RESPIRATORY CARE Paper in Press. Published on June 30, 2020 as DOI: 10.4187/respcare.07608

A Comprehensive Bench Assessment of Automatic Tube Compensation in ICU Ventilators for Better Clinical Management

Louis-Marie Galerneau, Nicolas Terzi, Emanuele Turbil, Zakaria Riad, Carole Schwebel, Martin Cour, Laurent Argaud, Claude Guérin, and Bruno Louis

BACKGROUND: Automatic tube compensation (ATC) unloads endotracheal tube (ETT) resistance. We conducted a bench assessment of ATC functionality in ICU ventilators to improve clinical management. METHODS: This study had 2 phases. First, we performed an international survey on the use of ATC in clinical practice, hypothesizing a rate of ATC use of 25%. Second, we tested 7 modern ICU ventilators in a lung model mimicking a normal subject (Normal), a subject with ARDS, and a subject with COPD. Inspiratory effort consisted of esophageal pressure over 30 consecutive breaths obtained in a real patient under weaning. A brand new 8-mm inner diameter ETT was attached to the lung model, and ATC was set at 100% compensation for the ETT. The 30 breaths were first run with ATC off and no ETT (ie, reference period), and then with ATC on and ETT (ie, active period). The primary end point was the difference in tidal volume (V_T) between reference and active periods. We hypothesized that the V_T difference should be equal to 0 in an ideally functioning ATC. V_T difference was compared across ventilators and respiratory mechanics conditions using a linear mixed-effects model. RESULTS: The clinical use of ATC was 64% according to 644 individuals who responded to the international survey. The V_T difference varied significantly across ventilators in all respiratory mechanics configurations. The divergence between V_T difference and 0 was small but significant: the extreme median (interquartile range) values were −0.013 L (–0.019 to −0.002) in the COPD model and 0.056 L (0.051–0.06) in the Normal model. V_T difference for all ventilators was 0.015 L (95% CI 0.013–0.018) in the ARDS model, which was significantly different from 0.021 L (95% CI 0.018–0.024) in the Normal model (*P* < .001) and 0.010 L (0.007–0.012) in the COPD model (*P* = .003). CONCLUSIONS: ATC is used more frequently in clinical practice than expected. In addition, V_T delivery by ATC differed slightly though significantly between ventilators. *Key words: automatic tube compensation; airflow resistance; weaning; endotracheal tube; mechanical ventilation.* [Respir Care 0;0(0):1–●. © 0 Daedalus Enterprises]

Introduction

The aim of automatic tube compensation (ATC) is to compensate for the pressure drop across the endotracheal tube (ETT) or tracheostomy prosthesis and is an option available in most ICU ventilators.[1] The pressure drop across an ETT essentially depends on ETT (or tracheostomy prosthesis) resistance, which in turn depends on both ETT inner diameter (ID) and length: the smaller the former or the longer the latter, the higher the resistance in the ETT

Dr Galerneau, Dr Terzi, and Dr Schwebel are affiliated with Médecine Intensive Réanimation, Université de Grenoble-Alpes, Grenoble, France. Dr Galerneau, Dr Terzi, and Dr Schwebel are affiliated with INSERM 1042, Grenoble, France. Dr Turbil is affiliated with the Anesthesiology and Critical Care Department, Università degli studi di Sassari, Italy. Dr Riad is affiliated with the Anesthesiology Department, Groupement Hospitalier Est, Lyon, France. Dr Cour, Dr Argaud, and Dr Guérin are affiliated with Médecine Intensive Réanimation, Groupement Hospitalier Centre, Hopital Edouard Herriot, Université de Lyon, Lyon, France. Dr Guérin is affiliated with INSERM 955, Créteil, France. Dr Louis and Dr Guérin are affiliated with Institut Mondor de Recherche Biomédicale, Université Paris Est Créteil, INSERM 955, Créteil, France.

Dr Terzi prsented a version of this paper at the 32nd European Society of Intensive Care Medicine (ESICM) Annual Congress, held September 28 to October 1, 2019, in Berlin, Germany.

Supplementary material related to this paper is available at http://www.rcjournal.com.

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(or tracheostomy prosthesis) and the greater the pressure drop for a given air flow. With ATC on, the ventilator continuously provides pressure assistance during both insufflation and exsufflation by continuously computing tracheal pressure in adding the pressure drop across the ETT from the measured airway pressure (P_{aw}).[2] In this way, ATC works as a closed loop within the cycle, and the ventilator therefore regulates the tracheal pressure.

We recently reported[3] that breathing power was significantly higher with ATC than with low pressure support ventilation mode, both including a low PEEP, indicating that low pressure support ventilation provides pressure assistance beyond the pressure drop across ETT compensation.[4] Nevertheless, our previous work[3] used one brand of ventilator (Evita XL, Dräger, Germany) with all subjects, and the results may be different from those obtained with other ICU ventilators given that the algorithms governing ATC may differ. To explore this question further, we first performed an international survey to determine the rate of use ATC in daily practice. Based on these results, we then performed an in vitro study to explore the ATC function of different ICU ventilators. We hypothesized that if ATC works properly, the tidal volume (V_T) should be the same whether ATC was off with no ETT or on with an ETT in place. We tested this hypothesis on the bench with 7 currently available ICU ventilators. Because ATC was under investigation, we refined the lung model by using an inspiratory effort from an actual subject enrolled in our previous study.[3]

> **QUICK LOOK**
>
> **Current knowledge**
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> Automatic tube compensation (ATC) unloads endotracheal tube resistance, reduces the work of breathing, and may facilitate weaning from invasive mechanical ventilation in patients in the ICU. The rate of use of ATC is not clear, and the performance of ATC delivery across ICU ventilators is poorly investigated.
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> **What this paper contributes to our knowledge**
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> A survey of ICU physicians revealed that about two thirds of them used ATC in clinical practice. In a bench study, we observed that the difference in tidal volume delivered with and without ATC was small, but across 7 ICU ventilators it was significantly different. When the use of an endotracheal tube was modeled, the variability in tidal volume delivery increased.

Methods

The survey, created with the free Survey Monkey tool, was endorsed by the Acute Respiratory Failure section and the Clinical Trials group of the European Society of Intensive Care Medicine (ESICM). It was sent out via email on June 27, 2019, from the desk of the administrative person in charge of the worldwide ESICM membership. The closed-ended questions included respondent's country, years of experience in the ICU, type of ICU, type of hospital, type of ventilator, ATC use (never, always, or in some patients), reasons for using ATC or not, and ventilatory mode in which ATC is used (see the supplementary materials at http://www.rcjournal.com). The database was frozen on August 1, 2019, after 2 reminders. The results were retrieved as an anonymized spreadsheet. The in vitro bench study was performed in a dedicated room in the medical ICU of Grenoble-Alpes University Hospital in Grenoble, France.

Set up

The following components were used (see the supplementary materials at http://www.rcjournal.com). An ASL 5000 lung model (Ingmar Medical, Pittsburgh, Pennsylvania) was used to mimic representative ICU patients.[5,6] Representative respiratory mechanics of ICU patients were obtained from a recent study performed by Arnal et al[7] for normal subjects (Normal) and for subjects with ARDS or COPD. We set linear compliance and resistance as equal during inspiration and expiration. At the patient effort step of the ASL 5000 script, we used the analog output of the esophageal pressure tracing in a representative subject included in the previously mentioned study comparing pressure support ventilation to ATC[3] (see the supplementary materials at http://www.rcjournal.com). The same subject's effort was used in all combinations throughout the study.

Seven ICU ventilators equipped with the ATC mode were tested. Two were those used in the medical ICU in Grenoble-Alpes University Hospital (Evita XL and Evita V500 ventilators, Draeger, Lübeck, Germany), and the others were provided by the French representatives of the manufacturers (PB980 ventilator by Med-tronic, Dublin, Ireland; C6 and S1 ventilators by Nihon Kohden Europe, Roshbach, Germany; Elisa 800 ventilator by Löwenstein Medical, Bad Ems, Germany; and Carescape860 ventilator by GE Health Care, Chicago Illinois).

We used ETTs of 7.0 and 8.0 mm ID (Hi Contour oral/nasal cuffed ETT, Shiley, Covidien, Mansfield, Massachusetts) and of 9.0 mm ID (Supersafetyclear, Rüsch, Rüschelit, Teleflex Medical, Athlone, Ireland). Airflow was measured with a linear pneumotachograph (3700

The authors have disclosed no conflicts of interest.

Correspondence: Claude Guérin MD PhD, Médecine Intensive Réanimation, Groupement Hospitalier Centre, Hôpital Edouard Herriot, 5 Place d'Arsonval, 69003 Lyon, France. E-mail: claude.guerin@chu-lyon.fr.

DOI: 10.4187/respcare.07608

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series, Hans Rudolph, Shawnee, Kansas) and P_{aw} was measured at the ETT proximal tip (see the supplementary materials at http://www.rcjournal.com). P_{aw} was connected to a pressure transducer (Gabarith PMSET 1DT-XX, Becton Dickinson, Singapore). Analog signals of flow and P_{aw} were sent to a datalogger (Biopac MP150, Biopac, Goleta, California) (Figure 1). We used wireless double-limb ventilator circuit with a 22-mm ID and length of 1.6 m (Intersurgical, Berkshire, United Kingdom).

Protocol

Before the experiment, each ventilator was fully checked according to the procedure described in the user manual, and the P_{aw} transducer and pneumotachograph were calibrated using a manometer (717 1G, Fluke Biomedical, Everett, Washington) and a precision rotameter (Houdec Glass, Martin Medical, Lyon, France), respectively, at room temperature. Room temperature and humidity the day of the experiment were recorded. For each ventilator, the following steps were taken. First, the ventilator was set on pressure support ventilation mode with the following settings: pressure support ventilation level 0 cm H_2O, PEEP 4 cm H_2O, F_{IO_2} 0.21, fastest pressurization rate, inspiratory trigger at the lowest without auto-triggering, expiratory trigger 25% of maximum inspiratory flow, flow-by, and maximum inspiratory time set at default (see the supplementary materials at http://www.rcjournal.com). The ventilator was then connected to the ASL lung model with no ETT and ATC off. The 3 respiratory mechanics conditions (Normal, ARDS, and COPD) were then tested to define each condition's reference values. Second, the ATC option was switched on and information about the ID of the ETT and amount of compensation provided were recorded. At this step, we used an 8-mm ID ETT (ETT8) and 100% compensation. The ventilator was connected to an ETT8 and the 3 respiratory mechanics were run, which defined the active condition for each respiratory mechanics with an ETT8. Third, leaving the ATC settings unchanged, the ventilators were run again across a 7-mm ID ETT (ETT7), and then once more with a 9-mm ID ETT (ETT9) for each respiratory mechanics. This third step was performed to test to what extent the ATC option was able to adjust in case of inadequate or mistaken ATC settings.

Statistical Analysis

We used the gross national income per capita (in USD) provided by the World Bank in 2016 to transform the respondent's country into a geo-economic variable with 3 levels: Europe-High, non-Europe-High and Middle country.[8] The ATC variable was recorded as yes or no by merging the levels always in some patients into a single modality. The primary end point was the rate of ATC use. The hypothesis of the survey was that < 25% of the respondents would report using ATC. Variables were expressed as counts and percent per group. Groups were compared with the chi-square test. A logistic regression analysis was performed to explore the contributing factors to ATC use. In this analysis, the following covariates were studied: geo-economic region, type of hospital and of ICU, years in ICU, and type of ventilator.

The primary end point was inspiratory V_T difference between the reference condition (ie, no ATC and no ETT) and the active condition (ie, ATC on with an ETT8). We defined paired breaths in each reference and active condition, and we ordered them by using their rank in the script. This means that the first of the 30 breaths was always the same in each condition. We then measured the difference in every paired V_T between the reference condition and the active condition and corrected for body temperature pressure saturated conditions. The null hypothesis was that the V_T difference was 0, and the alternate hypothesis that V_T difference was different from 0. A positive difference meant that the ATC mode undercompensated for the given pressure drop across the ETT, and a negative difference meant that the ATC mode overcompensated for the given pressure drop across the ETT. Inspiration was defined from the flow signal at zero crossing. The secondary endpoints were the V_T difference for ETT7 and ETT9, inspiratory and expiratory times, PEEP, and triggering pressure and time. Triggering pressure was the maximum negative P_{aw} after onset of inspiratory effort from PEEP, and triggering time was the time delay for P_{aw} to recover baseline PEEP after the beginning of effort.

For the primary end point, we assessed the effect on V_T difference of ventilator and respiratory mechanics conditions by using a linear mixed-effects model.[9] Between ventilators, comparisons with post hoc pairwise comparisons were done with the Durbin test. For the secondary end points, V_T differences for the ETT7 and ETT9 were analyzed as above for the ETT8. The other secondary end points related to the basic ventilator functioning measured during the active (ATC) period were compared across ventilators with using Kruskal-Wallis tests for each ETT in each respiratory mechanic condition, with pairwise comparisons between ventilators performed with the Dunn test adjusted for the Bonferroni correction. Variables are expressed as median (interquartile range) unless otherwise stated. A *P* value < .05 was taken as the level for statistical significance. All statistical analyses were performed with RStudio 1.153 (RStudio, Boston Massachusetts) and R 3.5.2 (The R Foundation for Statistical Computing, Vienna, Austria).

Results

Survey

We received 644 responses from 72 countries. There were no duplicate entries, but 6 of the 644 surveys were

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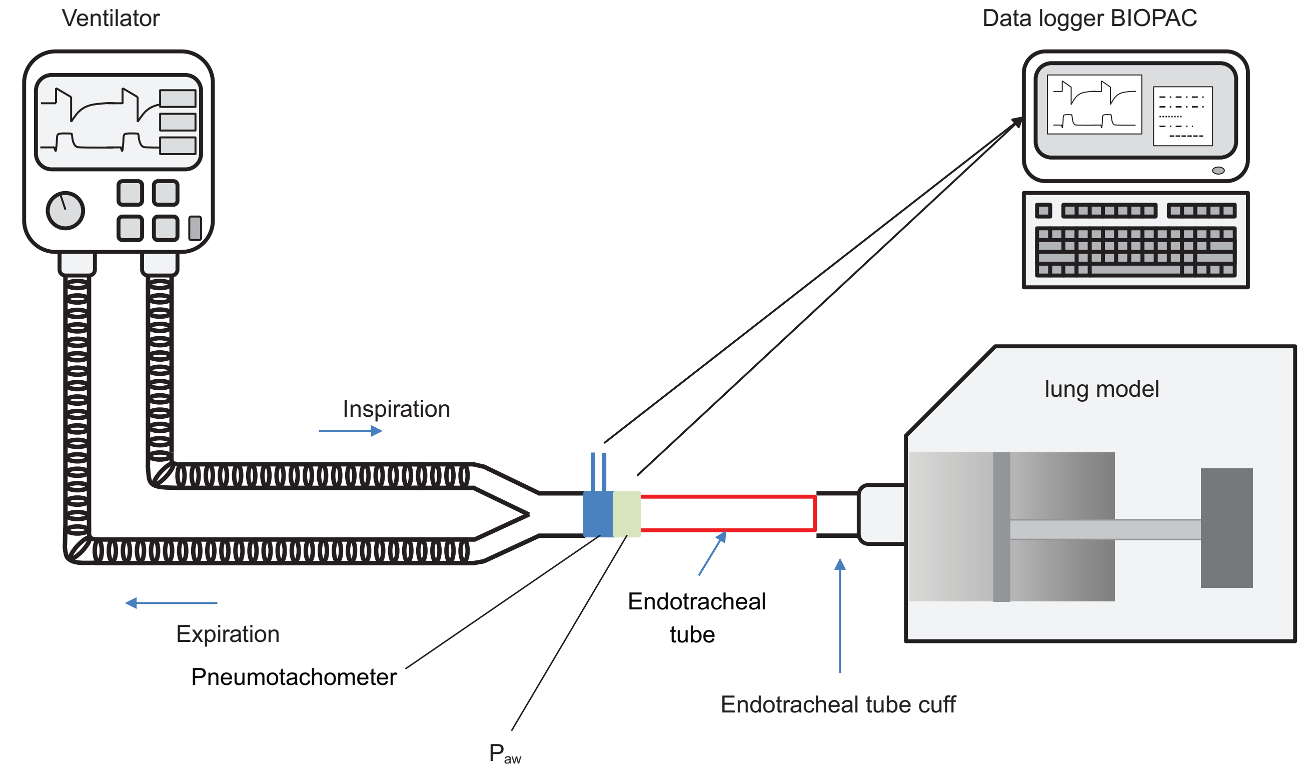

Fig. 1. Diagram of the experimental set up. P_{aw} = airway pressure.

not completed. Of the 638 viable surveys retained, 409 respondents used ATC always or in some patients (ie, 64% ATC rate of use). This rate did not differ between the geo-economical regions, ICUs, hospitals, or years in the ICU. For those respondents who did not use ATC, the reasons were ATC mode not available in ICU ventilators (41.9%), ATC mode not helpful (36.7%), ATC not known (18.8%), and ATC provides too much pressure assistance (5.7%). For those respondents who used ATC, the reasons were helpful in weaning (68.2%), set by default (30.5%), and physiological benefit (1.2%). ATC was used during spontaneous breathing trials (30.4%), with any assisted mode (27.9%), and with specific modes (11.7%). No risk factors were found to be associated with ATC use in the logistic regression model (data not shown).

Bench Study

The mean ± SD inspiratory time of the subject's inspiratory effort profile from 30 consecutive breaths was 0.94 ± 0.23 s, and the mean expiratory time was 1.18 ± 0.2.5 s. The mean esophageal pressure swings were −13.5 ± 1.3 cm H_2O (coefficient of variation 10%) with a minimum value of 11.15 and a maximum value of −16.8 cm H_2O. The rank of breath (ie, from 1 to 30) had no significant effect on V_T difference throughout the experiment (*P* = .98).

V_T Differences With Different ETTs

As shown in Figure 2, there were significant differences in V_T across the ICU ventilators for ETT8 (primary end point). For the sake of clarity, Figure 2 only shows the differences that were statistically significant between ventilators.

When the ventilators were connected to ETT7, the ATC was still adjusted to provide 100% compensation for ETT8. We therefore expected a lower V_T in the active condition, and consequently a larger difference in V_T than when the ventilators were connected to ETT8. This was found to be true, particularly for the Carescape860, Evita XL, and Evita V500 ventilators (Fig. 3). For the sake of clarity, Figure 3 only shows the differences that were statistically significant between ventilators.

When the ventilators were connected to ETT9, the ATC was still adjusted to provide 100% compensation for ETT8. We therefore expected a higher V_T in the active condition, and consequently a smaller difference in V_T, including negative values or more negative values, than when the ventilators were connected to ETT 8. This was found to be true overall (Fig. 4), with the exception of the Carescape860 in the COPD configuration, where V_T difference was positive. For the sake of clarity, Figure 4 only shows the differences that were statistically significant between ventilators.

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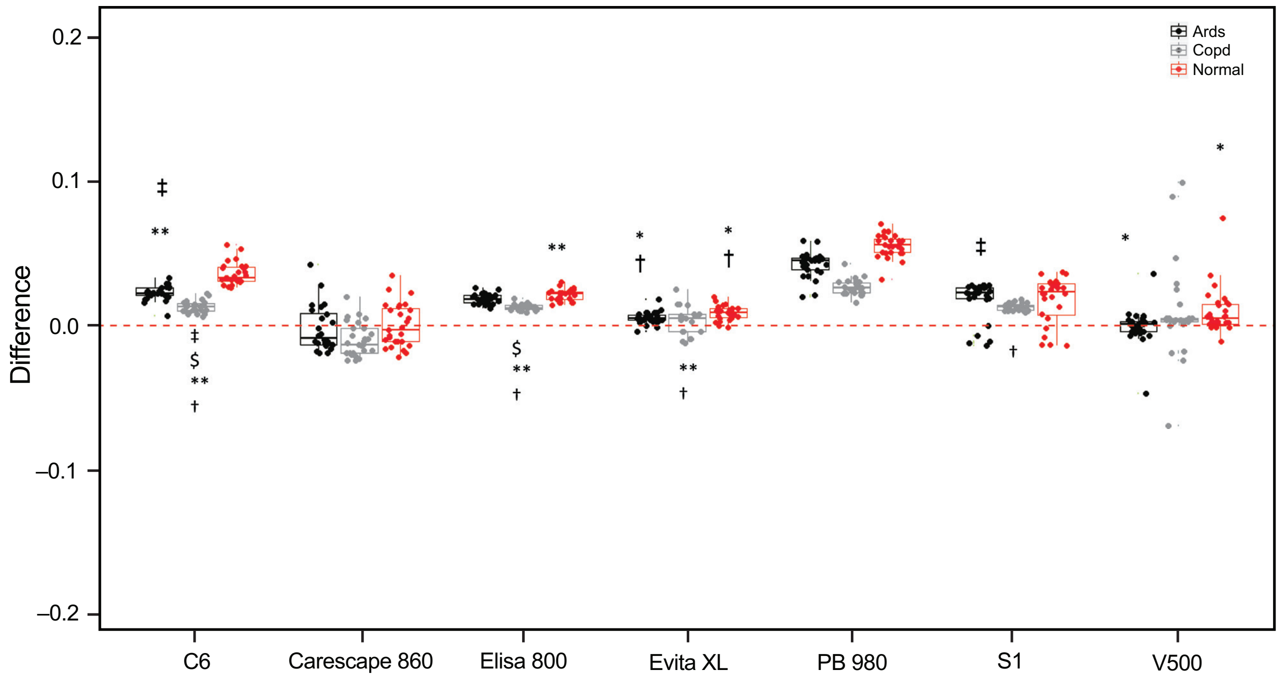

Fig. 2. Box and whiskers plots of change in tidal volume between reference (V_T without ATC and no ETT) and active condition (V_T with ATC and an ETT with an 8-mm ID) for Normal (red), ARDS (green), and COPD (black) respiratory mechanics across 7 ICU ventilators. All pairwise differences are not significant ($P > .05$) except for *vs Carescape860, **vs S1, †vs V500, ‡vs Elisa 800, and $vs Evita XL. V_T = tidal volume; ATC = automatic tube compression; ETT = endotracheal tube; ID = inner diameter.

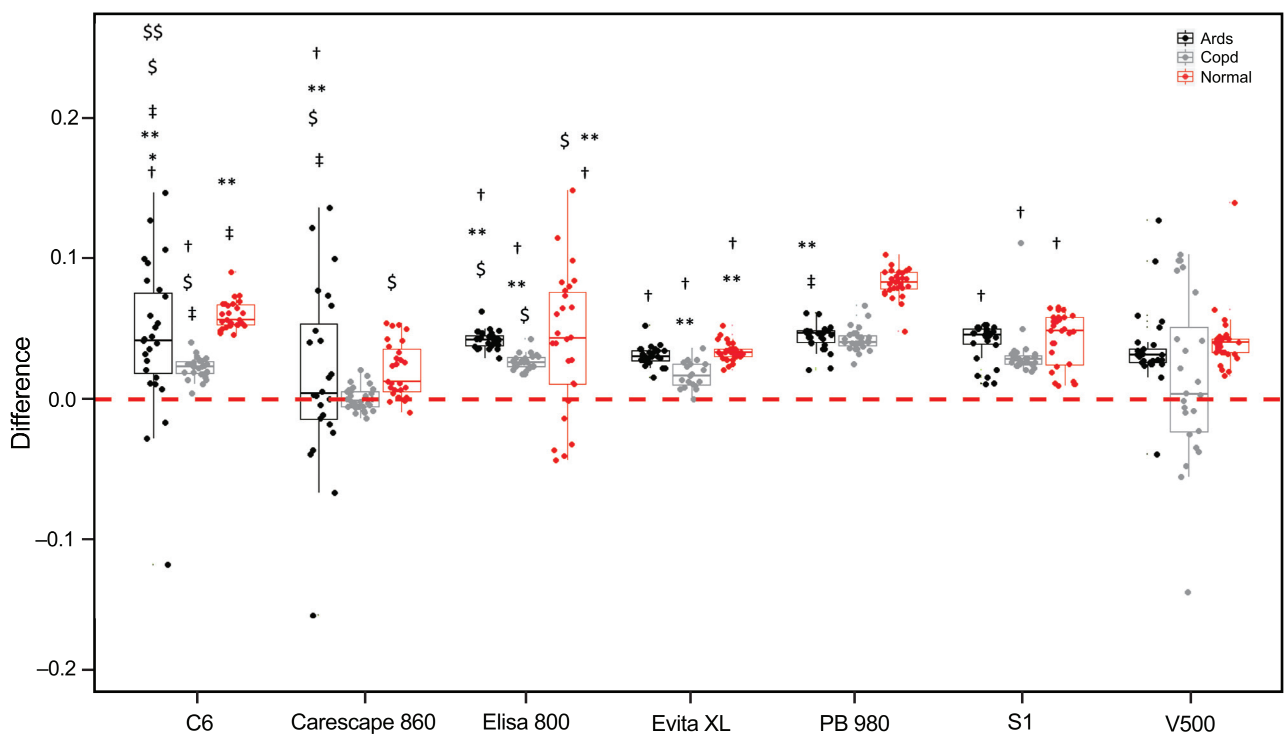

Fig. 3. Box and whiskers plots of change in tidal volume between reference (V_T without ATC and no ETT) and active condition (V_T with ATC and an ETT with an 7-mm ID) for Normal (red), ARDS (green), and COPD (black) respiratory mechanics across 7 ICU ventilators. All pairwise differences are not significant ($P > .05$) except for: *vs Carescape860, **vs S1, †vs V500, ‡vs Elisa 800, $vs Evita XL, and $$vs PB980. V_T = tidal volume; ATC = automatic tube compression; ETT = endotracheal tube; ID = inner diameter.

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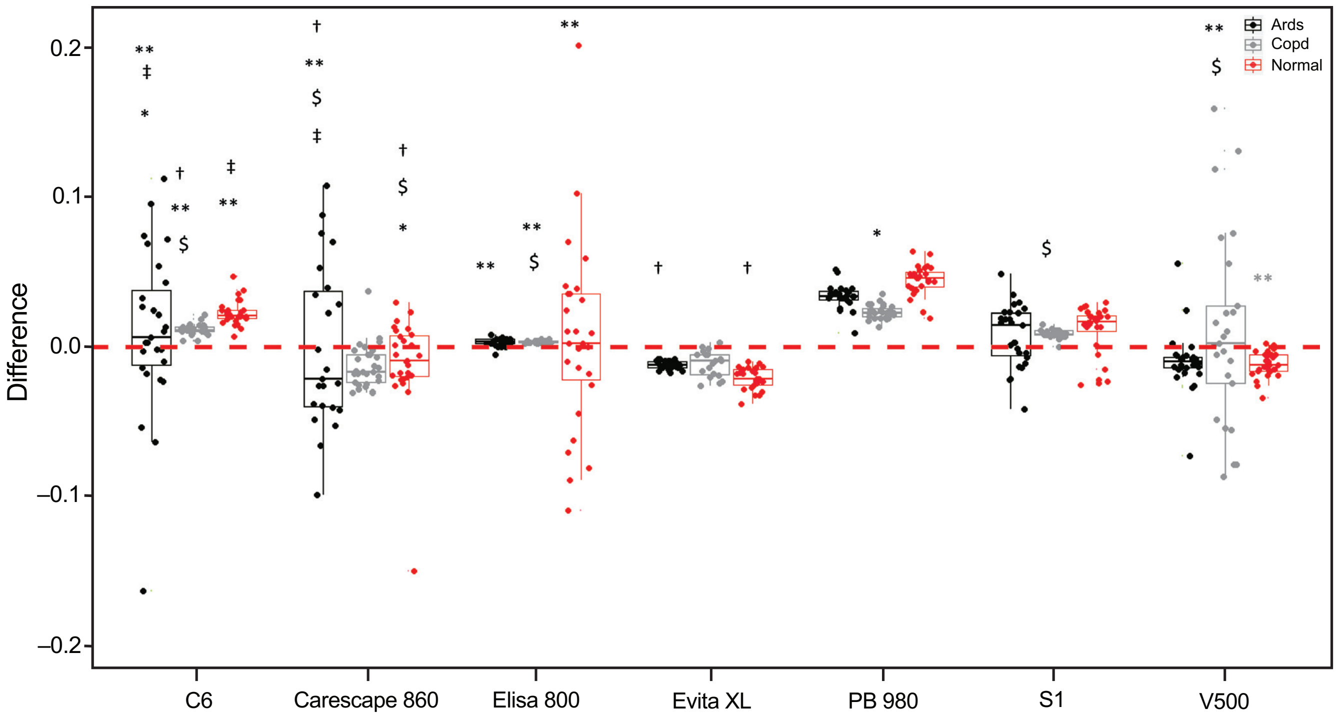

Fig. 4. Box and whiskers plots of change in tidal volume between reference (V_T without ATC and no ETT) and active condition (V_T with ATC and an ETT with an 9-mm ID) for Normal (red), ARDS (green), and COPD (black) respiratory mechanics across 7 ICU ventilators. All pairwise differences are significant ($P > .05$) except for: *vs Carescape860, **vs S1, †vs V500, ‡vs Elisa 800, and $vs Evita XL. V_T = tidal volume; ATC = automatic tube compression; ETT = endotracheal tube; ID = inner diameter.

V_T Differences for Different Diseases

With ETT8, among the 21 pairwise differences between ventilators tested in each respiratory mechanic condition, 16 were significant for Normal subjects, 11 were significant for ARDS, and 11 were significant for COPD. V_T difference was not statistically significantly different from 0 for the Carescape860 in Normal subjects, the Carescape860 and Evita V500 in ARDS, and the Evita XL in COPD, but it was for all other ventilators. Even though V_T difference significantly departed from 0, the divergence was overall small; the extreme median (interquartile range [IQR]) V_T differences ranged from −0.013 L (−0.019 to −0.002) with Carescape860 in COPD to 0.056 L (0.051–0.060) with PB980 in Normal subjects. When the ventilators were pooled, the estimated V_T difference was 0.015 L (95% CI 0.013–0.018) in ARDS, which was significantly different from 0.021 L (0.018–0.024) the Normal condition ($P < .001$) and 0.010 L (0.007–0.012) in the COPD condition ($P = .003$).

In the part of the experiment using an ETT7, among the 21 pairwise differences between ventilators tested in each respiratory mechanic condition, 12 were significant for Normal subjects, 4 for subjects with ARDS, and 12 for subjects with COPD. This step tended to reduce the between-ventilator difference for Normal subjects and especially for subjects with ARDS. The V_T difference was not significantly different from 0 for the Carescape860 in subjects with COPD, but it was for all the others. The ventilators worked consistently as they undercompensate V_T delivery as expected.

In the part of experiment using an ETT9, among the 21 pairwise differences between ventilators tested in each respiratory mechanics condition, 12 were significant for Normal subjects, 12 for subjects with ARDS, and 12 for subjects with COPD. V_T difference was not statistically significantly different from 0 for the Carescape860 and Elisa 800 in Normal subjects, for all but PB980 in subjects with ARDS, and for the Elisa 800, Evita XL, S1, and Evita V500 in COPD. This finding suggests that the ventilators worked better in this mistaken setting (ie, for an ETT9) than in the proper one. The fourth figure in the online supplementary material shows Figures 2-4 with the same scale for V_T difference (see the supplementary materials at http://www.rcjournal.com). This highlights the effect of increased ETT resistance with the decreasing ID. Furthermore, the variability of the response of ATC in terms of V_T difference can clearly be seen.

Variables Related to Ventilator Functioning

Variables related to ventilator functioning were significantly different for all of the ventilators for Normal subjects

T1,AQ:H T2-3 and for subjects with ARDS or COPD with ETT8 (Table 1, Table 2, Table 3), as well as for ETT7 and ETT9 (data not shown).

Discussion

There are 4 main findings of this study. First, almost two thirds of the survey respondents reported using ATC in clinical practice, suggesting there is a real need to assess the physiological effects of ATC to improve clinical management. Second, there was a significant difference between ventilators in terms of expected V_T delivery when ATC is properly set according to ETT size. Third, the median differences were < 0.1 L with each ventilator in each respiratory mechanical condition. Finally, inappropriate ETT size setting at the ventilator resulted in the expected direction of the V_T change, namely V_T underdelivery when ETT use was simulated.

The substantial use of ATC reported in the survey was greater than that hypothesized. Nevertheless, this finding should be interpreted with caution because the survey was more likely to be returned by users of ATC than by nonusers. Furthermore, this potential selection bias could mean that respondents were more accustomed to using ATC than those who did not respond; however, 36% of the respondents did mention that they were not ATC users). Although we were unable to measure this bias, it would appear that ATC use is quite common, making the present results relevant for ATC use.

Methodological Considerations

Before discussing the results from the bench study, some methodological considerations should be acknowledged. First, we used an inspiratory effort signal recorded in a real patient during weaning from mechanical ventilation. This option is made available in the ASL 5000 script (step 3: choose a patient effort model), but to our knowledge using a real subject's effort in the lung model has not been reported to date. On one hand, including this step mimics real-life clinical practice. On the other hand, because there is no previous comparison of a strategy using the common schematic inspiratory effort built into the ASL 5000 script with a strategy using a subject's effort, it is unknown whether this would influence the results. For this study, we ran the same subject's effort for each condition tested with every ventilator. Second, our aim was to assess the accuracy of ventilator functioning during ATC. Basically, the output of respiratory assistance generates V_T at a certain frequency. We applied a breathing frequency of 27 breaths/min, which is the frequency provided by the clinical scenario on which we modeled inspiratory effort. The V_T is the result of the combination of the subject's inspiratory effort and the amount of breathing assistance. In our

Table 1. Variables Related to Ventilator Functioning for Brand New 8 mm Inner Diameter Endotracheal Tube and Normal Respiratory Mechanics

	C6	Carescape 860	Elisa 800	Evita XL	PB980	S1	Evita V500	*P*
PEEP, cm H_2O	4 (4–4)	3 (3–3)	4 (4–4)	4 (4–4)	3 (3–3)	6 (6–6)	3 (3–3)	< .001
DP_{trig}, cm H_2O	−0.2 (−0.2 to −0.1)	−1.4 (−1.4 to −1.2)	−0.9 (1.2 to −0.1)	−0.4 (−0.6 to −0.3)	−1.7 (−2.0 to −1.4)	0.1 (0.1–0.2)	−0.4 (−1.2 to −0.1)	< .001
DT_{trig}, s	0.950 (0.844–0.992)	0.147 (0.140–0.165)	0.417 (0.342–0.807)	0.090 (0.055–0.117)	0.610 (0.542–0.688)	1.203 (1.164–1.241)	0.150 (0.003–0.245)	< .001
T_i, s	0.965 (0.891–1.000)	0.930 (0.855–0.955)	0.980 (0.901–1.011)	0.980 (0.898–1.019)	1.067 (1.000–1.111)	1.218 (1.171–1.272)	1.020 (0.917–1.064)	< .001
T_e, s	1.337 (1.279–1.371)	1.320 (1.275–1.395)	1.288 (1.249–1.346)	1.288 (1.239–1.375)	1.205 (1.150–1.250)	1.022 (0.975–1.059)	1.277 (1.234–1.366)	< .001

Data are presented as median (interquartile range). *P* values were determined with the Kruskal-Wallis rank sum test.
DP_{trig} = maximum negative airway pressure after onset of inspiratory effort
DT_{trig} = time to airway pressure recover PEEP after onset of inspiratory effort
T_i = inspiratory length
T_e = expiratory length

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Table 2. Variables Related To Ventilator Functioning For Brand New 8 mm Inner Diameter Endotracheal Tube of and Acute Respiratory Distress Syndrome

	C6	Carescape 860	Elisa 800	Evita XL	S1	PB980	Evita V500	*P*
PEEP, cm H_2O	4 (4–4)	3 (3–3)	4 (4–4)	4 (4–4)	3 (3–3)	6 (6–6)	3 (3–3)	< .001
DP_{trig}, cm H_2O	−0.2 (−1.2 to −0.1)	−1.4(−1.6; −1.3)	−0.9 (1.3 to −0.1)	−0.3 (−0.4 to −0.2)	0.1 (0.1–0.2)	−1.8 (−2.0 to −1.5)	−0.5 (−1.1 to −0.2)	< .001
DT_{trig}, s	0.905 (0.578–0.970)	0.147 (0.140–0.165)	0.975 (0.918–1.031)	0.085 (0.046–0.095)	1.210 (1.154–1.238)	0.600 (0.470–0.688)	0.117 (0.011–0.215)	< .001
T_i, s	0.965 (0.913–0.991)	.935 (.887; .955)	0.965 (0.920–1.005)	0.955 (0.909–0.991)	1.220 (1.169–1.248)	1.055 (1.012–1.090)	0.960 (0.925–1.024)	< .001
T_e, s	1.320 (1.265–1.375)	1.320 (1.274–1.384)	1.285 (1.255–1.340)	1.285 (1.245–1.360)	1.020 (0.992–1.060)	1.195 (1.157–1.257)	1.275 (1.232–1.374)	< .001

Data are presented as median (interquartile range). *P* values were determined with the Kruskal-Wallis rank sum test.
DP_{trig} = maximum negative airway pressure after onset of inspiratory effort
DT_{trig} = time to airway pressure recover PEEP after onset of inspiratory effort
T_i = inspiratory length
T_e = expiratory length

Table 3. Variables Related To Ventilator Functioning For Brand New 8 mm Inner Diameter Endotracheal Tube of and Chronic Obstructive Pulmonary Disease

	C6	Carescape 860	Elisa 800	Evita XL	PB980	S1	Evita V500	*P*
PEEP, cm H_2O	4 (4–4)	3 (3–3)	4 (4–4)	4 (4–4)	3 (3–3)	6 (6–6)	3 (3–3)	< .001
DP_{trig}, cm H_2O	−0.2 (−0.2 to −0.0)	−1.1 (−1.2 to −1.1)	−0.1 (−0.2 to −0.0)	−0.2 (−0.4 to 0.0)	−1.2 (−1.4 to −1.0)	−0.0 (−0.1 to 0.0)	−0.6 (−1.0 to −0.4)	< .001
DT_{trig}, s	0.870 (0.297–0.998)	0.185 (0.170–0.205)	0.900 (0.790–0.903)	0.035 (0.005–0.095	0.583 (0.452–0.695)	1.215 (1.165–1.287)	0.160 (0.120–0.220)	< .001
T_i, s	0.975 (0.890–1.005)	0.950 (0.870–0.975)	0.970 (0.895–0.995)	0.978 (0.894–1.020)	1.047 (0.969–1.076)	1.215 (1.165–1.300)	0.972 (0.905–1.000)	< .001
T_e, s	1.295 (1.250–1.365)	1.340 (1.280–1.390)	1.305 (1.250–1.350)	1.277 (1.219–1.333)	1.248 (1.183–1.286)	1.047 (0.975–1.075)	1.295 (1.261–1.343)	< .001

Data are presented as median (interquartile range). *P* values were determined with the Kruskal-Wallis rank sum test.
DP_{trig} = maximum negative airway pressure after onset of inspiratory effort
DT_{trig} = time to airway pressure recover PEEP after onset of inspiratory effort
T_i = inspiratory length
T_e = expiratory length

RESPIRATORY CARE Paper in Press. Published on June 30, 2020 as DOI: 10.4187/respcare.07608

experiment, the breathing assistance was the ATC mode, the goal of which is essentially to compensate for a pressure drop across a brand new ETT (or tracheostomy prosthesis). Therefore, it makes sense to speculate that, if ATC works properly, the resulting V_T should be the same without ATC and ETT as with ATC and ETT. This was our hypothesis when designing the study, and it seems robust. Any departure from a zero difference (ie, the ideal) between these 2 conditions indicates that ATC does not work perfectly, either by overcompensating and hence overassisting the patient (ie, negative difference) or by undercompensating and hence underassisting (ie, positive difference).

Previous Bench Studies of ATC

The novelty of our study is that it compares ATC across the various ICU ventilators commonly available in Europe. Previous comparisons of ATC were based on older version of ICU ventilators. The performance of ATC of the Evita 4, Evita 2, and NPB840 was significantly lower than that of the original prototype to compensate for the additional work of breathing due to ETT.[10] This was explained by different algorithms used to compensate for pressure drop across the ETT. A linear and quadratic term was used in the original prototype (Pressure drop = K_1 Flow + K_2 Flow^2), whereas a quadratic term only (Pressure drop = K Flow^2) was used in the Evita 2 and Evita 4. Fujino et al[11] reported that the bench performance of the NPB840 was insufficient to compensate for the additional work of breathing due to ETT. In comparison with the study by Maeda et al,[12] which was conducted with the oldest ventilators (ie, NPB840 and Evita 4), we noted a better triggering time/triggering pressure product for PB980, Evita XL, and V500, implying an improved triggering system in the newer ventilators. This point is important for the ATC procedure.[13] Theoretically, at any time during the respiratory cycle in ATC mode, the ventilator should evaluate the flow, compute the pressure drop across ETT due to this flow, and then pressurize the entry of the ETT at this computed pressure. Obviously this pressurization is ineffective between $t = 0$ and $t =$ triggering time. An ideal ATC mode requires a good triggering time. With a very long triggering time (Table 1, Table 2, Table 3), it is hardly surprising that the PB980 and the Elisa 800 undercompensated for the pressure drop across the ETT (Fig. 2). In terms of V_T difference, the effect of any error in ATC compensation also depends on the respiratory mechanics condition. The relation between airway pressure (P), flow ($\dot{V}$) and V_T is given by the classic equation of motion: $P = (R_{ETT} + R)\dot{V} + \frac{V}{C}$, where R_{ETT} is the resistance of the ETT, and R and C are the resistance and the compliance of the respiratory system, respectively. When R is big or when C is small, the contribution of R_{ETT} to P is negligible, V is little affected by the presence of the ETT, and the V_T difference should be small with or without effective ATC compensation. This may explain why the V_T difference seems closer to zero in Normal subjects than in subjects with COPD or ARDS. It is, however, worth mentioning that even though the differences in V_T across the ventilators are statistically significant, they are usually small and may not be clinically relevant.

Limitations and Strengths

The first limitation of this study is, of course, its bench nature. The study is also limited by the fact that we did not set a pressure support level > 0 cm H_2O. However, this reflects what happens during spontaneous breathing trials. Another limitation is that we used brand new ETTs. Oto et al[14] reported that when ATC is applied to used ETTs, in which the pressure drop across the ETT was 10–25% higher than in a new ETT of the same ID, the compensation for the resistive load by ATC was lower. Our results support this with the data obtained when a 7-mm ID was used with an expected compensation set to an ETT of 8-mm ID. The strength of this study is that we used the effort of a real subject under weaning, which may partly address the gap between bench and clinical domains. Furthermore, this is the first bench study to assess ATC mode in a large range of modern ICU ventilators.

Clinical Implications

The results of the survey suggest that ATC use is relatively common in clinical ICU practice. Our analysis informs the clinician about the performance of current day ventilators, should they need to perform ATC. These results may also help remind clinicians about the differences among ventilators, even with the same mode or function. The assistance that a patient receives from ATC varies with different respiratory mechanics.

Conclusions

This bench study suggests that V_T delivery with ATC is slightly but significantly different between ventilators. In addition, ATC appears to be used more frequently than expected in clinical practice.

REFERENCES

1. Fabry B, Guttmann J, Eberhard L, Wolff G. Automatic compensation of endotracheal tube resistance in spontaneously breathing patients. Technol Health Care 1994;1(4):281-291.
2. Haberthür C, Mehlig A, Stover JF, Schumann S, Möller K, Priebe HJ, et al. Expiratory automatic endotracheal tube compensation reduces dynamic hyperinflation in a physical lung model. Crit Care 2009;13 (1):R4.
3. Guérin C, Terzi N, Mezidi M, Chebib N, Baboi L, Yonis H, et al. Low pressure support vs automatic tube compensation during spontaneous breathing trial for weaning. Ann Intensive Care 2019;9(1):137.

4. Brochard L, Rua F, Lorino H, Lemaire F, Harf A. Inspiratory pressure support compensates for the additional work of breathing caused by the endotracheal tube. Anesthesiology 1991;75(5):739-745.
5. Oto J, Chenelle CT, Marchese AD, Kacmarek RM. A comparison of leak compensation in acute care ventilators during noninvasive and invasive ventilation: a lung model study. Respir Care 2013;58(12):2027-2037.
6. Daoud EG, Katigbak R, Ottochian M. Accuracy of the ventilator automated displayed respiratory mechanics in passive and active breathing conditions: a bench study. Respir Care 2019;64(12):1555-1560.
7. Arnal JM, Garnero A, Saoli M, Chatburn RL. Parameters for simulation of adult subjects during mechanical ventilation. Respir Care 2018; 63(2):158-168.
8. Laffey JG, Madotto F, Bellani G, Pham T, Fan E, Brochard L, et al. Geo-economic variations in epidemiology, patterns of care, and outcomes in patients with acute respiratory distress syndrome: insights from the LUNG SAFE prospective cohort study. Lancet Respir Med 2017;5(8):627-638.
9. Pinheiro AC, Bates DM. Mixed-effects models in S and S-PLUS. New York: Springer; 2004.
10. Elsasser S, Guttmann J, Stocker R, Mols G, Priebe HJ, Haberthur C. Accuracy of automatic tube compensation in new-generation mechanical ventilators. Crit Care Med 2003;31(11):2619-2626.
11. Fujino Y, Uchiyama A, Mashimo T, Nishimura M. Spontaneously breathing lung model comparison of work of breathing between automatic tube compensation and pressure support. Respir Care 2003;48 (1):38-45.
12. Maeda Y, Fujino Y, Uchiyama A, Taenaka N, Mashimo T, Nishimura M. Does the tube-compensation function of two modern mechanical ventilators provide effective work of breathing relief? Crit Care 2003;7(5):R92-R97.
13. Lofaso F, Louis B, Brochard L, Harf A, Isabey D. Use of the Blasius resistance formula to estimate the effective diameter of endotracheal tubes. Am Rev Respir Dis 1992;146(4):974-979.
14. Oto J, Imanaka H, Nakataki E, Ono R, Nishimura M. Potential inadequacy of automatic tube compensation to decrease inspiratory work load after at least 48 hours of endotracheal tube use in the clinical setting. Respir Care 2012;57(5):697-703.