The Role of Ventilator Graphics When Setting Dual-Control Modes

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Summary

Dual-control ventilation modes were introduced with the goal of combining the advantages of volume-control ventilation (constant minute ventilation) and pressure-control ventilation (rapid, variable flow). Dual-control ventilation modes have gained popularity despite little evidence to support routine use. The individual operation and response of the dual-control modes must be understood by the clinician to allow safe and effective use. Graphic displays of pressure, volume, and flow can aid the clinician in detecting inappropriate use of dual-control modes and adjusting settings accordingly. Inspecting the waveforms will lead clinicians to the realization that dual-control does not guarantee a set tidal volume and that variability in delivered tidal volume is greater with dual-control than with pressure control. These realizations have important implications for low-tidal volume strategies. *Key words: dual-control ventilation, mechanical ventilation, waveforms..*
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Introduction

Closed-loop control of mechanical ventilation includes various techniques, ranging from the relatively simple to the complex. We and others have written extensively on this subject in the last decade.[1–8] This article will evaluate the waveforms of dual-control modes of ventilation and the information from these waveforms that can aid the bedside clinician.

The dual-control modes are not new breath-delivery types, but rather conventional breath delivery controlled by various targets.[2–7] From a classification standpoint, all of the dual-control modes are pressure-control breaths. That is, each is pressure-limited, using a descending flow waveform for breath delivery. Volume is variable with changing patient effort and pulmonary impedance. The dual-control modes can be patient-triggered or time-triggered, and flow-cycled or time-cycled. Compared to traditional pressure-controlled ventilation, the dual-control modes differ only in the ability to change the output (pressure) based on a measured input (volume). The one exception is adaptive support ventilation, which allows the ventilator not only to switch between dual-control, pressure-limited, time-cycled ventilation and pressure-limited, flow-cycled ventilation, but also to alter the respiratory frequency and the inspiratory-expiratory ratio in the absence of patient effort.

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Dual-Control Ventilation

"Dual-control" refers to a mode of ventilation that allows setting a volume target while the ventilator delivers pressure-controlled breaths. These modes are dual-control within-a-breath (intrabreath) or dual-control breath-to-breath (interbreath).[2–4] Dual-control within-a-breath describes a mode in which the ventilator switches from pressure control to volume control during a single breath. These techniques are known as *volume-assured pressure support* and *pressure augmentation*. Dual-control breath-to-breath is simpler because the ventilator operates in either the pressure support or pressure control mode. When the feedback loop is operative, the pressure limit is increased or decreased automatically to maintain a clinician-selected tidal volume (V_T). Breath-to-breath dual-control modes are analogous to having a respiratory therapist at the bedside increasing or decreasing the pressure limit of each breath based on the V_T of the previous breath.

Volume Assured Pressure Support and Pressure Augmentation

The proposed advantage of dual-control within-a-breath is reduced work of breathing while maintaining a minimum minute volume ($\dot{V}_E$) and a minimum V_T. Conceptually, volume-assured pressure support (available on the Bird 8400Sti and Tbird ventilators) and pressure augmentation (available on the Bear 1000 and the Avea ventilators) combine the high initial flow of a pressure-limited breath with the possibility of switching to a constant flow, normally associated with a volume-limited breath. This results in a minimum guaranteed V_T. However, during volume-assured pressure support the V_T can be larger than the set V_T. Volume-assured pressure support does not have the ability to decrease support to control V_T.

When the breath is initiated, the initial pressure target is the pressure support level. Selecting the appropriate pressure support level is critical for the successful use of volume-assured pressure support, yet no studies have reported the best method for choosing that pressure. One approach is to set the pressure support at a level equivalent to the plateau pressure obtained during a volume-controlled breath at the appropriate V_T. The peak flow setting is also important and should be adjusted to allow for an appropriate inspiratory time for the patient. Equally important is adjusting inspiratory flow to allow sufficient expiratory time and to prevent intrinsic positive end-expiratory pressure (auto-PEEP).

A volume-assured pressure support or pressure-augmentation breath may be patient-triggered (flow or pressure) or ventilator-triggered (time). Once the breath is triggered, the ventilator attempts to reach the pressure support setting as quickly as possible. That portion of the breath is

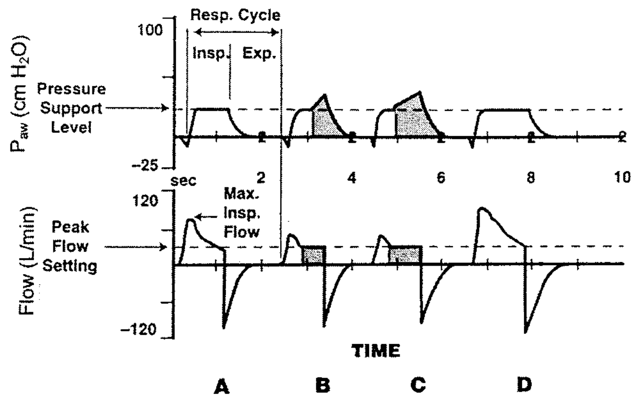

Fig. 1. The possible breath types during volume-assured pressure support ventilation. In breath A the set tidal volume (V_T) and delivered V_T are equal. This is a pressure support breath (patient-triggered, pressure-limited, and flow-cycled). Breath B represents a reduction in patient effort. As flow decreases, the ventilator determines that delivered V_T will be less than the minimum set volume. At the shaded portion of the waveform, the breath changes from a pressure-limited to a volume-limited (constant-flow) breath. Breath C demonstrates a worsening of compliance and the possibility of extending inspiratory time to assure the minimum V_T delivery. Breath D represents a pressure support breath in which the V_T is greater than the set V_T. This kind of breath allowed during volume-assured pressure support may aid in reducing work of breathing and dyspnea. P_{aw} = airway pressure.

the pressure-limited portion and is associated with a high variable flow that may reduce the work of breathing. As the pressure support level is reached, the ventilator's microprocessor starts a continuous comparison between the volume that has been delivered and the desired V_T. If the microprocessor finds that the desired V_T will not be obtained, inspiration continues according to the peak flow setting; that is, the breath changes from pressure-limited to volume-limited. Note that the ventilator monitors the delivered V_T and not the exhaled V_T, so as to provide control within the breath rather than on the subsequent breath. Additionally, if there were a leak in the system (around the tracheal tube, through chest tubes, or in the circuit), monitoring only exhaled V_T would lead to important errors. Leaks in the patient ventilator system can obfuscate the control algorithm and create problems during ventilation with dual-control modes.

There are several differences in ventilator output based on the relationship between the volume delivered and the minimum set V_T (Fig. 1). If the delivered V_T and set V_T are equal, the breath is a pressure support breath. That is, the breath is pressure-limited at the pressure support setting and flow-cycled. With the Viasys ventilators this occurs at 25% of the initial peak flow. If the patient's inspiratory effort is diminished, the ventilator delivers a smaller volume at the set pressure level. When delivered and set volume are compared, the microprocessor will determine that the minimum set V_T will not be delivered

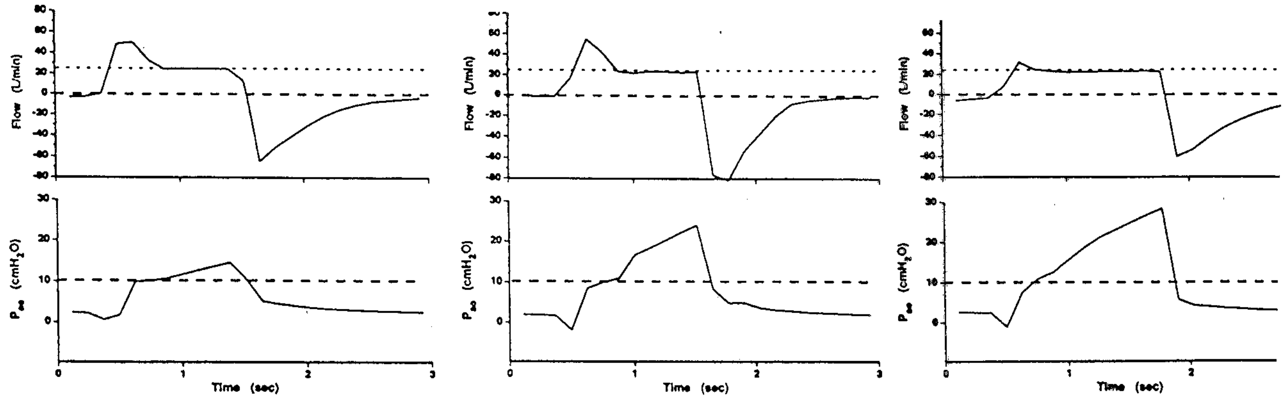

Fig. 2. Effects of increased resistance and compliance on airway pressure (P_{aw}) and flow waveforms during volume-assured pressure support/pressure augmentation. In the first breath, compliance is 40 mL/cm H_2O and resistance is 5 cm H_2O/L/s. In the second breath, compliance is 20 mL/cm H_2O and resistance is 5 cm H_2O/L/s. In the third breath, compliance is 20 mL/cm H_2O and resistance is 20 cm H_2O/L/s. Note the lengthening inspiratory time and progressive increasing peak inspiratory pressure. V_T = tidal volume.

based on the current flow and normal flow cycle criteria. As the flow decreases and reaches the set peak flow, the breath changes from a pressure-limited to a volume-limited breath. Flow remains constant, increasing the inspiratory time until the volume has been delivered. It is important to remember that the controlled volume is volume exiting the ventilator, not exhaled V_T. During this volume-limited portion of the breath, airway pressure will rise above the set pressure support setting, so the high-pressure alarm is important during volume-assured pressure support. There are secondary cycle characteristics for these breaths, and a breath with inspiratory time longer than 3 seconds will be automatically time-cycled.

Finally, if the patient's inspiratory effort increases, volume-assured pressure support allows the patient a V_T larger than the set volume. This is one other important distinction between intrabreath and interbreath control. Intrabreath control increases or decreases support to maintain a minimum V_T. If V_T remains greater than the set minimum, the ventilator operates in the pressure support mode and makes no manipulations.

Choosing the appropriate pressure and flow settings is critical to successfully using volume-assured pressure support and pressure augmentation. If the pressure is set too high, all breaths will be pressure support breaths and the minimum V_T guarantee will be provided without any feedback operation. The same problem applies to selecting too low a minimum V_T. If the constant-flow setting is too high, all the breaths will switch from pressure-control to volume-control. If the peak flow is set too low, the switch from pressure to volume will occur late in the breath and inspiratory time may be unnecessarily prolonged.

If the clinician observes frequent transitions from pressure to volume control, the cause(s) should be identified. Potential causes include decreased patient effort or lung compliance, increased airway resistance, airway secretions, and problems with the artificial airway. Figure 2 illustrates the effects of increasing impedance (resistance and compliance) in a volume-assured, pressure support breath. The waveforms in Figure 2 are based on a lung model without any patient effort. From left to right, compliance falls and resistance increases, demonstrating the switch from a pressure-limited to a volume-limited breath. As the inspiratory time lengthens, there is the possibility of air-trapping and auto-PEEP.

Figure 3 depicts pressure and flow waveforms from a patient on volume-assured pressure support. The top panel represents all pressure support breaths with the V_T exceeding the minimum set volume. In the lower panel, the patient's effort diminishes as she falls asleep. The bottom panel demonstrates the transition of flow from a descending ramp to a constant-flow pattern. That flow change creates a characteristic flattening that Neil MacIntyre refers to as the "back porch" of the breath. Of important note is that while this flow transition guarantees the minimum V_T, it does not necessarily equate to improved patient-ventilator interaction.

Figure 4 demonstrates pressure and flow waveforms in a patient with high inspiratory flow demand. The top panel demonstrates continuous mandatory ventilation with volume-controlled ventilation and a constant-flow waveform. The deep pressure fluctuations (arrows) at the initiation of inspiration reflect inadequate flow, compared to patient demand. In the lower panel, volume-assured pressure support is initiated. The first 2 breaths show transition from pressure-controlled to volume-controlled breaths. The third breath demonstrates a pressure-limited, flow-cycled breath in which the delivered volume exceeds the set volume. These breath types are possible during volume-assured pressure support, which is based on patient effort and changes in impedance.

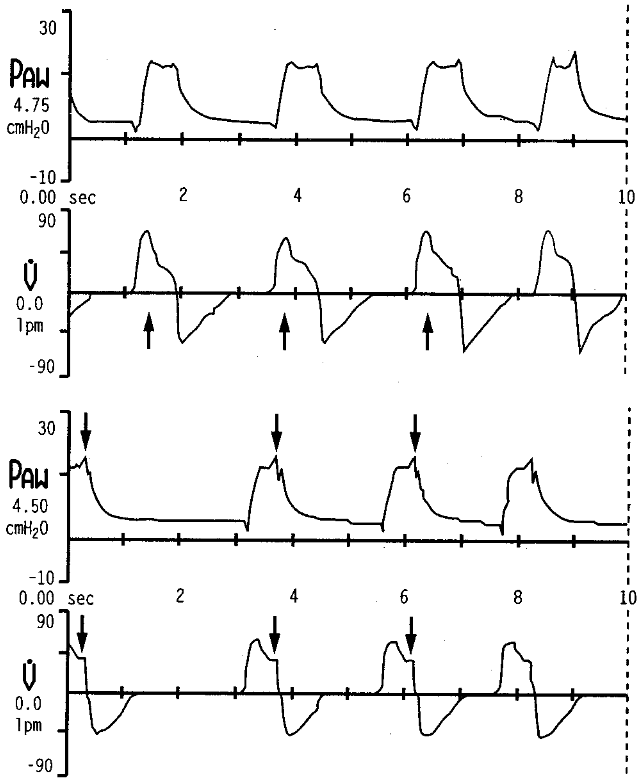

Fig. 3. The top panel shows pressure support breaths during volume-assured pressure support. The bottom panel shows the characteristic shape of the flow waveform during volume-assured pressure support when the breath transitions from pressure control to volume control (see text). P_{aw} = airway pressure. $\dot{V}$ = flow.

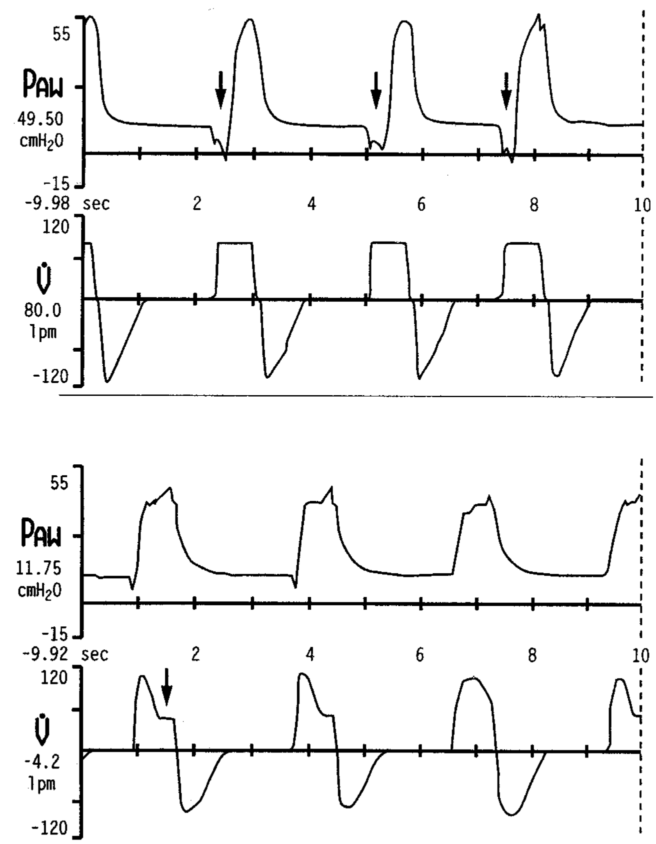

Fig. 4. The top panel shows patient effort causing large deflections in airway pressure at the start of inspiration (arrows). In the bottom panel the rapid flow associated with volume-assured pressure support reduces those pressure deflections, perhaps improving patient comfort (see text). P_{aw} = airway pressure. $\dot{V}$ = flow.

The literature on volume-assured pressure support, a decade since its introduction by Amato et al, remains meager.[9–11] Concerns over inability to limit V_T, altered inspiratory-expiratory ratio, and somewhat complex operation appear to have-limited the adoption of volume-assured pressure support.

Volume-Support Ventilation and Variable Pressure Support

The proposed advantages of volume-support ventilation (available on the Siemens 300 and Servo*i* ventilators) and variable pressure support (available on the Cardiopulmonary Corporation's Venturi) are to provide the positive attributes of pressure support ventilation with the constant $\dot{V}_E$ and V_T seen with volume-controlled ventilation. Because the reaction of dual-control pressure support ventilation is similar to dual-control pressure-limited time-cycled ventilation, example waveforms will be shown in that section. The only difference in response is that one mode is flow-cycled and the other is time-cycled. Additionally, these modes are purported to allow automatic reduction of pressure support as lung mechanics improve and/or patient effort increases. This technique is a closed-loop control of pressure support ventilation. Volume-support ventilation is pressure support ventilation that uses V_T as a feedback control for continuously adjusting the pressure support level. All breaths are patient-triggered, pressure-limited, and flow-cycled. When using the Siemens 300 ventilator, volume-support ventilation is initiated by delivering a "test breath" with a pressure support of 5 cm H_2O. The delivered V_T (again, this is not exhaled V_T, but volume exiting the ventilator) is measured, and the apparent dynamic compliance of the respiratory system is calculated. The following 3 breaths are delivered at a pressure support level of 75% of the pressure calculated to deliver the minimum set V_T. From breath-to-breath, the maximum pressure change is 3 cm H_2O and can range from zero cm H_2O above PEEP to 5 cm H_2O below the high-pressure alarm setting. All breaths are pressure support breaths, and cycling normally occurs at 5% of the initial peak flow. A secondary cycling mechanism is activated if inspiratory time exceeds 80% of the set total cycle time. There is also a relationship between the set ventilator frequency and V_T.

If the desired V_T is 500 mL and the respiratory frequency is set at 15 breaths/min, the $\dot{V}_E$ setting will be 7.5 L/min. If the patient's respiratory frequency decreases below 15 breaths/min, the V_T target will be automatically increased by the ventilator, up to 150% of the initial value, to maintain a constant minimum $\dot{V}_E$.

If the pressure level increases in an attempt to maintain V_T to a patient who has airflow obstruction, auto-PEEP may result, which is a potentially dangerous situation. The problem of neural-mechanical asynchrony during pressure support ventilation, which has been addressed by several authors,[12–14] is exacerbated by a high level of pressure support in patients with chronic obstructive pulmonary disease. During conventional pressure support ventilation, the prolonged inspiratory time caused by pressure support causes the patient to activate expiratory muscles in an effort to exhale. This often leads to air-trapping, auto-PEEP, and missed trigger efforts. This problem is further amplified by volume-support ventilation. As auto-PEEP increases, the same pressure limit results in a smaller V_T. This causes the volume-support algorithm to increase the pressure limit, which increases V_T, worsens air-trapping, and further contributes to patient-ventilator asynchrony. This can lead to a vicious circle of increasing pressure support, worsening air-trapping, and inability to trigger the ventilator. If this results in a respiratory rate less than the set rate on the ventilator, the V_T is further increased. Setting appropriate alarms for $\dot{V}_E$, high pressure, and respiratory rate is critically important for safely implementing volume-support ventilation.

In cases of hyperpnea, as patient demand increases, ventilator support will decrease, which may be the opposite of the desired response. As patient demand increases, the ventilator responds by decreasing airway pressure. The inability of all the dual-control modes to distinguish between improved pulmonary compliance and increased patient effort remains a major drawback. Additionally, if the minimum V_T chosen by the clinician exceeds the patient demand, the patient may remain at that level of support, and weaning may be delayed.

Like volume-assured pressure support, the literature regarding volume-support ventilation is sparse.[15,16] Sottiaux recently reported 3 cases of asynchrony and V_T instability in adult patients receiving volume-support ventilation.[15] In that case series the researchers observed the theoretical limitations discussed above. That is, in the presence of auto-PEEP, volume-support ventilation responded to a V_T reduction by increasing airway pressure, as dictated by the ventilator algorithm. This occurs because auto-PEEP limits the pressure change between end-expiratory pressure and the pressure support setting, causing a lower-than-anticipated V_T delivery. As an example, if PEEP is 5 cm H_2O and the volume-support algorithm calculates pulmonary compliance at 50 mL/cm H_2O, then a pressure of 12 cm H_2O is necessary to deliver a V_T of 600 mL. In that scenario, if total PEEP is 10 cm H_2O (5 cm H_2O of auto-PEEP), the pressure change is only 7 cm H_2O, potentially delivering a V_T of only 350 mL (7 cm H_2O × 50 mL/cm H_2O). Volume-support ventilation responds by increasing pressure on the next breath, which further aggravates auto-PEEP in a patient with airflow obstruction. As auto-PEEP increases, the patient may be unable to trigger the ventilator, and these missed efforts lead to further asynchrony (Figure 5).

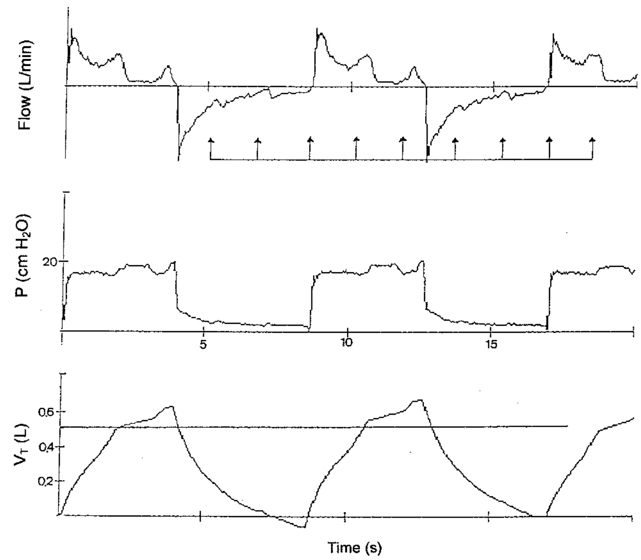

Fig. 5. Flow pressure (P), and tidal volume (V_T) waveforms from a patient after thoracic surgery. Volume-support ventilation was applied with a target V_T of 0.5 L and a frequency of 10 breaths/min. The patient's activity is clearly observed on the flow/time and pressure/time curves. The patient's breathing frequency is 35 breaths/min, while the ventilator frequency reaches 7 breaths/min, so the ventilator/patient ratio is 1:5. In this case the new target V_T averages 0.7 L. (From Reference 15.)

Sottiaux also found that when volume-support ventilation leads to missed triggers, the measured respiratory frequency may fall below the set ventilator frequency.[15] During volume-support ventilation the clinician must set the respiratory rate, even though there are no mandatory breaths. The frequency setting controls the limit for inspiratory time and sets a minimum $\dot{V}_E$. In the volume-support ventilation algorithm, if the patient's respiratory frequency falls below the set frequency, the algorithm will attempt to maintain $\dot{V}_E$ (set frequency × target V_T). The result is an increase in V_T, up to 150% of the clinician-set value. This phenomenon was seen in one of the cases reported by Sottiaux.[15] Figures 6 and 7 illustrate this problem. The late flow-termination of the pressure support breath used by the Siemens 300 ventilator (5%) may have further contributed to this problem.

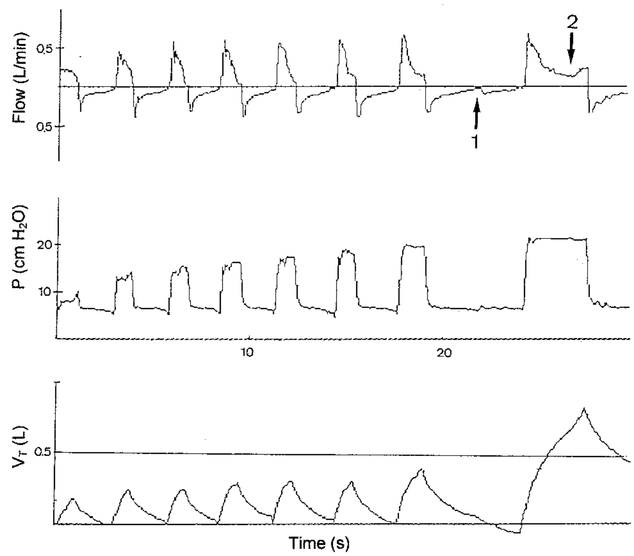

Fig. 6. Waveforms demonstrating a missed trigger (arrow 1) and response to perceived decrease in respiratory rate (arrow 2). The last breath exceeds the target tidal volume (V_T). (From Reference 15.)

Dual-Control, Breath-to-Breath, Pressure-Limited, Time-Cycled Ventilation

Dual-control, breath-to-breath, pressure-limited, time-cycled ventilation is available as "Pressure-Regulated Volume Control" on the Siemens 300, "Adaptive Pressure Ventilation" on the Hamilton Galileo, "Autoflow" on the Dräger Evita 4, "VCV+" on the Puritan Bennett 840, and "Variable Pressure Control" on the Cardiopulmonary Corporation Venturi. Proposed advantages of this approach are the positive attributes of pressure-control ventilation with constant $\dot{V}_E$ and V_T, and automatic reduction of the pressure limit as lung mechanics improve and/or patient effort increases.

Each of these modes are forms of pressure-limited, time-cycled ventilation that use V_T as a feedback control for continuously adjusting the pressure limit. This is another example of an interbreath, negative-feedback controller. In general, the volume signal used for ventilator feedback is not exhaled V_T, but volume exiting the ventilator. This prevents runaway that could occur if a leak in the circuit prevented accurate measurement of exhaled V_T. Though each manufacturer's mode has a different name, the operation is fairly consistent between devices. All breaths in these modes are time-triggered or patient-triggered, pressure-limited, and time-cycled. One difference between devices is that the Siemens 300 allows only pressure-regulated volume control in the continuous-mandatory-ventilation mode. The other ventilators allow dual-control breath-to-breath using continuous mandatory ventilation or synchronized intermittent mandatory ventilation. During synchronized intermittent mandatory ventilation the mandatory breaths are the dual-control breaths. Volume measurement for the feedback signal is also different between ventilators. The Siemens 300 uses the volume leaving the ventilator, as measured by the internal inspiratory flow sensor. The Hamilton Galileo uses the flow sensor at the airway, and the actual V_T is estimated as the average between inspiratory and expiratory V_T measured at the airway opening, which eliminates the effect of gas compression and of leaks in the circuit, and may be the preferred method of volume monitoring in dual-control.

Because these modes are pressure-limited, time-cycled ventilation with a fluctuating pressure limit based on a measured V_T, any errors in V_T measurement will result in decision errors. If the patient's demand increases during assisted breaths, the pressure level may diminish at a time when support is most necessary. Additionally, as the pressure level is reduced, mean airway pressure will fall, eliminating potential advantages.[17–22] However, those studies were of short duration and failed to demonstrate any changes in important clinical outcomes (eg, survival or duration of ventilation).

In discussions of dual-control, pressure-limited, time-cycled ventilation, it is often said that this mode allows a guaranteed V_T at the lowest possible peak airway pressure. The following example waveforms demonstrate that that is far from true. In Figure 8 a patient ventilated with volume-controlled ventilation at a V_T of 400 mL is transitioned to Autoflow on the Dräger Evita 4. Note the shape of the airway pressure and flow signals in the first 13 breaths. On the 14th breath the ventilator delivers a test breath, using a constant flow. The ventilator then approaches the target V_T by increasing the peak airway pressure until the 400-mL V_T is reached. In this case of a heavily sedated patient, this requires 3 breaths, and the final series of 7 breaths is constant at the target V_T.

Figures 9-13 show good examples of the response of dual-control. In Figure 9, Autoflow is used to ventilate a passive test lung with a compliance of 40 mL/cm H_2O. After the fourth breath the compliance is reduced to 20 mL/cm H_2O. The following breath shows a V_T-reduction of approximately 50%. The dual-control algorithm then increases airway pressure on a breath-to-breath basis over the next 4 breaths to restore the delivered V_T. Figure 10 illustrates the opposite event: test lung compliance is increased by 50%, and the first breath after that change exceeds the target by 600 mL. In this instance only 2 breaths are required to return the volume to 600 mL.

Figure 11 illustrates how the initial test breath provides information for the Autoflow algorithm. That breath is followed by a rise in airway pressure to reach the 600-mL target V_T. The last 4 breaths demonstrate simulated patient effort. Each breath is flow-triggered and the deflection in airway pressure can be seen. The result is a gradual decrease

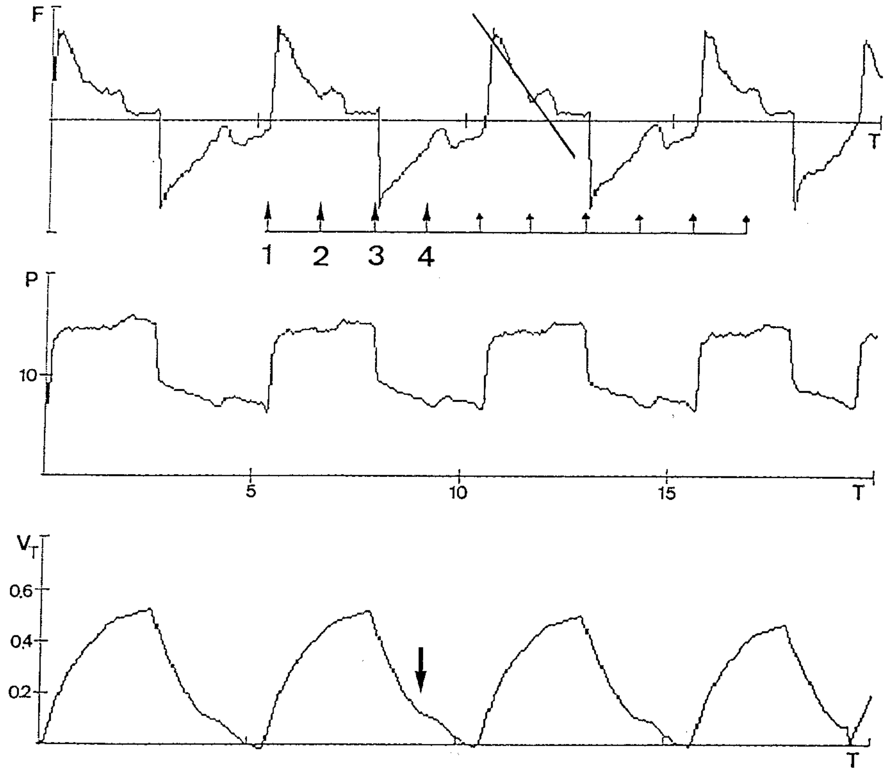

Fig. 7. Flow, pressure, and volume curves in a patient of VSV with a target tidal volume of 0.5 L. The ventilator detects a respiratory frequency of 12 breaths per minute, while the patient breathing frequency is 49 breaths per minute. Only 1 out of every 4 breaths triggers the ventilator. In the flow tracing the arrow marked 1 triggers a breath, while the arrows 2–4 go unrecognized (missed triggers). (From Reference 15.)

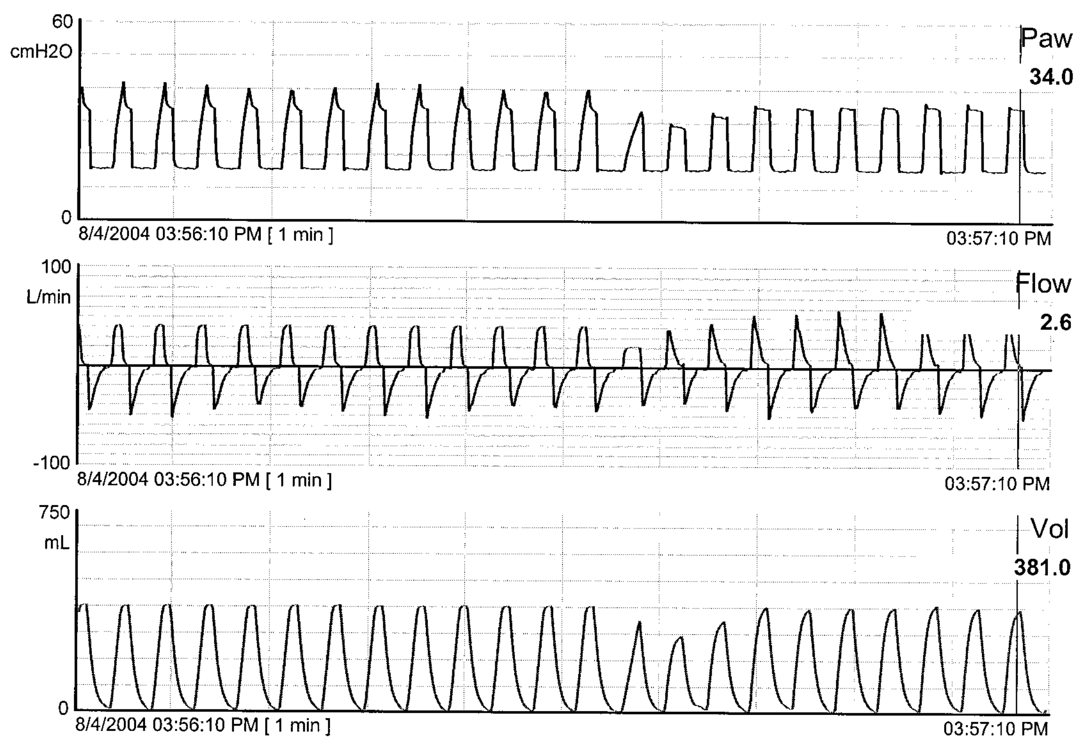

Fig. 8. Volume-control ventilation at a tidal volume (V_T) of 400 mL changed to Autoflow during ventilation of a patient with acute lung injury (see text). P_{aw} = airway pressure.

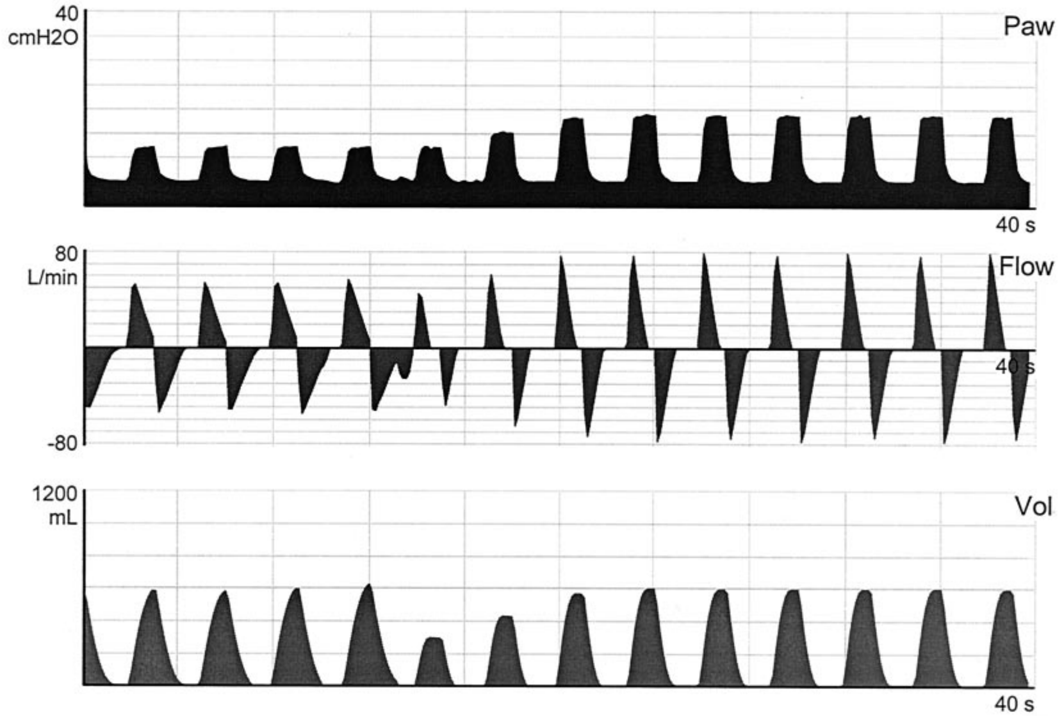

Fig. 9. Effects of a decrease in test-lung compliance on airway pressure (P_{aw}) and flow during dual-control ventilation with a target tidal volume (V_T) of 600 mL (see text).

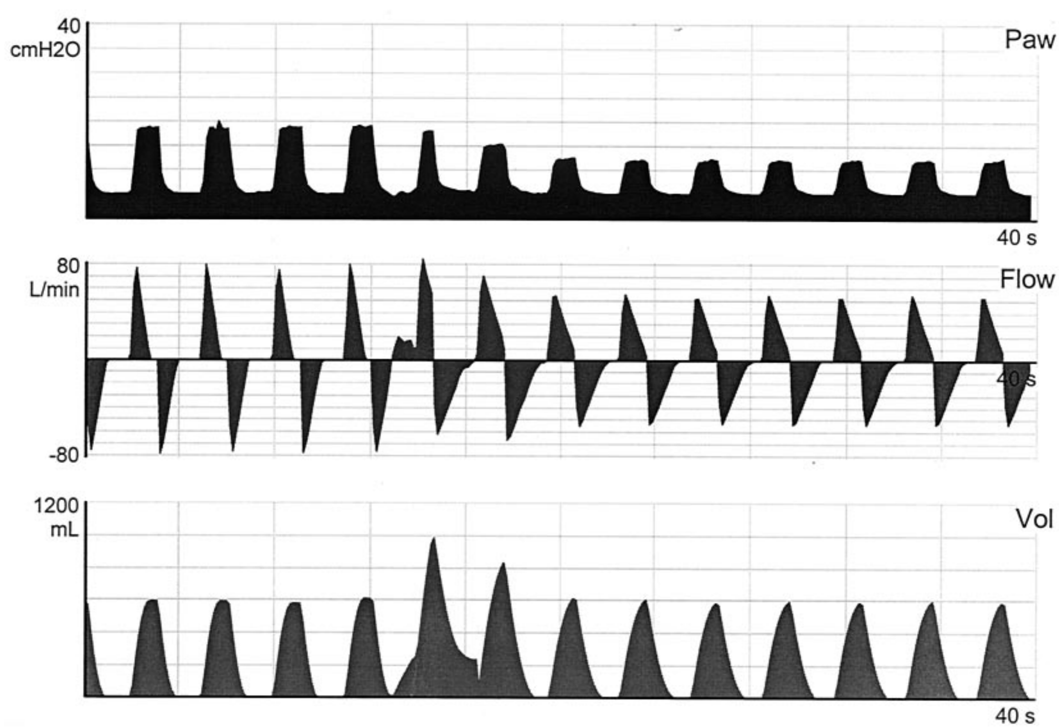

Fig. 10. Effects of an increase in test-lung compliance on airway pressure (P_{aw}), volume, and flow during dual-control with a target tidal volume (V_T) of 600 mL (see text).

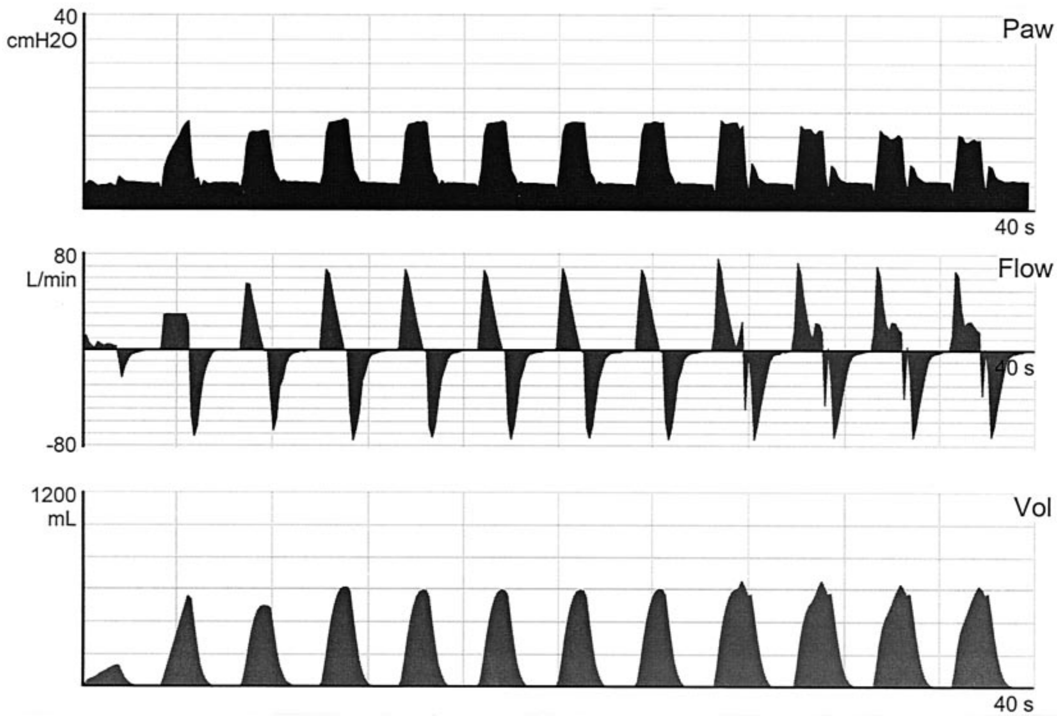

Fig. 11. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the change from volume-control ventilation to dual-control (first breath) and the effects of simulated effort on the dual-control response (see text).

in peak airway pressure, as the active test lung provides more of the power of breathing.

Figure 12 demonstrates the changes that occur when the lung becomes passive. The sudden loss of effort on breath 5 results in a low flow and small V_T. Interestingly, the target V_T is 600 mL, but the delivered volume during activity is 670 mL. The ventilator's algorithm then slowly increases the airway pressure to meet the volume target of 600 mL.

Figure 13 demonstrates the response of the dual-control algorithm to a leak in the system (temperature probe removed). The excessive flow and volume after the 8th breath feed the leak. Following resolution of the leak, the ventilator's algorithm re-establishes the target V_T. This case demonstrates how the initial low volumes after the leak cause the algorithm to overshoot the V_T and re-adjust the airway pressure to meet the target in the last 3 breaths.

Figure 14 demonstrates the use of dual-control during synchronized intermittent mandatory ventilation. Only the mandatory breaths are controlled by the algorithm. In this active model, the algorithm has no difficulty maintaining a constant V_T, despite the spontaneous breaths.

Dual-control mode can deliver a consistent V_T when there is no patient effort or a consistent patient effort. Figure 15 demonstrates pressure, flow, and volume waveforms from a patient with acute lung injury, with a target V_T of 650 mL. The airway pressure waveform shows that there is no patient effort. All the breaths are time-triggered and the breaths appear identical.

Figure 16 depicts pressure, flow, and volume waveforms from a patient with a variable respiratory rate over the course of a minute. This variable V_T-delivery (target V_T is 500 mL) is common during dual-control. Changes in respiratory rate can lead to auto-PEEP and a decrease in measured V_T, followed by increases in airway pressure. This can create a vicious circle of air-trapping and progressive increases in airway pressure, followed by worsening air-trapping.

Figure 17 shows airway pressure, flow, and volume waveforms from a patient with a closed head injury and acute lung injury. The patient was on synchronized intermittent mandatory ventilation, with a target V_T of 550 mL. PEEP was set at 12 cm H_2O and pressure support was 5 cm H_2O above PEEP. The authors were called to see the patient, who had worsening oxygenation. The first 2 mandatory breaths (breaths 1 and 3) demonstrate vigorous patient effort and a V_T twice the target V_T. The peak airway pressure was only 8 cm H_2O above PEEP, which is a common occurrence when patient demand exceeds the target V_T. In this instance the patient's head injury resulted in a substantial respiratory drive. Airway occlusion pressure 0.1 s after the onset of inspiratory effort ($P_{0.1}$) was 7.2 cm H_2O. Understanding this possibility is critical to care of the patient with acute lung injury or acute respiratory dis-

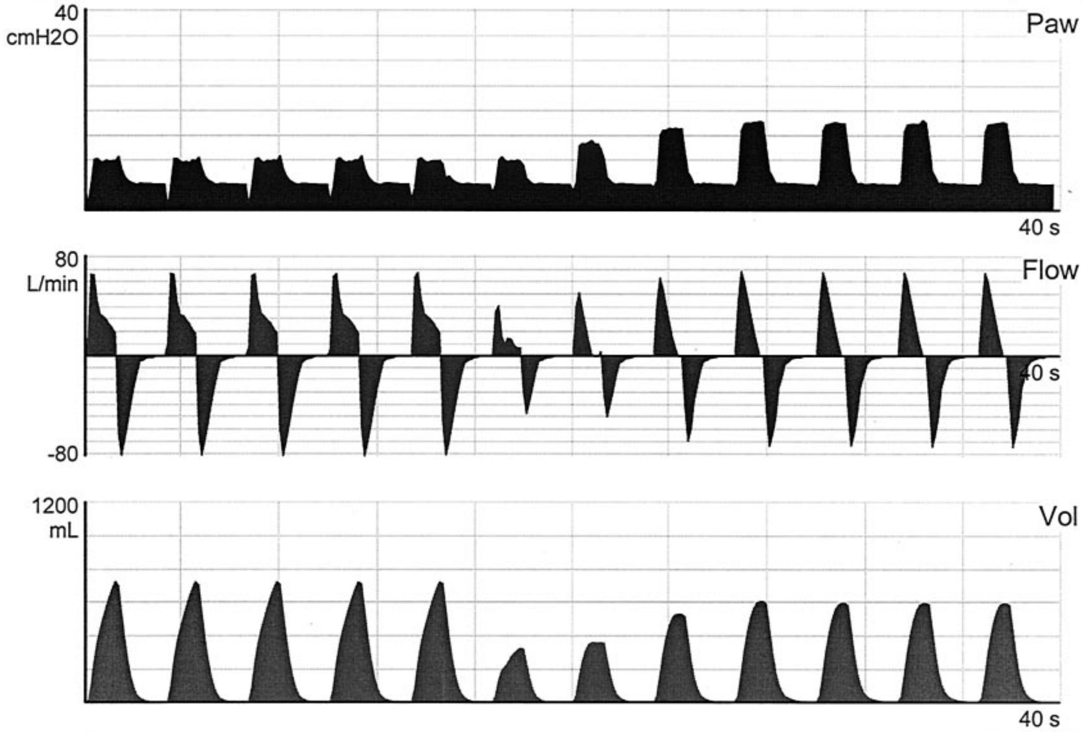

Fig. 12. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the response of a dual-control algorithm when simulated effort is abolished (see text).

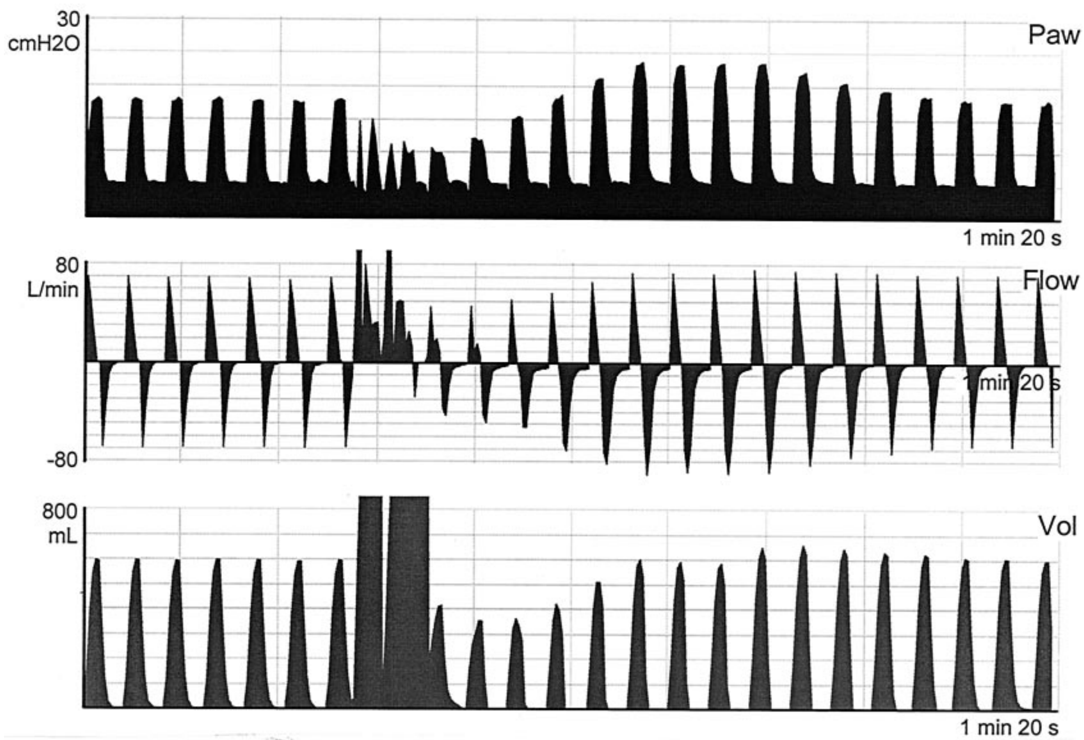

Fig. 13. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the response of a dual-control algorithm during and after the occurrence of a leak in the circuit (see text).

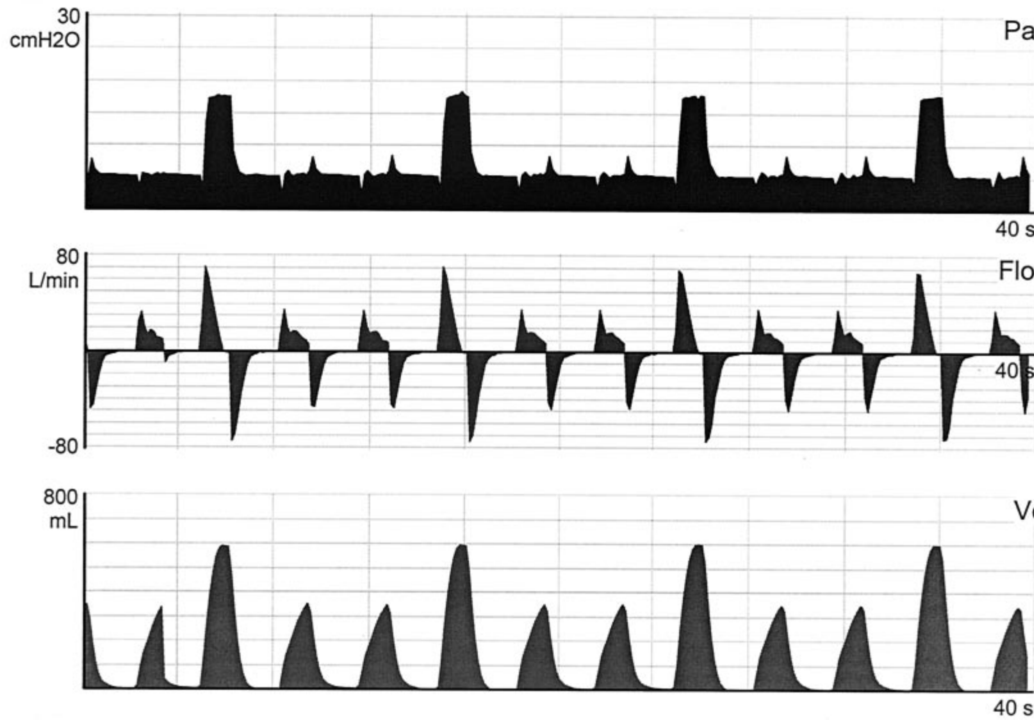

Fig. 14. Dual-control mode during synchronized intermittent mandatory ventilation. P_{aw} = airway pressure.

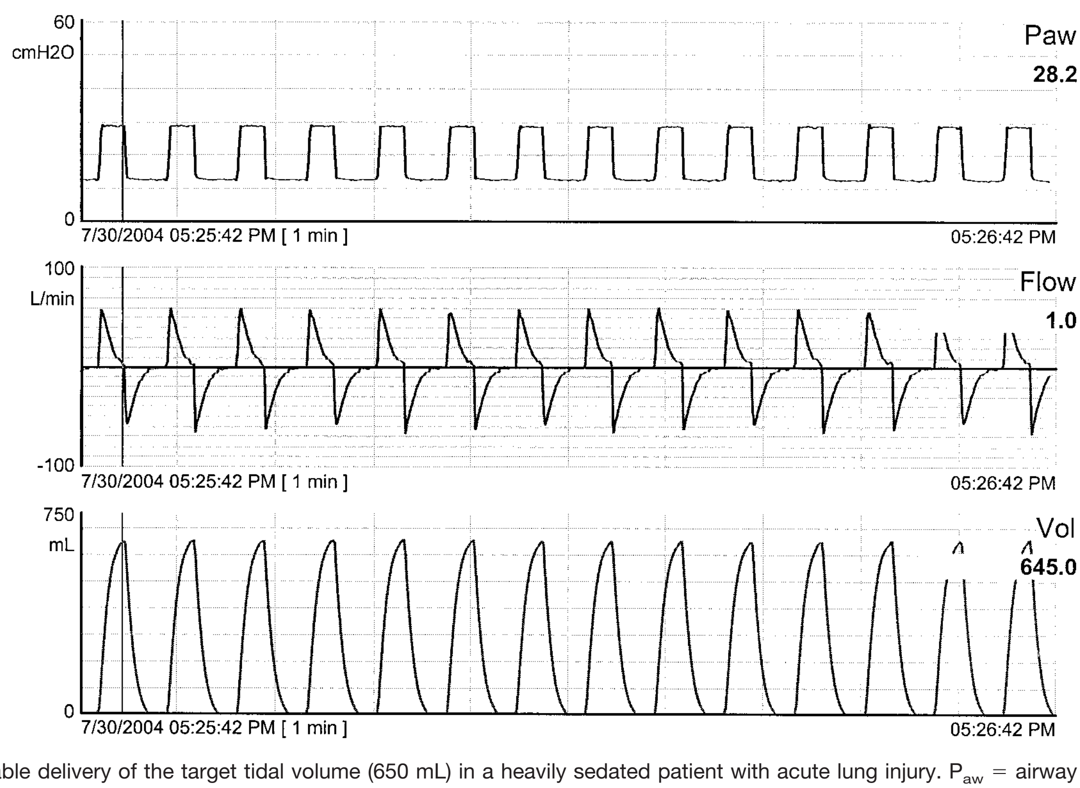

Fig. 15. Stable delivery of the target tidal volume (650 mL) in a heavily sedated patient with acute lung injury. P_{aw} = airway pressure.

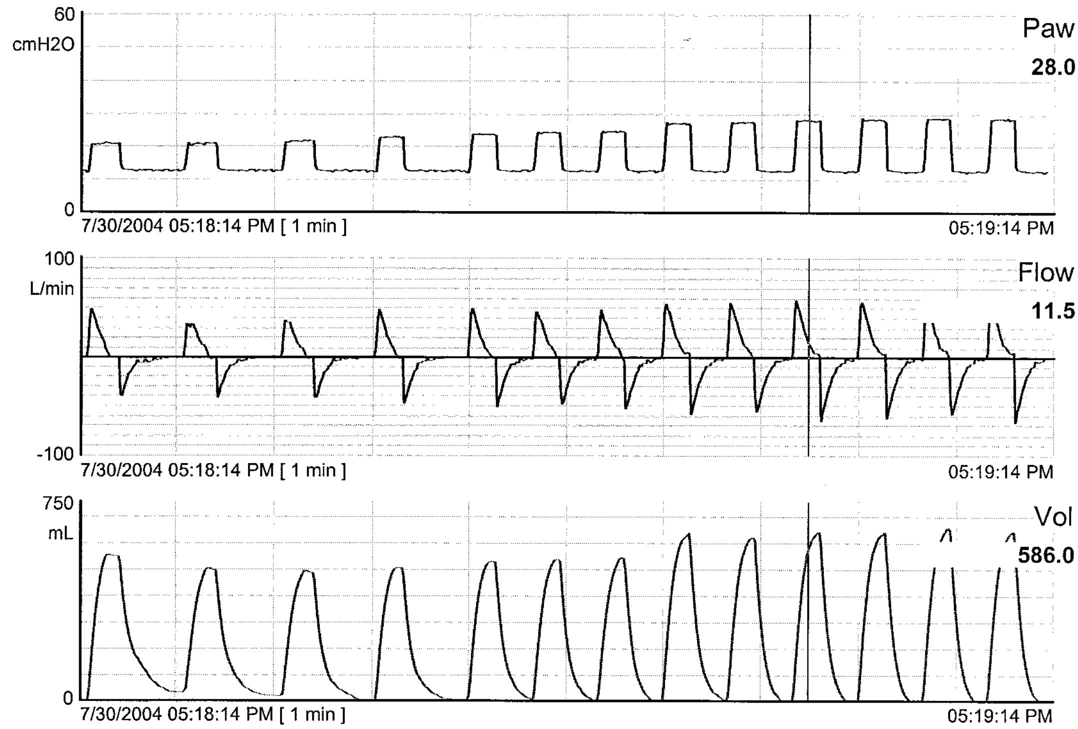

Fig. 16. Response of a dual-control algorithm to a variable patient respiratory rate (see text). P_{aw} = airway pressure.

Fig. 17. Effects of vigorous inspiratory efforts on airway pressure (P_{aw}), flow, and volume waveforms during synchronized intermittent mandatory ventilation and pressure support. The target tidal volume was 550 mL, but the delivered tidal volume is over 1,000 mL (see text).

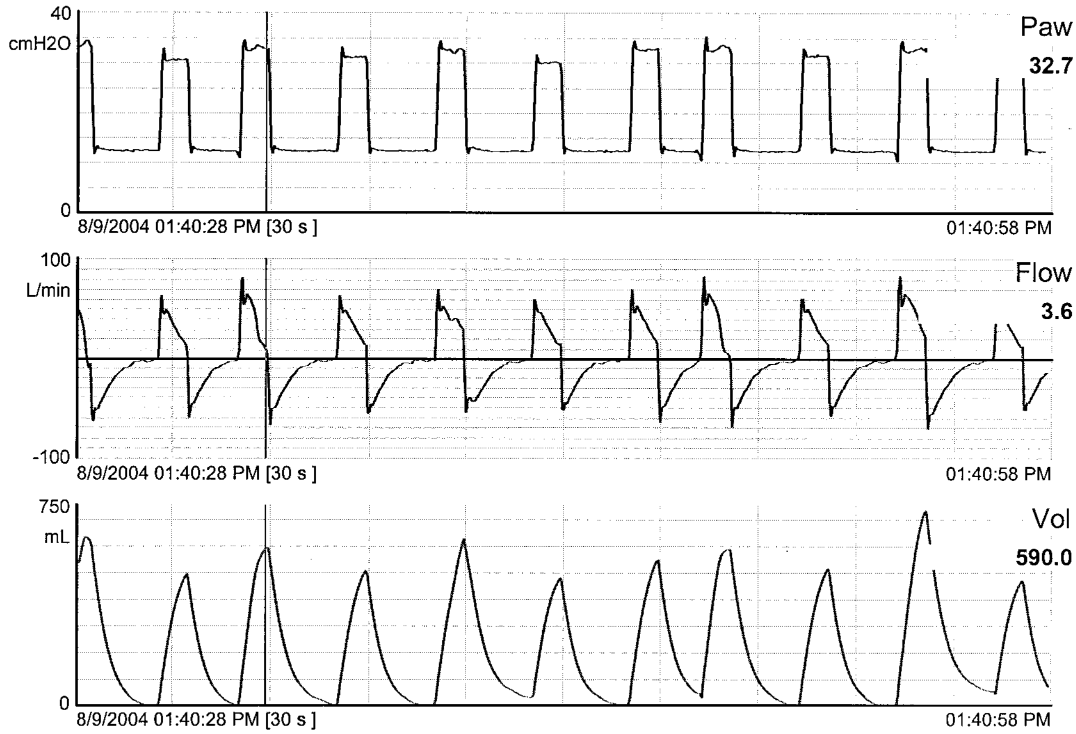

Fig. 18. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the response of a dual-control algorithm to variable patient effort and timing. Note the effects of intrinsic positive end-expiratory pressure on the volume waveform (which fails to return to baseline), and the resulting wandering of P_{aw}, searching for the volume target (see text).

tress syndrome. If a low-V_T strategy is desired and the patient's effort is not met, dual-control will not limit the V_T unless the high-V_T limit is set! In many cases, the use of dual-control obfuscates a low-V_T strategy. The patient was given a bolus of fentanyl and propofol and the remaining breaths returned to the desired V_T.

Figure 18 also shows the variability of volume delivered during dual-control. This patient with acute lung injury was triggering the ventilator, although $P_{0.1}$ was only 3.1 cm H_2O. The airway pressure, flow, and volume waveforms show the effects of auto-PEEP on the dual-control algorithm. In 3 instances air-trapping is evident: the V_T is not fully exhaled prior to the beginning of the next inspiration. The target V_T in this case was 500 mL, but in this 30-second period, V_T ranged from 450 mL to 750 mL. This example also serves to warn clinicians that the guaranteed V_T during dual-control may not be consistent with patient activity.

Figures 19 and 20 illustrate changes in airway pressure, flow, and volume during dual-control ventilation. In Figure 19 the target V_T is 400 mL. Beginning at the 7th breath, the ventilator increases PEEP by 5 cm H_2O as part of the intermittent PEEP function. Despite the change in lung volumes, the algorithm maintains the target V_T in a fairly narrow range. Figure 20 demonstrates wandering airway pressure and V_T during dual-control. Patient activity is variable and the target V_T is 500 mL. As a result of patient activity ($P_{0.1}$ was 4.5 cm H_2O), the mean V_T was 570 mL (range 350–630 mL) during this 2-minute period.

In our opinion, these waveforms demonstrate 2 important facts: (1) waveforms are critical in understanding ventilator function and patient-ventilator interaction, and (2) understanding the first point allows us to design safe and effective ventilatory support regimens for our patients.

Automode and Variable Pressure Support/Variable Pressure Control

Automode is available on the Siemens 300A and variable pressure support/variable pressure control is available on the Cardiopulmonary Systems Venturi. Both were designed for automated weaning from pressure control to pressure support, and for automated escalation of support if patient effort diminishes below a selected threshold. Those 2 modes operate similarly, so we will describe only one of them. Automode combines volume-support ventilation and pressure-regulated volume control into a single mode. The ventilator provides pressure-regulated volume control if the patient is paralyzed. All the breaths are mandatory, time-triggered, pressure-limited, and time-cycled. The pressure limit increases or decreases to maintain the desired V_T set by the clinician. If the patient triggers 2 consecutive breaths, the ventilator

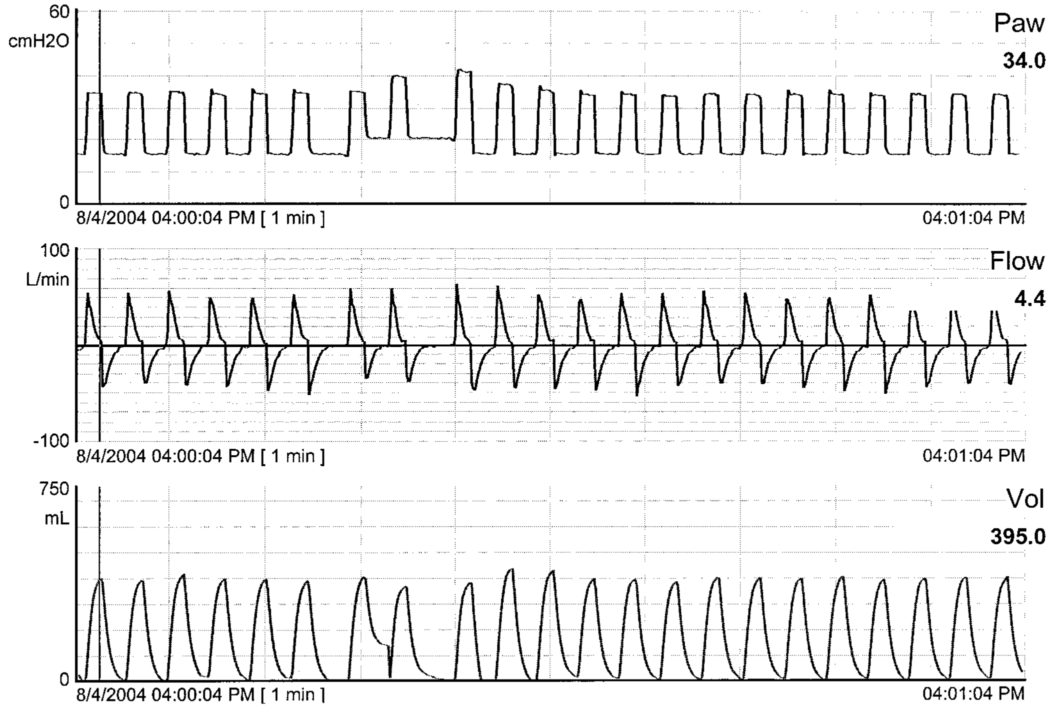

Fig. 19. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the response of a dual-control algorithm during an increase in positive end-expiratory pressure for 3 breaths (see text).

Fig. 20. Airway pressure (P_{aw}), flow, and volume waveforms demonstrating the response of a dual-control algorithm over a 2-min period with varying patient effort. The tidal volume varies above and below the target (500 mL) by as much as 150 mL. In our experience this is a common occurrence during dual-control ventilation with an active patient (see text).

switches to volume support. If the patient becomes apneic for 12 seconds (8 seconds with a pediatric patient, or 5 seconds with a neonatal patient), the ventilator switches to pressure-regulated volume control.[23,24] The change from pressure-regulated volume control to volume support is accomplished at equivalent peak pressures. Automode also switches from pressure control to pressure support, or from volume control to volume support. In the volume-control to volume-support switch, the volume-support pressure limit will be equivalent to the pause pressure during volume control. If an inspiratory plateau is not available, the initial pressure level is calculated as:

$$(\text{peak pressure} - \text{PEEP}) \times 50\% + \text{PEEP}$$

One concern is that during the switch from time-cycled to flow-cycled ventilation, mean airway pressure could fall, which could cause hypoxemia in a patient with acute lung injury. The ventilator's algorithm is simple, with the patient either triggering all or none of the breaths. The waveforms for Automode simply demonstrate the movement from all pressure-limited time-cycled breaths to all pressure-limited flow-cycled breaths. In each breath type, dual-control allows an increase or decrease in pressure limit, as we have seen with the previous modes.[23,24]

Summary

Dual-control modes allow for a wide variety of airway pressure, flow, and volume waveforms. We have shown that dual-control does not always guarantee a V_T and that patient activity can complicate the ventilator's operation. Clinicians should understand the operation of dual-control modes and the appropriate application of these techniques in critically ill patients.*

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* Mr Branson was unable to attend the conference and his presentation was via DVD. Because of this, there was no discussion.