The effects of automatic tube compensation on tracheal pressure and inspiratory rise time during controlled ventilation: an experimental study

SJH Heines¹, U Strauch¹, PMH Roekaerts¹, B Winkens², DCJJ Bergmans¹

¹Department of Intensive Care Centre Maastricht, Maastricht University Medical Centre+, Maastricht, The Netherlands
²Department of Methodology and Statistics, Maastricht University, Maastricht, The Netherlands

Abstract - Introduction Previous research on automatic tube compensation (ATC) mainly investigated work of breathing in spontaneously breathing patients. However, ATC also compensates the increase in resistance in a controlled mechanical ventilation mode. We designed an experimental study to investigate the effects of ATC on pressures and inspiratory rise time during controlled ventilation.

Methods A ventilator was connected to an artificial lung. Two sets of experiments were performed: ‘Pressure constant experiment’: fixed inspiratory pressure (Pinsp) (25 mbar), three respiratory rates (10, 30 and 50 breaths min⁻¹). ‘Frequency constant-experiment’: fixed respiratory rate (15 breaths min⁻¹), three Pinsp (15, 30 and 45 mbar). Measurements of maximum pressure on the ventilator, proximal and distal of the endotracheal tube were performed. In addition, mean pressure and inspiratory rise time distal of the endotracheal tube were determined. All measurements were performed at each setting with ATC on and ATC off, and with an endotracheal tube with an internal diameter ID of 7.0 and 9.0 mm. Results The pressure distal of the tube never exceeded the set pressure level on the ventilator. The time needed to reach the set inspiratory pressure distal of the tube was shorter with ATC than without ATC. (668±2.9 msec versus 1694±2.5 msec respectively for tube ID 7.0 and Pinsp 30 mbar and 1070±4.7 msec versus 1435±2.2 msec respectively for tube ID 9.0 and Pinsp 30 mbar). On ATC the pressure at the distal end of the endotracheal tube did not exceed the set inspiratory pressure on the ventilator. Moreover, ATC resulted in a shorter inspiratory pressure rise time at the tracheal level and a significantly higher mean airway pressure as compared to mechanical ventilation without using ATC.

Keywords - Automatic tube compensation, rise time, tracheal pressure, airway resistance, endotracheal tube, additional work of breathing

Introduction

The work of breathing (WOB) in a patient on mechanical ventilation in spontaneous breathing mode is determined by airway resistance, intrinsic positive end-expiratory pressure and respiratory elastance [1]. The endotracheal tube (ETT) and its diameter in particular, have an important impact on respiratory resistance as well does inspiratory flow and patient characteristics. Decreases in diameter raise airway resistance to the fourth power according to the Hagen-Poiseuille law. Therefore, being the narrowest connection between patient and ventilator, the ETT causes additional resistance. A primary objective in invasive mechanical ventilatory support is to alleviate the effort of spontaneous breathing while allowing the patient to perform enough work to prevent respiratory muscle atrophy. Automatic tube compensation (ATC) was therefore developed to minimize the breathing workload. In modern mechanical ventilators on the ATC setting, pressure assistance is increased during inspiration and decreased during expiration, thereby compensating exclusively the WOB that is caused by the ETT [2].

Most of the previous research on ATC investigated WOB, patient comfort and alveolar ventilation in spontaneously breathing patients [2-9]. However, ATC also compensates the increase in resistance caused by the ETT in a controlled mechanical ventilation mode, which may result in high peak pressures being measured in the ventilator or even at the tracheal level that exceed the preset inspiratory pressure on the ventilator. The application of ATC could also result in reaching the preset inspiratory pressure in a shorter time, thereby enhancing efficient alveolar ventilation. To our knowledge, there are no published reports on the effects of ATC during controlled mechanical ventilation.

Therefore, we designed this experimental study to evaluate the effects of ATC during controlled ventilation on pressures proximal and distal to the ETT and on inspiratory rise time.

Materials and methods

An Evita-4 (Draeger, Lubeck; Germany) with ATC software (version 1.14) was connected to a standard adult ventilator circuit from DAR breathing systems, to a swivel (standard 15mm, “Catheter mouth breathing system DAR” consisting of a double swivel connector with extensive tube 10 cm, 15F/15M connector) and to a Heat and Moisture Exchange Filter (HMEF) Hygrobac DAR ISO standard 15mm/22mm fitting. The total compliance of the Evita-4, ventilator circuit, HMEF and swivel was 1.3 ml/mbar. The system was connected to an ETT with an internal diameter (ID) of 7 or 9 mm (Mallinckrodt ID 7.0 and 9.0 Ireland). Via an artificial trachea with an ID of 12mm, the system was connected to an artificial lung (Draeger, Lubeck; Germany. Demonstration thorax SR 442), with a compliance of 44 ml/mbar. Measured pressures
are expressed in mbar (1 mbar represents 1.0197 cmH2O) with the Spiro+ (Saime, France; Sept 2003, software “Spiroscope: V2.4 Saime 2002”; flow sensor Mergina Saime (sensitivity: ±5% + 1 L min\(^{-1}\) maximum, range: 5-280 L min\(^{-1}\) ); pressure sensor electronic Piezo Resistif (sensitivity: ±1% + 0.1 mbar maximum, range: 0-76 mbar). Pressure samples were determined at a rate of 100Hz and displayed once per 10 msec. Pressure was registered just before the ETT (= proximal) and in the artificial trachea 3 cm distal to the end of the ETT (= distal). Fixed settings on the Evita-4 were biphasic positive airway pressure without assisted spontaneous breathing, positive end-expiratory pressure (PEEP) 8 mbar, inspiratory to expiratory ratio (I:E-ratio) 1:1, FiO\(_2\) 21% and rise time 0.0 seconds.

**Experimental protocol**

Two sets of experiments were performed. In the pressure constant experiment, the preset inspiratory pressure was fixed at 25 mbar and the respiratory frequency setting was changed from 10 breaths min\(^{-1}\) to 30 breaths min\(^{-1}\) to 50 breaths min\(^{-1}\). The frequency constant-experiment had a fixed respiratory frequency of 15 breaths min\(^{-1}\) while the preset inspiratory pressure setting was changed from 15 mbar to 30 mbar to 45 mbar. Measurements were performed at each of the settings described above with an ETT ID 7.0 mm and ID 9.0 mm during 20 consecutive inspirations with ATC on [100 %, adjusted to the ID of the ETT] and ATC off. The measurements included: peak ventilator pressure, maximum pressure proximal to the ETT, maximum pressure distal to the ETT, mean inspiratory pressure distal to the ETT and time to reach the preset inspiratory pressure distal to the ETT.

**Statistics**

Data are given as mean ± SEM and visually presented by scatter plots. The effect of ATC on the deviation between set inspiratory pressure and the mean pressure at the distal end of the tube was tested using the independent-samples t-test. P-values ≤ 0.05

**Table 1. Maximum pressures with and without ATC at different ventilator settings**

<table>
<thead>
<tr>
<th></th>
<th>ETT ID 7.0</th>
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<th>ETT ID 9.0</th>
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<tbody>
<tr>
<td></td>
<td>ATC off</td>
<td>ATC on</td>
<td>ATC off</td>
<td>ATC on</td>
</tr>
<tr>
<td><strong>P(_{\text{insp}}) 25 mbar</strong></td>
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<td></td>
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<tr>
<td>Freq 10 min(^{-1})</td>
<td></td>
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</tr>
<tr>
<td>Evita</td>
<td>25.45 ± .114</td>
<td>31.50 ± .115</td>
<td>25.40 ± .112</td>
<td>27.10 ± .069</td>
</tr>
<tr>
<td>prox</td>
<td>25.16 ± .008</td>
<td>28.92 ± .018</td>
<td>25.16 ± .031</td>
<td>25.45 ± .036</td>
</tr>
<tr>
<td>dist</td>
<td>25.15 ± .017</td>
<td>25.12 ± .014</td>
<td>25.10 ± .015</td>
<td>25.08 ± .016</td>
</tr>
<tr>
<td>Freq 30 min(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evita</td>
<td>25.00 ± .000</td>
<td>30.10 ± .069</td>
<td>25.00 ± .000</td>
<td>27.00 ± .000</td>
</tr>
<tr>
<td>prox</td>
<td>24.67 ± .005</td>
<td>28.09 ± .008</td>
<td>23.85 ± .834</td>
<td>25.04 ± .039</td>
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<tr>
<td>dist</td>
<td>23.94 ± .005</td>
<td>25.28 ± .010</td>
<td>24.43 ± .006</td>
<td>25.06 ± .012</td>
</tr>
<tr>
<td>Freq 50 min(^{-1})</td>
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</tr>
<tr>
<td>Evita</td>
<td>25.00 ± .000</td>
<td>29.00 ± .000</td>
<td>25.00 ± .000</td>
<td>27.00 ± .000</td>
</tr>
<tr>
<td>prox</td>
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<td>24.03 ± .017</td>
<td>25.31 ± .034</td>
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<td>dist</td>
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<td>24.84 ± .006</td>
<td>23.37 ± .007</td>
<td>24.36 ± .010</td>
</tr>
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<td><strong>Freq 15 min(^{-1})</strong></td>
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<td><strong>P(_{\text{insp}}) 15 mbar</strong></td>
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<tr>
<td>Evita</td>
<td>15.00 ± .020</td>
<td>16.00 ± .000</td>
<td>15.00 ± .024</td>
<td>16.00 ± .000</td>
</tr>
<tr>
<td>prox</td>
<td>15.00 ± .018</td>
<td>15.71 ± .018</td>
<td>15.01 ± .024</td>
<td>15.87 ± .018</td>
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<tr>
<td>dist</td>
<td>15.00 ± .018</td>
<td>15.02 ± .009</td>
<td>15.05 ± .011</td>
<td>15.02 ± .008</td>
</tr>
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<td><strong>P(_{\text{insp}}) 30 mbar</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Evita</td>
<td>30.00 ± .000</td>
<td>39.50 ± .115</td>
<td>30.20 ± .092</td>
<td>33.45 ± .114</td>
</tr>
<tr>
<td>prox</td>
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<td>30.20 ± .018</td>
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<tr>
<td>dist</td>
<td>30.26 ± .027</td>
<td>30.23 ± .018</td>
<td>30.15 ± .020</td>
<td>30.13 ± .020</td>
</tr>
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<td><strong>P(_{\text{insp}}) 45 mbar</strong></td>
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<tr>
<td>Evita</td>
<td>46.65 ± .109</td>
<td>64.65 ± .109</td>
<td>46.00 ± .000</td>
<td>51.10 ± .069</td>
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<td>prox</td>
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<td>57.28 ± .027</td>
<td>45.29 ± .016</td>
<td>46.26 ± .045</td>
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<td>dist</td>
<td>44.22 ± .006</td>
<td>45.42 ± .011</td>
<td>45.13 ± .009</td>
<td>45.52 ± .035</td>
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</tbody>
</table>

Maximum pressure in the ventilator and at the proximal and distal end of the endotracheal tube before and after the application of automatic tube compensation at different ventilator settings.

Data are mean pressure in mbar ± SEM.

Abbreviations: ETT: endotracheal tube ; ID : internal diameter; ATC: automatic tube compensation; Evita: in the ventilator, Prox: proximal of the ETT; Dist: distal of the ETT; Pinsp: preset inspiratory pressure on the Evita in mbar; Freq: set respiratory frequency in breaths min \(^{-1}\)
were considered as statistically significant. Data were analyzed using SPSS version 16.0.

**Results**

Although only small differences were observed between the preset inspiratory pressures and the measured peak inspiratory ventilator pressures without ATC, the measured peak ventilator pressures were increased with ATC. The increase was larger with an ETT ID 7.0 than with an ETT ID 9.0.

ATC increased the pressures proximal to the ETT at all sample points as compared with the pressures without using ATC.

In the pressure constant experiment at a frequency of 10 breaths min\(^{-1}\), ATC did not increase the pressures measured at the distal end of the endotracheal tube. At the higher frequencies of 30 and 50 breaths min\(^{-1}\), ATC increased the pressures measured at the distal end of the ETT (Table 1), resulting in a decrease of the deviations from the preset inspiratory pressure as shown in Figure 1. In the frequency constant experiment, ATC only slightly increased the pressures measured at the distal end of the ETT at the higher preset inspiratory pressure of 45 mBar.

In Figure 2, the time to reach the preset inspiratory pressure at the distal end of the ETT is presented. Without ATC, the time to reach the preset inspiratory pressure distal to the ETT is longer with the smaller ID than with the larger ID. ATC shortened the time to reach the preset inspiratory pressure at the distal end of the ETT compared with not using ATC. Shortening was more pronounced in the setting with a smaller ETT (Figure 2).

Using an ETT ID 7.0, ATC off and an inspiratory preset pressure of 45 mbar (resulting in a delta pressure of 37 mbar), the inspiratory preset pressure was not reached at the distal end of the ETT after 2 seconds of inspiration time (respiratory rate 15 min\(^{-1}\), I:E-ratio 1:1). With ATC on, the preset pressure was reached before the next respiratory cycle.

In general, including all measurements regardless of setting, the deviation of mean inspiratory airway pressure at the distal end of the tube and set inspiratory pressures was significantly smaller with ATC than without ATC (0.89±0.26 mbar versus 2.00±0.58 mbar respectively, P=0.019).

**Discussion**

This study showed that the application of ATC during controlled mechanical ventilation ensured that pressure at the distal end of the ETT did not exceed the preset pressure level on the ventilator. Moreover, ATC correctly increases the pressures measured at the distal tracheal end of the ETT as compared with not using ATC if the set inspiratory pressure was not reached. Finally, ATC shortens the inspiratory rise time and increases the mean airway pressure at the distal end of the ETT.

![Figure 1. Deviations of pressures distal to the ETT and set inspiratory pressures with and without ATC.](image-url)
Automatic tube compensation causes an increase in peak pressure at the proximal end of the ETT. This increase in pressure is obviously necessary to compensate for the increase in airway resistance. Only a few studies have analyzed the pressure at the tracheal level. We found that ATC increased pressures at the distal end of the tube. However, these small differences in pressures do not appear to be clinically relevant since the pressures never exceeded the set pressure level on the ventilator by more than a 1.16% increase in the pressure amplitude. Moreover, the pressures measured after the application of ATC were usually similar to and sometimes even lower than the preset inspiratory pressures. Maeda and colleagues measured tracheal pressure only with a respiratory frequency of 10 breaths min\(^{-1}\) so that no intrinsic PEEP was created that could induce trigger problems. In line with our findings, tracheal pressure stayed below the set inspiratory pressure without ATC. With ATC 100%, the tracheal pressure nearly reached the preset pressure at the end of inspiration when using a Draeger Evita-4 or Puritan Bennett 840. Unfortunately, exact data on the pressures measured were not presented in that study [7].

Figure 2. Time to reach the preset inspiratory pressure distal to the ETT.

Wrigge and co-workers compared ATC with no ATC in patients with acute lung injury ventilated with airway pressure release ventilation, and determined the effects of ATC on haemodynamic parameters [8]. Automatic tube compensation did decrease WOB, and resulted in higher alveolar ventilation without interfering with haemodynamics. Moreover, there was an increase in end-expiratory lung volume. The data on tracheal pressures presented in that study were not measured but calculated. The authors concluded that, at the tracheal level, the pressure is higher when using ATC compared to no ATC. However, the differences were not significant; therefore, it can be assumed that differences at the alveolar level also are not significant. If the pressures at the tracheal level ever exceeded the preset inspiratory pressures, was not reported. Unfortunately, no data on the time needed to reach the preset inspiratory pressure at the tracheal level were presented.

If ATC was not used in our experiment, the preset inspiratory pressure was not always reached at the distal end of the ETT, especially at higher respiratory frequencies. This can be explained by a decreased time for inspiration due to the higher respiratory rate, while the inspiratory to expiratory ratio is constant.

As expected, the preset inspiratory ventilator pressure was reached sooner at the tracheal level using ATC. The Evita-4 with 100% ATC proportionally compensates more with an ETT ID 7.0 than with an ETT ID 9.0. When the preset inspiratory ventilator pressure is reached sooner at the distal end of the ETT, this actually means that there is a faster rise time at the tracheal level when using ATC. Therefore, we assume that pressure propulsion at the alveolar level will also be faster.

Most studies on ATC were performed in spontaneously breathing patients or tested in models mimicking spontaneous breathing. In spontaneously breathing patients ventilated with pressure support, the inspiratory rise time is an important factor related to the WOB. A shorter rise time results in higher inspiratory peak flow, thereby creating lower inspiratory WOB [9-13]. There are no studies referring to the effect of ATC on pressure propulsion. Our data from a non-spontaneously breathing model show that ATC shortens inspiratory pressure rise time at the tracheal level resulting in a higher mean airway pressure. This fast pressure propulsion probably causes better alveolar ventilation, as was observed in several human studies on ATC [8]. Based on our data, we assume that in non-spontaneously breathing patients the alveolar ventilation also increases when applying ATC while maintaining the same ventilator settings. In ventilatory strategies using higher respiratory frequencies or in cases of high airway resistance, the flow curve does not go to baseline during inspiration. ATC could be used in these situations to increase alveolar ventilation or could even be used to ventilate patients with lower inspiratory pressures. Limiting the magnitude of inspiratory pressures may reduce the development of ventilator-associated lung injury (VALI), especially if high inspiratory pressures are needed. These are potential benefits since our study was performed in a laboratory setting and should be confirmed in non-spontaneously breathing patients. Also, the relation between rise time and the pathophysiology of VALI warrants further research.
It has previously been shown that different PEEP levels do not have a significant effect on the pressures measured [7]. Therefore, in our experimental set-up, all tests were performed at a PEEP level of 8 mbar. Increasing $P_{\text{insp}}$ incrementally did increase the pressure at the proximal end of the ETT due to the increase in delta pressure. This increase would not occur by increasing PEEP only.

We did not measure WOB because we used a model without spontaneous breathing. Most of the previous research on ATC mainly investigated WOB in spontaneously breathing patients [7,14,15]. From these studies it can be concluded that ATC might not always be able to compensate for the total increase in WOB in the presence of an ETT.

Conclusions
We conclude from our experimental study that controlled mechanical ventilation with ATC using an Evita-4 Draeger ventilator increased the pressures measured at the distal tracheal end of the endotracheal tube in some cases. These increased pressures, as compared with the preset inspiratory pressures, were not considered clinically relevant since the pressures never exceeded the set pressure level on the ventilator by more than 1.16% increase in the pressure amplitude. The pressures distal to the ETT, measured after the application of ATC were usually similar and sometimes even lower than the preset inspiratory pressures. ATC resulted in a shorter inspiratory pressure rise time at the tracheal level and in a higher mean airway pressure. The potential benefits of the use of ATC during controlled mechanical ventilation in several clinical conditions are improvement of alveolar ventilation [8] and reduction of set inspiratory pressures enabled by a higher mean airway pressure. If this is clinically relevant needs to be determined.

List of abbreviations used
WOB: work of breathing
ETT: endotracheal tube
ATC: automatic tube compensation
HMEF: heat and moist exchange filter
ID: internal diameter
I:E-ratio: inspiratory to expiratory ratio
PEEP: positive end-expiratory pressure

Competing interests
The authors declare that they have no competing interests.

Figure 3. Deviations of mean pressures distal to the ETT and set inspiratory pressures with and without ATC.

Deviation of the mean pressure at the distal end of the tube and the set inspiratory pressure ($P_{\text{insp}}$) before and after the application of automatic tube compensation at different ventilator settings and tube ID 7.0 and ID 9.0. The solid (red) line indicates the $P_{\text{insp}}$. The $P_{\text{insp}}$ at a frequency of 10, 30 and 50 was 25 mbar. At a frequency of 15 the $P_{\text{insp}}$ was 15, 30 and 45 mbar.

Abbreviations: ETT: endotracheal tube; ID: internal diameter; ATC: automatic tube.
References


