Pressure and Flow Limitations of Anesthesia Ventilators

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The effect of increasing airway pressure on the mean inspiratory flow and maximum minute ventilation ($V_i$) capabilities of five anesthesia ventilators (Ohio Anesthesia, Airshields Ventimeter, Ohmeda 7000, Draeger AV-E and Siemens 900D) was compared to identify mechanical factor(s) limiting intraoperative ventilation of the lungs of patients with acute respiratory failure. The effect of increasing airway pressure on mean inspiratory flow was determined by cycling each ventilator through increasing resistors. Maximum $V_i$ was measured under three study conditions using a test lung: 1) low compliance (10–30 ml/cmH$_2$O) and minimal airflow resistance; 2) positive end-expiratory pressure (PEEP) of 0, 10, and 20 cmH$_2$O at a compliance of 20 ml/cmH$_2$O with minimal airflow resistance; and 3) increased resistance (19 ± 11 cmH$_2$O·l$^{-1}$·s$^{-1}$) and compliance of 30 ml/cmH$_2$O. As airway pressure increased from 0 to 80 cmH$_2$O, mean inspiratory flow decreased markedly for all ventilators except the Siemens. The Siemens ventilator delivered the greatest $V_i$ under all three conditions and maintained $V_i$ when airway pressure increased due to decreased compliance or the application of PEEP; all other ventilators markedly decreased $V_i$ under these conditions. The addition of airway resistance reduced maximal $V_i$ for all ventilators by limiting the maximal inspiratory duty cycle ($T_i/T_{TOT}$). Thus, mean inspiratory flow of conventional anesthesia ventilators decreases with increasing airway pressure. The decreased inspiratory flow limits maximum $V_E$ when airway pressure is elevated because of decreased lung–thorax compliance and/or increased airway resistance, such that characterizing patients with acute respiratory failure. Significant airway resistance further limits maximum $V_E$ by limiting the maximal $T_i/T_{TOT}$ that can be used without increasing end-expiratory lung pressure. The data indicate that a critical care type ventilator with pressure-independent inspiratory flow should be considered for intraoperative ventilation when $V_E$ exceeds 15 l/min or peak airway pressures exceed 50 cmH$_2$O. (Key words: Equipment, ventilators: characteristics. Lungs: airway resistance; compliance. Ventilator: mechanical.)

Patients with acute respiratory failure requiring mechanical ventilation often undergo general anesthesia and surgery. Ventilatory support may require a high minute ventilation ($V_i$), increased peak inspiratory airway pressures (PIP), and high levels of positive end-expiratory pressure (PEEP). For example, at San Francisco General Hospital between 1984 and 1986, 302 patients whose lungs were being mechanically ventilated and who were hospitalized in the intensive care units (ICU) required general anesthesia and surgery; preoperative ventilatory requirements included a $V_E = 14.0 ± 6.1$ l/min, $PIP = 40 ± 13$ cmH$_2$O, and $PEEP = 6.3 ± 5.2$ cmH$_2$O (mean ± S.D.).

In our experience, when $V_E$ requirements and/or PIP are elevated, typical anesthesia ventilators are either unable to deliver the required $V_E$ or can do so only by markedly increasing the inspiratory duty cycle (the ratio of inspiratory time [$T_i$] to total breathing cycle duration [$T_{TOT}$]). Failure to deliver the required $V_E$ results in intraoperative hypercapnia and possibly hypoxemia. An increase in the inspiratory duty cycle ($T_i/T_{TOT}$) may result in gas trapping, a rise in the end-expiratory lung pressure, and potential barotrauma or hemodynamic compromise. These complications can be avoided by knowing which anesthesia ventilators can deliver the required $V_E$ in an acceptable inspiratory time when airway pressure is elevated.

Manufacturer specifications could be used to predict the maximum $V_E$ for a ventilator. Specifically, knowledge of mean inspiratory flow ($V_i$) and the maximum $T_i/T_{TOT}$ permit calculation of a theoretical maximum $V_E$ ($V_E = V_i \times [T_i/T_{TOT}]$). Currently, however, manufacturers provide maximal inspiratory flow rates [Operators Manual Ohmeda 7000 Electronic Ventilator (Madison: BOC Health Care), Operators Manual Isolette Ventimeter Ventilator (Warminster: NARCO, 1973), Service Manual Ohio Anesthesia Ventilator (Madison Aircos), Ventilator Instruction Manual North American Draeger AV-E (Telford, Pennsylvania)]. Substituting maximal inspiratory flow for mean inspiratory flow results in a predicted maximum $V_E$ for five commonly used anesthesia ventilators much greater than we have observed clinically (table 1). The overestimation of maximal $V_E$ occurs because the ventilators are unable to maintain maximal inspiratory flow with increasing airway pressure. Possible mechanisms for the decrease in inspiratory flow are compression of gases in the breathing circuit, distension of the breathing circuit, and failure of the ventilators’ flow generator (the device providing the gas flow that compresses the bellows).

Previous studies of anesthesia ventilators examined the effect of minor increases in airway pressure (generally less

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than 25 cmH₂O peak airway pressure) and only measured peak inspiratory flow.⁴,⁷,⁸ No attempt was made to correlate decreases in inspiratory flow with limitations in maximal \( \dot{V}_E \). The increase in the number of patients with acute respiratory failure undergoing general anesthesia and surgery necessitated a reexamination of the pressure and flow limitations of anesthesia ventilators and the effect of these limitations on maximum \( \dot{V}_E \) capabilities. Accordingly, we determined the maximum \( \dot{V}_E \), and the factors limiting ventilation, of five commonly used anesthesia ventilators during conditions simulating the pulmonary diseases that result in elevated airway pressures in patients with acute respiratory failure. We postulated that we would find important differences in maximum \( \dot{V}_E \) between ventilators due primarily to differences in mean inspiratory flow.

Materials and Methods

The five anesthetic ventilators studied included two older fluidic ventilators still widely used (Airshields Ventimeter™ and Ohio Anesthesia™), two newer electronically controlled ventilators (Draeger Narkomed AV-E™ and Ohmeda 7000™), and an electronically controlled ICU ventilator adapted for use in the operating room (Siemens 900D™). All ventilators were inspected and calibrated to manufacturer specifications prior to study. Each ventilator was tested as part of the anesthesia machine provided by the manufacturer. An airflow of 5 l/min was provided via the fresh gas outlet for all ventilators except the Siemens, which was powered by its own blender. Low compliance tubing (Dart Respiratory) was used to complete the breathing circuit. A Jaeger pneumotachograph, positioned immediately distal to the y-piece of the circuit, measured inspiratory and expiratory time and tidal volume (\( V_T \)) (fig. 1).

The pneumotachograph and pressure transducers were calibrated before each ventilator study. The pneumotachograph was calibrated at ambient temperature and pressure with a Fisher Porter flow tube for flow and a 500 ml Warren Collins super syringe for volume. Pressure transducers were calibrated against a water column. Signals from the pneumotachograph and pressure transducers were recorded on a strip chart recorder (Gould) at 50 mm/s. Inspiratory and expiratory time, \( V_T \), and airway pressure were obtained by caliper analysis of 10 respiratory cycles.

The study was conducted in three parts. In part 1 we measured the effect of increasing airway pressure on mean inspiratory flow by cycling each ventilator/anesthesia machine through progressively increasing restrictors (progressively smaller endotracheal tubes) into the room (infinite compliance) (fig. 1A). Ventilator settings were adjusted to achieve maximal inspiratory flow and a \( V_T \) of 800 ml. Mean inspiratory flow was calculated as \( V_T / T_1 \). In part 2 we used the same technique to determine the effect of increasing airway pressure on the mean inspiratory flow of each ventilators' flow generator. This was accomplished by removing all compressible volume (ab-

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**Table 1. Predicted Maximum Minute Ventilation Using Manufacturers’ Specifications**

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Pressure (cmH₂O)</th>
<th>Inspiratory Flow (l/min)</th>
<th>T₁/Tₚrier</th>
<th>Predicted ( \dot{V}_E^* ) (l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airshields Ventimeter</td>
<td>60</td>
<td>60</td>
<td>0.7</td>
<td>42</td>
</tr>
<tr>
<td>Ohio Anesthesia</td>
<td>55</td>
<td>85</td>
<td>0.7</td>
<td>60</td>
</tr>
<tr>
<td>Draeger AV-E</td>
<td>100</td>
<td>100</td>
<td>0.5</td>
<td>50</td>
</tr>
<tr>
<td>Ohmeda 7000</td>
<td>70</td>
<td>60</td>
<td>0.5</td>
<td>30</td>
</tr>
<tr>
<td>Siemens 900D</td>
<td>120</td>
<td>200</td>
<td>0.5</td>
<td>100</td>
</tr>
</tbody>
</table>

* Predicted maximum minute ventilation \( (\dot{V}_E) = (\text{inspiratory flow}) \times (T_1/T_{prier}) \).
Fig. 2. Model for determining maximum minute ventilation. Each ventilator/ anesthesia machine was connected via an endotracheal tube to a test lung with adjustable compliance. Resistance was altered by changing the diameter of the endotracheal tube. A separate transducer measured pressure inside the test lung.

sorber, bellows, and circle system) from the ventilator/ anesthe sia machine and connecting the pneumotachograph directly to the source of flow that compressed the bellows (fig. 1B). The Siemens ventilator was excluded from part 2 because it does not have removable compressible volume. By comparing the results obtained in part 2 (figs. 1A and 1B), we were able to determine whether the effect of increasing airway pressure on mean inspiratory flow was due to compressibility and/or failure of the flow generator.

In part 3 of the study, we measured maximal $V_E$ under three different conditions by connecting the breathing circuit to a test lung (Training Test Lung, Michigan Industries) having adjustable resistance and compliance (fig. 2). The end-expiratory pressure inside the test lung was measured using a separate transducer. During all three study conditions, $V_T$ was set at 800 ml (when permitted by the pressure limit of the ventilator), and maximal $V_E$ was obtained by increasing frequency ($60/T_{TOT}$) until the ventilator’s frequency limit was reached, $V_T$ could not be maintained, or the amount of gas trapping exceeded a specific end-expiratory lung pressure (usually 5 cmH$_2$O). A lower limit for end-expiratory lung pressure was not possible due to the presence of 3–4 cmH$_2$O of PEEP in the circle system with a 5 l/min fresh gas flow. Maximal $V_E$ was calculated as $(V_T) \times (60/T_{TOT})$.

For condition 1, maximal $V_E$ was measured over a series of decreasing compliances (30, 20, 15, and 10 ml/cmH$_2$O) during minimal airway resistance (10 mm internal diameter [ID], 15 cm long endotracheal tube [ETT] connection between the pneumotachograph and the test lung). End-expiratory pressure was limited to 5 cmH$_2$O.

For condition 2, maximal $V_E$ was measured at 0, 10, and 20 cmH$_2$O of PEEP at a compliance of 20 ml/cmH$_2$O, minimal airflow resistance (same as condition 1), and an end-expiratory lung pressure limit of 5 cmH$_2$O above the PEEP level. A Vital Signs™ spring loaded PEEP valve was used with all machines except for the Siemens, which has its own built in PEEP valve.

For condition 3, maximal $V_E$ was measured at increased airway resistance, a compliance of 30 ml/cmH$_2$O, and an end-expiratory lung pressure limit of 5, 10, 15, 20, and 25 cmH$_2$O. Increased airway resistance was achieved by using a 5.5 mm ID 29 cm long ETT connection between the pneumotachograph and the test lung (mean resistance $19 \pm 11$ cmH$_2$O $l^{-1} s^{-1}$).

### Results

The Siemens ventilator delivered the greatest mean inspiratory flow at all airway pressures, and its inspiratory flow was largely pressure-independent at airway pressures less than 80 cmH$_2$O (fig. 3). Mean inspiratory flow decreased markedly with increasing airway pressure in all other ventilators. The flow generators of the Airshields and Ohmeda ventilators maintained mean inspiratory flow with increasing airway pressure (fig. 4). In contrast, mean inspiratory flow from the flow generators of the Ohio and
Draeger ventilators decreased progressively with increasing airway pressure (fig. 4).

The Siemens ventilator delivered greater $\dot{V}_E$ than the other ventilators during decreased compliance with no airway resistance (condition 1) (table 2). As compliance progressively decreased, the Siemens ventilator maintained $\dot{V}_E$ while all other ventilators showed decreasing $\dot{V}_E$ (table 2). The fluidic Ohio and Airshields ventilators delivered higher $\dot{V}_E$ than the electronic Draeger and Ohmeda ventilators but spent 70% of the respiratory cycle in inspiration to do so. The fluidic ventilators also could not maintain $V_T$ at 800 ml at compliances below 20 cmH₂O because the required PIP exceeded their pressure limit. Except for the Siemens, $\dot{V}_E$ also progressively decreased with the application of PEEP (condition 2) in all ventilators (table 3). The fluidic ventilators again could not maintain $V_T$ during PEEP (table 3).

During increased airway resistance (condition 3) at an end-expiratory lung pressure of 5 cmH₂O, $\dot{V}_E$ and $T_{I/T_TOT}$ were lower than at the same compliance without airway resistance in all ventilators (table 4). As $\dot{V}_E$ was increased by increasing respiratory frequency, end-expiratory lung pressure rose rapidly for all ventilators (fig. 5). For any $\dot{V}_E$, however, the Siemens ventilator caused the least elevation of end-expiratory lung pressure.

**Discussion**

The commonly used anesthesia ventilators decrease mean inspiratory flow with increasing airway pressure. Inspiratory flow decreases because of compressibility (compression of gases and distension of the breathing circuit [ventilator bellows, absorber and connecting tubing]) and the type of flow generator used.

In ventilators with flow generators that are pressure-independent (Airshields and Ohmeda), compressibility is responsible for the decrease in mean inspiratory flow from the ventilator/anesthesia machine (fig. 3 vs. fig. 4). A typical adult circle circuit with ventilator has a compression volume of 6–7 l and a compressibility of 6–12 ml/cmH₂O. In ventilators with pressure-dependent flow generators (Ohio and Draeger), both compressibility and decreasing flow from the flow generator contribute to the decrease in flow from the ventilator/anesthesia machine (fig. 3 vs. fig. 4). This accounts for the greater rate of decrease in mean inspiratory flow in the Draeger and Ohio ventilators/anesthesia machines compared with the Airshields and Ohmeda ventilators/anesthesia machines (fig. 3). The fresh gas flow partially compensates for decreased flow in an amount equal to the product of the fresh gas flow (l/min) and the $T_{I/T_TOT}$.

In contrast to the typical anesthesia ventilators, the Siemens ventilator maintains constant flow up to airway pressures of 80 cmH₂O. Flow is maintained because the Siemens has minimal compressible volume and a flow generator that is pressure-independent until the working pressure limit of the flow generator is approached. If the working pressure limit is not set at maximum (120 cmH₂O), then flow will not be as well maintained as airway pressure increases.

The decrease in inspiratory flow that occurs with increasing airway pressure limits the maximum $\dot{V}_E$ of typical anesthesia ventilators ($\dot{V}_E = \dot{V}_1 \times [T_{I/T_TOT}]$). Minute ventilation could be maintained by increasing $T_{I/T_TOT}$, but this may result in gas trapping depending on the specific lung–thorax compliance and airway resistance. When
compliance is reduced out of proportion to an increase in airway resistance (conditions 1 and 2), the time constant for lung emptying is short and $T_1/T_{TOT}$ is limited primarily by the internal timing mechanism of the ventilator. When airway resistance is increased (condition 3), the time constant for lung emptying is longer and $T_1/T_{TOT}$ is limited by the longer expiratory time necessary to avoid increased end-expiratory lung pressure. The shorter $T_1/T_{TOT}$ accounts for the reduced $\dot{V}_E$ compared with conditions with the same compliance without increased airway resistance (table 4). The Siemens ventilator delivered the greatest $\dot{V}_E$ under conditions of increased resistance, but the difference between it and the other ventilators was less than in conditions 1 and 2. Several features of the Siemens ventilator decrease its performance during increased resistance by further limiting the duration of inspiratory flow. These include a built-in 10% inspiratory pause and the use of click-stop inspiratory time selectors (25%, 33%, and 50%), rather than a continuously selectable I:E ratio.

The pressure and flow limitations of typical anesthesia ventilators have important clinical implications when patients with increased $\dot{V}_E$ requirements and increased PIP require anesthesia and surgery. Typical anesthesia ventilators may be unable to deliver the required $\dot{V}_E$ or can do so only by using a long inspiratory duty cycle ($T_1/T_{TOT}$). Failure to deliver the required $\dot{V}_E$ results in intraoperative hypercarbia and possibly hypoxemia. A long $T_1/T_{TOT}$ may result in gas trapping and potential barotrauma or hemodynamic compromise. To avoid these complications, it is important to know when a critical care ventilator will be required.

In patients whose lungs are being mechanically ventilated preoperatively, a theoretical maximum $\dot{V}_E$ can be calculated for a specific anesthesia ventilator using the

\[
\dot{V}_E = \frac{T_1}{T_{TOT}} \times \dot{V}_i
\]

where $\dot{V}_E$ is the minute ventilation (L/min), $T_1$ is the inspiratory time (s), $T_{TOT}$ is the total time (s), and $\dot{V}_i$ is the inspiratory flow rate (L/s). The peak inspiratory pressure, $P_{IP}$, and the maximal allowable $T_1/T_{TOT}$ can be calculated as

\[
P_{IP} = \frac{\dot{V}_i}{\dot{V}_E} \times P_{aw}
\]

where $P_{aw}$ is the airway pressure (cm H₂O).

**Table 3. Effect of PEEP on Minute Ventilation (\(\dot{V}_E\)) and Inspiratory Duty Cycle (\(T_1/T_{TOT}\)) at a Compliance of 20 ml/cm H₂O and Minimal Airway Resistance**

<table>
<thead>
<tr>
<th>PEEP</th>
<th>Siemens 900D</th>
<th>Drager AV-E</th>
<th>Ohio Anesthesia</th>
<th>Airshields Ventimeter</th>
<th>Ohmeda 7000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>42</td>
<td>29</td>
<td>30</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>$\dot{V}_E$</td>
<td>0.33</td>
<td>0.50</td>
<td>0.64</td>
<td>0.68</td>
<td>0.48</td>
</tr>
</tbody>
</table>

| 10   | 44           | 27          | 24†             | 25‡                  | 20         |
| $\dot{V}_E$ | 0.50        | 0.50        | 0.60            | 0.64                 | 0.44       |

| 20   | 43           | 25          | 22§             | 21¶                  | 18         |
| $\dot{V}_E$ | 0.50        | 0.50        | 0.58            | 0.56                 | 0.44       |

* End expiratory lung pressure limited to 5 cm H₂O above the PEEP level.
† $V_T = 700$ ml.
‡ $V_T = 750$ ml.
§ $V_T = 580$ ml.
¶ $V_T = 550$ ml.

**Table 4. Minute Ventilation (\(\dot{V}_E\)) and Inspiratory Duty Cycle (\(T_1/T_{TOT}\)) during Minimal and Increased Airway Resistance**

<table>
<thead>
<tr>
<th>Resistance</th>
<th>Siemens 900D</th>
<th>Drager AV-E</th>
<th>Ohio Anesthesia</th>
<th>Airshields Ventimeter</th>
<th>Ohmeda 7000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal</td>
<td>44</td>
<td>26</td>
<td>32</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>$T_1/T_{TOT}$</td>
<td>0.33</td>
<td>0.40</td>
<td>0.61</td>
<td>0.60</td>
<td>0.47</td>
</tr>
<tr>
<td>Increased</td>
<td>22</td>
<td>17</td>
<td>20</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>$T_1/T_{TOT}$</td>
<td>0.25</td>
<td>0.33</td>
<td>0.49</td>
<td>0.47</td>
<td>0.38</td>
</tr>
</tbody>
</table>

* End respiratory lung pressure limited to 5 cm H₂O and compliance = 30 ml/cm H₂O.

![Fig. 5. Effect of increasing minute ventilation on end-expiratory lung pressure during increased airway resistance (condition 3). At any minute ventilation, the Siemens 900D ventilator had the lowest end-expiratory lung pressure.](http://anesthesiology.pubs.asahq.org/pdfaccess.ashx?url=/data/journals/jasa/931360/ on 06/23/2017)
operative PIP, and the pressure-flow curve for the Draeger ventilator (best pressure flow capabilities of the typical anesthesia ventilators, fig. 3). Based on a comparison of the preoperative $V_E$ requirements with the calculated maximum $V_E$, 33% of the patients would have required a critical care type ventilator for intraoperative ventilation.

While selection of an intraoperative ventilator must be based on each individual patient's ventilatory requirements, the pressure/flow analysis indicates that a critical care type ventilator should be considered for intraoperative ventilation when preoperative $V_E$ exceeds 15 l/min and/or peak airway pressures exceed 50 cmH$_2$O. These guidelines will ensure adequate intraoperative CO$_2$ elimination and oxygen gas exchange. Providing optimal perioperative oxygen gas exchange, however, may require more conservative guidelines for selection of a critical care ventilator due to intraoperative changes in respiratory mechanics and distribution of inspired gas. Although many critical care ventilators have the required pressure/flow capabilities, only the Siemens 900D has the capability for delivering anesthetic gases. Use of other critical care ventilators would either require special adaptation for delivering anesthetic gases or would require using intravenous anesthetics.

In summary, ventilators selected for intraoperative ventilation of patients with acute respiratory failure should be able to deliver a high mean inspiratory flow at increased airway pressures. In general, this means selecting a ventilator with a pressure-independent flow generator and minimal compressible volume, such as the Siemens 900D. As new anesthesia ventilators become available, manufacturers should provide a graph of mean inspiratory flow versus airway pressure (for the ventilator/anesthesia machine circuit as well as the ventilator flow generator) as part of the operator's manual. This information would best permit clinicians to predict whether a ventilator is capable of providing the required $V_E$ for a particular clinical situation.

References