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J. Guttmann
H. Bernhard
G. Mols
A. Benzing
P. Hofmann
C. Haberthür
D. Zappe
B. Fabry
K. Geiger

# Respiratory comfort of automatic tube compensation and inspiratory pressure support in conscious humans

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J. Guttmann (✉) · H. Bernhard · G. Mols · A. Benzing · P. Hofmann · K. Geiger
Section of Experimental Anaesthesiology, Clinic of Anaesthesiology (University of Freiburg), Hugstetterstrasse 55, D-79106 Freiburg, Germany
FAX: +49 (761) 2702396

C. Haberthür · D. Zappe · B. Fabry
Division of Clinical Physiology, Clinic of Cardiac and Thoracic Surgery, University Hospital, Basel, Switzerland

**Abstract** *Objective:* To compare the new mode of ventilatory support, which we call automatic tube compensation (ATC), with inspiratory pressure support (IPS) with respect to perception of respiratory comfort. ATC unloads the resistance of the endotracheal tube (ETT) in inspiration by increasing the airway pressure, and in expiration by decreasing the airway pressure according to the non-linear pressure-flow relationship of the ETT.
*Design:* Prospective randomized single blind cross-over study.
*Setting:* Laboratory of the Section of Experimental Anaesthesiology (Clinic of Anaesthesiology; University of Freiburg).
*Subjects:* Ten healthy volunteers.
*Interventions:* The subjects breathed spontaneously through an ETT of 7.5 mm i. d. Three different ventilatory modes, each with a PEEP of 5 $cmH_2O$, were presented in random order using the Dräger Evita 2 ventilator with prototype software: (1) IPS (10 $cmH_2O$, 1 s ramp), (2) inspiratory ATC (ATC-in), (3) inspiratory and expiratory ATC (ATC-in-ex).
*Measurements and main results:* Immediately following a mode transition, the volunteers answered with a hand sign to show how they perceived the new mode compared with the preceding mode in terms of gain or loss in subjective respiratory comfort: "better", "unchanged" or "worse". Inspiration and expiration were investigated separately analyzing 60 mode transitions each. Flow rates were continuously measured. The transition from IPS to either type of ATC was perceived positively, i. e. as increased comfort, whereas the opposite transition from ATC to IPS was perceived negatively, i. e. as decreased comfort. The transition from ATC-in to ATC-in-ex was perceived positively whereas the opposite mode transition was perceived negatively in expiration only. Tidal volume was 1220 ± 404 ml during IPS and 1017 ± 362 ml during ATC. The inspiratory peak flow rate was 959 ± 78 ml/s during IPS and 1048 ± 197 ml/s during ATC.
*Conclusions:* ATC provides an increase in respiratory comfort compared with IPS. The predominant cause for respiratory discomfort in the IPS mode seems to be lung overinflation.

**Key words** Automatic tube compensation (ATC) · Inspiratory pressure support (IPS) · Respiratory comfort

## Introduction

The endotracheal tube (ETT) poses an additional, predominantly resistive, load for the tracheally intubated spontaneously breathing patient [1–3]. The ETT is not a constant but a non-linear, flow-dependent resistive load [4]. To overcome this resistance the patient has to perform a considerable amount of additional work of breathing during both inspiration and expiration [5]. New modes of ventilatory support such as inspiratory pressure support (IPS) have been introduced to support the spontaneously breathing patient and to reduce such additional work of breathing.

It has been argued that IPS fully compensates for the ETT resistance in spontaneously breathing patients [2, 6, 7]. From a theoretical point of view this is correct only for a constant flow rate [4]. Since the pressure drop across the ETT is flow-dependent, it is obviously not possible to compensate adequately for the endotracheal tube resistance with one constant positive pressure during inspiration, as applied in IPS. Consequently, patients most often receive too much or too little pressure support with respect to their actual flow rate, which may be an important source for respiratory discomfort.

During expiration, the ETT also limits flow, thereby considerably increasing the time-constant of passive expiration [8], which can be prevented by adequately supporting expiration. Our newly developed ATC (automatic tube compensation) mode fully compensates for flow-dependent tube resistance during both inspiration and expiration [9]. The ventilator measures flow and airway pressure and continuously calculates the pressure drop across the ETT ($\Delta P_{ETT}$). The ventilator raises airway pressure during inspiration and lowers it during expiration according to $\Delta P_{ETT}$. Consequently, the pressure support closely follows the pressure/flow curve of the ETT.

We assume that the better the tube resistance is compensated for, the better will the natural breathing pattern be preserved. Or, expressed differently, the worse the tube resistance is compensated for, the more will the natural breathing pattern be impaired. We hypothesized that an inadequate compensation of tube resistance will be perceived subjectively as a decrease in comfort. Accordingly, the aim of this study was to investigate whether resistive unloading by either ATC or IPS has different effects on the subjective comfort of healthy volunteers breathing spontaneously through an ETT.

## Methods

Ten healthy volunteers (nine males, one female, aged 22–46 years) were studied. None was aware of the specific purpose and protocol of the study. The protocol was approved by the Ethics Committee of our institution. The volunteers wore noseclips, and breathed spontaneously through a 7.5 mm i.d. ETT (Mallinckrodt Laboratories, Athlone, Ireland). The tip of the ETT was fixed in a transparent tube of 21 mm i.d. by inflating the cuff. The tube was connected to the volunteer via a mouthpiece (SM25, Jaeger, Würzburg, Germany) with a cross-sectional area of 4.3 $cm^2$ resulting in a negligible airflow resistance of 0.003 $cmH_2O \cdot l^{-1} \cdot s$ at a flow rate of 1 l/s. This set-up was chosen to simulate the inspiratory/expiratory asymmetry in pressure drop between the tip of the ETT and the trachea due to the abrupt change in cross-sectional area [4]. The total dead-space including ETT, tube and mouth piece was 76 ml. The ETT was connected to a ventilator (Evita 2, Dräger, Lübeck, Germany) via a heated pneumotachograph (Fleisch No. 2, Metabo, Epalinges, Switzerland), conventional tubing and a humidifier. A differential pressure transducer (CPS1, Hoffrichter, Schwerin, Germany) for measuring the flow proportional pressure difference was close to the pneumotachograph (20 cm) in order to achieve good signal quality and low response time. The signals were digitized with 12-bit resolution and stored at a rate of 100 Hz in a computer for further analysis of breathing pattern. Maximal inspiratory and expiratory flow rates ($V'_{Imax}$, $V'_{Emax}$), tidal volume ($V_T$), inspiratory and expiratory time ($T_I$, $T_E$), and respiratory rate (RR) were calculated on a breath-by-breath basis. $V_T$ was calculated by numerical integration of V'. The ventilator was modified by the manufacturer for ATC (prototype software).

In the original ATC mode [9] the ventilator controls tracheal pressure ($P_{trach}$). $P_{trach}$ is calculated from measurements of flow and pressure at the proximal end of the ETT, and from coefficients describing the flow-dependent ETT resistance. The calculated $P_{trach}$ is fed into the ventilator, which then maintains $P_{trach}$ at a preset value [9]. In contrast to the original ATC system, the modified Evita 2 measures flow and pressure inside the ventilator and a simplified formula is used to calculate tracheal pressure ($P_{trach} = P_{aw} - (K \cdot V'^2)$, where $P_{aw}$ is airway pressure, V' is flow, and K is the tube coefficient describing the non-linear pressure/flow curve of the ETT). $\Delta P_{ETT}$ was assumed to be identical during inspiration and expiration. In contrast to the original ATC system, the Evita 2 ventilator did not produce subatmospheric pressure. During expiration, airway pressure can only be lowered to atmospheric pressure. Consequently, the maximum pressure difference which can be used for expiratory tube compensation equals the difference between PEEP and atmospheric pressure. Thus, full expiratory tube compensation is only possible at high PEEP levels or low expiratory flow rates.

### Study protocol

Three different ventilatory modes with 5 $cmH_2O$ PEEP were selected in random order, (1) IPS (10 $cmH_2O$ above PEEP, 1 s ramp), (2) inspiratory ATC (ATC-in, tube-coefficient $K = 9.5\ cmH_2O \cdot s^2/l^2$), and (3) inspiratory and expiratory ATC (ATC-in-ex, tube coefficient $K = 9.5\ cmH_2O \cdot s^2/l^2$). Each ventilatory mode was kept unchanged for at least five consecutive breaths. Subsequently, the ventilatory mode was changed and the volunteer was notified of this change. However, the volunteer was unaware of the mode chosen. A total of nine transitions was evaluated: six "real" transitions between the three different ventilatory modes (i.e., IPS ↔ ATC-in, IPS ↔ ATC-in-ex, ATC-in ↔ ATC-in-ex) and three "placebo" transitions (i.e., IPS → IPS, ATC-in → ATC-in, ATC-in-ex → ATC-in-ex). The placebo transitions were announced to the volunteers the same way the real transitions were. Immediately following the transition from one mode to another the volunteers indicated with a hand sign how they perceived the new mode compared to the preceding mode in terms of gain or loss in subjective comfort: "better", "unchanged" or "worse". The corresponding grading numbers are: +1 = better, 0 = unchanged, –1 = worse. Inspiratory and expiratory comfort were evaluated separately by means of two consecutive investigations: 60 mode transitions were presented in random order and the volunteers estimated the change in inspiratory comfort; subsequently the 60 identical mode transitions were presented again and the volunteers estimated the change in expiratory comfort.

### Statistical analysis

In the investigation of inspiratory and expiratory comfort each of the nine possible mode transitions was performed seven times on average (7 ± 2; mean ± SD) in random order. A mean value of perception (a number between +1 and –1) was calculated in each volunteer for each mode transition as derived from the individual grading numbers. The mean values of perception were compared with zero, which is the grading number of unchanged perception. For statistical analysis the Wilcoxon matched pairs signed rank test was used. A probability value of less than 0.05 was accepted as statistically significant. The same statistical test was used to compare the parameters of breathing pattern obtained during IPS with those obtained during ATC.

## Results

In inspiration (Fig. 1) the majority of volunteers perceived the transition from IPS to either type of ATC positively, i.e. as increased comfort, whereas the opposite transition from ATC to IPS was perceived negatively, i.e. as decreased comfort ($p < 0.01$). The transition from ATC-in to ATC-in-ex was positively perceived ($p < 0.01$) whereas the opposite mode transition was not perceived as a change in comfort.

Figure 2 summarizes the results for expiration. As in inspiration, the transitions from ATC to IPS and vice versa were perceived as increases and decreases in subjective comfort, respectively. The transitions from ATC to IPS were negatively perceived, whereas the opposite transition from IPS to ATC was positively perceived in the case of ATC-in-ex ($p < 0.01$), and not clearly perceived as a change in comfort in the case of ATC-in (n. s.). The transition from ATC-in to ATC-in-ex tended to be perceived positively (n. s.) whereas the opposite mode transition was perceived negatively ($p < 0.05$).

Figure 3 summarizes the results for all placebo transitions investigated during both inspiration and expiration. The results show that the volunteers did not perceive the three placebo transitions as a change in subjective comfort.

Table 1 shows the parameters of breathing pattern measured in nine subjects (in one subject the flow data were invalid due to technical problems during data acquisition). Maximal expiratory flow rate, tidal volume and inspiratory time are significantly larger in the selected IPS mode than in the ATC mode. Maximal inspiratory flow rate and respiratory rate tend to be higher in the ATC mode (n. s.). Furthermore, the scatter of the

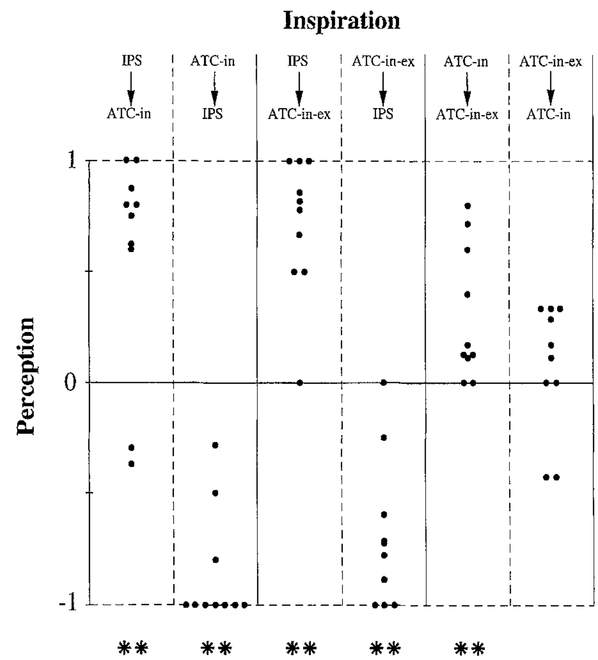


**Fig. 1** Perception of inspiratory comfort during six respiratory mode transitions: 1 = increase, 0 = no change, –1 = decrease in comfort. The kind of mode transition is indicated on top. Each dot represents the mean value of several perceptions obtained in one volunteer. For reasons of clarity, the respective transitions in opposite directions are listed next to each other (* $p < 0.05$; ** $p < 0.01$)

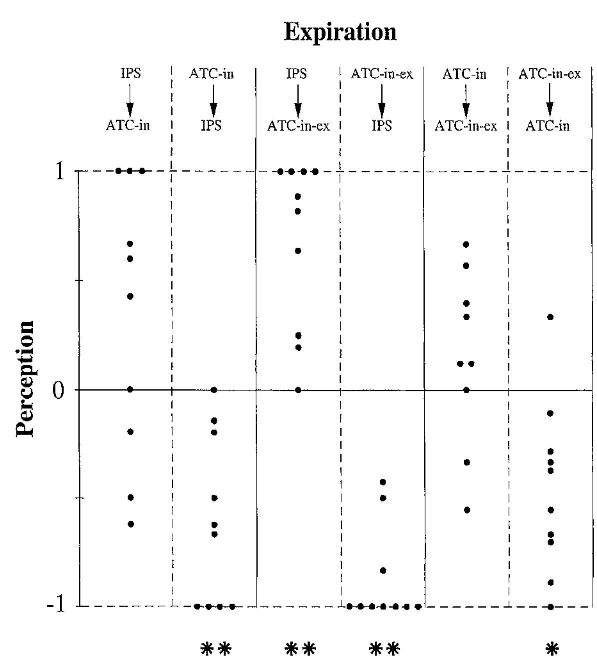


**Fig. 2** Perception of expiratory comfort during six respiratory mode transitions. See Fig. 1 for further details (* $p < 0.05$; ** $p < 0.01$)

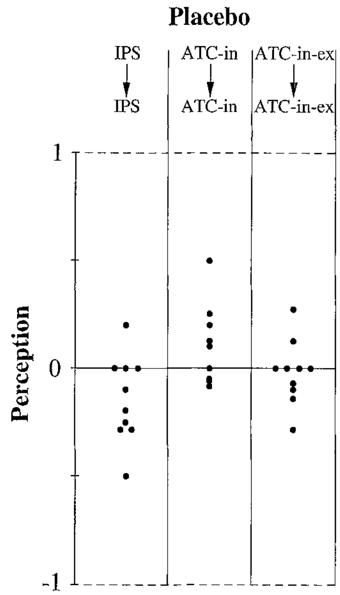


**Fig. 3** Perception of inspiratory and expiratory comfort during three placebo respiratory mode transitions

peak flow rates is considerably larger in the ATC mode than in the IPS mode, which is an indirect indicator that the breathing pattern shows a greater variability during ATC compared with IPS.

## Discussion

In the present study we posed a non-linear resistive ventilatory load by means of a 7.5 mm i. d. ETT to conscious humans and investigated their perception of resistive unloading using either inspiratory pressure support (IPS) or automatic tube compensation (ATC). We found that the volunteers could clearly differentiate between real and placebo mode transitions. The main result of our study is that changes in ventilatory mode between IPS and either type of ATC are accompanied by a change in subjective breathing comfort. Except for the transition from IPS to inspiratory ATC during the expiration study, the transition from IPS to either type of ATC was always perceived as an increase in subjective comfort during both inspiration and expiration, whereas the opposite transition from ATC to IPS was perceived as a decrease in subjective breathing comfort. Thus, our findings confirm that the transitions between IPS and ATC in both directions are well above the threshold for conscious perception, i.e. above the threshold levels for both detection and discrimination [10, 11].

Conscious humans can detect resistive loads greater than 1.17 $cmH_2O \cdot l^{-1} \cdot s$ applied to the respiratory system [12]. A 7.5 mm i. d. ETT of original length, as used in our study, creates an inspiratory resistance of 8.41 $cmH_2O \cdot l^{-1} \cdot s$ at 1 l/s and an expiratory resistance of 9.28 $cmH_2O \cdot l^{-1} \cdot s$ at 1 l/s [4]. This resistive load is seven times greater than the detection threshold and was, therefore, easily perceived by our volunteers.

To compensate for the resistive load of an ETT, an adequate pressure support is required. As each spontaneous breath is supported by a constant positive pressure during IPS, several authors have argued that IPS totally compensates for the tube resistance [2, 6, 7]. The authors derived their conclusions from determining the work of breathing. However, our volunteers clearly preferred ATC. Obviously, breathing comfort is not primarily a question of eliminating the work of breathing but rather of correct resistive unloading, i.e. unloading in proportion to the resistive load, which is considerably non-linear in the case of the ETT [4]. By providing a non-linear flow-dependent pressure support, the new ATC mode will automatically adjust the pressure support to the momentary pressure drop across the ETT. Thus, from a systematic point of view ATC is a non-linear flow-proportional pressure assist [13].

Figure 4 illustrates this point by analyzing the non-linear pressure/flow curve of an ETT of 7.5 mm i. d. of original length as determined in a laboratory investigation [4]. The horizontal line indicates an IPS of 10 $cmH_2O$. Since the pressure drop across the ETT is flow-dependent, it is obviously not possible to compensate correctly for the ETT resistance with a constant positive pressure as applied in IPS. Depending on the patient's actual ventilatory demand, one can distinguish between three conditions:

(1) at low flows, IPS over-compensates for tube resistance;

**Table 1** Mean (SD) values of breathing pattern in volunteers ($n = 9$) under inspiratory pressure support (IPS) and automatic tube compensation (ATC) ($V'_{Imax}$, $V'_{Emax}$ maximal inspiratory and expiratory flow rate, $V_T$ tidal volume, $T_I$ inspiratory time, $T_E$ expiratory time, *RR* respiratory rate)

| Ventilatory support mode | $V'_{Imax}$ ml/s | $V'_{Emax}$ ml/s | $V_T$ ml-BTPS | $T_I$ ms | $T_E$ ms | RR 1/min |
|---|---|---|---|---|---|---|
| IPS | 959 ± 78 | 848 ± 76** | 1220 ± 404** | 1950 ± 632** | 2701 ± 1062 | 13.8 ± 4.6 |
| ATC[a] | 1048 ± 197 | 720 ± 117 | 1017 ± 362 | 1783 ± 629 | 2740 ± 1191 | 14.6 ± 5.5 |

** $p < 0.01$ in comparison to value obtained during ATC
[a] ATC-in and ATC-in-ex

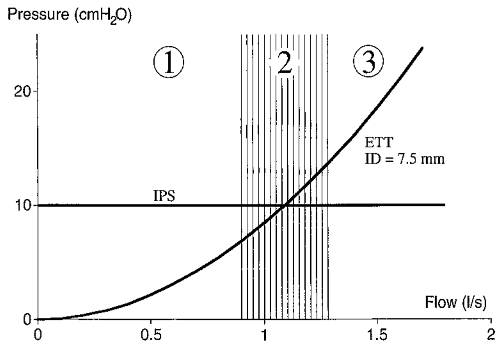


**Fig. 4** Inspiratory pressure/flow curve of an endotracheal tube (ETT) of 7.5 mm i.d. of original length (IPS inspiratory pressure support). See text for details

(2) at medium flows, IPS compensates for tube resistance;
(3) at high flows, IPS under-compensates for tube resistance.

Only at the point of intersection between the two curves (in our example at a flow rate of about 1 l/s) will IPS of 10 $cmH_2O$ correctly compensate for the pressure drop across a 7.5 mm ETT.

We selected an IPS of 10 $cmH_2O$ above PEEP in order to compensate for the tube resistance of a 7.5-ETT at flow rates of about 1 l/s. In fact, the peak inspiratory flow rate in our volunteers was about 1 l/s during IPS. However, during spontaneous respiration the ventilatory demand, and thus the flow rate generated by the respiratory muscles, changes considerably within one breath and from breath to breath [14]. Due to this variable flow, it is likely that IPS over-compensates for the tube resistance, particularly later in inspiration. We assume that discrepancies between respiratory demand and ventilatory supply are a major source of respiratory discomfort. The capability of a ventilator to provide appropriate ventilatory adjustments in response to spontaneous changes in ventilatory demand must be expected to be an important characteristic in terms of respiratory comfort. Discrepancy between demand and supply, which happens when supply is fixed (as in IPS) while ventilatory demand varies, will inevitably lead to discomfort [15].

The results of our breathing pattern analysis indicate that the predominant cause for breathing discomfort in the selected IPS mode is lung over-inflation. In the IPS mode, tidal volume was larger than in the ATC mode, by 200 ml. The larger tidal volume in the IPS mode is accompanied by a longer inspiratory time and a larger maximal expiratory flow rate compared with the breathing pattern in the ATC mode. The latter may be necessary to exhale the enlarged $V_T$.

It is well known that the expiratory tubing, the exhalation valves and the PEEP devices of the ventilator pose an additional expiratory flow resistance [16]. In addition, the ETT acts as an expiratory flow limitation, which considerably increases the time constant of passive expiration [8]. Consequently, a support mode for expiratory resistive unloading is needed. Resistive unloading during expiration can eliminate the flow limitation, thus shortening the exhalation phase. However, one serious restriction from the standpoint of technical safety may be the need for a negative (subatmospheric) pressure source incorporated into the ventilator. In contrast to the original ATC system [9], the ventilator used in our study was not equipped with a negative pressure source, i.e. the lowest airway pressure which could be generated by the ventilator was atmospheric. Thus, the pressure reserve to compensate for the tube resistance equalled the PEEP value. If the pressure drop across the ETT exceeds the preset PEEP value, the expiratory tube compensation will be incomplete. In our study the volunteers breathed at a PEEP of 5 $cmH_2O$. A pressure drop of 5 $cmH_2O$ across a 7.5 mm-ETT, the ventilatory tubing and the expiratory valve of the ventilator is reached at an expiratory flow rate of about 590 ml/s [4], i.e. the expiratory ATC works up to this expiratory flow. Above this flow rate the expiratory unloading will be incomplete. With 720 ml/s the expiratory peak flow rate measured in our volunteers during ATC clearly exceeded the limit of expiratory tube compensation. We hypothesize that this incomplete expiratory unloading was the reason for the lack of perception of a clear difference in subjective comfort between inspiratory and expiratory ATC. Nevertheless, we used the ventilator without negative pressure source since this ventilator type, being equipped with industrially manufactured ATC software, can be expected to be available for clinical routine in the near future.

Furthermore, our results clearly show that the difference in subjective comfort between IPS on the one hand, and ATC-in and ATC-in-ex on the other was perceived even during expiration. This could have two possible explanations, (1) IPS changes the inspiratory breathing pattern in such a way that expiration is impeded and, thus, negatively perceived, (2) the ETT itself poses an expiratory resistive load.

We investigated mode transitions in order to enable the subjects directly to compare the actual mode of assisted ventilation with the immediately preceding one with respect to respiratory comfort. Another reason for investigating the perception of transitions is the so-called first-breath ventilatory response, which means that the ventilatory response following a transition is nearly complete within the first breath after transition. This is in line with the findings of Puddy and Younes in normal and conscious subjects [17]. They showed that the ventilatory response (i.e., change in respiratory rate) following a transition in inspiratory flow rate was nearly complete within the first breath after transition.

The importance of the first-breath ventilatory response to added mechanical loads is further underlined by the investigation of Axen and Haas in 80 healthy men [11].

In recent studies, intensivists have focused their attention on the perception of respiratory comfort in tracheally intubated patients receiving ventilatory support [18, 19]. Clearly, the results of our study obtained in healthy volunteers without bypassed upper airways cannot be directly transferred to tracheally intubated patients: tracheally intubated patients show an additional increase in resistance due to reflex narrowing of the airways distal to the tube [20], the pattern of spontaneous breathing is considerably influenced by the ETT resistance [21], and tracheal receptors are stimulated by the ETT. We cannot exclude mouth and upper airway sensors as a source of respiratory comfort or discomfort. But, the comments of the volunteers after terminating the study indicated that the thorax is the main location for feelings of discomfort during mechanically assisted breathing. Since healthy subjects perceived the differences between different modes of ventilatory support we would expect that the intubated patient should also perceive such differences in terms of subjective breathing comfort. This, however, must be proven clinically. In this regard our study presents a pilot study for the investigation of breathing comfort in tracheally intubated patients. Further research is needed to prove respiratory comfort gain by ATC in the clinical setting as well. These investigations will be a basis for discussing the risk/benefit ratio of this new respiratory mode.

In conclusion, for conscious humans breathing spontaneously through an ETT, ATC provides an increase in respiratory comfort, compared with IPS.

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