Automatic Tube Compensation During Weaning From Mechanical Ventilation

Evidence and Clinical Implications

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PRIME POINTS

- Gas flow through an endotracheal tube during spontaneous breathing generates a pressure gradient between the 2 ends of the tube and increases the work of breathing.

- Automatic tube compensation reduces the work of breathing associated with an endotracheal tube and helps in optimizing work of breathing.

- Automatic tube compensation may provide comfort for patients being weaned from mechanical ventilation and may be useful in predicting the outcome of extubation.

Management of critically ill patients is a multidisciplinary effort, and critical care nurses are key members of the health care team, particularly during weaning from mechanical ventilation. Automatic tube compensation (ATC) is a relatively new mode of mechanical ventilation available on newer mechanical ventilators and is used during weaning from mechanical ventilation. Adequate assessment of patients receiving ATC ventilatory support requires a clear understanding of the characteristics of this mode. In this article, we review the effects of endotracheal tubes in spontaneously breathing patients, mechanisms and advantages of ATC, ATC use during the final phase of weaning from mechanical ventilation, and clinical implications of ATC use.

Effects of Endotracheal Tubes in Spontaneously Breathing Patients

Respiratory Workload Imposed by the Endotracheal Tube

In healthy persons, respiration occurs with little effort. Respiratory work is required, however, to overcome the natural forces that oppose inhalation, such as the elasticity and resistance of the respiratory system, which is termed respiratory load. The ability to overcome the respiratory load is determined by respiratory muscle capability, especially diaphragm capability. Respiratory muscle capability is impaired by prolonged mechanical ventilation and conditions such as sepsis and chronic obstructive pulmonary disease. In addition, drugs such as neuromuscular blocking agents and corticosteroids may also impair...
muscle capability. An imbalance between respiratory load and respiratory muscle capability is one cause of unsuccessful weaning from mechanical ventilation. The presence of an endotracheal tube augments respiratory load in spontaneously breathing patients who are receiving mechanical ventilation.

When gas flows through an endotracheal tube into the lungs during spontaneous inspiration, a pressure gradient is generated between the 2 ends of the tube (Figure 1). Pressure at the carinal end of the tube (P\text{trach}) is greater than that at the opposite end (P\text{ETT}). Pressure at P\text{trach} generated by inspiratory muscle is diminished at P\text{ETT} because of the resistance of the endotracheal tube. Diminished pressure at P\text{ETT} indicates that greater inspiratory force (greater negative pressure) is required to inspire a sufficient volume of air (Figure 1).

Greater flow rate in the endotracheal tube generates a greater pressure gradient between the entrance and the end of the tube, so resistance is greater. The amount of resistance is determined by the length and diameter of the tube. Narrow and longer tubes create greater resistance than do wide and shorter tubes (Figure 2). During spontaneous respiration, greater force (ie, greater negative pressure) is required to move the same volume of air through a narrow endotracheal tube than through a wide endotracheal tube (Figure 2A). In addition, breathing through the endotracheal tube itself requires greater force than does breathing through the natural trachea (ie, without an endotracheal tube). Artificially created positive pressure (pressure-support ventilation [PSV] or ATC)

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Figure 1 When inspiration occurs, flow is generated from the outside of the endotracheal tube to the inside of the lungs, and a pressure gradient occurs. Pressure at the proximal end of the tube (P\text{ETT}) is greater than that at the distal side of the tube (P\text{trach}).
is applied to the endotracheal tube (Figure 2B) to decrease a patient's respiratory work caused by the resistance of the endotracheal tube.

**Significance of Reduction in Workload Imposed by the Endotracheal Tube**

Optimizing the work of breathing (WOB) is a key component in successful weaning from mechanical ventilation. The WOB is the work required to breathe against a respiratory load. In patients treated with mechanical ventilation, WOB consists of 2 components: physiological and imposed. Physiological WOB is the work required to overcome the elastic lung forces during inflation and the resistive lung forces (airway resistance). When respiratory system compliance decreases, as it does during acute lung injury and pulmonary fibrosis, the WOB needed to inflate the lung against the elastic forces increases. Similarly, when airway resistance increases, as in bronchial asthma, the WOB against resistive forces increases. In intubated patients receiving mechanical ventilation, the endotracheal tube, ventilator circuits, and other system valves also add to the WOB. The increase in WOB added by equipment is termed imposed WOB. The total WOB for an intubated patient receiving mechanical ventilation is therefore a combination of physiological and imposed WOB.

The WOB imposed by an endotracheal tube also depends on the patient’s effort (because respiratory resistance depends on flow rate in an endotracheal tube), ventilation mode, and the diameter and length of the endotracheal tube. In an investigation of the relationship between the diameter of endotracheal tubes and the WOB in 3 healthy volunteers, the smaller the tube diameter, the greater was the WOB, and as minute ventilation (high inspiratory flow rate) increased, so did the work. Thus, WOB increased exponentially on the basis of minute ventilation, and the differences in WOB associated with various tube diameters were enhanced in patients with high minute ventilation. Hence, in terms of WOB, use of tubes with a greater diameter would be advantageous in patients with high minute ventilation. Although PSV has been used to compensate for the increased resistance caused by the endotracheal tube, several issues still remain. A patient’s inspiratory flow is highly variable from breath to breath and even within each single breath. Therefore, PSV cannot provide constant adjustments in response to the changes in resistance caused by...
changes in the patient’s inspiratory effort, resulting in less than optimal reduction in WOB. If the pressure support delivered by PSV is less than the pressure gradient in the endotracheal tube, the patient must make an additional inspiratory effort, resulting in undercompensation. On the other hand, if the pressure support delivered by PSV is more than the pressure gradient in the endotracheal tube, overcompensation occurs. In overcompensation, the patient may feel uncomfortable, a situation that could potentiate patient-ventilator dyssynchrony. Use of PSV rarely achieves complete reduction of WOB caused by an endotracheal tube. ATC was developed to achieve optimal tube compensation.

**Mechanisms and Advantages of ATC**

**Mechanisms**

Some of the newer ventilators in use today include ATC (eg, Evita XL and Evita 4, Dräger Medical, Lübeck, Germany; Nellcor Puritan Bennett 840, Puritan Bennett, Pleasanton, California). ATC compensates for resistance associated with an endotracheal tube via closed-loop control of continuously calculated tracheal pressure. A remarkable feature of ATC that makes it superior to PSV is that the intratracheal pressure at the carinal end of the endotracheal tube is used to control flow. In contrast to ATC, in PSV, pressure is generally monitored at the Y-piece or close to the expiration valve of the ventilator. In ATC, intratracheal pressure is calculated on the basis of the patient’s inspiratory flow, the circuit pressure, and properties of the endotracheal tube, which are set by the operator in advance.

Figure 3 shows changes in pressure at the ventilator circuit and Ptrach during both PSV and ATC. Compared with the situation in PSV, in ATC, Pptrach is relatively constantly maintained. In some ventilators, tube resistance is compensated for during expiration as well as inspiration by a reduction in airway pressure during the expiratory phase.

**Comparison Between ATC and PSV**

Reduction of respiratory work-load via ATC has been investigated. Haberthür et al found that total WOB was markedly decreased with ATC compared with PSV and continuous positive airway pressure (CPAP; Figure 4) in 10 ventilator-dependent patients who had tracheostomies (but with a longer, 13-cm tracheal tube). Fabry et al investigated respiratory patterns and the WOB imposed by both the endotracheal tube and the demand valve in 2 different populations of patients: postoperative patients with no lung injury and critically ill patients whose respiratory demand was increased. The researchers compared ATC and various settings of PSV. In postoperative patients, the imposed WOB was compensated for with ATC and with PSV settings of 10.2 and 15.3 cm H₂O. A PSV of 5.1 cm H₂O did not compensate for the WOB. In critically ill patients, none of the PSV levels compensated for the imposed WOB.
WOB; only ATC was able to compensate for the imposed WOB. In the critically ill patients, respiratory demand was high, resulting in a high inspiratory flow rate. Fabry et al emphasized that the advantage of ATC over PSV may vary according to a patient’s pulmonary status.

These findings suggest that ATC is advantageous in reducing WOB in patients who require high inspiratory flow. Use of ATC to reduce WOB may not have much advantage over PSV in patients with relatively normal inspiratory flow; in these patients, PSV levels of 10 to 15 cm H₂O may be sufficient. However, if patients require high levels of PSV to reduce workload, and overcompensation results in discomfort and dyssynchrony, then ATC may be a better choice.

During spontaneous breathing in healthy persons, ATC can provide greater comfort than PSV can. Enhancing comfort can reduce use of sedatives and patient-ventilator dyssynchrony. This characteristic is especially advantageous during the weaning phase, because discomfort is a common cause of unsuccessful weaning.

**ATC During the Final Weaning Phase**

**Significance of Compensation for Workload Imposed by the Endotracheal Tube**

ATC may be useful during the final phase of a weaning trial. Use of a spontaneous breathing trial (SBT) before extubation is important to detect readiness for extubation. PSV, CPAP, and T-piece breathing have been used during the SBT. The goal of an SBT is to approximate respiratory conditions that will be present after extubation. After extubation, airway inflammation and edema commonly occur, creating resistance to airflow that may be equal to or higher than that created by the endotracheal tube during intubation. If all of the resistance of the endotracheal tube is removed during the SBT through use of PSV, CPAP, or ATC, then the trial is not an optimal test of a patient’s ability to overcome the airway resistance that might occur after extubation. In a clinical study, WOB was greater after extubation than during SBT with PSV at 5 cm H₂O, CPAP, or a T-piece (Figure 5). This finding was consistent with the results of a clinical study by Ishaaya et al. Similarly, Straus et al found that WOB after extubation was similar to WOB at the end of SBT with a T-piece and concluded that SBT with a T-piece mimics the WOB after extubation. If so, some methods of SBT that reduce resistance associated with use of an endotracheal tube might increase the number of unsuccessful extubations.

The Spain Lung Failure Collaborating Group conducted a large randomized controlled trial comparing weaning outcomes between SBTs with a T-piece and SBTs with PSV of 7 cm H₂O. This level of PSV was considered sufficient to compensate for the resistance imposed by an endotracheal tube. As expected, the proportion of patients with an unsuccessful SBT was significantly higher when a T-piece was used (22%) than when PSV was used (14%). As some investigators have suggested, if WOB after extubation is equal to or higher than WOB during an SBT with a T-piece, extubation probably would be unsuccessful in some patients who tolerate the T-piece trial. In addition, unsuccessful extubation is even more likely in patients in whom the SBT with PSV is successful.

![Figure 4](image-url)
However, in the Spain Lung Failure Collaborating Group study, the percentage of patients in whom extubation was unsuccessful did not differ significantly according to the weaning method (T-piece, 18.7%; PSV, 18.5%). These data suggest that some patients who could not tolerate the SBT with a T-piece may still tolerate extubation, indicating that SBTs with a T-piece may result in a high number of false-negatives. This assumption was supported by a recent study by Ezingeard et al, who attempted to perform SBTs with PSV in patients in whom an SBT with a T-piece was unsuccessful. A total of 21 of 31 patients tolerated the SBT with PSV, and 17 patients were extubated successfully. However, these findings contradict those of previous studies in which WOB after extubation was greater with a T-piece than with PSV or CPAP. Even after extubation, the stress response remained higher in patients who had weaning with a T-piece than in the other 2 groups. This stress response likely causes cardiovascular complications in critically ill patients.

In addition, use of a T-piece requires additional equipment (ie, circuit and humidifier) than does use of PSV or ATC, which do not need additional equipment. During SBT with a T-piece, heat and moisture exchangers for airway humidification are avoided because they increase resistance in the breathing circuit. A large-volume nebulizer is generally used, and condensates must be drained frequently to avoid increases in respiratory resistance and infection.

**Table 5** Work of breathing (WOB) under continuous positive airway pressure (CPAP), T-piece, or pressure-support ventilation (PSV) at 5 cm H2O during a spontaneous breathing trial (SBT) and at 15 and 60 minutes, respectively, after extubation (Ext).

Data from Mehta et al.

Advantages of ATC Versus Use of a T-Piece During Weaning

In 60 patients who underwent weaning with a T-piece, CPAP, or PSV, Koksal et al found that the endocrine stress response was greater with a T-piece than with PSV or CPAP. Even after extubation, the stress response remained higher in patients who had weaning with a T-piece than in the other 2 groups. This stress response likely causes cardiovascular complications in critically ill patients.

In summary, SBTs with PSV may improve weaning success without increasing the number of unsuccessful extubations, although consensus on this issue has not been reached. There is no harm in compensating for imposed workload during an SBT if this intervention does not adversely affect the rate of successful extubations.

**ATC as an Appropriate Mode for Weaning**

To date, the effect of ACT on weaning outcomes (ie, reintubation) has been investigated in 2 randomized control trials. In Switzerland, Haberthür et al randomized 90 intensive care unit patients receiving mechanical ventilation into 3 groups of 30 patients per group (ATC, 5 cm H2O of PSV, and T-piece) during a 2-hour SBT. The success rate for the SBT was higher in patients in whom ATC was used (97%) than in the other 2 groups (PSV, 83%; T-piece, 80%), but differences between the 3 weaning modes were not significant. In this study, 7 of 11 patients who did not tolerate the first SBT with PSV or a T-piece tolerated an SBT when ATC was used and were successfully extubated. Haberthür et al stated that SBT with ATC appeared
to result in inadequate withholding of extubation less often than did SBT with PSV or a T-piece, because tube resistance is a primary reason patients do not tolerate an SBT.

In a larger study in Israel, Cohen et al32 studied 99 adult patients who met weaning criteria. The patients were randomly assigned to undergo a 1-hour SBT with ATC and CPAP or with CPAP alone. A total of 49 of the 51 patients (96%) in whom ACT plus CPAP was used tolerated the SBT compared with 41 of the 48 patients (85%) in whom CPAP alone was used; the difference between the 2 groups was not significant ($P = .08$). However, compared with the CPAP group (31 of 48 patients; 65%), significantly more patients in the ATC group (42 of 51 patients; 82%) met the criteria for extubation ($P = .04$). Therefore, use of ATC during SBTs may be beneficial to increase the number of successful extubations.

Clinical Implications of ATC Use

ATC Options

Currently, several ventilators incorporate ATC, although the settings and algorithms for ATC use vary. In this review, we have focused on ATC function during the inspiratory phase; however, pressure gradients between both ends of the endotracheal tube are also generated during the expiratory phase. During expiration, pressure at the carinal side of an endotracheal tube is greater than the pressure at the circuit side of the tube because in this phase, air is flowing from the lungs to the circuit. A carinal-side pressure greater than the clinician-selected positive end-expiratory pressure (PEEP) may inhibit a patient’s exhalation. For example, even if PEEP is set at 5 cm H$_2$O, the carinal pressure is not necessarily 5 cm H$_2$O at end expiration. Because of the resistance of the endotracheal tube, carinal pressure probably is greater than 5 cm H$_2$O. In order to avoid this phenomenon, ATC automatically controls PEEP by using calculated carinal pressure to maintain 5 cm H$_2$O of PEEP at the carinal side of the endotracheal tube during end expiration. Specifically, ATC temporarily reduces PEEP at the circuit (or inside the ventilator) during expiration. This expiratory ATC function is available in the Evita XL and Evita 4 ventilators; in other ventilators (Nellcor Puritan Bennett 840; Avea, VIASYS Healthcare Inc, Palm Springs, California) ATC can be used only during inspiration.

Although it has generally been used only with PEEP for patients during the weaning phase, ATC can also be added to other modes (eg, synchronized intermittent mandatory ventilation) in some ventilators. Specifically, ATC can be combined with synchronized intermittent mandatory ventilation and other modes in the Evita 4 and Evita XL ventilators. In some ventilators, continuous visual monitoring of calculated pressure at the carinal end of the endotracheal tube is available (Figure 6).

ATC Settings

When ATC is used, several variables are entered into the ventilator system, including the internal diameter of the endotracheal tube, the type of tube, the percentage of support, and additional general settings (eg, trigger sensitivity; Figure 7). Information on the type of the tube (endotracheal or tracheostomy) is required to determine the length of the tube. The manufacturers recommend 100% support, and currently, no empirical data are available on the effect of any other setting.33

Precautions for ATC Use

Precautions associated with use of ATC include ensuring that it is used appropriately, determining and maintaining correct settings, and continually monitoring for adverse effects. First, many patients who are breathing spontaneously need not only compensation for the workload imposed by the tracheal tube but also additional ventilatory support because of their pathophysiological status. They may need ventilatory support modes such as PSV, proportional assist ventilation, and synchronized intermittent
mandatory ventilation to prevent ventilatory failure.

Second, correct settings for the internal diameter and the type of tube are crucial. Setting an internal diameter lower than the actual diameter leads to overcompensation, which can result in discomfort and dysynchrony. On the other hand, setting the internal diameter higher than the actual diameter leads to undercompensation. Because incorrect input for the tube type also leads to undercompensation or overcompensation, the settings for the type of tube and the internal diameter of the tube should be reset after any tube change (eg, tracheostomy, reintubation). When ATC is used for expiratory compensation, temporary reductions in airway pressure may cause airway collapse, especially in patients with chronic obstructive pulmonary disease. Therefore, deactivation of expiratory compensation may be appropriate for patients with chronic obstructive pulmonary disease to avoid airway closure.

Third, the importance of continual monitoring cannot be overemphasized. The adequacy of a patient’s ventilation, such as tidal volume and respiratory rate, should be monitored continually once ATC is set. Tube compensation should be provided by the mechanical ventilator on the basis of the calculated pressure, not the measured pressure, at the carinal end of the endotracheal tube. As described previously, the calculation is based on the diameter and length of the endotracheal tube. Secretions, condensate, and kinks in the tube can cause a narrowing of the diameter of the tube to a value that is less than the input value. In this situation, calculated carinal pressure inaccurately alters actual pressure at the carinal end of the endotracheal tube. The tube should be periodically assessed for these airway obstructions, and any obstruction present should be removed. It is widely known that during mechanical ventilation endotracheal tubes become narrowed by the accumulation of secretions and debris.

Most likely this narrowing will affect the magnitude of tube compensation. Unfortunately, to date, no clinical tool exists for detecting narrowing of an endotracheal tube. Even when all settings are correct, the success of reducing the WOB should be assessed, as indicated by no use of accessory muscles, abdominal paradoxical movements, or increases in dyspnea, discomfort, and diaphoresis.

Conclusion

ATC is a new ventilatory support feature that shows promise for enhancing weaning processes and outcomes. ATC may be useful to provide comfort during the weaning process for spontaneously breathing patients receiving mechanical ventilation and to enhance respiratory status after extubation.

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1. Which of the following augments respiratory load in spontaneously breathing patients who are receiving mechanical ventilation?
   a. Neuromuscular blocking agents
   b. An endotracheal tube (ETT)
   c. Pressure support ventilation
   d. Automatic tube compensation (ATC)

2. Which of the following ETTs produces the greatest resistance to airflow?
   a. Narrow and shorter tubes
   b. Wide and shorter tubes
   c. Narrow and longer tubes
   d. Wide and longer tubes

3. Optimizing which of the following components is key to successful weaning from mechanical ventilation?
   a. Lung compliance
   b. Minute ventilation
   c. Respiratory load
   d. Work of breathing

4. ATC compensates for ETT resistance through control of which of the following mechanisms?
   a. Tracheal pressure
   b. Minute ventilation
   c. Cuff pressure
   d. Tidal volume

5. Which of the following pressure support ventilation (PSV) levels may be sufficient in reducing work of breathing in patients with normal inspiratory flow?
   a. 5 to 10 cm H₂O
   b. 10 to 15 cm H₂O
   c. 15 to 20 cm H₂O
   d. 20 to 25 cm H₂O

6. Which of the following weaning methods was associated with a higher unsuccessful spontaneous breathing trial conducted by the Spain Lung Failure Collaborating Group?
   a. ATC
   b. PSV
   c. CPAP
   d. T-piece

7. Which percentage of ATC patients met the criteria for extubation in the trial by Cohen et al?
   a. 55%
   b. 64%
   c. 82%
   d. 96%

8. For expiratory compensation, ATC uses calculated carinal pressure to maintain which of the following levels of positive end-expiratory pressure?
   a. 5 cm H₂O
   b. 7 cm H₂O
   c. 10 cm H₂O
   d. 12 cm H₂O

9. Which of the following percentages of support is recommended for ATC?
   a. 10%
   b. 40%
   c. 70%
   d. 100%

10. Which of the following ventilator settings is crucial when ATC is used?
    a. Diameter of the ETT
    b. Trigger sensitivity
    c. Tidal volume
    d. Length of the ETT

11. The type of tube and the internal diameter of the tube should be reset after which of the following?
    a. Weaning trial
    b. ETT repositioning
    c. Tracheostomy
    d. ETT obstruction

12. Which of the following parameters should be monitored continually to determine the adequacy of a patient’s ventilation during ATC?
    a. Inspiratory pressure
    b. Tidal volume
    c. Tracheal pressure
    d. ETT diameter

Test answers: Mark only one box for your answer to each question. You may photocopy this form.

1.  a  2.  a  3.  a  4.  a  5.  a  6.  a  7.  a  8.  a  9.  a  10.  a  11.  a  12.  a
   a  b  c  d  a  b  c  d  a  b  c  d  a  b  c  d

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