Intensive Care Med (1999) 25: 514–519

BRIEF REPORT

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Additional inspiratory work of breathing imposed by tracheostomy tubes and non-ideal ventilator properties in critically ill patients

Received: 12 August 1998
Final revision received: 22 February 1999
Accepted: 24 February 1999

Financial Support: Swiss National Science Foundation Grant No. 3200–39 382.93

Part of the work has been presented at the 10th European Congress of Intensive Care Medicine, Paris 7.–10. 9. 1997

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Abstract *Objective*: To determine the tracheostomy tube-related additional work of breathing (WOB_{add}) in critically ill patients and to show its reduction by different ventilatory modes.
Design: Prospective, clinical study.
Setting: Medical ICU of a university teaching hospital.
Intervention: Standard tracheostomy due to prolonged respiratory failure.
Measurements and results: Ten tracheostomized, spontaneously breathing patients were investigated. As the tube resistance depends on gas flow, patients were subdivided according to minute ventilation into a low ventilation group (= 10 l/min; $n = 5$) and a high ventilation group (> 10 l/min; $n = 5$). The WOB_{add} due to tube resistance and non-ideal ventilator properties was calculated on the basis of the tracheal pressure measured. Ventilatory modes investigated were: continuous positive airway pressure (CPAP), inspiratory pressure support (IPS) of 5, 10, and 15 cm H_2O above PEEP, and automatic tube compensation (ATC). In the low ventilation group, WOB_{add} during CPAP was 0.382 ± 0.106 J/l. It was reduced to below 15 % of that value by ATC or IPS more than 5 cm H_2O. In the high ventilation group WOB_{add} during CPAP increased to 0.908 ± 0.142 J/l. In this group, however, only ATC was able to reduce WOB_{add} below 15 % of the value observed in the CPAP mode.
Conclusions: The results indicate that, depending on respiratory flow rate, (1) tracheostomy tubes can cause a considerable amount of WOB_{add}, and (2) ATC, in contrast to IPS, is a suitable mode to compensate for WOB_{add} at any ventilatory effort of the patient.

Key words Work of breathing · Tracheostomy tube · Ventilator weaning · ATC · Upper airway resistance

Introduction

It is widely accepted that additional inspiratory work of breathing (WOB_{add}) caused by endotracheal tubes and non-ideal demand-flow characteristics of the ventilator should be compensated for by using appropriate pressure support [1]. This should also be the case for tracheostomized patients if the resistance of tracheostomy tubes, and thus WOB_{add}, for tracheostomized patients is clinically relevant. Conventional patient-triggered inspiratory pressure support (IPS) does not adequately compensate for WOB_{add} caused by the resistance of the endotracheal tube, as the pressure drop across the tube is non-linear (i.e., flow-dependent) whereas pressure support is constant during IPS [2]. In contrast, the new automatic tube compensation (ATC) mode, which con-

Table 1 Patient characteristics (*COPD* chronic obstructive pulmonary disease, *CAD* coronary artery disease)

Patient [no]	Age [years]	Sex	Reason for intubation	Comorbid conditions	Tube		Duration of ventilation[a] [days]	PaO_2/FIO_2[a] [kPa/frac]	Minute ventilation[b] [l/min]
					i. d. [mm]	length [cm]			
Low ventilation group (n = 5)									
3	68	f	Coma	Intracerebral bleeding	8.0	13	16	42.0	9.4
4	53	m	Resuscitation	Cardiogenic shock	8.0	13	7	39.8	8.4
5	64	m	Resuscitation	Cardiogenic shock	9.0	13	9	32.7	9.8
7	65	f	Coma	Intracerebral bleeding	8.0	13	6	46.0	9.5
8	53	f	Pneumonia, Sepsis	–	8.0	13	14	47.0	10.0
mean ± SD	61 ± 7				8.2 ± .4	13 ± 0	10 ± 4	41.5 ± 5.7	9.4 ± 0.6
High ventilation group (n = 5)									
1	54	m	Surgery	Locked-in syndrome	8.0	13	12	20.0	13.2
2	70	m	Pneumonia	COPD; CAD	9.0	13	21	25.5	16.4
6	62	m	Pneumonia	Cerebral infarction	9.0	13	26	28.7	14.5
9	63	f	Pneumonia	Immunosuppression	8.0	13	19	22.7	12.7
10	58	f	Pneumonia, ARDS	Diabetes mellitus	8.0	13	28	25.0	15.5
mean ± SD	61 ± 6				8.4 ± .6	13 ± 0	21 ± 6	24.4 ± 3.3	14.5 ± 1.6

[a] prior to investigation
[b] in the ATC mode

Table 2 Results (mean ± SD)

		CPAP	IPS 5	IPS 10	IPS 15	ATC	*p* values[a]		
							between groups	within groups	inter-action
Low ventilation group (n = 5)									
WOB_{add}	[J/l]	0.382 ± 0.106	0.163 ± 0.126	0.027 ± 0.022	0.009 ± 0.006	0.048 ± 0.027	< 0.001	< 0.001	0.001
Peak/Flow	[l/s]	0.71 ± 0.14	0.87 ± 0.14	1.02 ± 0.11	1.17 ± 0.17	0.75 ± 0.34	< 0.001	0.011	0.004
f	[l/min]	28.1 ± 6.5	26.8 ± 5.0	26.5 ± 5.9	24.0 ± 8.7	27.0 ± 5.7	0.922	0.149	0.303
T_i/T_{tot}		0.38 ± 0.05	0.36 ± 0.04	0.34 ± 0.03	0.32 ± 0.03	0.37 ± 0.06	0.009	0.059	0.106
V_T	[ml]	384 ± 80	387 ± 69	407 ± 84	492 ± 131	388 ± 101	0.043	< 0.001	0.283
V_E	[l/min]	9.7 ± 0.9	10.0 ± 0.8	10.0 ± 0.8	10.2 ± 1.1	9.4 ± 0.6	0.006	0.005	0.011
$eE\text{-}CO_2$	[%]	4.6 ± 0.9	4.5 ± 0.8	4.4 ± 0.7	4.4 ± 0.8	4.6 ± 0.8	0.988	0.092	0.241
High ventilation group (n = 5)									
WOB_{add}	[J/l]	0.908 ± 0.142	0.680 ± 0.160	0.411 ± 0.246	0.286 ± 0.204	0.111 ± 0.058	< 0.001	< 0.001	0.001
Peak/Flow	[l/s]	1.34 ± 0.17	1.39 ± 0.23	1.47 ± 0.33	1.57 ± 0.37	2.12 ± 0.25	< 0.001	0.011	0.004
f	[l/min]	26.8 ± 6.6	26.9 ± 7.2	25.6 ± 6.2	25.5 ± 5.6	25.5 ± 6.6	0.922	0.149	0.303
T_i/T_{tot}		0.28 ± 0.06	0.27 ± 0.05	0.27 ± 0.04	0.27 ± 0.04	0.24 ± 0.07	0.009	0.059	0.106
V_T	[ml]	475 ± 70	503 ± 85	555 ± 97	614 ± 55	551 ± 59	0.043	< 0.001	0.283
V_E	[l/min]	11.9 ± 2.0	12.9 ± 3.0	13.6 ± 2.7	15.3 ± 2.1	14.5 ± 1.6	0.006	0.005	0.011
$eE\text{-}CO_2$	[%]	4.7 ± 1.7	4.6 ± 1.6	4.4 ± 1.4	4.3 ± 1.2	4.3 ± 1.3	0.988	0.092	0.241

[a] Significant contrasts between the ventilatory modes are indicated in Figs. 1 and 2

tinuously compensates for the pressure drop across the tube has been shown to compensate for WOB_{add} in such patients [2].

It was the aim of this study, (1) to measure the additional work of breathing caused by tracheostomy tubes and by the non-ideal demand-flow characteristics of the ventilator during inspiration in tracheostomized critically ill patients, and (2) to compare the effect of different levels of conventional IPS with that of the new ATC mode on the reduction of WOB_{add} and the corresponding changes in the breathing pattern.

Materials and methods

Ten consecutive, critically ill patients receiving ventilatory support through tracheostomy tubes were studied during weaning from mechanical ventilation. Patients were intubated with tracheostomy tubes of 13 cm length and of inner diameters between 8 and 10 mm (TracheoSoft, Mallinckrodt Laboratories, Athlone, Ireland). A standard 15 mm bent swivel connector (Portex No. 100/250/001, Portex, Hythe, Kent, UK) was mounted on the proximal end of the tracheostomy tube. Since the resistance of such a device is flow-dependent [3, 4], patients were assigned either to a group with normal or slightly increased minute ventilation (V_E = 10 l/min; low ventilation group) or to a group with markedly increased minute ventilation (V_E > 10 l/min; high ventilation group). Five of the ten patients enrolled had a V_E greater than 10 l/min in the

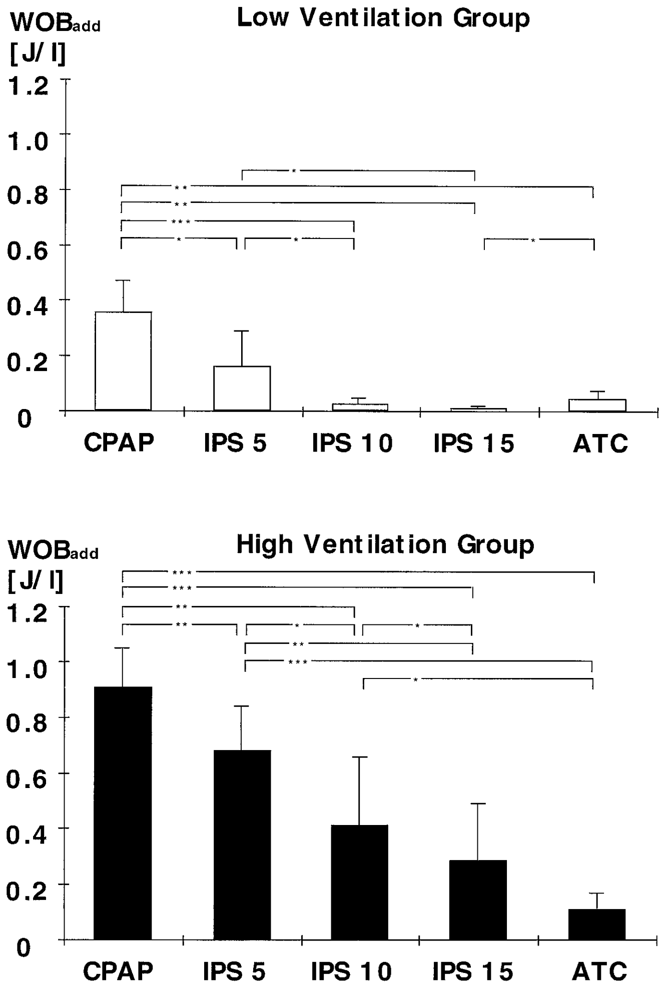

Fig. 1 Additional work of breathing WOB_{add} during CPAP, IPS, and ATC in tracheostomized patients with normal or slightly increased minute ventilation (*top*) and with markedly increased minute ventilation (*bottom*). Mean values ± SD; significant differences between the ventilatory modes within each group are given by * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

ATC mode and were allocated to the high ventilation group. The characteristics of all patients are listed in Table 1. The study protocol was approved by the Ethical Committee of the University Hospital of Basel. Informed consent was obtained from the closest available relative. At study entrance all patients were breathing spontaneously in the IPS mode, and they received an inspiratory pressure support of 10–15 cm H_2O above positive end-expiratory pressure (PEEP), a PEEP of 5–8 cm H_2O and an inspiratory oxygen concentration (FIO_2) sufficient to maintain arterial oxygen tension above 10 kPa (75 mm Hg). At the time of the investigation all patients were in stable clinical condition and slightly sedated (midazolam) but were judged not to be ready for extubation.

For the purpose of the study, patients were ventilated with five different ventilatory modes: with patient-triggered IPS of 5 cm H_2O, 10 cm H_2O, and 15 cm H_2O; with ATC; and without any pressure support in the continuous positive airway pressure (CPAP) mode. In the IPS modes, the pressure rise time was set at 0.2 s. Other parameters, such as PEEP and FIO_2, were not changed during the time of investigation. The five ventilatory modes were chosen in random order to avoid time-dependent bias. To allow the patients to become accustomed to the ventilatory modes, they were breathing in each mode for at least 10 min. Only the last 5 min were used for data analysis.

In all ventilatory modes, we used an EVITA-1 ventilator (Drägerwerk, Lübeck, Germany). For the ATC mode, the EVITA-1 ventilator was modified as described elsewhere [2, 5]. The additional inspiratory work of breathing was calculated according to a method developed in our laboratory [2]. Flow ($\dot{V}$) was measured using a Fleisch No. 2 pneumotachograph (Metabo, Epalinges, Switzerland), which was placed at the proximal end of the bent swivel connector mounted on the proximal end of the tracheostomy tube. Airway pressure (P_{aw}) was measured between the pneumotachograph and the proximal end of the bent swivel connector. Tracheal pressure (P_{trach}) was measured by introducing a 1.6 mm o.d. catheter with two side holes and no end hole (K-33, Baxter, Trieste, Italy) into the tracheostomy tube with its tip protruding 3 cm beyond the tip of the tracheostomy tube [3, 6]. To eliminate the influence of this measuring catheter on the pressure-drop relationship of tracheostomy tubes, the measurement of P_{trach} was corrected for by a linear interpolation algorithm [7]. Pressure transducers for measuring P_{aw} and P_{trach} (32NA-005D: IC senor, Milpitas, (A, USA) and differential pressure transducers for measuring $\dot{V}$ (CPS 10: Hoffrichter, Schwerin, Germany) were placed only 20 cm away from the tube in order to achieve good signal quality and short response time [5]. The signals measured were digitized with 12-bit resolution and stored at a rate of 100 Hz in a personal computer for further analyses. Respiratory rate (f), inspiratory to duty cycle time (T_i/T_{tot}), minute ventilation (V_E), tidal volume (V_T) and WOB_{add} were calculated on a breath-by-breath basis. V_T was calculated by numerical integration of $\dot{V}$. Values of WOB_{add} were normalized to 1 l of the inspired volume. All breath-by-breath values were averaged over 5 min of undisturbed breathing (no coughing).

Statistical analyses were performed using SYSTAT, Version 5.2 [8]. Differences of WOB_{add} and the parameters of the breathing pattern between the five ventilatory modes were assessed by an analysis of variance for repeated measures with 1 between factor (group) and 5 repeated within factors (ventilatory modes). For within factor comparison the overall significance was expressed as the arithmetic mean of Greenhouse-Geisser's and Huynh-Feldt's adjusted p values. If the overall model was significant, contrasts between the ventilatory modes were calculated. Significant interactions denote that the groups differed in their response to the ventilatory modes. A value of p less than 0.05 was considered significant. All data presented are mean values ± SD.

Results

Maximal WOB_{add} caused by tracheostomy tubes and the demand-flow characteristics of the ventilator becomes visible when patients are forced to breathe through tracheostomy tubes without any pressure support in the CPAP mode. In patients with normal or slightly increased ventilatory demand (low ventilation group) WOB_{add} was 0.382 ± 0.106 J/l. In patients with markedly increased ventilatory demand (high ventilation group) WOB_{add} in the CPAP mode was 0.908 ± 0.142 J/l. With increasing levels of pressure support in the IPS mode, WOB_{add} gradually decreased in both patient groups (Table 2 and Fig. 1). Whereas a pressure support of more than 5 cm H_2O in the IPS mode made

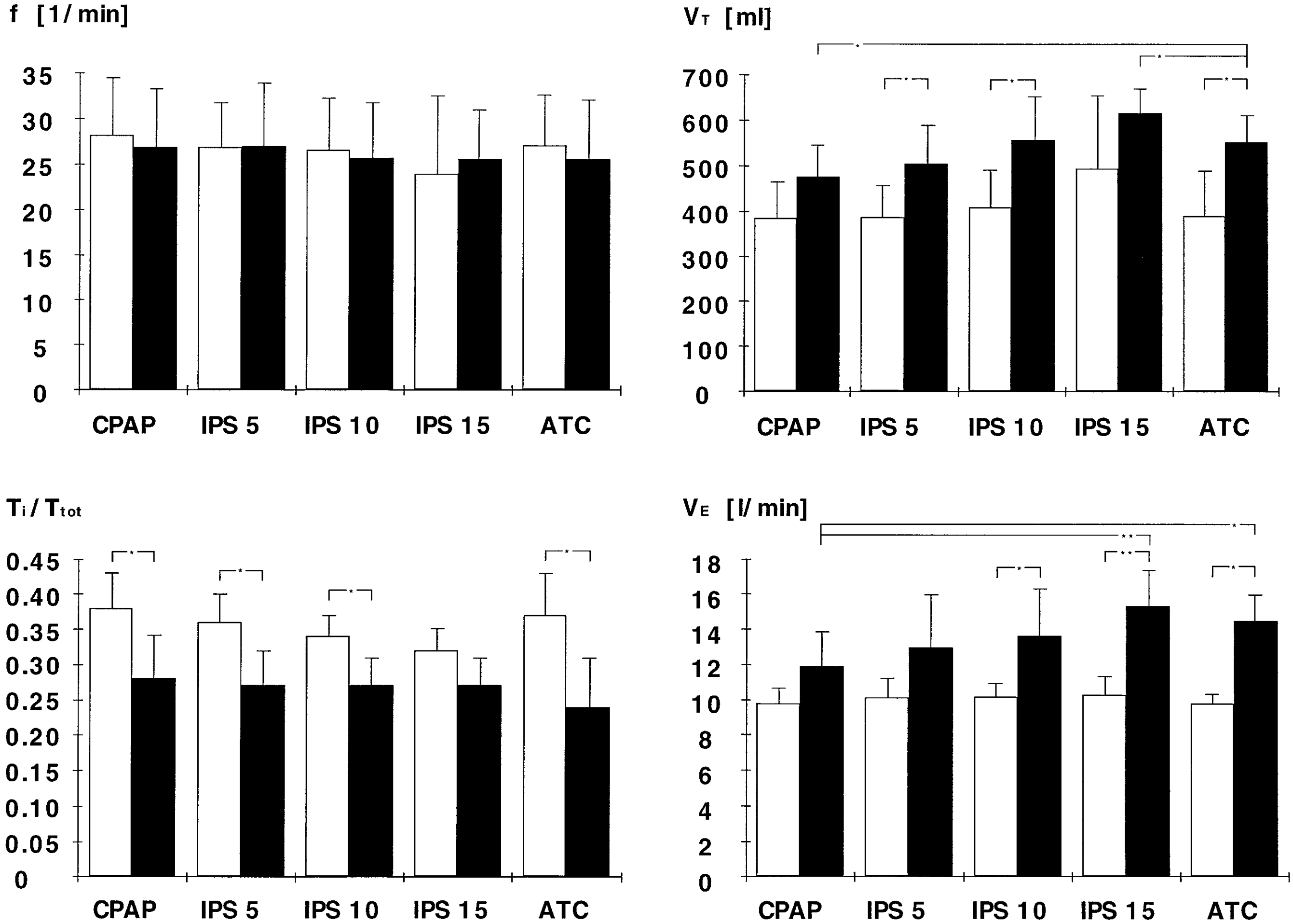

Fig. 2 Breathing pattern (respiratory rate f, tidal volume V_T, inspiratory to duty cycle time T_i/T_{tot}, and minute ventilation V_E) during CPAP, IPS, and ATC in tracheostomized patients with normal or slightly increased minute ventilation (*white bars*) and with markedly increased minute ventilation (*black bars*). Mean values ± SD; significant differences between the groups and between the ventilatory modes, respectively, are given by * $p < 0.05$, ** $p < 0.01$

up for nearly the entire WOB_{add} in patients of the low ventilation group, WOB_{add} remained above 0.25 J/l even with a pressure support of 15 cm H_2O in patients of the high ventilation group. In contrast, ATC was able to reduce WOB_{add} effectively in both groups, i.e. independently of the patient's ventilatory demand.

According to the protocol chosen, V_E was significantly higher in the high ventilation group than in the low ventilation group ($p < 0.01$) as shown in Table 2 and Fig. 2. High levels of V_E in patients of the high ventilation group were the result of significantly higher V_T compared to patients of the low ventilation group ($p < 0.05$). Respiratory rate (f) did not significantly differ between the two groups but T_i/T_{tot} was significantly lower in patients of the high ventilation group compared with those in the low ventilation group ($p < 0.01$). With increasing levels of pressure support in the IPS mode, V_E increased in patients of the high ventilation group ($p < 0.05$) due to an increase in V_T ($p < 0.01$) with no significant change in f. By contrast, patients of the low ventilation group were able to keep V_E constant under increased levels of pressure support by counterbalancing the increase in V_T ($p < 0.05$) by a gradual (not significant) decrease in f. With the exception of V_T in the high ventilation group, the breathing pattern did not significantly differ between ATC and IPS of 5, 10, and 15 cm H_2O.

It has to be noted that desynchronisation between the patient and the ventilator did not occur during any mode investigated, although desynchronisation had to be expected especially under higher levels of conventional pressure support in the high ventilation group [9].

Discussion

The main finding of this study is that the resistance of tracheostomy tubes and ventilator properties can markedly increase the inspiratory work of breathing: in the CPAP mode, the mean WOB_{add} was 0.381 J/l and 0.908 J/l for patients of the low and the high ventilation groups, respectively. WOB_{add} is added to the patient's preexisting ventilatory work necessary to overcome the (possibly impaired) mechanical properties of his/her respiratory system.

During ATC or IPS of more than 5 cm H_2O, tracheostomized, critically ill patients with normal or slightly increased minute ventilation do not have to perform major WOB_{add}. WOB_{add} under ATC arises mainly from the non-ideal demand-flow characteristics of the ventilator. However, if pressure support in the IPS mode is reduced or withheld during the course of weaning, tracheostomized patients with normal or slightly increased minute ventilation can also have major WOB_{add}. This can increase even further if these patients are forced to breathe through a heat and moisture exchanger connected to the tracheostomy tube.

In tracheostomized patients with increased minute ventilation, a pressure support of even 15 cm H_2O in the IPS mode cannot completely compensate for the inspiratory resistance of the tracheostomy tube. Theoretically, WOB_{add} can be reduced with higher levels of pressure support. However, this is not always a practical solution, as it also leads to an end-inspiratory positive pressure excess which might be associated with discomfort for the patient [10] and might promote patient-ventilator desynchronisation [9]. Additionally, it becomes more difficult at higher levels of pressure support to determine whether the ventilator only compensates for the resistance of the tracheostomy tube or whether the ventilator effectively augments the patient's ventilation. In contrast to CPAP and IPS of 10 cm H_2O or less, WOB_{add} during ATC is only slightly increased, i.e. to only 12%, 16%, and 27% of the corresponding values in the CPAP, IPS 5, and IPS 10 mode, respectively.

It may be argued that compensation of the pressure drop from the ventilator to the carina is far from being a physiological situation, since the physiologic resistance of the upper airways (i.e., pharyngeal and laryngeal resistance) is also compensated for by the same means. On the one hand, however, the pressure drop across the laryngeal airways from the supraglottic region down to the trachea has been found to be of 0.2 cm H_2O at a flow of 0.3 l/s and to increase to 3.9 cm H_2O at a flow of 2 l/s [11]. The pressure drop across the pharyngeal airways from the mouth to the supraglottic region has been shown to be about 1.0 cm H_2O at a flow rate of 1 l/s [12, 13]. Therefore, the pressure drop across the entire upper airways should lie in the range of 1.2 cm H_2O at a flow rate of 0.3 l/s and rise to 5.2 cm H_2O when the flow rate is increased to 2.0 l/s. Upper airway resistance might be higher in patients who have been mechanically ventilated through an endotracheal tube for days or even weeks. However, Straus and co-workers [14] found a similar level of pharyngeal resistance in 14 extubated patients after they had been orotracheally intubated for 7.6 days (range: 2–23 days). Thus, in the absence of laryngeal edema (which has been shown to occur in 4% of extubated patients [15]), the pressure drop across the upper airways is far below what we have seen in our tracheostomized patients with increased ventilatory demand, where there was a drop of tracheal pressure up to 20 cm H_2O below the target PEEP level. On the other hand, due to non-ideal ATC (i.e., due to the finite response time of the ventilatory system used in this study) there remains a non-compensated pressure drop from 2 to 5 cm H_2O at corresponding flow rates between 0.75 and 2.12 l/s. This pressure drop during non-ideal ATC is similar to the pressure drop across the upper airways in non-intubated conditions. It is thus likely that the work of breathing dissipated in the upper airways does not substantially differ from that dissipated in the tube due to non-ideal ATC.

Increasing the level of pressure support in the IPS mode has different effects on the breathing pattern of critically ill patients, depending on their ventilatory demand. Assuming that a patient's control of breathing is adequate and that V_E represents his/her true ventilatory demand, the increase in V_T resulting from increases in pressure support should be counterbalanced by a decrease in f. This was, in fact, the case in our patients with normal or slightly increased mean ventilatory demand (low ventilation group). By contrast, patients of the high ventilation group did not counterbalance the increase in V_T (resulting from additional pressure support) by a decrease in f, but rather used additional pressure support to further augment V_E. A possible explanation for that behavior is that only V_E at IPS levels of 10 cm H_2O or more (and during ATC) might delineate the true ventilatory demand of patients with increased mean inspiratory flow rate. At lower levels of IPS and during CPAP, these patients are possibly prevented from attaining their required levels of V_E due to the resistance of the tracheostomy tube. At high flow rates this resistance may well become the major determinant of the overall mechanical properties of the respiratory system. With the exception of V_T in the high ventilation group, the breathing pattern did not significantly differ between ATC and IPS of 5, 10, and 15 cm H_2O. This might be related to the small number of patients investigated in each group. However, when focusing on mean values it seems that V_T and V_E under ATC and IPS of 10 cm H_2O are quite similar, whereby T_i/T_{tot} was smaller under ATC than under any other mode investigated.

In summary, the breathing pattern response on pressure support differs between critically ill patients with different ventilatory demand. Depending on respiratory flow rates, tracheostomy tubes can cause a considerable amount of WOB_{add} for the patient. ATC, in contrast to IPS, is a suitable mode to reduce WOB_{add} in tracheostomized patients adequately at any ventilatory effort.

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