Effects of Fresh Gas Flow, Respiratory Rate, and Mode of Ventilation on Recovery of Tidal Volume after Circuit Disconnection

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INTRODUCTION

The development of an automatic ventilator has drastically changed practice in the operating room and intensive care unit. However, disconnection of the circuit can happen at any time during ventilatory care. In the ASA Closed Claims database between 1961 and 1994, gas delivery equipment failure accounted for 72 of 3,791 claims (2%).(1) Among these claims, almost all adverse events occurred in the operating room (n=62, 86%), and the breathing circuit was the most common source of failure (n=28, 39%). Misconnection or disconnection of the circuit was the largest contribution to injury (n=25, 35%). The most common adverse events were death and brain damage (76%). Disconnections in the breathing system can lead to life-threatening complications due to hypoxia.(2)

Depending on the method of delivery of breathing gas, ventilators are categorized as mechanically driven piston-type or air-filled bellow-type. The bellow-type ventilator is divided into ascending-type and descending-type in accordance with the direction of the movement of the bellow during expiration. The bellow-type ventilator traditionally has a double circuit, which is separated into breathing gas and ventilator gas flows. The bellow is located in a position such that it interacts with both circuits. The gas filling the bellow is a mixture of breathing gas, ventilator-driven gas, and fresh gas. The ascending type-ventilator cannot fill the bellow if the circuit is disconnected. It is easy to detect circuit disconnection in the ascending bellow-type ventilator because bellow filling is detectable. The piston-type ventilator has one circuit, so it has an effective gas supply without using ventilator gas and can supply accurate tidal volume. However, circuit disconnection and gas leakage are more difficult to detect in the piston-type ventilator, which also operates relatively quietly. If circuit disconnection or leakage occurs in a piston type ventilator, the air mixture can result in hypoxia or awakening due to dilution of the inhalation gas.(3,4)

Regardless of the ventilator type, if disconnection occurs, it takes time to recover the pre-set tidal volume (TV) after reconnection of the circuit. However, fast recovery of ventilation is essential after reconnection of the circuit, especially when apnea time is prolonged due to ventilator disconnection alarms failure(5-10) or if the patient cannot maintain arterial oxygen saturation.
because of pulmonary problems. Although many studies have been performed to attempt to address this issue(11-17), disconnection of the breathing circuit remains one of the most common types of anesthetic incidents. Despite the restarting of ventilation after circuit reconnection, hypoxemia can develop or worsen in seconds if the disconnection is detected late.

When hypoxemia develops or is anticipated, the ventilator setting needs to be changed for fast recovery of the tidal volume. The recovery time of the tidal volume (TV) can differ by ventilator type and ventilation settings. The ascending bellow-type ventilator takes time to fill the bellow after beginning ventilation. In addition, the TV recovery time can be affected by the fresh gas flow (FGF) or respiratory rate (RR). Thus, the aim of this study was to determine the optimal FGF and RR for rapid recovery of TV and to compare ventilator types and the effects of positive end-expiratory pressure (PEEP) and ventilation mode.

MATERIALS AND METHODS

As this study was a laboratory investigation, approval by the local Ethical Committee was not needed. We collected data using two anesthesia machines that included an ascending bellow-type ventilator (S/5 Avanceanesthesia machine; GE Datex-ohmeda, US) and a piston-type ventilator (Fabius GS anesthesia machine; Dräger, Germany). We connected a breathing bag to the end of the circuit to create a simple lung model, and both ventilators were set to a TV of 500 ml, a 1:2 ratio of inspiration to expiration (I:E ratio), and a 0.5 fraction of inspired oxygen (FiO₂) with oxygen and air.

The primary measured parameters were TV recovery time (sec) according to change in FGF from 1 to 15 L/min with a fixed RR (10 breaths/min) in order to determine the optimal FGF. The measurement started at the end of expiration. Because TV frequently did not reach 500 ml, we decided to set the TV recovery goal to 450 ml, or 90% of the pre-set TV. Each measurement was performed 10 times. For the secondary results, at the optimal FGF, we measured the TV recovery time (sec) according to change in RR from 8 to 20 breaths/min to determine the optimal RR. Additionally, with fixed FGF (5 L/min) and RR (20 breaths/min), we compared the effect of PEEP (5 cmH₂O) in the two models. We measured the TV recovery time (sec) with or without a PEEP of 5 cmH₂O. The bellow deflation time, time from circuit disconnection to complete deflation of the bellow, was measured in the ascending bellow-type ventilator during mechanical ventilation with FGF of 2 and 5 L/min, TV of 500 ml, and RR of 10 breaths/min. Finally, we compared volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) by measuring the TV recovery time with the fixed FGF of 5 L/min and RR of 20 breaths/min. Peak inspiratory pressure was set to 17 cmH₂O, which resulted in a TV of almost 500 ml with our breathing bag.

![Fig. 1. Change in tidal volume recovery time according to fresh gas flow. Respiratory rate was fixed at 10 breaths/min. The recovery time was measured until a tidal volume of 450 ml was achieved for each FGF with bellow-type and piston-type ventilators; FGF, fresh gas flow.](image-url)
RESULTS

1. Effect of increasing FGF from 1 to 15 L/min

In the piston-type ventilator, the TV recovery time to 450 ml was maintained at average 43.0±0.7sec regardless of changes in FGF from 1 to 15 L/min with RR 10 breaths/min (Fig. 3). On the other hand, in the ascending bellow-type ventilator, the TV recovery time with FGF of 1 L/min was 208.3±13.1sec and decreased rapidly until FGF reached 5 L/min (55.7±0.9 sec) (Fig. 1). The TV recovery times between the two ventilators were nearly the same with an FGF of 8 L/min (43.6±1.2 sec, ascending bellow-type ventilator). Hence, we determined that the optimal FGF was 8 L/min in ascending bellow-type ventilators. Figure 2 shows the change in TV recovery time with different FGF (from 1 to 10 L/min).

2. Effect of increasing respiratory rate from 8 to 20 breaths/min

In the piston-type ventilator, the TV recovery time to 450 ml was decreased until the RR reached 20
Table 1. Comparison of tidal volume recovery time between PEEP 0 cmH₂O and PEEP 5 cmH₂O

<table>
<thead>
<tr>
<th></th>
<th>PEEP: 0 cmH₂O</th>
<th>PEEP: 5 cmH₂O</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellow-type</td>
<td>42.9±1.2</td>
<td>47.7±3.9</td>
<td>0.005</td>
</tr>
<tr>
<td>Piston-type</td>
<td>18.3±1.3</td>
<td>22.0±1.2</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Values are mean±SD (seconds); Values are tidal volume recovery time until reaching 450 ml with fresh gas flow of 5 L/min and respiratory rate of 20 breaths/min; PEEP, positive end-expiratory pressure.

Table 2. Deflation time in the ascending bellow-type ventilator

<table>
<thead>
<tr>
<th></th>
<th>FGF: 2 L/min</th>
<th>FGF: 5 L/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ TV: 500 ml</td>
<td>+ TV: 500 ml</td>
</tr>
<tr>
<td></td>
<td>+ RR: 10 breaths/min</td>
<td>+ RR: 10 breaths/min</td>
</tr>
<tr>
<td>PEEP: 0 cmH₂O</td>
<td>20 (4)</td>
<td>60 (10)</td>
</tr>
<tr>
<td>PEEP: 5 cmH₂O</td>
<td>1 (1)</td>
<td>1 (1)</td>
</tr>
</tbody>
</table>

Values are in seconds (ventilation cycles); Time from circuit disconnection to complete deflation of the bellow in the ascending bellow-type ventilator; FGF, fresh gas flow; TV, tidal volume; RR, respiratory rate; PEEP, positive end-expiratory pressure.

Table 3. Changes in tidal volume recovery time according to ventilation mode

<table>
<thead>
<tr>
<th></th>
<th>VCV</th>
<th>PCV</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellow-type</td>
<td>42.9±1.2</td>
<td>40.4±0.7</td>
<td>0.005</td>
</tr>
<tr>
<td>Piston-type</td>
<td>18.3±1.3</td>
<td>19.3±0.5</td>
<td>0.063</td>
</tr>
</tbody>
</table>

Values are mean±SD (sec); Values are tidal volume recovery time until reaching 450ml with pressure-controlled mode ventilation at a pre-set peak inspiratory pressure of 17 cmH₂O and with volume-controlled mode ventilation at a pre-set tidal volume of 500ml; VCV, volume-controlled mode ventilation; PCV, pressure-controlled mode ventilation.

breaths/min (18.3±1.3 sec) (Fig. 3). In the ascending bellow-type ventilator, the TV recovery time was decreased until the RR reached 15 breaths/min (26.1±1.7 sec) (Fig. 3). Hence, we determined the optimal RR to be 15 breaths/min.

3. Effect of PEEP

We investigated the effect of PEEP on TV recovery time with an FGF of 5 L/min and RR of 20 breaths/min. The recovery time was 47.7±3.9 sec with PEEP and 42.9±1.2 seconds without PEEP in the ascending bellow-type ventilator and was 22.0±1.3 sec with PEEP and 18.3±1.3 sec without PEEP in the piston-type ventilator (Table 1). The TV recovery time was significantly shorter in the absence of PEEP regardless of ventilator type.

Complete deflation of the bellow occurred immediately after circuit disconnection when PEEP was applied regardless of FGF (Table 2).

4. Effect of ventilation mode

The TV recovery time was significantly shorter with pressure-controlled ventilation than with volume-controlled ventilation in ascending bellow-type ventilator (Table 3).

DISCUSSION

In this study, we showed that TV recovery time after breathing circuit disconnection is influenced by FGF and RR. This is particularly apparent in the ascending bellow-type ventilator. In the ascending bellow-type ventilator, TV recovery time after breathing circuit disconnection decreased with increasing FGF. In our study, TV recovery time was 208.3±13.1 seconds with an FGF of 1 L/min and 118.7±4.9 sec with an FGF of
2 L/min but only 55.7±0.9 seconds with an FGF of 5 L/min. As the FGF increased to 5 L/min, the TV recovery time rapidly decreased. When the FGF was higher than 8 L/min, the TV recovery time plateaued, with the two types of ventilators showing nearly the same recovery time. Therefore, we determined that the ascending bellow-type ventilator had an optimal FGF of 8 L/min. In the piston-type ventilator, the changes in FGF had no effect on TV recovery time. We also investigated the effect of RR on recovery time with an FGF 8 L/min. As the RR increased to 20 breaths/min, the TV recovery time decreased in the piston-type ventilator. However, in the bellow-type ventilator, the shortest recovery time was at an RR of 15 breaths/min.

Currently, low-flow anesthesia is widely used because it is environmentally friendly and cost-effective. In our results, the TV after reconnection with an FGF 1 L/min was 110.3±67.5 ml after 160 seconds. With an FGF of 1 L/min, it took 150 seconds to reach a TV of 100 ml, suggesting that the risk of hypoxemia due to circuit disconnection is increased in low-flow anesthesia. Although the oxygen flush button can be used to fill an emptying bellow, this has the potential to result in barotrauma.(18)

When ventilation is well-maintained during mechanical ventilation, immediate circuit reconnection is not likely to cause hypoxemia. However, if the arterial oxygen tension is low due to preexisting pulmonary problems or a low FiO2, desaturation can develop earlier. Although many studies have been published on the early detection or prevention of circuit disconnection,(19,20) this complication can be missed due to alarm failure, resulting in more severe hypoxia.(5-7) Even when ventilation is resumed after reconnection, hypoxia can develop or worsen in seconds if the disconnection is detected late. If desaturation occurs, increasing FGF and RR will shorten TV recovery time and improve arterial oxygen saturation. Although oxygen flush valve can be used for bellow filling, it has a potential risk of barotrauma.(18)

Our study has some limitations. First, we did not consider the length of the breathing circuit. Although we used the same circuit length throughout the study, the dead space in the circuit can affect the results. Second, we replaced lung with a breathing bag. Further experiment is needed in clinical practice. However, we presented rationale for rapid recovery of tidal volume after bellow emptying.

CONCLUSIONS

In conclusion, in order to reduce TV recovery time after reconnection of a disconnected circuit, we recommend increasing the FGF to 8 L/min, increasing the RR to 15 breaths/min, and discontinuing PEEP, especially in the ascending bellow-type ventilator. Greater vigilance for circuit disconnection is needed when using.
the ascending bellow-type ventilator with low flow anesthesia and PEEP, especially in patients vulnerable to desaturation. Further study is required to confirm these findings in clinical practice.

CONFLICT OF INTEREST

None of the authors has received any financial support for the work and any conflict of interest in the material submitted.

ABSTRACT

Purpose: The aim of this study was to determine the optimal fresh gas flow (FGF) and respiratory rate (RR) for rapid recovery of the tidal volume (TV) after breathing circuit disconnection.

Methods: We collected data using two anesthesia machines with either an ascending bellow-type ventilator or piston-type ventilator. The primary measured parameters were the TV recovery time (sec) according to change in FGF from 1 to 15 L/min in order to determine the optimal FGF. For the secondary results, at the optimal FGF, we measured the TV recovery times (sec) according to change in RR from 8 to 20 breaths/min to determine the optimal RR.

Results: In the piston-type ventilator, the recovery time to a TV of 450 ml was about 43.0±0.7 sec regardless of changes in FGF from 1 to 15 L/min with an RR of 10 breaths/min and was decreased until achieving an RR of 20 breaths/min (18.3±1.3 sec). In the ascending bellow-type ventilator, the TV recovery time with an FGF of 8 L/min was 43.6±1.2 sec and was the shortest at RR of 15 breaths/min (26.1±1.7 sec).

Conclusions: In order to reduce the TV recovery time after reconnection of an accidentally disconnected circuit, we recommend increasing the FGF to 8 L/min, increasing the RR to 15 breaths/min, especially in the ascending bellow-type ventilator. More vigilance for circuit disconnection is needed when the ascending bellow-type ventilator with low-flow anesthesia and PEEP is used in patients who are vulnerable to desaturation.

Key Words: Breathing circuit, Disconnection, Fresh gas flow, Tidal volume, Respiratory rate

REFERENCES

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