Journal of Clinical Anesthesia (2005) **17**, 8–15

ELSEVIER

Journal of Clinical Anesthesia

Original contribution

Effect of inspiratory time on tidal volume delivery in anesthesia and intensive care unit ventilators operating in pressure control mode

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Received 21 July 2003; accepted 24 February 2004

Keywords:
Anesthesia ventilator;
Inspiratory flow;
Pressure control;
Respiratory rate;
Ventilators

Abstract

Study Objective: To compare the effect of inspiratory time and lung compliance on tidal volume (VT) delivery in anesthesia and intensive care unit (ICU) ventilators operating in pressure control mode.
Setting: Respiratory research laboratory of a tertiary care medical center.
Design: Two anesthesia ventilators with pressure control capability (Narkomed 6000, Dräger Medical, Inc, Telford, Pa, and the Datex-Ohmeda Aestiva 5, Datex-Ohmeda, Inc, Madison, Wis) and one critical care ventilator (Puritan Bennett 7200, Puritan-Bennett, Pleasanton, Calif) were studied under varying inspiratory time and lung compliance conditions using a mechanical lung model.
Intervention: Each ventilator was set to pressure control mode at a fixed inspiratory/expiratory (I/E) ratio. The respiratory rate (RR) was varied between 6 and 28 breaths per minute. Lung compliance and inspiratory time settings were set to simulate clinical conditions known to affect anesthesia ventilator performance.
Measurements: Inspiratory flow, VTs, and peak airway pressures were measured using the on-board monitor for each ventilator, and confirmed with the Bicore CP-100 pulmonary mechanics monitor (Bicore Monitoring Systems, Inc, Irvine, Calif). To assess differences in inspiratory flow between ventilators, airway pressures were continuously monitored during inspiration.
Main Results: Increasing RRs caused delivered VTs to decrease for all ventilators. However, decreases in VTs were significantly larger for anesthesia than for ICU ventilators. At a lung compliance of 0.02 L/cm H_2O and set VT of 700 mL, VT delivery for the Puritan Bennett 7200 ventilator remained at 88% of baseline, but decreased to 76% for the Aestiva 5 when RRs were increased from 6 to 28 breaths per minute ($P < .0025$). Airway pressure tracings demonstrated a slower increase in inspiratory airway pressure for the Aestiva 5 than for the other ventilators.
Conclusion: Differences in inspiratory flow delivery between ICU and anesthesia ventilators can cause differences in VT delivery when the pressure control mode is used at high RRs. These differences can significantly impact the perioperative care of critically ill patients requiring ventilatory support.

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doi:10.1016/j.jclinane.2004.02.005

1. Introduction

Most older anesthesia ventilators provide only a volume control mode of positive pressure ventilation, in which tidal volumes (VTs) and inspiratory gas flow rates are preset and airway pressures vary with changes in lung mechanics. Several newer anesthesia ventilators, however, also offer a pressure control mode where inspiratory airway pressure is set, and gas flow rates are continually adjusted to maintain that airway pressure. Although long-term use of pressure control ventilation in the intensive care unit (ICU) has not improved mortality, such a mode may confer short-term advantages in patients with acute respiratory distress syndrome [1], in pediatric patients or those with partially occluded endotracheal tubes [2,3], or during 1-lung ventilation [4].

In pressure control mode, the inspiratory phase is characterized by an initial transition period where relatively high gas flow rates rapidly increase airway pressures from expiratory to inspiratory levels. In theory, gas flow during this period depends only on the difference between inspiratory and expiratory pressures and respiratory system resistance [5]. In practice, however, many ventilators deliver less inspiratory flow than this equation demands [5], slowing the delivery of VT and prolonging the transition from expiratory to inspiratory airway pressure. When inspiratory times begin to encroach on the time required for the ventilator to reach the full preset inspiratory pressure, VT delivery can depend on inspiratory flow capacity, which may differ between ventilators.

Flow capabilities of most ICU ventilators are sufficiently similar that standard anesthesia and critical care textbooks [6-8] do not identify ventilator-based inspiratory flow limitations as an important issue in the use of pressure control mode. When airway pressures are high, however, most anesthesia ventilators deliver significantly less flow than do their ICU counterparts [9,10]. We hypothesized that an anesthesia ventilator operating in an environment with short inspiratory times and high airway pressures would produce smaller VTs than would an ICU ventilator with identical settings. To test our hypothesis, we compared the effect of reducing inspiratory time on VT delivery during pressure control mode in a Puritan Bennett 7200 ICU ventilator (Puritan Bennett, Pleasanton, Calif), an anesthesia/ICU hybrid (Narkomed 6000, Dräger Medical, Inc, Telford, Pa), and an anesthesia ventilator (Datex-Ohmeda Aestiva 5, Datex-Ohmeda, Inc, Madison, Wis).

2. Materials and methods

All experiments were performed in the respiratory therapy laboratory at the University of Chicago. We tested the Datex-Ohmeda Aestiva 5 anesthesia ventilator (standard bag-in-bottle design), the Narkomed 6000 anesthesia/ICU hybrid (mechanical piston design), and the Puritan Bennett 7200 ICU ventilator (microprocessor-controlled solenoid valve design). All ventilators were inspected and certified before use by the Department of Respiratory Therapy at the University of Chicago. Each ventilator was connected to a standard test lung (Michigan Instruments model 1600i, Grand Rapids, Mich) via a standard adult circle breathing system (King Systems, Noblesville, Ind), with each limb extended to 90 cm. Compliance of the circuit itself was 0.21 mL/cm H_2O. Circuit resistance was set by placing RP5 resistors (Michigan Instruments), as directed by this manufacturer, to simulate normal resistance. Tidal volumes, inspiratory and expiratory airway pressures, and peak inspiratory pressure flow rates (PIPs) were recorded using the on-board monitor for each ventilator and confirmed with a Bicore CP-100 respiratory monitor [11]. Airway pressures were continuously recorded for each ventilator using an external pressure transducer (Abbott Critical Care, Chicago, Ill) connected to a strip chart recorder (Datex-Ohmeda).

To simulate the lung compliance of patients typically requiring pressure control mode, test lung compliance was initially set to 0.02 L/cm H_2O. Each ventilator was set to pressure control mode with inspiratory airway pressure of 40 cm H_2O and end-expiratory pressure of 5 cm H_2O. The inspiratory/expiratory ratio (I/E) was fixed at 1:2, and the ventilator rate was set to 6 breaths per minute. The inspired oxygen concentration (FIO_2) was set to 0.40 on the ICU ventilator, and each anesthesia ventilator was adjusted to provide the same FIO_2 at a total fresh gas flow rate of 5 L/min.

Tidal volumes, inspiratory and expiratory airway pressures, and PIP flow rates were measured after a 60-second equilibration period. The respiratory rate (RR) was then increased in 2-breath increments from 6 to 28. After each change, the system was allowed to reequilibrate for 1 minute, and all measurements were repeated.

When each ventilator had been tested as above, we varied the ventilator and test lung settings. First, we reduced the inspiratory airway pressure setting to 22.5 cm H_2O and repeated the above protocol with all other settings (I/E ratio, test lung compliance, end-expiratory pressure) held constant. We then increased test lung compliance from 0.02 to 0.04 L/cm H_2O and repeated the above procedure while maintaining the inspiratory airway pressure at 22.5 cm H_2O and all other settings unchanged.

For each ventilator, continuous recordings of airway pressure versus time were obtained via a sensor placed at the junction of the ventilator circuit and test lung. The time required to transition fully from expiratory to inspiratory airway pressure was then determined by visually inspecting the pressure versus time waveform and locating the earliest point at which the preset inspiratory pressure was reached.

2.1. Data analysis

Overall, we performed 3 trials on each ventilator: one at "low" compliance (0.02 L/cm H_2O) and "high" airway pressures (40 cm H_2O), one at “low” compliance and “normal” airway pressures (0.02 L/cm H_2O, 22.5 cm H_2O), and one at “normal” compliance and “normal” airway pressures (0.04 L/cm H_2O, 22.5 cm H_2O). Tidal volume delivery, RR, and peak and mean inspiratory flow rates during the transition from expiratory to inspiratory pressure were compared between ventilators. Peak inspiratory flow rates were measured using the Bicore CP-100 respiratory monitor, and mean inspiratory flow was calculated by dividing the delivered VT by the time required for each ventilator to increase airway pressure to the preset inspiratory value. Each trial was conducted 4 times for each condition for the Aestiva 5 and Puritan Bennett ventilators and once for the Narkomed 6000.

Between-groups analyses were conducted separately for each of the 3 experimental conditions. Regression analysis was used to model a quadratic relationship between VT (expressed as a percentage of baseline volume) and RR simultaneously for all 3 ventilators. Potential correlation within replicates was incorporated by including replicate nested within machine as a random factor, using a first order auto-regressive AR [1] covariance structure. Residual plots and fit statistics (Akaike and Bayesian information criteria) were used to evaluate goodness of fit. Models were fit using the MIXED procedure in SAS version 8.0 (SAS Institute, Cary, NC).

Tests of differences between ventilators were based on fitted regression models. For each condition, the overall difference between ventilators was tested first, with additional tests conducted to identify RRs at which differences in VTs became significant. For comparisons at specific RRs, a Bonferroni adjustment for multiple testing ($k = 20$) was used; a P value <.0025 was required for significance.

3. Results

At the initial ventilator settings described above (RR = 6 breaths per minute, I/E ratio = 1:2, PIP = 40 cm H_2O, positive end-expiratory pressure [PEEP] =5 cm H_2O, and test lung compliance = 0.02 L/cm H_2O]), VT delivery for all ventilators was close to the predicted value of 700 mL (Table 1). Throughout the range of RRs tested, neither the I/E ratio nor the end-expiratory pressure changed significantly. The time required for each ventilator to transition from expiratory to inspiratory airway pressure also did not change with RR, but varied with different airway pressure and test lung compliance settings.

When RRs were increased from 6 to 28 breaths per minute at the above settings, a threshold RR was identified for all ventilators beyond which VTs progressively decreased (Fig. 1). Both the Puritan Bennett 7200 ICU ventilator and the Narkomed 6000 delivered more than 95% of baseline VTs until the RR had been increased to 24 breaths per minute. At 28 breaths per minute, delivered VTs with the Puritan Bennett 7200 had decreased to 88% of baseline and to 93% with the Narkomed 6000. Delivered VTs with the Datex-Ohmeda Aestiva 5 ventilator decreased faster with RR, however, decreasing below 95% of baseline levels at a rate of only 18 breaths per minute (inspiratory time = 1.11 seconds) and below 76% of baseline at 28 breaths per minute. Tidal volumes were significantly higher in the Puritan Bennett 7200 than the Aestiva 5 on average ($P = .0001$) and at RRs of more than 18 breaths per minute ($P < .0025$) and were significantly higher in the Narkomed 6000 than the Aestiva 5 on average ($P = .0001$) and at RR of more than 18 breaths per minute ($P < .0025$).

Observations of airway pressure and inspiratory time suggested that the differences between ventilators that we observed resulted from differences in the time required for each ventilator to transition from expiratory to inspiratory airway pressure. For all 3 ventilators, increases in RR above the threshold not only reduced VT delivery, but decreased PIP as well. This finding suggests that the threshold RR represented an inspiratory time short enough to prevent the ventilator from fully reaching the preset inspiratory pressure. We therefore compared the time required for each ventilator to reach the inspiratory airway pressure to the

Table 1 Initial airway pressures and tidal volumes for all tested ventilators

Ventilator	Test lung compliance (L/cm H_2O)	Inspiratory airway pressure (actual) cm H_2O	Expiratory airway pressure (actual) cm H_2O	Tidal volume (mL)	Time to achieve preset airway pressure (s)	Peak inspiratory flow (L/s)	Mean inspiratory flow (L/s)
Puritan Bennett 7200	0.02	45	5	750	0.92	2.12	0.82
	0.02	27	5	360	0.92	0.98	0.39
	0.04	27	5	760	1.9	1.07	0.4
Narkomed 6000	0.02	43	6	724	0.76	1.26	0.95
	0.02	25	5	320	0.6	1.20	1.2
	0.04	25	5	720	1.2	1.21	0.6
Aestiva 5	0.02	44	5	700	1.3	1.31	0.54
	0.02	24	5	300	1.1	0.67	0.27
	0.04	24	5	725	1.6	0.91	0.45

Each ventilator was tested under 3 different airway pressure/lung compliance conditions: low compliance/high airway pressure, low compliance/normal airway pressure, and normal compliance/normal airway pressure.

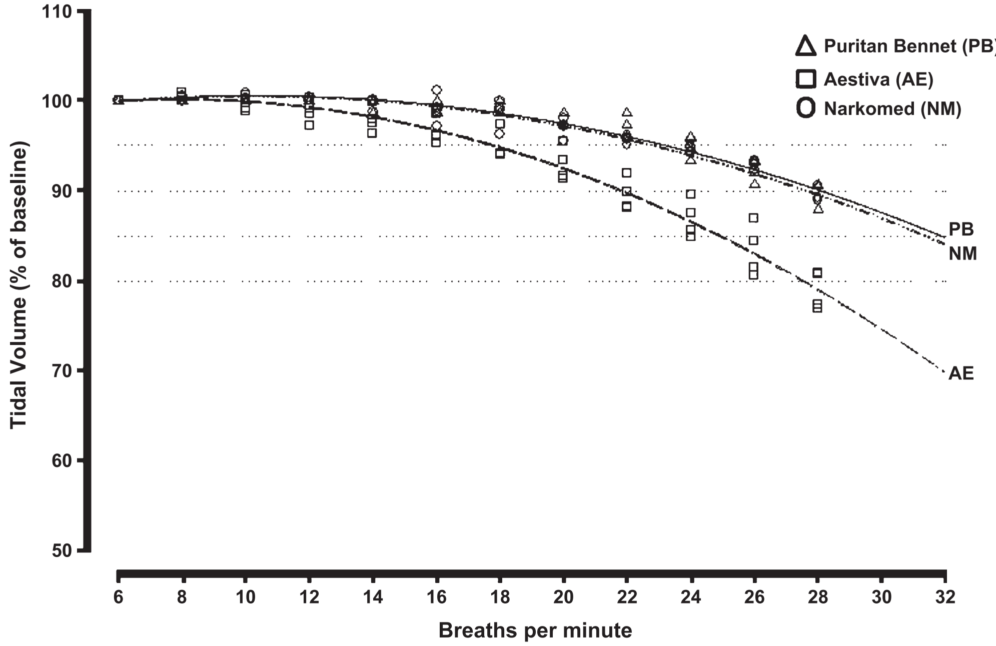

Fig. 1 Changes in tidal volume (VT) delivery with increases in RR. For all ventilators, test lung compliance = 0.02 L/cm H_2O, set airway pressure = 40 cm H_2O, and PEEP = 5 cm H_2O. Tidal volumes for all RRs are expressed as percent of VTs obtained at an RR of 6 breaths per minute. Fitted lines from the quadratic regression model overlay the image.

inspiratory time corresponding to our observed RR threshold. The Puritan Bennett 7200, for example, required 0.92 seconds to reach an airway pressure of 40 cm H_2O at a compliance of 0.02 L/cm H_2O. At an I/E ratio of 1:2, this time translated to an RR of 22 breaths per minute, close to the observed threshold of 24 breaths per minute. Similarly, the Narkomed 6000 required 0.76 seconds to reach the same inspiratory pressure, resulting in a calculated RR threshold

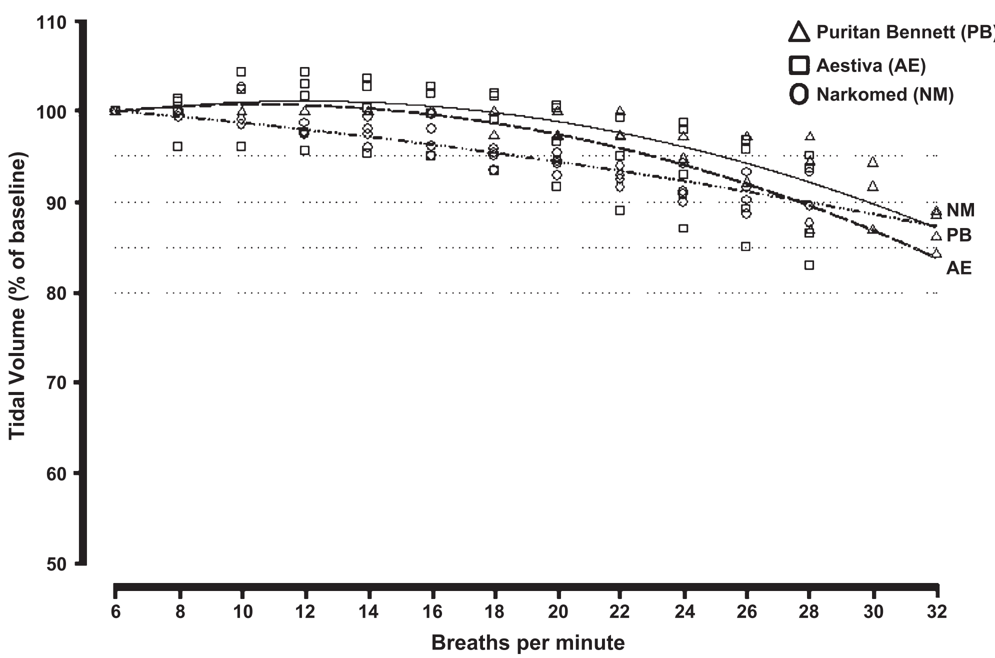

Fig. 2 Changes in tidal volume (VT) delivery with increases in RR. For all ventilators, test lung compliance = 0.02 L/cm H_2O, set airway pressure = 22.5 cm H_2O, and PEEP = 5 cm H_2O. Tidal volumes for all RRs are expressed as percent of VTs obtained at an RR of 6 breaths per minute. Fitted lines from the quadratic regression model overlay the image.

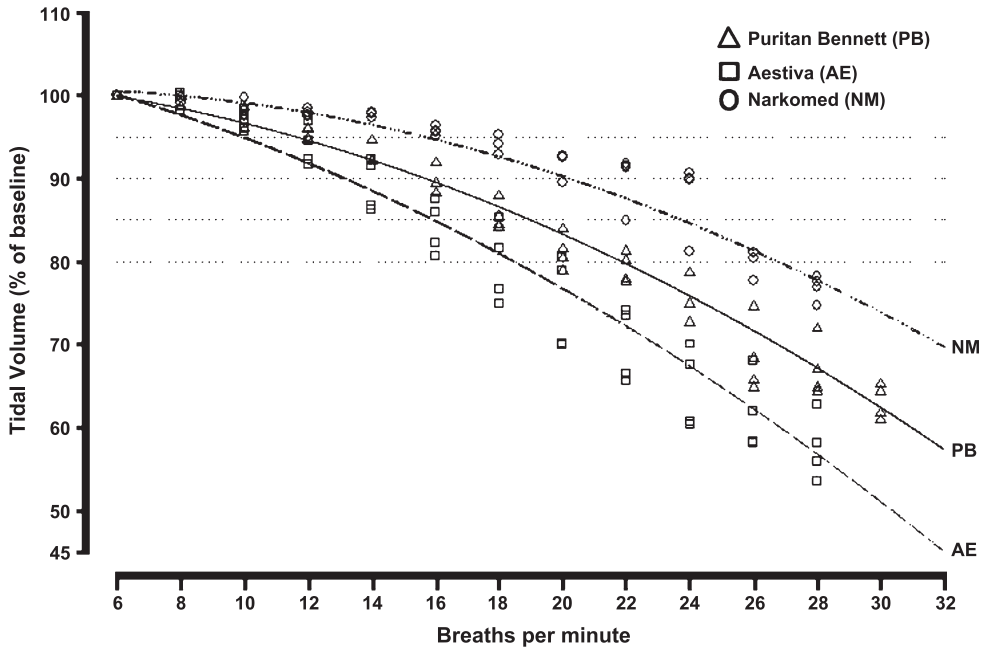

Fig. 3 Changes in tidal volume (VT) delivery with increases in RR. For all ventilators, test lung compliance = 0.04 L/cm H_2O, set airway pressure = 22.5 cm H_2O, and PEEP = 5 cm H_2O. Tidal volumes for all RRs are expressed as percent of VTs obtained at an RR of 6 breaths per minute. Fitted lines from the quadratic regression model overlay the image.

of 26 breaths per minute (observed = 24 breaths per minute). The Aestiva 5 ventilator required 1.36 seconds to reach the preset airway pressure, predicting a threshold RR of 16 breaths per minute, similar to the observed value (18 breaths per minute).

When each ventilator was retested at the same compliance but a lower inspiratory pressure setting (22.5 cm H_2O), these differences between ventilators narrowed (Fig. 2). With both the Puritan Bennett 7200 and the Narkomed 6000 ventilators, VT delivery remained higher than 95% of baseline until RRs had increased to 28 (Puritan Bennett 7200) and 24 breaths per minute (Narkomed 6000), respectively. Tidal volume delivery with the Datex-Ohmeda Aestiva 5 ventilator, however, decreased below 95% of baseline at an RR of 18 breaths per minute.

Decreases in delivered VTs with increasing RR was worst for all 3 ventilators when the inspiratory pressure setting was lowered to 22.5 cm H_2O, and test lung compliance was raised to 0.04 L/cm H_2O (Fig. 3). The Narkomed 6000 ventilator performed best under these conditions, maintaining VTs higher than 95% of baseline up to an RR of 18 breaths per minute (vs 16 breaths per minute for the Puritan Bennett 7200). Tidal volume delivery with the Aestiva 5 ventilator decreased below 95% of baseline at an RR of only 12 breaths per minute. Tidal volumes overall were significantly lower for the Aestiva 5 than for the other 2 ventilators (P = .0032 vs Puritan Bennett 7200; P = .0003 vs Narkomed 6000), and VTs, as a percentage of baseline, were significantly higher with the Puritan Bennett 7200 than the Aestiva 5 at RRs of more than 18 breaths per minute and

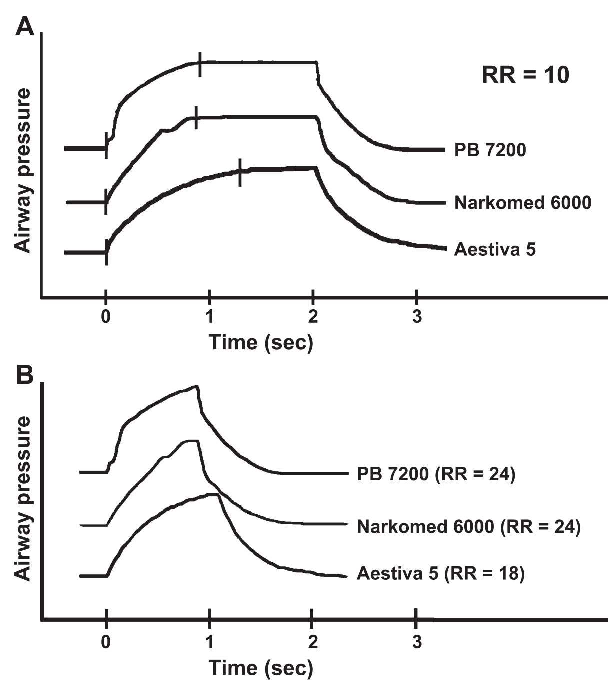

Fig. 4 Airway pressure versus time waveforms during inspiration. A, Inspiratory pressure waveforms at RR = 10 breaths per minute, test lung compliance = 0.02 L/cm H_2O, and set airway pressure = 40 cm H_2O. Vertical marks indicate the period of transition from expiratory to inspiratory airway pressure for each ventilator. B, Inspiratory pressure waveforms at the threshold RR for each ventilator under similar compliance/airway pressure conditions. Fitted lines from the quadratic regression model overlay the image.

with the Narkomed 6000 at RRs of more than 12 breaths per minute ($P < .0025$). Tidal volumes, as a percentage of baseline, were also significantly higher with the Narkomed 6000 than the Puritan Bennett 7200 overall ($P = .0018$) and at RRs of more than 18 breaths per minute ($P < .0025$).

Visual inspection of the airway pressure versus time waveform for the Narkomed 6000 ventilator suggested a flow pattern different from that observed for the other 2 ventilators (Fig. 4). With the Puritan Bennett 7200 and Aestiva 5 ventilators, the initial increase in airway pressure appeared to decrease exponentially as airway pressures approached the preset value. However, with the Narkomed 6000, increases in airway pressure appeared to be more linear, corresponding to a constant flow pattern. This difference in flow pattern explained the lower peak flow but higher mean flow rates with the Narkomed 6000 than with either of the other 2 ventilators.

4. Discussion

Pressure control ventilatory modes have recently been introduced as readily available options on newer anesthesia ventilators. Differences between pressure and volume control modes, however, raise unique monitoring issues for the anesthesiologist. In a volume control mode, changes in airway resistance or lung compliance are reflected in changes in PIP [12]. With pressure control mode, however, airway pressures are fixed by design, and detecting changes in airway resistance or respiratory system compliance thus requires monitoring VT delivery [13]. In addition, in volume control mode, VTs may be based initially on patient weight alone, whereas initial ventilator settings in pressure control mode must be carefully individualized to avoid either hypoventilation or hyperventilation [14].

Differences in inspiratory flow delivery between anesthesia and ICU ventilators may also affect clinical care. Unlike modern ICU ventilators, which vent exhaled gases to the atmosphere and directly release gas from the wall outlet into the circuit, anesthesia ventilators recirculate exhaled gases into the inspiratory limb. This feature mandates a large internal volume, which reduces inspiratory flow capacity when airway pressures are high [9]. During volume control ventilation, where inspiratory flow rates normally range between 40 and 60 L/min [10], such limitations rarely affect clinical care. In pressure control mode, however, inspiratory flow rates are based on the following relationship: flow = $(P_{preset} - P_{airway})/R$, where R is the respiratory system resistance and can exceed 100 L/min [15]. For the Puritan Bennett 7200, which delivers up to 180 L/min in pressure control mode [16], inspiratory times short enough to prevent a full transition to the preset inspiratory pressure rarely occur in clinical practice. However, most anesthesia ventilators deliver significantly less inspiratory flow than do their ICU counterparts [9]. The Aestiva 5 ventilator, for example, specifies a maximum inspiratory flow rate of 120 L/min for the drive gas circuit only [17], with much lower flow rates for the actual ventilator circuit. The higher flow requirements of pressure control mode may then cause anesthesia and ICU ventilators with identical settings to behave differently, particularly when inspiratory times are short.

Unlike most ICU ventilators, anesthesia ventilators in pressure control mode operate with a preset I/E ratio. Under these conditions, increasing the RR progressively shortens inspiratory time. In this study, we found that when operating in pressure control mode with a fixed I/E ratio, RR increases reduced VT delivery to a higher degree with the Aestiva 5 anesthesia ventilator than with either the Narkomed or Puritan Bennett ventilators. In addition, we found that the RR threshold for each ventilator could be predicted by determining the length of the transition period necessary for each ventilator to raise airway pressures from expiratory to preset inspiratory levels. This finding suggests that the differences we observed in VT delivery resulted from differences in inspiratory flow capability. These differences allowed the set inspiratory pressure (and thus the delivered VT) to be achieved at shorter inspiratory times (and thus higher RRs) with the Narkomed 6000 and Puritan Bennett 7200 ventilators than with the Aestiva 5. Measurements of PIP and mean inspiratory flow rates also supported the hypothesis that limitations in inspiratory flow were responsible for the differences in ventilator performance that we observed. Particularly at high airway pressures, both PIP and mean inspiratory flow rates were higher for the Puritan Bennett 7200 than the Aestiva 5 ventilator and were reflected in the length of the transition periods for each ventilator. However, the Narkomed 6000 ventilator demonstrated an unusual pattern of inspiratory flow, with lower and more uniform peak flow rates and higher mean flow rates than the Puritan Bennett 7200. We attributed this discrepancy to the unusual design of the relatively new Narkomed ventilator. Unlike most anesthesia ventilators, in which a separate drive gas circuit (usually filled with oxygen) is used to pressurize the bellows, the Narkomed 6000 employs a servo-controlled, mechanical piston that directly compresses gas in the ventilator circuit [18]. Visual inspection of the Narkomed 6000 airway pressure waveform indicates that instead of an exponentially changing inspiratory flow pattern, the Narkomed piston delivers a near-constant inspiratory flow rate under all conditions until the preset airway pressure is reached. This difference in flow delivery is reflected by uniform peak flow rates with the Narkomed 6000 despite differences in respiratory system compliance and resistance and by the relatively higher mean inspiratory flow rates. This difference also explains performance similarities between the Narkomed 6000 and Puritan Bennett 7200 ventilators despite significant differences in PIP flow rate. As a result, the Narkomed 6000 ventilator may preserve VT delivery to a higher degree than the Aestiva 5 when critically ill patients are ventilated in pressure control mode intraoperatively.

Because one possible intraoperative use of pressure control mode is to ventilate patients with acute respiratory distress syndrome, we initially set test lung compliance to simulate the ventilatory characteristics of such patients. Normalizing either test lung compliance or preset inspiratory pressure altered the extent of the differences between ventilators, but did not change the relationship between the Aestiva 5 and the other 2 ventilators that we tested. When the inspiratory pressure setting was reduced from 40 to 22.5 cm H_2O and test lung compliance increased from 0.02 to 0.04 L/cm H_2O, both the Narkomed 6000 and Puritan Bennett 7200 ventilators continued to preserve V_T delivery up to a higher RR (20 and 28 breaths per minute, respectively) than the Aestiva 5 ventilator (18 breaths per minute). These observations suggest that the differences in ventilator performance that we observed were intrinsic to the ventilator and not a function of the ventilator settings themselves. Our finding, that no significant differences existed between ventilators when the airway pressure was 22.5 cm H_2O and test lung compliance was 0.02 L/cm H_2O over the range of RRs tested, also suggests that for any ventilator operating in pressure control mode, differential effects of inspiratory time on V_T delivery will be smaller with lower inspiratory airway pressures and/or lower lung compliance.

In otherwise healthy patients, little reason exists to use a mode other than the familiar and near universally available volume control mode. In critically ill patients with lung injury, however, ventilation in pressure control mode may improve oxygenation and produce better V_Ts at similar PIPs [19]. Trauma patients with pulmonary contusions and burn patients with inhalation injury are plausible examples of patients with both acute lung injury and a need for surgery. In these patients, the differences between ventilators observed in this study have 2 important consequences. Because clinically relevant increases in RR can result in decreased V_T delivery, specific attention should be paid to delivered V_Ts when changing RR on an anesthesia ventilator operating in pressure control mode. In addition, when patients whose lungs are ventilated in pressure control mode are transferred from an ICU to an anesthesia ventilator, delivered V_Ts may change. Because ventilatory strategies for patients with lung injury can be associated with RRs as high as 30 breaths per minute [20], implementing such a strategy with an anesthesia ventilator may result in decreased V_T delivery and less minute ventilation than with an identically set ICU ventilator.

In summary, we observed in this study that differences between anesthesia and ICU ventilators in inspiratory flow capability can cause anesthesia ventilators operating in pressure control mode to behave differently from their ICU counterparts. Specifically, we found that when operating the Aestiva 5 ventilator in pressure control mode with high airway pressures, reducing inspiratory time by increasing the RR decreased V_T delivery sooner than with either the Puritan Bennett 7200 or Narkomed 6000 under identical conditions. This difference between the Aestiva 5 and the other ventilators resulted from differences in the time required for each ventilator to reach the preset inspiratory airway pressure, and persisted at all ventilator and test lung compliance settings. These differences suggest that when inspiratory times are short and lung compliance is low, ventilator settings may not be readily transferable between ICU and anesthesia ventilators. In addition, reduced flow capabilities of anesthesia ventilators imply that when pressure control ventilation is implemented on an anesthesia ventilator, V_T delivery should be specifically verified every time the RR setting is adjusted so as to avoid inadvertent changes.

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