Positive end-expiratory pressure and lung compliance: effect on delivered tidal volume

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The effects of positive end-expiratory pressure (PEEP) and lung compliance (C_L) on delivered tidal volume (V_{Tdel}) and ventilator output were evaluated in the following anaesthesia machine/ventilator systems: Narkomed III with a Model AV-E ventilator (III/AV-E system) and an Ohmeda Modulus II with either a 7810 anaesthesia ventilator (II/7810 system) or a Model 7000 anaesthesia ventilator (II/7000 system). With a standard circle anaesthesia breathing circuit connected to a test lung simulating C_L , gas flow was measured and integrated over time at each combination of V_T settings (V_{Tset}), 500 ml or 1000 ml; C_L settings, 0.15 to 0.01 $L \cdot cm H_2O^{-1}$ decreased incrementally; and PEEP settings, 0 to 30 $cm H_2O$ increased in 5- $cm H_2O$ increments. The integral of gas flow at the Y-piece of the breathing circuit was recorded as V_{Tdel} and at the output of the ventilator bellows as ventilator output. As C_L decreased to 0.01 $L \cdot cm H_2O^{-1}$ and PEEP increased to 30 $cm H_2O$, at V_{Tset} of 500 ml and 1000 ml, respective V_{Tdel} decreased linearly to 251 ± 6 ml and 542 ± 7 ml with the III/AV-E, 201 ± 5 and 439 ± 5 , with the II/7810, and 181 ± 4 and 433 ± 7 ml with the II/7000 ($P < 0.05$ among the three systems). Loss in V_{Tdel} due to PEEP alone, which increased only slightly when V_{Tset} was increased, accounted for an increasingly greater percentage of V_{Tset} as it was decreased, which was less pronounced with low C_L . Effects of PEEP and C_L on ventilator output were similar to those on V_{Tdel} but of lesser magnitude. During PEEP, V_{Tset} must be increased to compensate for loss in V_{Tdel} and expired V_T must be monitored to prevent hypoventilation.

Key words

ANAESTHESIA: equipment;

EQUIPMENT: ventilators;

LUNG: tidal volume.

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Les effets de la pression expiratoire positive (PEEP) et de la compliance pulmonaire (C_L) sur le volume courant généré (V_{Tdel}) et le débit du ventilateur mécanique sont évalués sur les appareils d'anesthésie équipés d'un ventilateur: Narkomed III avec un ventilateur AV-E (système III/AV-E) et un appareil d'anesthésie Ohmeda Modulus II équipé d'un ventilateur d'anesthésie 7810 (système II/7810) ou d'un ventilateur d'anesthésie 7000 (système II/7000). Avec une circuit standard avec absorption branché sur un poumon artificiel simulant la C_L , le débit gazeux est mesuré et intégré par rapport au temps pour chacune des combinaisons de réglage du V_T (V_{Tset}), 500 ml ou 1000 ml; de réglage de la C_L de 0,15 à 0,01 $L \cdot cm H_2O^{-1}$ diminuée par plateau; réglage du PEEP augmenté par plateau de 0 à 30 $cm H_2O$. Lorsque que la C_L à 0,01 $L \cdot cm H_2O^{-1}$ et que le PEEP augmente à 30 $cm H_2O$, aux V_{Tset} de 500 ml et 1000 ml, le V_{Tdel} diminue linéairement à 251 ± 6 ml et 542 ± 7 ml avec le III/AV-E, à 201 ± 5 et 439 ± 5 avec le II/7810, et à 181 ± 4 et 433 ± 7 ml avec le II/7000 ($P < 0,05$ entre les trois systèmes.) La perte de V_{Tdel} due au PEEP seul, qui n'augmente que légèrement quand le V_{Tset} est augmenté, explique un plus grand pourcentage de V_{Tset} quand celui-ci est diminué, ce qui est moins prononcé quand la C_L est basse. Les effets du PEEP et de la C_L sur le débit du ventilateur sont les mêmes que ceux notés sur le V_{Tdel} mais de moindre importance. Pendant le PEEP, V_{Tset} doit être augmenté pour compenser pour la perte de V_{Tdel} . Le V_T expiré doit être monitoré pour prévenir l'hypoventilation.

For controlled mechanical ventilation of anaesthetized patients during surgery, an anaesthesia machine is commonly connected in sequence with an anaesthesia ventilator. Patients with respiratory failure who undergo surgery may require high levels of minute ventilation, peak inspiratory airway pressure, and positive end-expiratory pressure (PEEP). The tidal volume delivered to the patient (V_{Tdel}) is usually determined not only by the tidal volume setting on the ventilator (V_{Tset}), but also by the fresh gas flow rate, the compliance of breathing circuit tubing, and the compressibility of gas.¹⁻⁴ The greater the peak inspiratory pressure, the greater is the compression of delivered gas volume and the more the

FIGURE 1 Diagram of experimental arrangement. The application of PEEP requires additional gas compression within the volume enclosed by the ventilator bellows, the CO₂ absorber, the inspiratory valve, and the PEEP valve to increase pressure from ambient (shaded area).

circuit tubing is distended; these effects decrease V_{Tdel} . Further, while it improves oxygenation in some patients,⁵ PEEP may also affect ventilator performance and, thus, decrease V_{Tdel} . This study was undertaken to quantify the effect of PEEP on V_{Tdel} at different levels of lung compliance (C_L) during mechanical ventilation with three commonly used anaesthesia machine/ventilator systems.

Methods

The following three commonly used anaesthesia machine/ventilator systems were evaluated:

- *III/AV-E*: A Narkomed III anaesthesia machine (North American Dräger) with the vaporizer turned off, an AV-E ventilator (North American Dräger, Telford, PA) and carbon dioxide absorber, 90 cm of 22-mm corrugated tubing connecting ventilator and absorber, and a disposable polyethylene circle breathing circuit (Intertech/Ohio, Bannockburn, IL).
- *II/7810*: A Modulus II anaesthesia machine (Ohmeda, Madison, WI) with the vaporizer turned off, a model 7810 ventilator (Ohmeda), a carbon dioxide absorber (GMS, Ohmeda), and a disposable polyethylene circle breathing circuit (Intertech/Ohio).
- *II/7000*: The same configuration as the II/7810 but with a model 7000 ventilator (Ohmeda).

For each system, a series of spring-loaded PEEP valves (Vital Signs, Totowa, NJ), in sequence from 5 to 30 cm H₂O, were placed at the junction of the expiratory valve and the expiratory limb of the circle breathing circuit (Figure 1). A pneumotachograph (model #2, Gleisch, Blue Bell, PA) and a differential pressure transducer (Statham-Gould, Anaheim, CA) were placed at the output of the ventilator bellows to measure ventilator output and at the connection of the Y-piece to an adult test lung (Michigan Instruments, Grand Rapids, MI) to measure V_{Tdel} (Figure 1). The adult test lung was used to simulate C_L . Flow signals were integrated (Grass Medical Instruments, Quincy, MA) to measure volume. The pneumotachograph was calibrated under ambient temperature and pressure with a calibration syringe (model #021156, WE Collins, Bantree, MA). The differential pressure transducer was calibrated against a water manometer (Wescor). The anaesthesia machine/ventilator systems were all tested (including for leaks) and calibrated according to manufacturers' recommendations before the study.

For the experiment, the anaesthesia machine and ventilator were set as follows: fresh gas flow of 0 L · min⁻¹, inspiratory-to-expiratory ratio of 1:2, and respiratory rate of 10 breaths · min⁻¹. Before data collection, ventilators

were calibrated at C_L of $0.15 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$, airway resistance of $2 \text{ cm} \cdot \text{L}^{-1} \cdot \text{sec}^{-1}$, PEEP of 0, and V_{Tset} of 500 and 1000 ml. These settings were used as the reference point of all corresponding comparisons of V_{Tdel} and ventilator output at the two levels of V_{Tset} with different combinations of PEEP and C_L as follows: PEEP was increased from 0 to 30 cm H_2O in 5-cm H_2O increments and C_L was decreased from 0.15 to 0.05, 0.03, 0.02, and $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$, consecutively. At each combination of PEEP, C_L , and V_{Tset} , measurements were repeated five times.

Unpaired t test with Bonferroni correction and analysis of variance (ANOVA) with *post hoc* Tukey testing was used for statistical comparison of V_{Tdel} and ventilator output among the three systems for each combination of PEEP, C_L , and V_{Tset} . Two-way ANOVA with *post hoc* Tukey testing was used to compare V_{Tdel} and ventilator output within each anaesthesia ventilator system at different settings of PEEP and C_L . The decrease in V_{Tdel} due to PEEP alone ($V_{TPEEPloss}$) was compared between two different levels of V_{Tset} for each of the anaesthesia ventilators by ANOVA and *post hoc* Tukey testing. $P < 0.05$ was considered significant.

Results

All anaesthesia machine-ventilator systems used in the study were well within acceptable operating specifications and had no leaks. The effects of PEEP and C_L on V_{Tdel} were similar among the three anaesthesia machine/ventilator systems at either V_{Tset} : V_{Tdel} was always $< V_{Tset}$. The difference (as a percentage of V_{Tset}) was always greater at V_{Tset} of 500 ml than 1000 ml (Figures 2 and 3), and the effect was most prominent with the II/7000 and least for the III/AV-E system.

Merely decreasing the simulated C_L from the reference value of 0.15 to $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ without PEEP decreased V_{Tdel} from V_{Tset} of 500 ml to 451 ± 6 ml with the III/AV-E, to 450 ± 4 ml with the II/7810, and to 412 ± 5 ml with the II/7000 ($P < 0.05$ comparing the II/7000 with the III/AV-E or the II/7810) and from V_{Tset} of 1000 ml to, respectively, 900 ± 9 , 872 ± 7 , and 842 ± 9 ml ($P < 0.05$ among the three systems). With simulated C_L remaining at $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ as PEEP was increased from 0 to 30 cm H_2O , V_{Tdel} further decreased from V_{Tset} of 500 ml to 340 ± 4 ml with the III/AV-E, to 303 ± 4 ml with the II/7810, and to 280 ± 6 ml with the II/7000 ($P < 0.05$ among the three systems), and from V_{Tset} of 1000 ml, respectively, to 782 ± 9 , 704 ± 9 , and 693 ± 7 ml ($P < 0.05$ comparing the III/AV-E with the II/7810 or the II/7000) (Figures 2 and 3).

Decreasing the simulated C_L from the reference setting of 0.15 to $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ without PEEP decreased

FIGURE 2 Delivered tidal volume (mean) at lung compliances of $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (open symbols) and $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (solid symbols) during positive end-expiratory pressure (PEEP) and ventilation with a tidal volume setting (V_{Tset}) of 500 ml on the following three anaesthesia machine/ventilator systems: Narkomed III and an AV-E ventilator (squares) and a Modulus II with either a 7810 ventilator (circles) or a 7000 ventilator (triangles). The SD for all measurements never exceeded 11.

FIGURE 3 Delivered tidal volume (mean) at lung compliances of $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (open symbols) and $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (solid symbols) during positive end-expiratory pressure (PEEP) and ventilation with a tidal volume setting (V_{Tset}) of 1000 ml on the following three anaesthesia machine/ventilator systems: Narkomed III and an AV-E ventilator (squares) and a Modulus II with either a 7810 ventilator (circles) or a 7000 ventilator (triangles). The SD for all measurements never exceeded 11.

V_{Tdel} from V_{Tset} of 500 ml to 320 ± 4 ml with the III/AV-E, to 289 ± 5 ml with the II/7810, and to 222 ± 5 ml with the II/7000 ($P < 0.05$ among the three systems) and from V_{Tset} of 1000 ml to, respectively, 623 ± 8 , 540 ± 11 , and 484 ± 7 ml ($P < 0.05$ among the three systems). With C_L remaining at $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ as PEEP was increased from 0 to 30 cm H_2O , V_{Tdel} further decreased from V_{Tset} of 500 ml to 251 ± 6 ml with III/AV-E, to 201 ± 5 with the II/7810, and to $181 \pm$

FIGURE 4 Ventilator output (mean) at lung compliances of $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (open symbols) and $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (solid symbols) during positive end-expiratory pressure (PEEP) and ventilation with a tidal volume setting (V_{Tset}) of 500 ml on the following three anaesthesia machine/ventilator systems: Narkomed III and an AV-E ventilator (squares) and a Modulus II with either a 7810 ventilator (circles) or a 7000 ventilator (triangles). The SD for all measurements never exceeded 11.

FIGURE 5 Ventilator output (mean) at lung compliances of $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (open symbols) and $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$ (solid symbols) during positive end-expiratory pressure (PEEP) and ventilation with a tidal volume setting (V_{Tset}) of 1000 ml on the following three anaesthesia machine/ventilator systems: Narkomed III and an AV-E ventilator (squares) and a Modulus II with either a 7810 ventilator (circles) or a 7000 ventilator (triangles). The SD for all measurements never exceeded 11.

4 with the II/7000 and from V_{Tset} of 1000 ml to, respectively, 542 ± 7 , 439 ± 5 , and $433 \pm 7 \text{ ml}$ ($P < 0.05$ among the three systems) (Figures 4 and 5). The $V_{TPEEPloss}$ increased only slightly but significantly when V_{Tset} was increased from 500 to 1000 ml (Table), thus, the decrease ($V_{TPEEPloss}$) as a percentage of V_{Tset} was greater at V_{Tset} of 500 than of 1000 ml.

The effect of PEEP and C_L on ventilator output was similar to that on V_{Tdel} , but of lesser magnitude (Figures 4 and 5). Compared with the ventilator output with the II/7810 and II/7000, that with the III/AV-E was affected least ($P < 0.05$). When C_L was decreased from 0.15 to $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$, ventilator output with the III/AV-E decreased less than 8% at V_{Tset} of 500 ml and less than 6% at a V_{Tset} of 1000 ml.

Discussion

We measured ventilator output at the ventilator bellows in order to evaluate the portion of change in V_{Tdel} due solely to ventilator performance, that is, the portion of V_{Tdel} independent of the breathing circuit and anaesthesia machine. The effect of PEEP on V_{Tdel} results from gas compression of the space within the ventilator bellows, the inspiratory valve, and the PEEP valve (Figure 1, shaded area), which is required to increase ambient pressure. The V_{Tdel} can be derived from the following equation.^{1,5,6}

$$V_{Tdel} = V_{Tset} + \text{fresh gas flow rate} \cdot \text{inspiratory time} - V_{TPEEPloss} - V_{T(C+CL)loss}$$

where $V_{T(C+CL)loss}$ is the loss due solely to C_L and com-

TABLE Loss of delivered tidal volume caused by positive end-expiratory pressure alone (PEEP) at different simulated lung compliances and different tidal volume settings (V_{Tset}) on three anaesthesia machine/ventilator systems

Anaesthesia/machine ventilator system	Loss of delivered V_T (ml) caused only by PEEP of $30 \text{ cm} \cdot \text{H}_2\text{O}^{-1}$			
	Lung compliance of $0.05 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$		Lung compliance of $0.01 \text{ L} \cdot \text{cm H}_2\text{O}^{-1}$	
	V_{Tset} of 1000 ml	V_{Tset} of 500 ml	V_{Tset} of 1000 ml	V_{Tset} of 500 ml
Narkomed III/AV-E	118 ± 7	111 ± 4	81 ± 9	$69 \pm 2^*$
Modulus II/7810	168 ± 7	$147 \pm 2^*$	101 ± 8	$88 \pm 5^*$
Modulus II/7000	149 ± 5	$132 \pm 4^*$	51 ± 8	$41 \pm 2^*$

Values are means $\pm$ SD. PEEP of $30 \text{ cm} \cdot \text{H}_2\text{O}$ represents the worst case.

* $P < 0.05$ compared with V_{Tset} of 1000 ml at the same lung compliance.

pression of circuit and gas. Fresh gas flow augments V_{Tdel} ,¹ therefore, we used a fresh gas flow rate of 0 in this study. The equation can then be reduced to:

$$V_{Tdel} = V_{Tset} - V_{TPEEPloss} - V_{T(C+C_L)loss}$$

Without PEEP, the total loss of V_T results only from compression of the circuit and gas to increase pressure from the level at end-expiration to that at peak inspiration. A typical adult anaesthesia circle circuit with ventilator has a compression volume of 6 to 7 L and a compressibility of 6 to 12 ml · cm H_2O^{-1} .⁷ With the addition of PEEP, however, additional gas compression is required to increase pressure from ambient to PEEP within the space enclosed by the ventilator bellows, the CO_2 absorber, the inspiratory valve, and the PEEP valve (Figure 1, shaded area).

Our results show that $V_{TPEEPloss}$ increased only slightly when V_{Tset} was increased while C_L remained constant (Table). Therefore, $V_{TPEEPloss}$ becomes a relatively greater percentage of V_{Tset} when V_{Tset} is lower, which supports others' findings.⁶ This study also confirms that PEEP alone decreases V_{Tdel} much less with the higher C_L typical of normal lungs than with the low C_L as would occur in patients with stiff lungs. Even before PEEP is applied, lower C_L alone already decreases V_{Tdel} . With low C_L , PEEP causes V_{Tdel} to begin to decrease at the flatter portion of the compliance curve. Nevertheless, even though the $V_{TPEEPloss}$ is less with low C_L , the decrease is still substantial. Therefore, patients with respiratory failure who undergo surgery, those who are most in need of a precise V_{Tdel} , are not likely to get it without proper adjustment of the ventilator, that is, without increasing V_{Tdel} .

In summary, adding PEEP to an anaesthesia breathing circuit decreases V_{Tdel} , and the effect becomes increasingly greater as V_{Tset} is decreased. Decreased C_L mitigates the effect of PEEP on V_{Tdel} . As PEEP is added or C_L is decreased or both occur simultaneously, expired V_T must be monitored and V_{Tset} adjusted to compensate for loss of V_{Tdel} and to prevent hypoventilation. Future anaesthesia machine/ventilator designs may be improved by adding a feedback mechanism to increase flow to the ventilator if measured V_{Tdel} does not approximate V_{Tset} , which would produce more reliable V_{Tdel} over a wider range of clinical conditions.

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