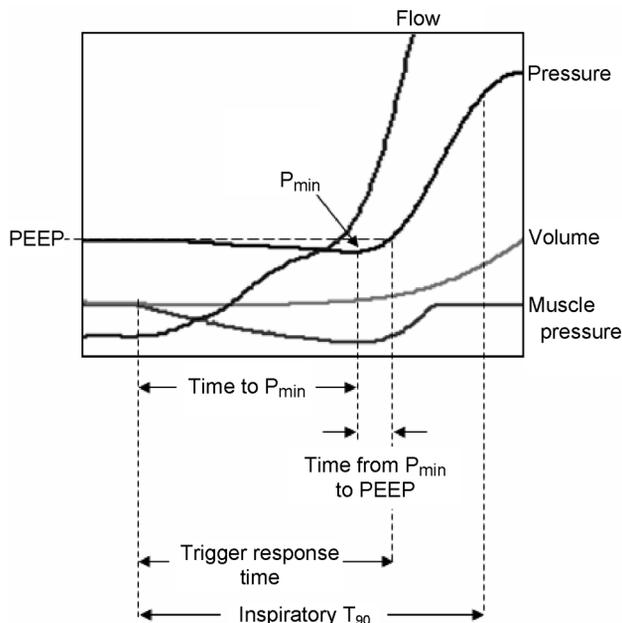


Fig. 4. Flow, pressure, volume, and muscle pressure waveforms to illustrate the definitions of ventilator-performance variables. Vertical axis is pressure ($\times 10$), volume, and flow ($\times 10$). Horizontal axis is time. P_{min} = change in airway pressure from PEEP to the minimum airway pressure. PEEP = positive end-expiratory pressure. T_{90} = time for airway pressure to rise to 90% of the steady-state value.

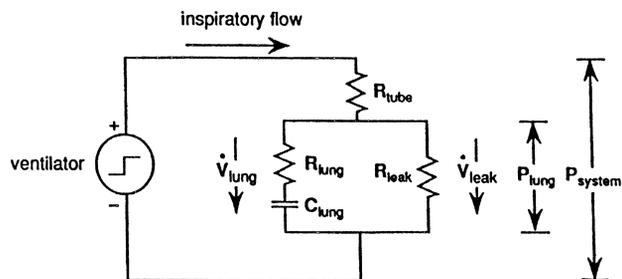


Fig. 5. Electrical circuit that models a leak in parallel with the respiratory system. R = resistance. Tube = endotracheal tube. \dot{V} = flow. C = compliance. P = pressure. (From Reference 8.)

tween volume control and pressure control. Shönhofer et al¹⁴ found that pressure control was successful in the majority of patients after an initial treatment with volume control. Two patients in that study had intractable flatulence with volume control but were adequately treated with pressure control (presumably due to a lower peak inspiratory pressure). One third of the patients who initially did well on volume control failed on pressure control, despite the fact that the 2 modes were matched for rate and V_T during the day. The authors speculated that one reason for not responding to pressure control may be the postural change of lung and chest wall mechanics during nocturnal ventilation, which leads to hypoventilation.

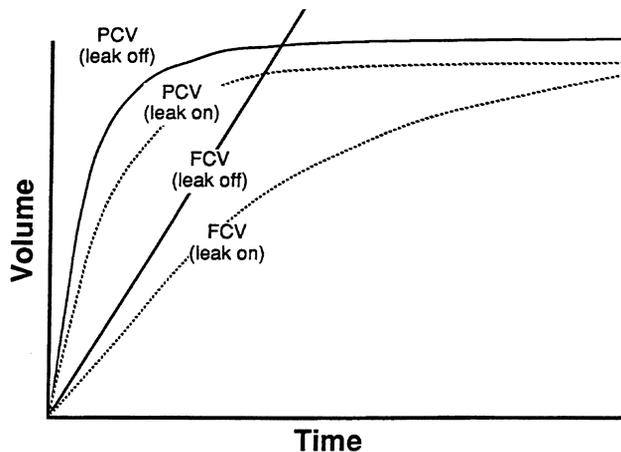


Fig. 6. Delivered volume as a function of time in pressure-controlled ventilation (PCV) or flow-controlled ventilation (FCV), which is synonymous with volume control. (From Reference 8.)

The main advantage of volume control is a more stable V_T with changing lung mechanics. The main advantages of pressure control are a more stable volume delivery with leak and better patient-ventilator synchrony because pressure control allows the patient to adjust inspiratory flow. Adaptive pressure control¹⁵ attempts to achieve both sets of advantages by making inspiration pressure-controlled but letting the ventilator automatically adjust the peak inspiratory pressure to achieve a preset target V_T . To date there have been no studies of NIV with adaptive pressure control, nor have there been any ventilators that use adaptive pressure control for their NIV modes. However, the Shönhofer et al¹⁴ study suggests that adaptive pressure control may have avoided the failure of those patients who hyperventilated at night with simple pressure control. On the other hand, a substantial leak might confound the adaptive control algorithm. More study of adaptive pressure control for NIV is warranted.

CMV Versus IMV Versus CSV

If, in general, comfort objectives tend to predominate with patients treated with NIV, then we can argue that CSV is better than CMV, because with CSV the patient can modify both the timing and size of the breath, which increases synchrony of breathing efforts with ventilator gas delivery and thus promotes comfort. With CMV, both the size of the breath and the T_I are arbitrarily set by the clinician. Excellent patient assessment in the moment can assure good synchrony with CMV, but the problem is that the operator is not always there to readjust the settings if the patient desires to change his or her breathing pattern. On the other hand, if safety concerns predominate, then CMV is a better option.

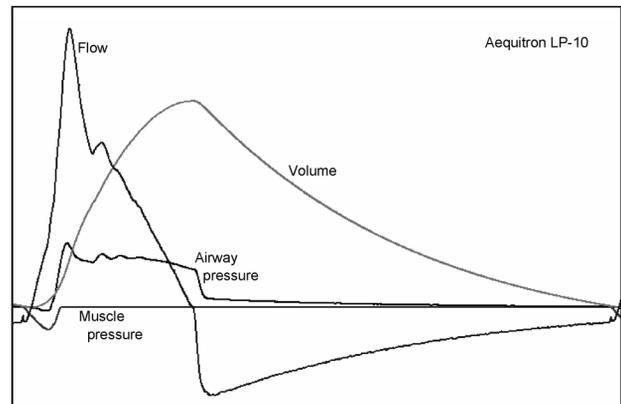


Fig. 7. Characteristic waveforms with the Aequitron LP10 ventilator during volume-control ventilation. Vertical axis is pressure ($\times 10$), volume, and flow ($\times 10$). Horizontal axis is time.

I can think of no argument (nor have I found any literature) to justify the use of IMV in the traditional sense, meaning the delivery of volume-controlled mandatory breaths along with pressure-controlled spontaneous breaths. That seems to me the worst of both worlds: possibly asynchronous mandatory breaths interspersed with variable-volume spontaneous breaths, which would result in a pattern of highly variable V_T delivery and work of breathing (ie, from breath to breath).

Fortunately, the IMV provided by specialized noninvasive ventilators is different from that provided by home-care and intensive care unit (ICU) ventilators. The definition of IMV is that spontaneous breaths can be delivered between mandatory breaths.⁴ Traditionally, IMV was implemented on ventilators as a preset backup rate for mandatory breaths, and they were delivered regardless of the spontaneous breathing activity. However, with noninvasive ventilators there may be 2 kinds of IMV. For example, with the Respironics BiPAP S/T ventilator, in the "timed" mode, IMV is delivered traditionally (ie, mandatory breaths are time-triggered, time-cycled, and delivered at the set rate, independent of the patient's spontaneous breathing efforts). However, in the "spontaneous/timed" mode, mandatory breaths (ie, time-triggered but flow-cycled) are delivered only if the spontaneous breath rate falls below the set IMV rate. This has clinical importance because the operator may be tempted to increase the rate (as with traditional IMV) for a patient who is hypoventilating (ie, rapid shallow breathing pattern), only to find that nothing happens, because the set rate is still below the patient's trigger rate. What is needed in that case is to increase the pressure-support level.

The need for routine use of a backup rate has not been established,¹⁶ although if patient safety is the priority, it makes sense to use CMV or IMV. For example, in patients with neuromuscular disease, setting the backup rate slightly

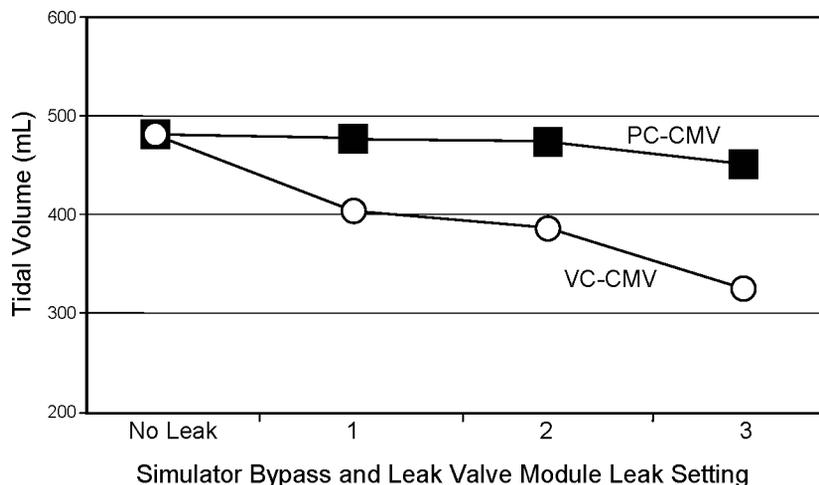


Fig. 8. Effect of leak size on delivered tidal volume. VC-CMV = volume-controlled continuous mandatory ventilation; PC-CMV = pressure-controlled continuous mandatory ventilation.

below the normal breath rate while the patient is awake should provide maximum respiratory muscle rest during sleep.¹⁷

The take-home message is that if the main objective is comfort, use CSV; otherwise, use CMV on a home-care ventilator, or IMV on a noninvasive ventilator or ICU ventilator that has an NIV option.

Pressure Support Versus Proportional Assist

If we pursue the idea of using CSV to promote comfort, we naturally ask how patient-ventilator synchrony can be enhanced. Much has been written about the possibility of asynchrony with PSV.¹⁸ As with other modes, trigger delay can increase the patient's work of breathing. The pressurization rate can be too slow (which causes the patient's feeling of not getting enough flow) or too fast (which causes the patient to reflexively activate expiratory muscles and prematurely terminate the breath). If the pressure-support level is set too low, the patient may not get a large enough V_T . This may also lead to an T_I shorter than the patient's neurological inspiratory drive time, which will cause double-triggering breaths and auto-PEEP. On the other hand, if the pressure-support level is set too high, the patient may feel overinflated and, again, actively exhale to terminate the breath, which increases the work of breathing. Setting the pressure-support level too high also tends to lengthen the T_I , because the peak inspiratory flow is higher, so the flow cycle threshold (which is usually set as a percent of peak flow) takes longer to reach, and, again, may urge the patient to actively terminate the breath. This effect may also be seen in patients with long respiratory system time constants. Finally, if the leak is large enough, inspiratory flow may never decay to the cycle threshold,

and, again, this forces the patient to actively terminate the breath, or to wait until the time-cycle backup mechanism is activated. Newer ventilators allow the operator to adjust the pressure rise time and the cycle threshold so that, with diligence and attention to both the patient and the ventilator graphics, PSV can be fine-tuned to be synchronous in most situations. But you can see the problem: a skilled operator with the time to do the fine-tuning is a scarce resource in most settings. Advanced PSV algorithms have been developed,¹⁹ and I would argue that the more fine-tuning the ventilator can do automatically, the better. We need to build more intelligence into ventilators, because we cannot guarantee it at the bedside.

PAV offers a theoretical advantage over PSV in that the inspiratory pressure and the inspiratory cycle threshold are both under more control of the patient and do not need breath-by-breath fine-tuning by an operator. Indeed, there have been numerous comparisons of PSV and PAV in the literature, with conflicting results. Compared to PSV, PAV has been found to reduce indices of inspiratory muscle effort,^{20,21} or not,²² to be associated with more rapid improvements in physiologic variables,²³ or not,²⁴ and is seen as more comfortable.^{22,23} Neurally adjusted ventilatory support seems promising for the same reasons as PAV, but we need more research to verify that assumption.

The take-home message seems to be that if you have PAV, use it in preference to PSV. Unfortunately, the only ventilator available in the United States with an approved PAV mode explicitly recommends that it not be used for NIV, because, in its present incarnation, PAV+ does not have leak compensation and therefore cannot properly evaluate lung mechanics with a mask.

In summary, if comfort is the primary objective, use PAV when available; if not, use PSV, making sure to

fine-tune pressure rise time, peak inspiratory pressure, and cycle threshold to assure synchrony. If safety is the primary objective, use PC-CMV or PC-IMV. In the rare case that the patient needs cough assist (and can be taught the skill), use VC-CMV.

Which Ventilators Best Provide the Modes?

There are 3 general classes of ventilator that can be used for NIV: devices specially designed for the task (I will call them “noninvasive ventilators”), standard home-care ventilators, and ICU ventilators.

Noninvasive Ventilators

Noninvasive ventilators are pressure controllers, and their “claim to fame” is that they are designed to perform well with relatively large system leaks. Noninvasive ventilators provide either PSV or PC-IMV. However, as described above, regardless of the backup rate, mandatory breaths are only delivered if the spontaneous breath rate falls below the set rate.

Simple Noninvasive Ventilators. Simple noninvasive ventilators (sometimes called “bi-level” or “BiPAP”) ventilators are inexpensive, small, and relatively easy to operate. A simple noninvasive ventilator requires an oxygen bleed-in modification to control the fraction of inspired oxygen (F_{IO_2}). Unlike other types of ventilators, a simple noninvasive ventilator does not use an exhalation valve. Instead, it regulates a constant flow of air up or down as needed to control airway pressure. As such, a simple noninvasive ventilator uses a single-limb patient circuit, and most such circuits have a fixed leak near the mask, to prevent rebreathing carbon dioxide. A simple noninvasive ventilator is typically powered by a blower, which consumes a relatively large amount of power, so few simple noninvasive ventilators operate on batteries (those that do, not for long). A simple noninvasive ventilator is more practical than an advanced noninvasive ventilator for home use, and simple noninvasive ventilators are also popular in hospitals. The operator interface is usually limited to a small liquid-crystal display screen that shows text messages only. Simple noninvasive ventilators offer pressure-support and CPAP, and a few have a ramp setting that gradually increases the CPAP level so the patient can more easily fall asleep (ie, for treating obstructive sleep apnea). Most simple noninvasive ventilators have no alarms, except perhaps an alert if the mask leak is too great. Figure 9 shows representative pressure, volume, and flow curves with BiPAP (with maximum leak setting 3 on the Simulator Bypass and Leak Valve Module).

Advanced Noninvasive Ventilators. Advanced noninvasive ventilators (eg, Respironics Vision and Hamilton Raphael) offer control over F_{IO_2} , graphic monitoring, and alarms. For instance, the alarms on the Respironics Vision include high-pressure limit, low-pressure limit, apnea, high rate, low rate, and low minute ventilation. Advanced noninvasive ventilators are most often used in hospitals, in both intensive and acute care areas. Figure 10 shows representative waveforms from a Respironics Vision.

Home-Care Ventilators

Small, piston-driven ventilators (eg, Lifecare PLV-100 and Aequitron LP-10) have been the standard home-care ventilator for decades. Such ventilators are well suited for patients who need continuous ventilatory support and those with severe chest-wall deformity or obesity, who need high inflation pressure.¹⁷ However, home-care ventilators are heavier and more expensive than simple noninvasive ventilators. Home-care ventilators are typically used for VC-CMV or VC-IMV, but some can be set to deliver pressure-control ventilation. These devices are easy to use, offer adequate alarms, and can operate on battery power, but require an oxygen bleed-in modification to control F_{IO_2} . The major concern about home-care ventilators for NIV is that they are not designed to compensate for leaks, which may cause triggering problems. Figure 7 shows characteristic waveforms from an Aequitron LP10.

ICU Ventilators

ICU ventilators were originally designed to ventilate intubated patients, with minimal or no leak. Although some early ventilators had ingenious leak-compensation devices, especially for infants with uncuffed tubes (eg, Bourne LS104–150), leaks have generally caused triggering problems with ICU ventilators. With the growing popularity of NIV, some newer ICU ventilators (eg, Maquet Servo-i, Hamilton G5, Dräger Evita XL, Newport e500, Viasys Vela, Respironics Esprit) have “noninvasive modes” along with their standard inventory of ventilatory patterns. These are really not unique ventilatory patterns; they are just PC-IMV, but when activated, the ventilator automates leak compensation (eg, adjusts bias flow and trigger sensitivity) and deactivates some nuisance alarms. The operator interfaces look different from other modes; the intent is to mimic the settings on noninvasive ventilators. The advantage of using an ICU ventilator is that you have all the sophisticated control and monitoring features you could want. The disadvantage, of course, is the higher cost and complexity. Figure 11 shows characteristic waveforms from a Hamilton G5.

Recently, Vignaux et al⁵ evaluated the performance of ICU ventilators with noninvasive modes. They con-

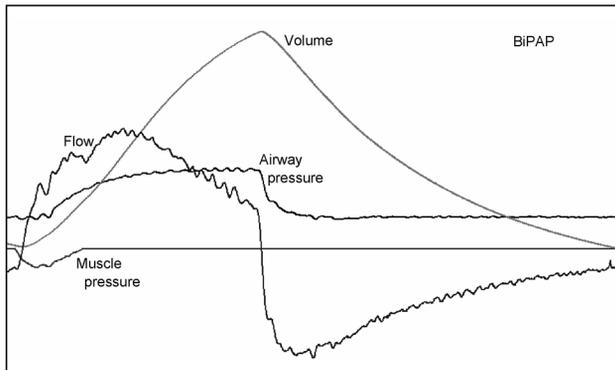


Fig. 9. Characteristic waveforms with bi-level positive airway pressure (BiPAP). Vertical axis is pressure ($\times 10$), volume, and flow ($\times 10$). Horizontal axis is time.

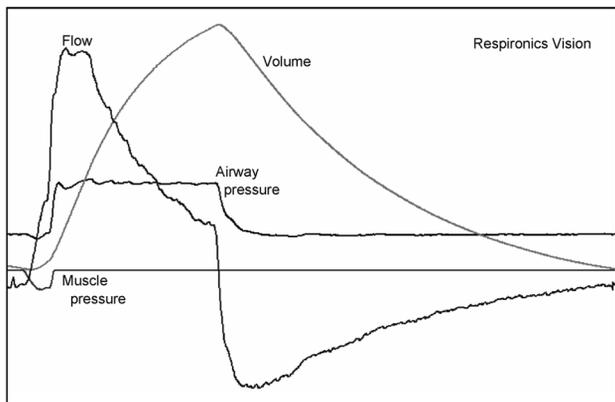


Fig. 10. Characteristic waveforms with the Respironics Vision ventilator. Vertical axis is pressure ($\times 10$), volume, and flow ($\times 10$). Horizontal axis is time.

cluded that leaks interfere with several key functions of ICU ventilators. There was auto-triggering, decreased pressurization rate, and delayed cycling. Activating the NIV modes on these ventilators corrected the auto-triggering on all the ventilators they tested, but pressurization and delayed cycling were corrected on only some of the ventilators. Vignaux et al noted a wide variation among the tested ventilators in the efficiency with which their NIV modes handled the various dysfunctions caused by leaks.

More recently, Ferreira et al⁷ conducted a similar study and found that at a baseline leak (that simulated proper mask fit) all the tested ventilators were able to deliver adequate V_T and maintain airway pressure and synchrony with the (simulated) patient. As the leak was increased, all the ventilators (except the Maquet Servo-i and the Respironics Vision) needed manual adjustment of sensitivity or cycling threshold to maintain adequate ventilation.

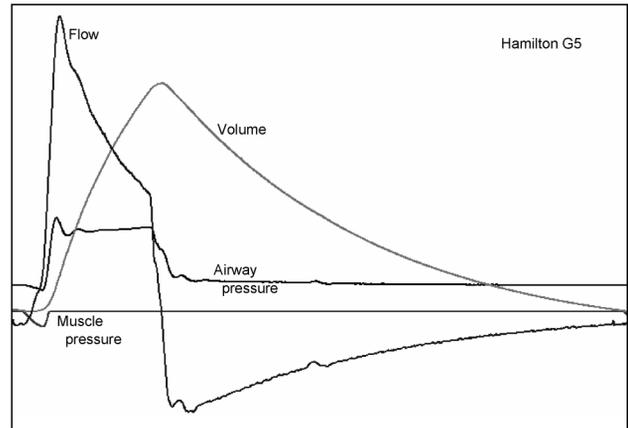


Fig. 11. Characteristic waveforms with the Hamilton G5 ventilator. Vertical axis is pressure ($\times 10$), volume, and flow ($\times 10$). Horizontal axis is time.

Performance Comparisons

I have collected representative performance data for the 3 types of ventilators used for NIV (see Table 5). The experiments were conducted with the Ingmar ASL 5000 lung simulator, as described above. Data were collected and analyzed with the ASL 5000's data-collection software, version 2.2. Only mean values (for a minimum of 10 breaths) are displayed, because the coefficients of variation were negligible for all variables. I tested leak conditions of no leak, baseline, and settings 1, 2, and 3 on the Simulator Bypass and Leak Valve Module. However, for simplicity, I report only the data for leak setting 3 (maximum).

With maximum leak, all the ventilators were able to deliver a V_T within 6% of the no-leak condition. As expected, the pressure drop during triggering was least for the dedicated noninvasive ventilators (Respironics BiPAP and Vision). Surprisingly, the G5 had the shortest trigger-response time, although it was the only ventilator that required manual adjustment of the sensitivity to prevent auto-triggering. Except for the (easily corrected) auto-triggering by the G5, all the ventilators operated without problems with all leaks.

I would like to call attention to one subtle aspect of ventilator-performance testing that I don't think has been discussed in the literature. As noted above, the Ingmar ASL 5000 can be set so that P_{mus} is modified by the airway pressure. The intent (according to the ASL 5000's operator manual) is to simulate the situation where a patient makes less effort during inspiration as the airway pressure rises. Of course, whether or not patients actually react that way is debatable. With this model, differences in airway pressure rise time will create differences in the P_{mus} profile. The problem is that there is a great deal of variability in

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Table 5. Performance Characteristics of Representative Ventilators Used for Noninvasive Ventilation*

Ventilator	Leak	Tidal Volume (mL)	Leak Volume (mL)	Drop to P_{\min} (cm H ₂ O)	Time to P_{\min} (ms)	Time from P_{\min} to PEEP (ms)	Trigger Response Time (ms)
Respironics BiPAP Pro	None	322	0	-0.3	83	75	158
	Maximum	320	2	-0.3	67	167	234
Respironics Vision	None	334	0	-0.6	88	66	154
	Maximum	323	11	-0.7	95	63	158
Aequitron LP 10	None	485	0	-1.1	146	39	185
	Maximum	454	31	-0.9	156	30	186
Hamilton Galileo	None	441	0	-0.8	117	18	135
	Maximum	464	-23	-0.9	102	19	121

* See text for definitions of performance characteristics.

the airway pressure waveforms of different ventilators. This means that any attempt to measure performance variables that depend on P_{mus} (eg, pressure-time product or imposed work of breathing) will suffer the confounding effect of having different simulated patient efforts. I believe this is a limitation of the data in Table 5, and therefore advise caution in the interpretation of that data. If I were to design a formal study for comparison of ventilators' performance characteristics, I would have done it differently. In short, if the intent of a study were, for example, to compare the work of triggering of various ventilators (and hence different pressure delivery patterns), then the patient effort should be kept constant (ie, deactivate the P_{mus} modified by P_{aw} or "backing off" feature of the Ingmar ASL 5000).

How to Choose the Right Technology

We lack robust evidence for choosing ventilators and modes for most (if not all) NIV applications in the acute-care setting. Therefore, we must rely on reasoning from first principles. Having reviewed the theory and evidence on modes and ventilators, we can establish a decision framework for matching the appropriate technology to a given patient and care environment. Figure 12 shows an algorithm that can be used as a general guide.

Key Decisions

The decision nodes (diamonds) in Figure 12 are numbered. The questions are:

1. Does the patient's condition prompt us to be more concerned about safety or comfort (see Table 3)?

2. If safety is the priority, the next question is whether the patient is in the hospital. If so, generally, more sophisticated ventilators will (or should) be available.

3. Is the patient in the ICU or emergency department? If so, the best option is to initiate PC-IMV with an advanced ICU ventilator that has an NIV option. These devices typically only provide IMV, and a backup rate is desirable because the priority is safety. An advanced ICU ventilator provides the flexibility to switch to or from NIV as required, without needing additional machines. If the patient is not in the ICU or emergency department, an advanced ventilator should still be provided, but the more practical (ie, less costly and easier to use) alternative to an ICU ventilator is a dedicated (advanced) noninvasive ventilator.

4. If the patient is not in the hospital, would the patient benefit from the cough assistance afforded by breath-stacking? If so, the only way to provide breath-stacking is with volume control on a home-care ventilator. (Airway clearance should not be an issue that guides ventilator selection in the hospital environment, because there are many alternative therapies and personnel to provide them.)

5. Advanced ventilators (in a hospital environment) can probably provide all the power necessary to ventilate any patient. In the home-care environment, however, patients with severe restriction (eg, obese patients and those with severe chest deformities) may need a higher ventilating pressure than can be provided by a simple noninvasive ventilator. There may be exceptions, of course, so you should check the available ventilators' specifications.

6. In a home-care environment, mobility may be an important issue, so consider whether a battery-powered ventilator is available. Newer, blower-type noninvasive ventilators may provide battery operation for a limited time (eg, about an hour). Again, check the manufacturer's specifications and remember that battery age can affect operating time.

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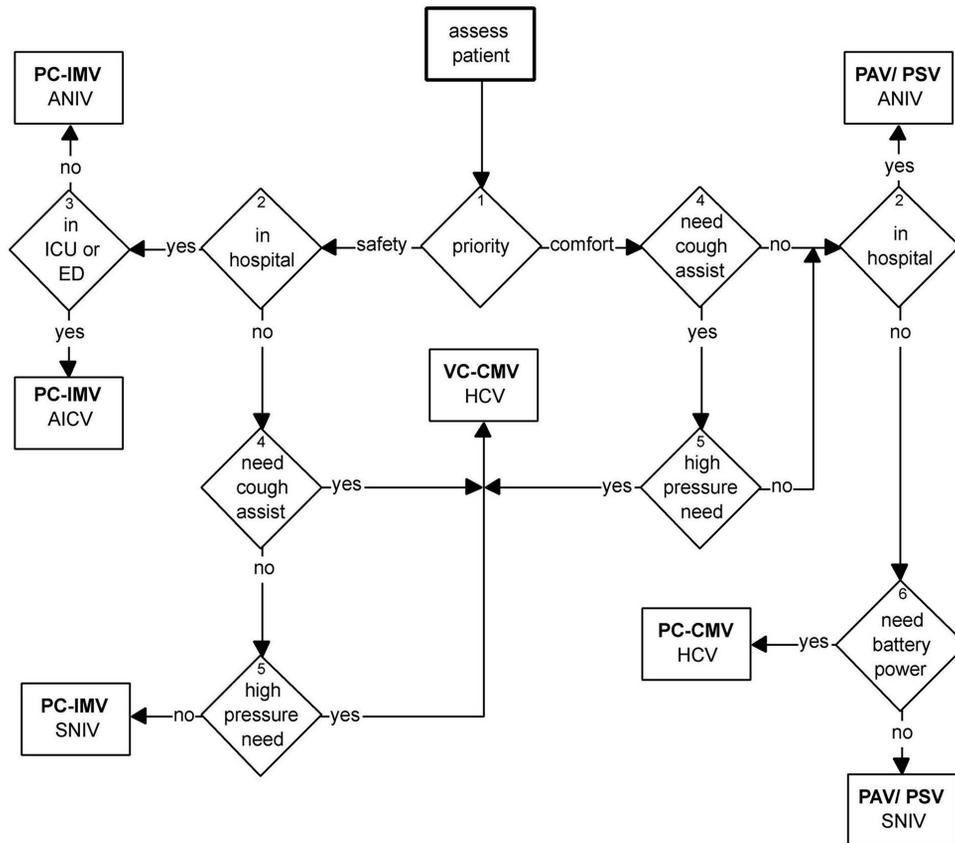


Fig. 12. Noninvasive ventilation (NIV) mode-selection algorithm for clinicians unfamiliar with NIV. SNIV = simple noninvasive ventilator. ANIV = advanced noninvasive ventilator. ICU = intensive care unit. ED = emergency department. AICV = advanced intensive care ventilator. HCV = home-care ventilator. PC-CMV = pressure-controlled continuous mandatory ventilation. VC-CMV = volume-controlled continuous mandatory ventilation. PC-IMV = pressure-controlled intermittent mandatory ventilation. PAV = proportional-assist ventilation. PSV = pressure-support ventilation.

Summary

A wide variety of ventilators and modes can be used to deliver NIV. To navigate successfully through the many options, the clinician must first have a clear understanding of the goals of NIV, particularly whether safety or comfort is most important factor for the patient in question. Pressure control is generally better able to compensate for patient/interface leaks than is volume control. Spontaneous-breathing modes such as pressure support and proportional-assist ventilation probably provide the best patient comfort.

REFERENCES

1. Kacmarek RM. Noninvasive positive pressure ventilation. In: Wilkins RL, Stoller JK, Kacmarek RM, editors. Egan's fundamentals of respiratory care. 9th edition. St. Louis: Mosby Elsevier; 2009:1091-1114.
2. Hill N. Noninvasive positive-pressure ventilation. In: Tobin MJ. Principles and practice of mechanical ventilation. 2nd edition. New York: McGraw-Hill; 2006:433-471.
3. Roy B, Cordova FC, Travaline JM, D'Alonzo GE Jr, Criner GJ. Full face mask for noninvasive positive-pressure ventilation in patients with acute respiratory failure. *J Am Osteopath Assoc* 2007;107(4): 148-156.
4. Michigan Instruments. The evolution of mechanical cardiopulmonary resuscitation (CPR) through the decades. <http://www.michiganinstruments.com>. Accessed November 3, 2008.
5. Vignaux L, Tassaux D, Jolliet P. Performance of noninvasive ventilation modes on ICU ventilators during pressure support: a bench model study. *Intensive Care Med* 2007;33(8):1444-1451.
6. IngMar Medical. Take flight with respiratory simulation: IngMar Medical breathing simulators, lung models, and test lungs. <http://www.ingarmed.com>. Accessed November 3, 2008.
7. Ferreira JC, Chipman DW, Kacmarek RM. Trigger performance of mid-level ICU mechanical ventilators during assisted ventilation: a bench study. *Intensive Care Med* 2008;34(9):1669-1675.
8. Chatburn RL, Volsko TA, El-Khatib M. The effect of airway leak on tidal volume during pressure- or flow-controlled ventilation of the neonate: A model study. *Respir Care* 1996;41(8):728-735.
9. Chatburn RL. Fundamentals of mechanical ventilation. Cleveland Heights: Mandu Press; 2003.
10. Navalesi P, Fanfulla F, Frigerio P, Gregoretti C, Nava S. Physiologic evaluation of noninvasive mechanical ventilation delivered with three

WHICH VENTILATORS AND MODES CAN BE USED TO DELIVER NONINVASIVE VENTILATION?

- types of masks in patients with chronic hypercapnic respiratory failure. *Crit Care Med* 2000;28(6):1785-1790.
11. Meecham Jones DJ, Paul EA, Grahame-Clarke, Wedzicha JA. Nasal ventilation in acute exacerbations of chronic obstructive pulmonary disease: effect of ventilator mode on arterial blood gas tensions. *Thorax* 1994;49(12):1222-1224.
 12. Girault C, Richard J, Chevron V, Tamion F, Pasquis P, Leroy J, Bonmarchand G. Comparative physiologic effects of noninvasive assist-control and pressure support ventilation in acute hypercapnic respiratory failure. *Chest* 1997;111(6):1639-1648.
 13. Vitacca M, Rubini F, Foglio K, Scalvini S, Nava S, Ambrosino N. Noninvasive modalities of positive pressure ventilation improve the outcome of acute exacerbations in COLD patients. *Intensive Care Med* 1993;19(8):450-455.
 14. Schönhofer B, Sonneborn M, Haidl P, Böhrer H, Köhler D. Comparison of two different modes for noninvasive mechanical ventilation in chronic respiratory failure: volume versus pressure controlled device. *Eur Respir J* 1997;10(1):184-191.
 15. Branson RD, Chatburn RL. Controversies in the critical care setting. Should adaptive pressure control modes be utilized for virtually all patients receiving mechanical ventilation? *Respir Care* 2007;52(4):478-485.
 16. Mehta S, Hill NS. Noninvasive ventilation. *Am J Respir Crit Care Med* 2001;163(2):540-577.
 17. Hill NS, Eveloff SE, Carlisle CC, Goff SG. Efficacy of nocturnal nasal ventilation in patients with restrictive thoracic disease. *Am Rev Respir Dis* 1992;145(2 Pt 1):365-371.
 18. Brochard L, Lellouche F. Pressure-support ventilation. In: Tobin MJ. *Principles and practice of mechanical ventilation*. 2nd edition. New York: McGraw-Hill; 2006:221-250.
 19. Du HL, Amato MB, Yamada Y. Automation of expiratory trigger sensitivity in pressure support ventilation. *Respir Care Clin North Am* 2001;7(3):503-517.
 20. Grasso S, Puntillo F, Mascia L, Ancona G, Fiore T, Bruno F, et al. Compensation for increase in respiratory workload during mechanical ventilation. *Am J Respir Crit Care Med* 2000;161(3 Pt 1):819-826.
 21. Wysocki M, Meshaka P, Richard J, Similowski T. Proportional-assist ventilation compared with pressure-support ventilation during exercise in volunteers with external thoracic restriction. *Crit Care Med* 2004;32(2):409-414.
 22. Varelmann D, Wrigge H, Zinserling J, Muders T, Hering R, Putensen C. Proportional-assist versus pressure support ventilation in patients with acute respiratory failure: cardiorespiratory responses to artificially increased ventilatory demand. *Crit Care Med* 2005;33(9):1968-1975.
 23. Gay PC, Hess DR, Hill NS. Noninvasive proportional assist ventilation for acute respiratory insufficiency. *Am J Respir Crit Care Med* 2001;164(9):1606-1611.
 24. Fernández-Vivas M, Caturla-Such J, González de la Rosa J, Acosta-Escribano J, Álvarez-Sánchez B, Cánovas-Robles J. Noninvasive pressure support versus proportional assist ventilation in acute respiratory failure. *Intensive Care Med* 2003;29(7):1126-1133.

Appendix

Review of Basic Modes of Ventilation

I have dealt with the issue of classifying ventilation modes elsewhere,¹ and I have been working with an International Standards Organization committee (ISO Technical Committee 121 Anaesthetic and Respiratory Equipment, ventilator subcommittee 3 Lung Ventilators and Related Equipment)² that is preparing standards for ventilator mode nomenclature, based (in current draft form) on that previous work. Here I will review a simplified classification scheme that I think will be consistent with the forthcoming ISO nomenclature standard.

A ventilation mode is a predefined pattern of interaction between the patient and the ventilator. The key theoretical concept that describes this interaction is the equation of motion for the respiratory system, which states that the pressure necessary to inflate the lungs and chest wall comes from the ventilatory muscles (P_{mus}) and/or the ventilator (transrespiratory pressure). Opposing this inflating force is the elastic recoil pressure (elastance \times volume) and the flow-resistive pressure (resistance \times flow). For the purpose of mode classification, the equation tells us that we can either control (as the independent variable) pressure, volume, or flow. Thus, a mode description reduces to a specification of the control variable and a description of how breaths are sequenced (ie, timing of mandatory vs spontaneous breaths). Further detail is added to distinguish similar modes by describing the variables that start (trigger) and stop (cycle) inspiration.

The control variable is, by convention, designated as either pressure or volume. Volume control means that the ventilator attempts to deliver volume or flow according to a predetermined output function, independent of changes in respiratory-system mechanics (ie, resistance, compliance, or inspiratory effort). The simplest output function is a constant value. More complex functions can include, for example, sinusoidal or ascending/descending ramps. Pressure control means that the ventilator attempts to deliver pressure according to a predetermined output function independent of changes in respiratory-system mechanics (ie, resistance, elastance, or inspiratory effort). The simplest output function is a constant value. More complex functions can include, for example, airway pressure as an exponential or sinusoidal function of time, or even as a function of other variables, such as volume and flow (eg, proportional-assist ventilation on the Puritan Bennett 840).

A spontaneous breath is one in which the inspiratory phase (period from the start of inspiratory flow to the start of expiratory flow) is triggered and cycled by some intrinsic property or action of the patient's respiratory system. That is, triggering and cycling are linked to the action of the patient's ventilatory muscles (or some related physiologic signal) or the mechanical response of pressure or flow determined by the patient's respiratory-system time constant (eg, flow cycling in pressure-support mode).

A mandatory breath is one in which the inspiratory phase is triggered and/or cycled by ventilator settings, independent of the status of the patient's respiratory system. Mandatory breaths are those for which (1) the inspiratory phase is triggered and cycled by the ventilator, or (2) the inspiratory phase is triggered by the patient and cycled by the ventilator, or (3) the inspiratory phase is triggered by the ventilator and cycled by the patient. The inspiratory phase is triggered by the ventilator when there is a preset frequency or expiratory time. The inspiratory phase is cycled by the ventilator when there is a preset inspiratory time or tidal volume.

Given 2 types of breaths (mandatory and spontaneous), there are 3 possible breath sequences: continuous mandatory ventilation (CMV), in which every breath is mandatory; intermittent mandatory ventilation (IMV), in which spontaneous breaths may occur with mandatory breaths; and continuous spontaneous ventilation (CSV), in which every breath is spontaneous.

The most basic mode description comprises the control variable (pressure or volume) and the breath sequence (CMV, IMV, or CSV). It follows that there are 5 basic ventilatory patterns: VC-CMV, VC-IMV, PC-CMV, PC-IMV, PC-CSV. There are 4 varieties of PC-CSV: continuous positive airway pressure (CPAP), pressure-support ventilation (PSV),³ proportional-assist ventilation (PAV),⁴ and neurally adjusted ventilatory support. CPAP maintains a constant pressure at the airway opening, to maintain lung volume (to improve oxygenation and possibly compliance) or patency of the upper airway (to prevent obstructive sleep apnea). Because CPAP delivers a constant pressure throughout the ventilatory cycle, it provides no ventilatory assistance to the patient (ie, the ventilator does no work on the patient). PSV, on the other hand, provides assistance by first initiating inspiratory flow in response to the patient's inspiratory effort (ie, pressure or flow trigger), raising airway pressure to some static set point (selected a priori by the operator), and then terminating inspiration when inspiratory flow decays to a preset threshold (ie, flow cycling with pressure cycling or time cycling backup in case of problems). PAV also delivers patient-triggered and patient-cycled breaths, but the inspiratory pressure is not a static set point. Rather, pressure is proportional to volume and flow, according to the equation of motion, and the constants of proportionality are the elastance and resistance the operator desires to support and, hence, presets. Neurally adjusted ventilatory support is a new form of assisted spontaneous ventilation that relies on the diaphragmatic electromyogram signal for manipulating the timing and size of the breath.

References

1. Chatburn RL. Classification of ventilator modes: update and proposal for implementation. *Respir Care* 2007;52(3):301-323.
2. Standards Development, Technical Committees. List of ISO technical committees. TC 121 Anaesthetic and Respiratory Equipment. http://www.iso.org/iso/iso_technical_committee.html?commid=51984. Accessed October 20, 2008.
3. MacIntyre NR. Respiratory function during pressure support ventilation. *Chest* 1986;89(5):677-683.
4. Younes M. Proportional assist ventilation, a new approach to ventilatory support. *Am Rev Respir Dis* 1992;145(1):114-120.
5. Sinderby C, Beck J, Spahija J, de Marchie M, Lacroix J, Navalesi P, Slutsky AS. Inspiratory muscle unloading by neurally adjusted ventilatory assist during maximal inspiratory efforts in healthy subjects. *Chest* 2007;131(3):711-717.

Discussion

Nava: I want to point out the difference between *synchrony* and *interaction*. People frequently call *synchrony* a problem when it's not, and I wonder if you agree with me. *Synchrony* comes from *chronos*, which is Greek for *time*, and is therefore a matching of the 2 phases: the start of inspiration and the end of inspiration. *Interaction* is related to timing but is more "gross" (eg, ineffective efforts, double-triggering, auto-triggering), right? The ideal ventilator should fit these two, but synchrony is especially difficult to measure, because even transdiaphragmatic pressure is not good enough; you would need electromyography. Interaction is another thing. Interaction is about auto-triggering, ineffective efforts, and double-triggering, which is very important. The only ventilation modality I know that looks at *chronos* is neurally activated ventilation. Which is more important: synchrony or interaction?

Chatburn: I am not sure I would agree with your distinction between synchrony and interaction. Auto-triggering, double-triggering, and ineffective efforts can be also defined in terms of time or *chronos*.

We need to work on the nomenclature of ventilator-patient interaction and sort out these details. Our view of reality has a lot to do with how we define words. The way I look at ventilator-patient interaction and synchrony versus asynchrony is that it relates to the 4 phases of a breath: the switch from exhalation to inhalation; the inspiratory phase; the switch from inspiration to expiration; and the expiratory phase. Things can go wrong in any of the phases, and most of them have to do with time.

In my bench studies, in trying to make a consistent volume pattern with the different ventilation modes I found that it often comes down to adjusting the inspiratory time: it's *chronos*. You want the mechanical inspiratory time

to be as consistent as possible with the neural inspiratory time, but there's also factors such as how much PEEP you apply in the inspiratory phase so that you can balance the intrinsic PEEP if there is any, and how high should the inspiratory pressure be? If it's too high or low, it's uncomfortable. It's not just timing; it has to do with the size of the breath as well.

Nava: Do you think it's important to quantify or estimate leaks? If you want to quantify leak during NIV, you need to measure both inspired and expired V_T .

Chatburn: Well, hopefully the ventilator is smart enough to manage leaks, and that seems to be the trend in ventilator design.

Gay: I don't think the portability and battery power of those ventilators is an issue, because we can put a battery on anything we want. But what I really want to talk about is your NIV algorithm. I think it's difficult to think this through because our priorities change continuously with virtually all of our NIV patients. One of the most fundamental priorities intervenes sometimes when these patients get comfortable enough to fall asleep, and then how do they behave? The synchronicity of their ventilatory problem often becomes apparent, so whether there is an important sleep/ventilation issue needs to be in the algorithm.

Chatburn: Do you think it's doable? To have a decision map like that, to give people some general way to go?

Gay: I think we need to address the chronic component of hypoventilation somewhere in there, because it's a different mindset as you start to think through these treatment models.

Kacmarek: My concern about your algorithm is that it is totally based on ventilation mode, and a given ventilation mode may function differently from one ventilator to another. The thing to emphasize more is the ventilator's capability to provide NIV. Every one of the ventilators on the market that has an NIV mode functions differently, and their ability to handle leaks and ensure synchrony is vastly different. So it would be wrong to assume that one ICU ventilator is equivalent to another for NIV. One ventilator may do a wonderful job with leak, whereas another one cannot compensate for any leak. So before we can use an algorithm like that, there has to be similarity in the operation of the NIV modes on ICU ventilators.

Chatburn: Absolutely true. The published study and your data emphasized that. Hopefully we'll get to some standardization of performance so we are comparing apples to apples.

Hill: I like the idea of an algorithm, but the devil is always in the details. How are you going to prioritize, for example, safety versus comfort? What about gas exchange? For example, some bi-level ventilators lack an oxygen blender and do a lousy job and may even be dangerous for hypoxemic patients. That should be in the algorithm. The available evidence is deficient on this topic. For instance, I don't think we have the evidence to say that an advanced critical care ventilator is more or less effective than an advanced noninvasive ventilator for different patients.

I also think it's a little premature to have cough assist in the algorithm, at least for acute care. In home care I think there's a lot more evidence to support it, but in the acute care setting, we really don't have any evidence other than from patients with neuromuscular disease. It's very important to start thinking about how to structure an algorithm, but we have to be very careful to specify where we

have evidence and where we don't. We have to be clear on our priorities and be prepared to change the algorithm as they change.

Also, when you get down to comparing the details of specific adjustments to flow and timing and so forth, you can make certain modes perform very much like other modes and get around a lot of the problems related to different performance characteristics. Should the algorithm consider that too? And are we going to see proportional-assist ventilation any time soon?

Chatburn: My comment about that is that you know too much. If you know enough about mechanical ventilation, you can ventilate anybody with anything. This algorithm is more for the uninitiated—somebody who knows something about ventilators but doesn't have much experience with NIV and doesn't know how to fine-tune NIV. There's got to be some high-level approach to put people on the right path, and *then* they can get experience and learn how to do the fine-tuning. That's just the way I look at it. Maybe that's impractical. I don't know.

Hess: I'm glad you brought up the issue of power and portability. A practical problem in the hospital is that if we start NIV in the emergency department or out in the ward and then we need to transfer the patient to the ICU,

sometimes interrupting NIV for just a few minutes results in the patient deteriorating. There are noninvasive ventilators that have internal batteries, and the other possibility is a medical grade uninterruptible power supply.

Chatburn: How long does it last?

Hess: You get 30 minutes to an hour for sure, and considerably more depending on the settings.

Kacmarek: If it's working right, it's supposed to last 8 hours.

Kallet: I'm glad you brought up the point about getting too fancy with the lung models. You can't mimic what the patient is going to do unless you have a neural network. I think with the IngMar ASL 5000 lung model you can vary the resistance and compliance, but you can't model a pleural pressure gradient. In other words, there's no sheet of scarred or edematous lung tissue that blunts the transmission of airway pressure. If there's nothing blunting that positive airway pressure when you're mimicking negative muscle pressure, then the ventilator's performance looks much different than you'd see with someone who has ARDS [acute respiratory distress syndrome]. When you can't easily transmit that positive airway pressure, you can't outpace the respiratory muscles. If you can't displace the chest

with the ventilator faster than the patient's muscles can, the patient will continue to perform a lot of work. It needs to be stressed that these models have limits. I think lung-model testing can deceive us as to how well these ventilators actually perform.

Chatburn: Those are excellent points. The value of a physical lung simulator or a mathematical model is that you get a basic understanding of what *should* happen in an ideal world. That is your base of reference, and then you go out and see what happens in the real world, and it's degraded to some extent, but it's a lot easier to go from theory of what should be—the pristine point of view—to the real world than to try to infer back the other way.

Kacmarek: The thing that's impossible to ensure is that a patient maintains exactly the same ventilatory pattern as 10 ventilators are applied. A patient's ventilatory pattern changes moment to moment. In addition, an IRB [institutional review board] would not approve a study in which there is a risk but no potential benefit to the patient. Lung-model studies must be taken for what they are. They simply evaluate the functioning of ventilators under the same, very well defined, consistent set of circumstances.