Accuracy of automatic tube compensation in new-generation mechanical ventilators*

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Objective: **To compare performance of flow-adapted compensation of endotracheal tube resistance (automatic tube compensation, ATC) between the original ATC system and ATC systems incorporated in commercially available ventilators.**

Design: **Bench study.**

Setting: **University research laboratory.**

Subjects: **The original ATC system, Dräger Evita 2 prototype, Dräger Evita 4, Puritan-Bennett 840.**

Interventions: **The four ventilators under investigation were alternatively connected via different sized endotracheal tubes and an artificial trachea to an active lung model. Test conditions consisted of two ventilatory modes (ATC vs. continuous positive airway pressure), three different sized endotracheal tubes (inner diameter 7.0, 8.0, and 9.0 mm), two ventilatory rates (15/min and 30/min), and four levels of positive end-expiratory pressure (0, 5, 10, and 15 cm H_2O).**

Measurements and Main Results: **Performance of tube compensation was assessed by the amount of tube-related (additional) work of breathing (WOB_{add}), which was calculated on the basis of pressure gradient across the endotracheal tube. Compared with continuous positive airway pressure, ATC reduced inspiratory WOB_{add} by 58%, 68%, 50%, and 97% when using the Evita 4, the Evita 2 prototype, the Puritan-Bennett 840, and the original ATC system, respectively. Depending on endotracheal tube diameter and ventilatory pattern, inspiratory WOB_{add} was 0.12–5.2 J/L with the original ATC system, 1.5–28.9 J/L with the Puritan-Bennett 840, 10.4–21.0 J/L with the Evita 2 prototype, and 10.1–36.1 J/L with the Evita 4 (difference between each ventilator at identical test situations, $p < .025$). Expiratory WOB_{add} was reduced by 5%, 26%, 1%, and 70% with the Evita 4, the Evita 2 prototype, the Puritan-Bennett 840, and the original ATC system, respectively. The expiratory WOB_{add} caused by an endotracheal tube of 7.0 mm inner diameter was 5.5–42.2 J/L at a low ventilatory rate and 19.6–82.3 J/L at a high ventilatory rate. It was lowest with the original ATC system and highest with the Evita 4 ventilator ($p < .025$).**

Conclusions: **Flow-adapted tube compensation by the original ATC system significantly reduced tube-related inspiratory and expiratory work of breathing. The commercially available ATC modes investigated here may be adequate for inspiratory but probably not for expiratory tube compensation. (Crit Care Med 2003; 31:2619–2626)**

KEY WORDS: endotracheal tube resistance; tube compensation; work of breathing; additional work of breathing; expiratory work of breathing

Automatic tube compensation (ATC) is a new ventilatory mode that compensates for the flow-dependent pressure decrease across an endotracheal tube (ETT) during inspiration and expiration (1). The principle of ATC is illustrated in Figure 1. When ATC is used, the pressure assist (P_{ATC}) is adjusted continuously during the ventilatory cycle to the change in flow rate and, thus, to the change in flow-dependent pressure decrease across the ETT. P_{ATC} is increased during inspiration and lowered during expiration. At low levels of positive end-expiratory pressure (PEEP) and/or high expiratory flow rates, airway pressure at the proximal end of the ETT has to be lowered to subatmospheric levels to achieve complete expiratory tube compensation. By this mechanism, ATC compensates exclusively for the tube-related additional work of breathing (2–5). In endotracheally intubated patients, this has been associated with reduced work of breathing (4, 5), preservation of the natural breathing pattern (6), improved synchronization between patient and ventilator (7, 8), and improved respiratory comfort (9, 10). Moreover, sufficient spontaneous breathing with ATC alone, without any additional ventilatory support, might be a useful predictor of successful extubation in the late phase of weaning from mechanical ventilation, especially in difficult to wean patients (11).

The technique of ATC requires continuous measurement of gas flow rate and airway pressure (proximal to the tube), a rapid (on-line) calculation of the respective pressure decrease across the ETT, and a meticulous and timely control of pressure support provided by the ventilator. Therefore, ATC requires far greater technical sophistication than most other modes of ventilatory support. Consequently, proper performance of ATC cannot be taken for granted in newly introduced equipment.

Following its introduction in an experimental ventilator (1), ATC has been

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***See also p. 2704.**

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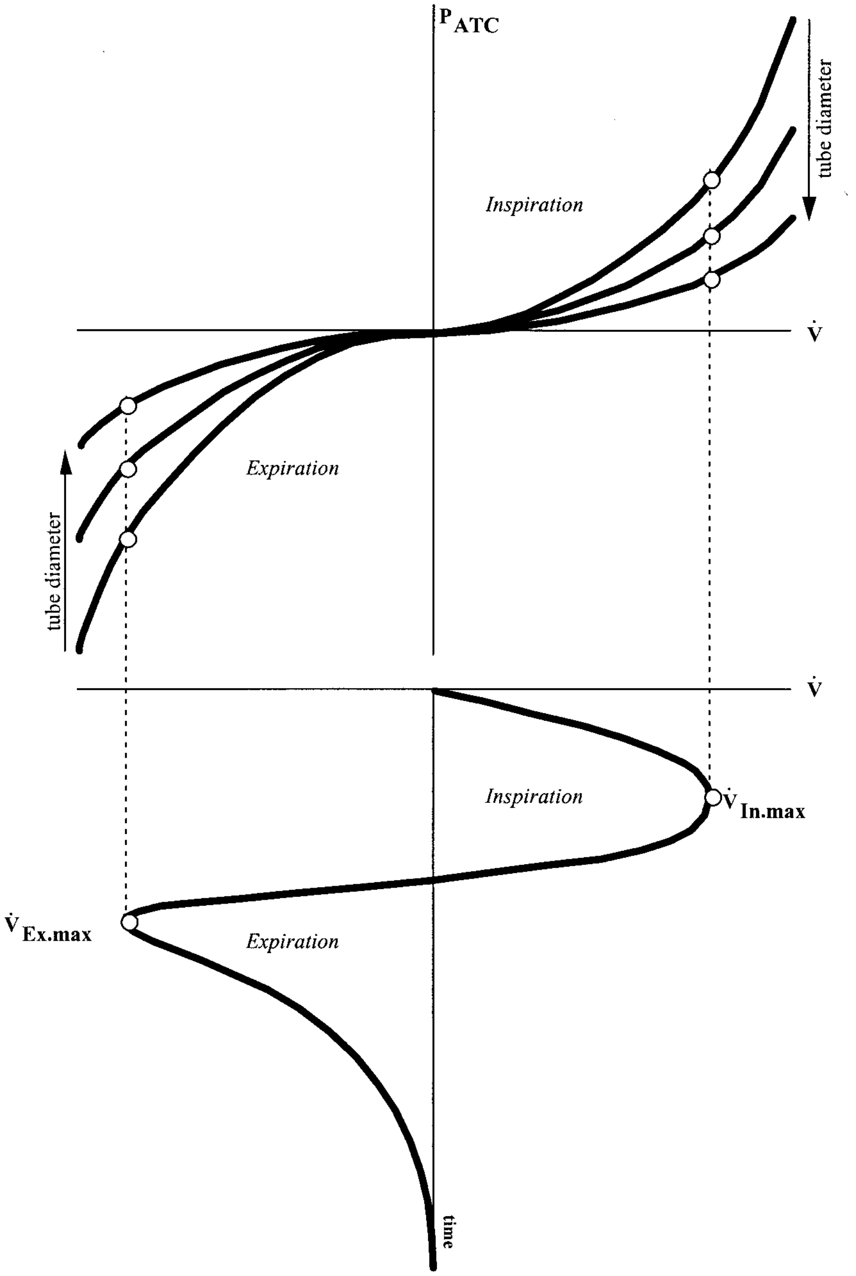

Figure 1. *Top*, principle of automatic tube compensation (*ATC*) illustrated by pressure-flow curves of differently sized endotracheal tubes. Inner diameter of the tube increases in the direction of arrows. During inspiration, the ventilator increases airway pressure by a flow-dependent pressure (P_{ATC}) that follows the inspiratory part of the pressure-flow curve. During expiration, the ventilator decreases airway pressure following the expiratory part of the curve. The respective pressure-flow curve is defined by the tube diameter. *Bottom,* flow curve of a spontaneous breath (rotated by 90°). The pressures required for tube compensation at inspiratory peak flow rate ($\dot{V}_{In.max}$) and expiratory peak flow rate ($\dot{V}_{Ex.max}$) are indicated as dots. They depend on tube size.

adapted and simplified by various manufacturers. This has been done in an attempt to provide robustness and reliability for routine clinical practice. ATC was first introduced in an Evita 2 prototype ventilator (Dräger, Lübeck, Germany) (12). Subsequently, the feature of flow-adapted tube compensation became available in commercial ventilators like the Evita 4 ventilator (ATC, Dräger) and the Puritan-Bennett 840 ventilator (TC, Mallinckrodt, St. Louis, MO). Other manufacturers of ventilators are following closely. Considering the many technical requirements for successful performance of ATC, we decided to assess the performance of new commercially available ATC systems. For this purpose, we compared commercially available ventilators with in-built ATC mode with the original ATC prototype ventilator in a laboratory setting.

MATERIALS AND METHODS

Determination of Additional and Reduced Work of Breathing. The deviation of the pressure in the trachea (P_{trach}) from PEEP is a measure of performance of tube compensation. If we quantify this deviation by measuring the area between P_{trach} below and above the PEEP level (4, 5), tube-related work of breathing (WOB) can be directly determined (13, 14), as illustrated in Figure 2. Any inspiratory deviation of P_{trach} below the PEEP level is due to an inspiratory effort (4, 5, 14). Accordingly, the corresponding area is termed additional inspiratory work of breathing ($WOB_{add,in}$). By contrast, any inspiratory deviation of P_{trach} above the PEEP level is due to either ventilator-supplied pressure support, asynchrony between patient and ventilator, or a combination of both (4, 5, 14). With effective ATC, P_{trach} theoretically should never deviate from the PEEP level. Therefore, in the absence of asynchrony between patient and ventilator, any increase in P_{trach} above the PEEP level reflects ventilatory assist beyond mere tube compensation, that is, overassist (4, 5, 14). The corresponding work is then called reduced inspiratory work of breathing ($WOB_{red.in}$). As quality of tube compensation depends not only on minimizing tube-related additional work of breathing ($WOB_{add.in}$) but also on avoiding any pressure assist beyond mere tube compensation (overassist), $WOB_{red.in}$ also should be as low as possible (4, 5). For expiration, we defined any expiratory deviation of P_{trach} above PEEP level as additional expiratory work ($WOB_{add.ex}$) and any expiratory deviation below PEEP level as reduced expiratory work of breathing ($WOB_{red.ex}$). To estimate the compensatory work that is applied automatically by the ventilator with the ATC mode, we also determined WOB based on airway pressure (Paw) at the proximal end of the ETT.

Experimental Setup. The experimental setup is shown in Figure 3. An LS4000 active lung model (Dräger) driven by an external sine wave oscillator (TM 504, Tektronix, Beaverton, OR) was used to generate a sinusoidal flow of room air with the ventilatory pattern under investigation. Compliance and resistance of the lung model were set at 50 mL/cm H_2O and 3 cm H_2O · sec/L, respectively. The flow was directed through an artificial trachea consisting of a transparent tube of 21 mm inner diameter connected to the LS4000 active lung model. An ETT was introduced into the artificial trachea. At its proximal end, the ETT was connected via a standard 15-mm bent swivel connector (Portex 100/250/001, Portex Ltd, Hythe, Kent, UK) to the Y-piece and the tubing system of the ventilator under investiga-

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tion. Flow was measured with a Fleisch 2 pneumotachograph (Metabo, Epalinges, Switzerland) connected to a differential pressure transducer (CPS 1, Hoffrichter, Schwerin, Germany). Paw was measured via a separate opening located in the wall of the connecting diffuser of the pneumotachograph. P_{trach} in the artificial trachea was determined via a ring channel located beyond the region of flow separation, that is, 60 mm below the tip of the ETT (15). Paw and P_{trach} were measured with pressure transducers (1210A ICSensors, Milpitas, CA). Flow and pressure signals were sampled at a rate of 100 Hz and digitized 12 bits wide for subsequent numeric analysis.

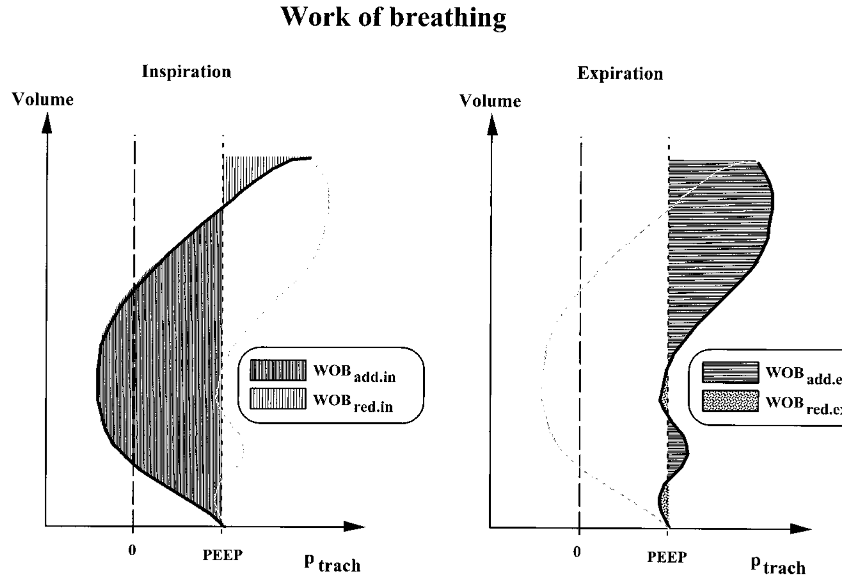

Figure 2. Schematic illustration of the concept of additional (WOB_{add}) and reduced work of breathing (WOB_{red}) during inspiration (*in*) and expiration (*ex*). *PEEP*, positive end-expiratory pressure; p_{trach}, pressure in the trachea.

Protocol. Performance of tube compensation was tested using an Evita 4 ventilator (ATC, Dräger), an Evita 2 prototype ventilator operated by prototype software for tube compensation (ATC, Dräger), a Puritan-Bennett 840 ventilator (TC, Mallinckrodt, St. Louis, MO), and the original ATC system (1). In addition, tube compensation by these ventilators was compared with unsupported breathing in the continuous positive airway pressure (CPAP) mode.

The four ventilators were connected alternatively to three types of ETTs (Hi-Lo Evac, Mallinckrodt Laboratories, Athlone, Ireland) with three different inner diameters each (7.0, 8.0, and 9.0 mm). Flow rate was modified indirectly by using two respiratory rates (15 and 30/min). Because we adjusted the sine wave generator to generate a tidal volume of 600 mL and an inspiratory to expiratory time ratio of 0.47, except for flow, rate ventilatory patterns were identical. All measurements

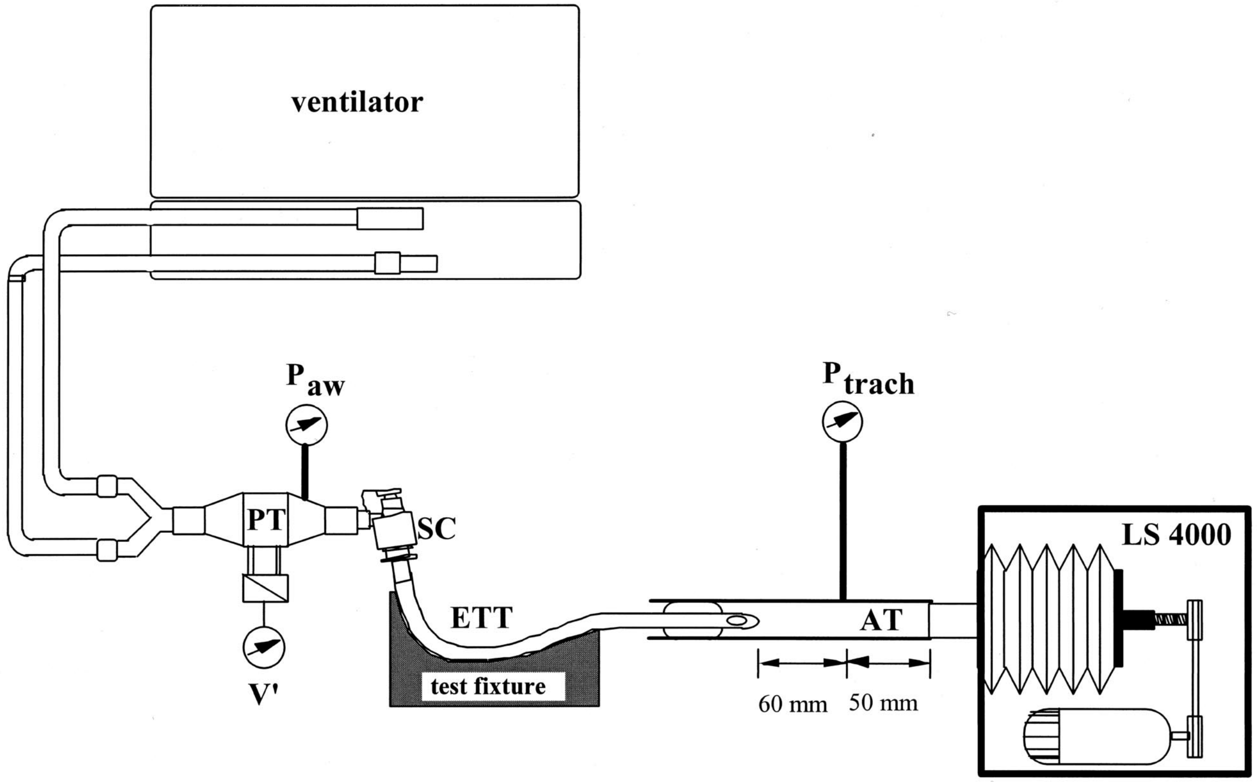

Figure 3. Laboratory setup: The lung model (LS 4000) simulates spontaneous breathing by producing a sinusoidal flow. The ventilator under test operating in the automatic tube compensation mode compensates for the air flow resistance of the endotracheal tube (*ETT*). Flow rate (*V'*) is measured using a pneumotachograph (*PT*). Airway pressure (P_{aw}) is measured outside the ETT and the swivel connector (*SC*). Tracheal pressure (P_{trach}) is measured in the artificial trachea (*AT*) by means of a ring channel at a distance of 60 mm from the tip of the ETT.

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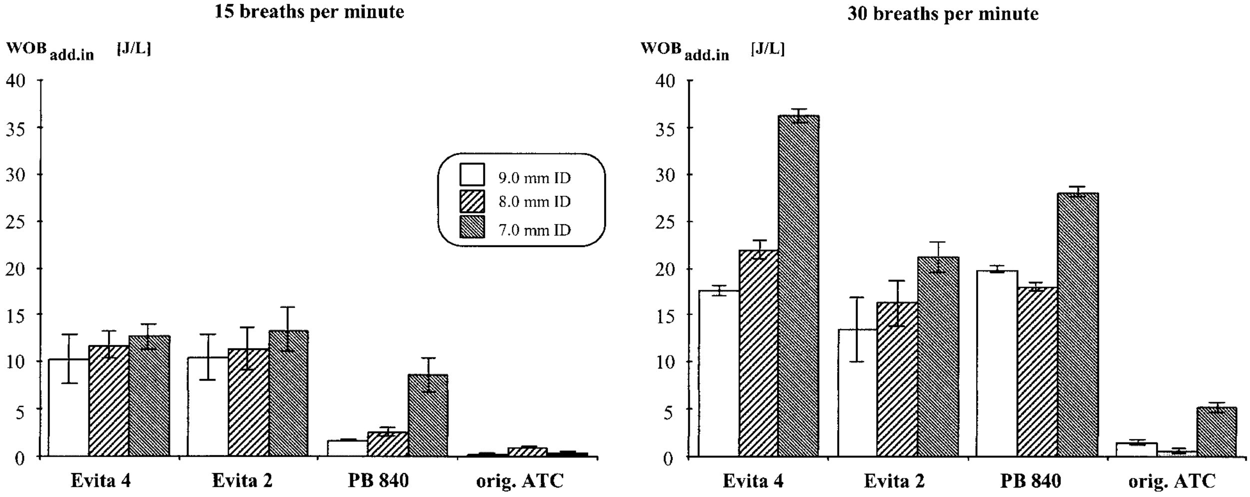

Figure 4. Tube-related (additional) work of breathing during inspiration (*$WOB_{add.in}$*) at low (*left panel*) and high (*right panel*) ventilatory rate at differently sized endotracheal tubes during PEEP 5 cm H_2O. At high ventilatory rate, $WOB_{add.in}$ differed significantly ($p < .025$) between all four ventilators. Findings were comparable at the lower ventilatory rate, except that there was no difference between Evita 4 and Evita 2 prototype. Columns and bars indicate means ± SD (see text for further description). *ID*, inner diameter.

were performed at different PEEP levels (i.e., 0, 5, 10, and 15 cmH_2O) because in the Evita 2 prototype and the Evita 4 ventilator, only PEEP can serve as a "pressure source" for expiratory tube compensation (12). The Puritan-Bennett 840 ventilator does not provide expiratory tube compensation, and in the original ATC system, expiratory ATC is supported by a negative pressure source (1). The different test combinations—consisting of four types of ventilators, two ventilatory modes, three types of ETTs, two respiratory rates, and four levels of PEEP—were investigated in random order. Each measurement lasted for either 3 mins (in case of a respiratory rate of 15/min) or 2 mins (in case of a respiratory rate of 30/min). Thus, a total of approximately 45–60 breaths per measurement served for subsequent statistical analysis.

Statistical Analysis. Differences between the four ventilators (group variable) at identical test conditions were assessed by one-way analysis of variance. If analysis of variance revealed a significant difference, Tukey's pairwise multiple comparison test was performed for subsequent identification of group differences. A two-tailed p value <.025 was considered as the limit of significance. All data are presented as mean ± 1 SD.

RESULTS

Inspiration. $WOB_{add,in}$ changed with inner diameter of the ETT, ventilatory rate, and make of the ventilator. At the higher ventilatory rate (and at identically sized ETTs and PEEP levels), $WOB_{add.in}$ differed significantly ($p < .025$) between all four ventilators (Fig. 4). Findings were comparable at the lower ventilatory rate, except that there was no difference between the Evita 4 and Evita 2 prototype. In support of those findings, the compensatory pressure work (automatically applied by the ventilator to compensate for inspiratory ETT resistance) showed a similar but inverse pattern (i.e., the higher the compensatory pressure work, the lower the $WOB_{add.in}$; Fig. 5). Compared with CPAP, ATC significantly reduced $WOB_{add.in}$ during all modes of ventilation (Table 1). As a reflection of overassist, during low ventilatory rate, $WOB_{red.in}$ was significantly higher with the Puritan-Bennett 840 ventilator and the original ATC system compared with the Evita 4 and the Evita 2 prototype ventilator (Fig. 6, *left*). During high ventilatory rate, $WOB_{red.in}$ increased with all ventilators but was lowest ($p < .01$) with the Puritan-Bennett 840 (Fig. 6, *right*). Note that the maximal value of $WOB_{red.in}$ was always <3.5 J/L.

Expiration. Depending on the ventilator used, the additional expiratory work of breathing ($WOB_{add.ex}$) caused by an ETT of 7.0 mm inner diameter varied between 5.5 and 42.2 J/L during low respiratory rate and between 19.6 and 82.3 J/L during high respiratory rate (Fig. 7). $WOB_{add.ex}$ was always lowest using the original ATC system and highest with the Evita 4 ventilator ($p < .01$). During all test conditions, it differed significantly ($p < .025$) between all ventilators. Compared with ventilatory support with CPAP (Table 2), $WOB_{add.ex}$ was reduced significantly ($p < .025$) at all ETT when using the Evita 2 prototype and the original ATC system but not when using the Evita 4 and the Puritan-Bennett 840. The reduction in $WOB_{add.ex}$ was significantly greater when using the original ATC system compared with the Evita 2. Contrary to theoretical expectations, $WOB_{add.ex}$ was not reduced with increasing levels of PEEP in the Evita 4 and the Evita 2 prototype ventilator. In support of these findings, the pressure work (negative pressure) automatically applied by the ventilators to compensate for expiratory tube resistance of a 7.0-mm sized ETT was negligible for the Puritan-Bennett 840 ventilator and highest for the original ATC system at both ventilatory rates (Fig. 8).

The decrease in P_{trach} below the targeted PEEP of maximally 0.4 cm H_2O and 0.8 cm H_2O at 15 and 30 breaths per minute, respectively, indicates that there could not have been any relevant expiratory pressure loss. This negligible decrease in P_{trach} was observed irrespective of the ventilator tested and despite the negative pressure source of the original ATC system.

DISCUSSION

The findings of this experimental study indicate that ATC can reduce inspiratory as well as expiratory tube-related work of breathing. ATC-induced reduction of inspiratory tube-related work of breathing previously has been demonstrated in tracheally intubated or tracheostomized patients (4, 5). By contrast, the finding of ATC-induced reduction of expiratory tube-related work of

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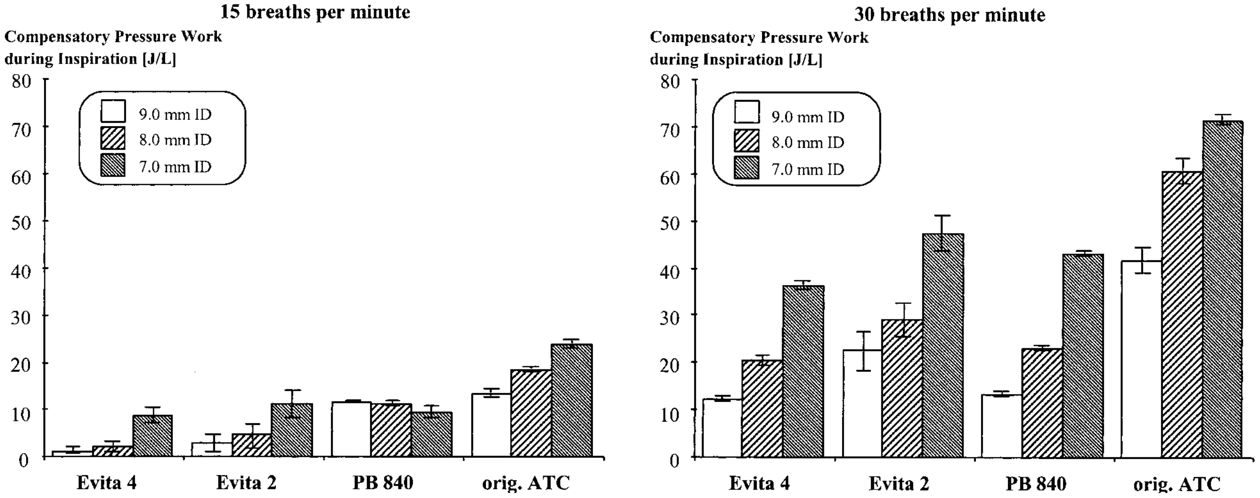

Figure 5. Compensatory pressure work (as applied automatically by the ventilator in the automatic tube compensation [*ATC*] mode to compensate for tube resistance during inspiration) at low (*left panel*) and high (*right panel*) ventilatory rate along differently sized endotracheal tubes at positive end-expiratory pressure of 5 cm H_2O. Columns and bars indicate means ± SD (see text for further description). *ID*, inner diameter.

Table 1. Inspiratory work of breathing (J/L) at positive end-expiratory pressure of 5 cm H_2O during automatic tube compensation (ATC) and continuous positive airway pressure (CPAP)

	Respiratory Rate 15/Min		Respiratory Rate 30/Min	
	CPAP	ATC	CPAP	ATC
7.0 ETT				
Evita 4	29.5 ± 1.0	12.6 ± 1.3[a]	87.4 ± 0.8	36.1 ± 0.8[a]
Evita 2	33.9 ± 1.6	13.2 ± 2.6[a]	88.3 ± 2.8	21.0 ± 1.7[a]
PB 840	14.4 ± 0.8	8.6 ± 1.7[a]	51.2 ± 1.4	28.0 ± 0.5[a]
Original ATC	29.3 ± 0.5	0.3 ± 0.02[a]	88.8 ± 0.9	5.1 ± 0.5[a]
8.0 ETT				
Evita 4	23.5 ± 1.0	11.7 ± 1.5[a]	73.4 ± 0.8	21.8 ± 1.0[a]
Evita 2	28.9 ± 1.6	11.3 ± 2.2[a]	75.3 ± 1.8	16.2 ± 1.4[a]
PB 840	9.3 ± 1.5	3.8 ± 0.3[a]	38.2 ± 1.4	17.8 ± 0.4[a]
Original ATC	24.3 ± 0.5	0.8 ± 0.0X[a]	77.8 ± 0.9	0.53 ± 0.1[a]
9.0 ETT				
Evita 4	21.0 ± 1.4	10.1 ± 2.8[a]	44.2 ± 0.8	17.5 ± 0.5[a]
Evita 2	25.8 ± 1.0	10.3 ± 2.5[a]	48.3 ± 1.6	13.4 ± 1.3[a]
PB 840	7.2 ± 0.1	2.9 ± 0.1[a]	33.9 ± 1.0	19.7 ± 0.3[a]
Original ATC	23.8 ± 0.5	0.1 ± 0.01[a]	43.4 ± 0.6	1.4 ± 0.2[a]

ETT; endotracheal tube. Values are mean ± SD.
[a] $p < .025$.

breathing is new. Especially the latter finding demonstrates the remarkable difference between commercially available ventilators and the original ATC system regarding efficacy of combined inspiratory and expiratory tube compensation.

The concept of ATC is characterized by CPAP at the tracheal level (1, 5). Whereas an ideal CPAP system should maintain PEEP during inspiration and expiration (13, 14), ideal ATC should achieve just that at the tracheal level (P_{trach}) (1, 5). Thus, the more P_{trach} deviates from PEEP, the less effective is the tube compensation (4, 5, 14). The deviation of P_{trach} from PEEP can be quantified by determining the WOB_{add} and WOB_{red} (13, 14). The amount of WOB_{add} and WOB_{red} serves as a measure of performance of ATC. Performance appears to differ significantly between commercially available ATC ventilators and the original ATC system.

In the commercially available ATC ventilators, Paw and gas flow are measured inside the ventilator, that is, approximately 1.8 m away from the patient. Although this might improve handling and safety of the ventilator compared with the original ATC system, other difficulties arise. Due to the finite velocity of sound propagation, gas flow and Paw signals inside the ventilator and those at the patient's airway opening are not in parallel. Furthermore, due to the compliance of the ventilator tubing, gas flow at the inspiratory valve is not equal to gas flow into the patient. The compliance of tubing usually is corrected for by mathematical means. However, such correction is limited by several factors. First, the compliance of the ventilator tubing depends on several factors (e.g., tubing material and water level in the vaporizer). Second, rapid changes in Paw cannot be measured instantaneously. Consequently, calculation of P_{trach} is inaccurate when changes in Paw or gas flow occur rapidly.

The difference between commercial ATC systems and the original ATC system also might be due to the simplified algorithm for the calculation of P_{trach}. Usually, P_{trach} can be calculated by subtracting the current pressure decrease across the ETT (Δp_{ETT}) from current airway pressure (15). Δp_{ETT} depends—among other things—on the inner diameter of the ETT and on the concurrent flow rate ($\dot{V}$). The dependency of Δp_{ETT} on flow is linear at low flow rates (laminar flow) but nonlinear (exponential) at high flow rates (turbulent flow). The critical flow rate at which laminar flow turns into turbulent flow is about 0.2 L/sec for an ETT of 8.0 mm inner diameter. This means that at the beginning and end of a spontaneous inspiration or expiration flow is predominantly laminar, but for the major portion of the respiratory cycle it is turbulent. In the original ATC system, a linear and a quadratic term are used to calculate

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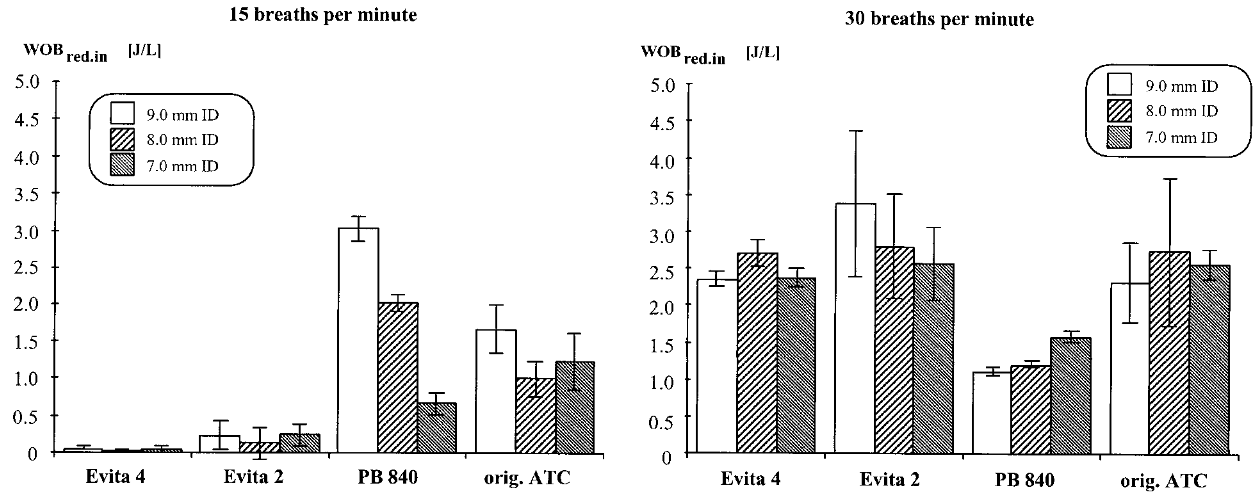

Figure 6. Reduced work of breathing during inspiration (*$WOB_{red.in}$*; as a reflection of overassist) at low (*left panel*) and high (*right panel*) ventilatory rate along differently sized endotracheal tubes at positive end-expiratory pressure of 5 cm H_2O. Note that $WOB_{red.in}$ was always <3.5 J/L, even at high ventilatory rate. Columns and bars indicate means ± SD (see text for further description). *ID*, inner diameter; *ATC*, automatic tube compensation.

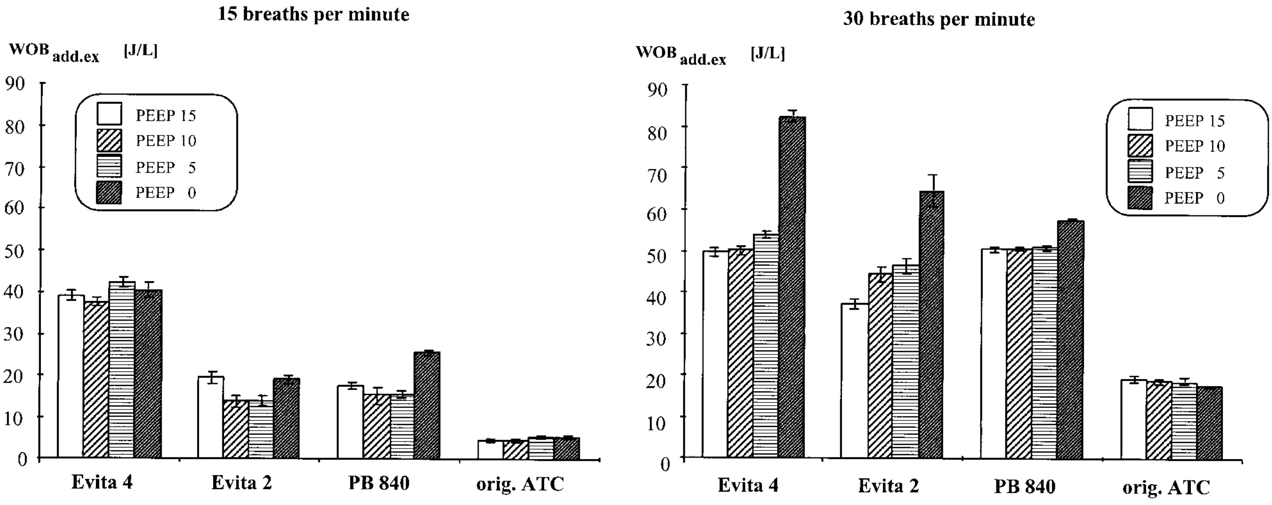

Figure 7. Tube-related (additional) work of breathing during expiration (*$WOB_{add.ex}$*) at low (*left panel*) and high (*right panel*) ventilatory rate along the four positive end-expiratory pressure (*PEEP*) levels during an endotracheal tube of 7.0 mm inner diameter. $WOB_{add.ex}$ was always lowest when using the original ATC system and highest with the Evita 4 ventilator ($p < .01$). During all test conditions, it differed significantly ($p < .025$) between all ventilators. Note that $WOB_{add.ex}$ was not reduced with increasing levels of PEEP in the Evita 4 and the Evita 2 prototype ventilator. Columns and bars indicate means ± SD (see text for further description). *ATC*, automatic tube compensation.

Δp_{ETT} ($\Delta p_{ETT} = k_1 \cdot \dot{V} + k_2 \cdot \dot{V}^2$). By contrast, in the Evita 2 prototype and the Evita 4 ventilator Δp_{ETT} is calculated only on the basis of the quadratic term ($\Delta p_{ETT} = k \cdot \dot{V}^2$). When using only a quadratic term and thus working with a left-hand shifted pressure-decrease/flow curve, overcompensation of ETT resistance inevitably will result. This could be attenuated by setting a threshold flow value for the beginning of tube compensation (e.g., > 0.2 L/sec) and/or by using a less accurate power function to characterize the flow-dependent pressure decrease across the tube. However, this will in turn inevitably result in less accurate tube compensation.

Once actual P_{trach} has been calculated by any of the algorithms mentioned previously, there are different ways to control gas flow delivery to minimize the deviation of actual P_{trach} from its targeted value (e.g., during ATC the targeted value is the PEEP level in the trachea). If gas flow delivery is very fast, the deviation of P_{trach} is corrected quickly but the risk of pressure overswing and, thus, of pressure oscillation around the targeted value will increase. This would then lead to both over- and undercompensation of tube resistance. By contrast, if gas flow is delivered more cautiously, pressure overswings can be avoided, but efficacy of tube compensation will suffer. In case of the original ATC system, considerable efforts have been made to achieve optimal control. In addition, the mechanical properties of the ventilator's pneumatic circuit (e.g., fast and precise high-pressure servo valves) are of greatest importance for accurate tube compensation. In our experience, this has been accomplished in each of the four ventilators tested.

In the present investigation, effective expiratory tube compensation was observed only with the original ATC system.

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The difference between the commercial ATC solutions and the original ATC system can be explained best by the negative pressure source that is incorporated only in the original ATC system. With this feature in place, the pressure available for expiratory tube compensation is not limited to a preset PEEP level. If necessary, pressure can be lowered up to 20 cm H_2O below atmosphere. This is technically realized by a small blower fitted to the expiratory limb of the ventilator whereby the blower is regulated by the ATC controller (1). In contrast to the original ATC system, the preset PEEP level is the only pressure source for expiratory tube compensation in the Evita 4 and Evita 2 prototype. Consequently, the higher the level of PEEP the larger is the pressure difference available for expiratory tube compensation and, thus, the better should expiratory ETT resistance be compensated for. To our surprise, we did not find any relevant effect of the level of PEEP on the amount of tube-related expiratory work of breathing in the Evita 4 and the Evita 2 prototype. By contrast, the Puritan-Bennett 840 ventilator is not at all equipped with expiratory tube compensation. This is reflected by the lack of relevant negative pressure work (delivered by the ventilator) to overcome expiratory tube resistance (Fig. 8). Despite this finding, the $WOB_{add.ex}$ was significantly lower with the Puritan-Bennett 840 ventilator than with the Evita 4 and the Evita 2 prototype. This is likely due to superior precision control (not related to ATC) in combination with very fast high-pressure servo valves in the Puritan-Bennett 840 ventilator (16). Such a possibility is supported by the finding of significantly smaller tube-related work of breathing during CPAP with the Puritan-Bennett 840 ventilator than with all other ventilators tested here (Tables 1 and 2).

Table 2. Expiratory work of breathing (J/L) at positive end-expiratory pressure of 5 cm H_2O during automatic tube compensation (ATC) and continuous positive airway pressure (CPAP)

	Respiratory Rate 15/Min		Respiratory Rate 30/Min	
	CPAP	ATC	CPAP	ATC
7.0 ETT				
Evita 4	41.2 ± 0.8	38.2 ± 1.1	53.9 ± 0.8	49.7 ± 1.0
Evita 2	20.0 ± 1.9	13.7 ± 1.1[a]	53.5 ± 2.8	44.4 ± 1.7[a]
PB 840	15.5 ± 0.2	15.7 ± 0.7	52.2 ± 1.4	50.9 ± 0.7
Original ATC	21.3 ± 0.3	5.5 ± 0.4[a]	52.2 ± 0.8	19.6 ± 0.9[a]
8.0 ETT				
Evita 4	40.8 ± 0.8	39.7 ± 1.4	49.9 ± 0.8	48.1 ± 1.7
Evita 2	18.0 ± 1.9	13.4 ± 1.1[a]	40.5 ± 2.8	28.0 ± 2.1[a]
PB 840	10.2 ± 0.3	10.0 ± 0.5	41.2 ± 1.4	42.2 ± 0.5
Original ATC	18.3 ± 0.3	4.7 ± 0.2[a]	41.2 ± 0.8	15.0 ± 0.6[a]
9.0 ETT				
Evita 4	30.5 ± 1.2	27.9 ± 1.8	47.1 ± 0.8	48.0 ± 0.8
Evita 2	14.2 ± 1.0	10.4 ± 0.9[a]	37.9 ± 2.3	27.0 ± 1.4[a]
PB 840	9.0 ± 0.2	9.3 ± 0.4	35.6 ± 0.7	35.4 ± 0.5
Original ATC	16.3 ± 0.3	3.9 ± 0.3[a]	33.5 ± 0.6	11.2 ± 1.1[a]

ETT, endotracheal tube. Values are mean ± SD.
[a] $p < .025$.

A shortcoming of the ATC systems is the overassist, especially at a high ventilatory rate (Fig. 6). Theoretically, adequate spontaneous breathing in the presence of overassist could give the false impression that the patient is ready for extubation when, in fact, he or she is dependent on respiratory support. This might then result in premature extubation. It has to be noted, however, that the maximal value of overassist was always <3.5 J/L, which is about ten times smaller than undercompensation of tube resistance (Fig. 4). Consistent with these findings, there was no evidence of premature extubation in a recent extubation trial using one of the ATC systems tested here (11). Nevertheless, further studies are needed to address the aspect of overassist.

Limitations. We did not investigate the effects of partial tube obstruction on

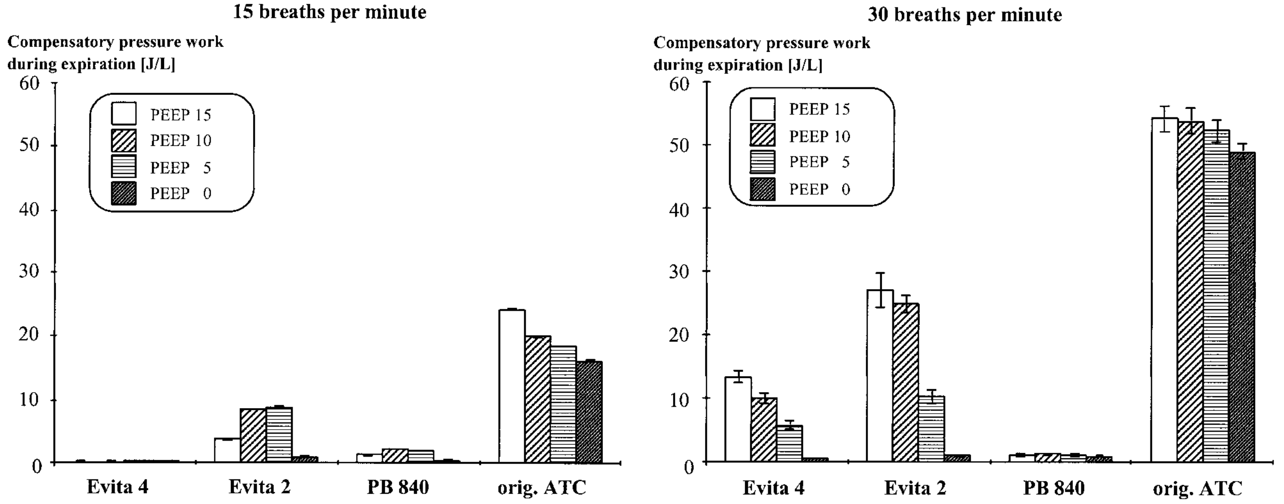

Figure 8. Compensatory pressure work (as applied automatically by the ventilator in the automatic tube compensation [*ATC*] mode to compensate for tube resistance during expiration) at low (*left panel*) and high (*right panel*) ventilatory rate along the four positive end-expiratory pressure (*PEEP*) levels with an endotracheal tube of 7.0 mm inner diameter. Note that the compensatory pressure work was highest for the original ATC system but was nearly zero for the Puritan-Bennett 840 ventilator because the latter is not equipped with the feature of expiratory ATC. Columns and bars indicate means ± SD (see text for further description).

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The commercially available automatic tube compensation modes investigated herein may be adequate for inspiratory but probably not for expiratory tube compensation.

performance of ATC. In clinical practice, partial tube obstruction might occur due to secretions, tube kinking, or external compression of the ETT. Partial tube obstruction reduces the cross-sectional area of an ETT. The subsequent changes in mechanical properties transform the pressure-flow curve of a given ETT to that of a tube of smaller inner diameter. An algorithm for automatic noninvasive detection of partial tube obstruction has been proposed (17). If partial tube obstruction should go undetected, compensation of ETT resistance will be incomplete.

Inspiratory and expiratory flows were provided by sinusoidal flow pattern. Whereas the inspiratory flow pattern mimics the situation in the spontaneously breathing patient, *in vivo* expiratory flow decreases exponentially after having reached its peak level in early expiration. Thus, the results of this bench study do not necessarily reflect clinical conditions. From a theoretical point of view, however, flow usually reaches higher peak values following an exponential rather than a sinusoidal pattern. As a consequence, the differences of expiratory work of breathing observed with sinusoidal flow in this *in vitro* study might be even more pronounced in the presence of exponential flow *in vivo*.

Clinical Implications. ATC is now incorporated in commercially available ventilators for both routine application and clinical studies, and the number of commercially available ATC systems is increasing. However, almost all studies published on ATC to date were performed with the two ATC systems that are not commercially available (i.e., the original ATC system and the Evita 2 prototype). Because we found inferior *in vitro* performance of commercially available ATC systems, we cannot rule out that this will also be the case when the commercially available ventilators (i.e., the Evita 4 and the Puritan-Bennett 840 ventilator) are used in the clinical setting. Therefore, when one is evaluating outcome data, critical assessment of the technical quality of the ATC system employed is of the utmost importance.

CONCLUSIONS

Compared with the original ATC system, the simplified commercially available ATC systems do not seem to adequately compensate for ETT resistance. Unless performance of these systems is improved, the advantages of ATC over conventional, nonflow-adapted pressure support for tube compensation (e.g., the pressure support ventilation) might become negligible.

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