WHAT CHANGES CAN BE EXPECTED DURING HIGH FREQUENCY JET VENTILATION WHEN THE RATE OF VENTILATION, THE I:E RATIO AND THE DRIVING PRESSURE ARE MODIFIED?

A Laboratory Study

M. FISCHLER, F. SEIGNEUR, B. BOURRELI, J. C. MELCHIOR, C. LAVAUD AND G. VOURC'H

During high frequency jet ventilation the absolute tidal volume delivered to the patient depends on the interplay of many factors. These can be classified broadly into three groups: adjustments made to the ventilator (driving pressure, inspiratory:expiratory (I:E) ratio, rate of ventilation), adjustments made to the injector (size and location of the injector, angle of injection), and the mechanical properties of the patient's respiratory system.

Results have been reported on the use of different sizes (Davey, Lay and Leigh, 1982) and locations (Rossing et al., 1984) of injector. Patients with different lung compliances have been studied during high frequency jet ventilation at different rates of ventilation, I:E ratios (Rouby et al., 1983) or driving pressure (Benhamou et al., 1984). However, no investigation has evaluated the changes in ventilation induced by the alteration of one of the three ventilator settings (driving pressure, I:E ratio, rate of ventilation). This lack of information can be explained in part by the technological difficulties of the measurement of the volumes of ventilation. It is also difficult to find a group of patients with similar respiratory mechanical properties, since differences in static respiratory compliance (Rouby et al., 1983) and airway resistance may interfere with the assessment of ventilation. However, this type of study can be performed easily using a lung model, as demonstrated in our previous paper which focused on the use of high frequency jet ventilation during bronchoscopy (Fischler et al., 1985). The purpose of the present study was to determine the effects on minute ventilation, tracheal airway pressure and functional residual capacity produced by alterations in three ventilator settings, the other factors (mechanics of the respiratory system and injection characteristics) remaining stable throughout the period of study.

SUMMARY

Changes in minute ventilation, tracheal airway pressure and lung volume have been measured using a jet ventilator (VS 600) during different rates of ventilation, I:E ratios and driving pressures. A lung model with a slightly increased compliance and an increased airway resistance was used. Five rates of ventilation (from 60 to 230 b.p.m.), three I:E ratios (0.25, 0.43, 0.67) and three driving pressures (200, 300 and 400 kPa) were studied. The increases in the rate of ventilation did not modify minute ventilation significantly, decreased peak airway pressure only slightly and increased end-expiratory pressure and lung volume. The increases in I:E ratio produced increases in minute ventilation, peak airway pressure, end-expiratory pressure and lung volume. The increases in driving pressure induced changes similar to those produced by the alterations in I:E ratio.
MATERIALS AND METHODS

The apparatus used was identical to that used in a previous study (Fischler et al., 1985), and is depicted in figures 1 and 2.

A Storz No. 8 rigid bronchoscope (i.e. 10 mm) was modified by welding a 2.5-mm brass injector channel on the side of the bronchoscope. This injector channel opened obliquely (60°) inside the bronchoscope 8 cm from the tip. An IDC jet ventilator model VS 600 (Acutronic, Medical System AG, Switzerland) was connected to the injector via a 100-cm low compliance catheter.

The bronchoscope was connected to a bialveolar lung model which had a maximal inspiratory capacity of 3.38 litre, and a functional residual capacity of 3.24 litre (helium dilution). (The lung model (GLEM, Fontenay-aux-Roses) has been approved as a reference by the ISO commission (International Meeting of the ISO Commission, June 1983, Stockholm).) The total deadspace of the apparatus was 130 ml: 52.5 ml from the injector to the lung model and 77.5 ml within the lung model. The model had a slightly increased static compliance of 1.41 litre kPa$^{-1}$ (138 ml/cm H$_2$O), and a bronchial resistance (a parabolic resistance) of 1.57 kPa/(litre s$^{-1}$)$^2$ (16.02 cmH$_2$O/(litre s$^{-1}$)$^2$) which was greater than
the physiological total airway resistance (linear resistance of 0.25 kPa/(litre s\(^{-1}\))).

Flow was measured with a Fleisch No. 1 pneumotachograph (Hewlett-Packard); this can measure a flow rate up to 2.6 litre s\(^{-1}\) and its linearity from 0 to 75% of maximum flow rate is 1.25%. Flow could, thus, be measured, since the maximum flow observed was 1.91 litre s\(^{-1}\). Tidal volumes were obtained by integrating the flow signal (Hewlett-Packard integrator 8816 A). Minute ventilation (litre min\(^{-1}\)) was calculated as the product of tidal volume \(\times\) frequency of ventilation.

Airway pressure was measured (Hewlett-Packard pressure transducer No. 270) laterally at the carina of the model (20 cm from the injector). Peak inspiratory and end-expiratory pressures are expressed as (cm H\(_2\)O).

Increases in functional residual capacity above the resting volume (air trapping) were assessed at the end of each period of ventilation when the lung model emptied.

All signals were amplified (HP 8802 A and 8805 C amplifiers) and recorded on an HP 7754 B four-channel recorder.

The responses in frequency of the pneumotachograph and of the pressure transducer were studied with a sinewave pressure generator (Institut National de la Santé et de la Recherche Médicale U 14, Nancy, France) and found to have a flat response up to 5 Hz (300 min\(^{-1}\)) for the pneumotachograph and up to 20 Hz for the pressure transducer.

The model was ventilated with air; the driving pressure was either 200 ±10, 300 ±10 or 400 ±10 kPa (the standard deviation represents the pressure fluttering during ventilation), the I:E ratio being either 0.25, 0.43 or 0.67. For each driving pressure and for each I:E ratio, five rates of ventilation were studied: 60, 90, 110, 170 and 230 b.p.m.

Because of limitations in the range of the pressure transducer, peak airway pressure could not be recorded when a 400 kPa driving pressure and a 0.67 I:E ratio were used.

The effects of the increase in driving pressure are reported as the mean ± SD of the measurements obtained using the three I:E ratios. The effects of the increase in I:E ratio are reported as the mean ± SD of the measurements obtained using the three driving pressures.

**RESULTS**

Although the measured rates of ventilation were different from those displayed on the ventilator, they were perfectly stable irrespective of the other modifications to the ventilator settings.

**Minute ventilation (fig. 3)**

Increases in the rate of ventilation, from 60 to 230 b.p.m. did not induce any significant change in minute ventilation.

The increases in the I:E ratio induced parallel increases in driving pressure.

**TABLE 1. Minute ventilation (litre min\(^{-1}\)) for several driving pressures and I:E ratios. Mean (± SD) of the five rates of ventilation**

<table>
<thead>
<tr>
<th>I:E ratio</th>
<th>200 kPa</th>
<th>300 kPa</th>
<th>400 kPa</th>
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<tbody>
<tr>
<td>0.25</td>
<td>15.36 ± 0.18</td>
<td>22.02 ± 0.54</td>
<td>27.66 ± 0.33</td>
</tr>
<tr>
<td>0.43</td>
<td>22.70 ± 0.26</td>
<td>30.50 ± 0.10</td>
<td>40.22 ± 0.11</td>
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<tr>
<td>0.67</td>
<td>25.60 ± 0.17</td>
<td>35.48 ± 0.57</td>
<td>45.28 ± 0.90</td>
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</table>
Increases in minute ventilation. When the I:E ratio was changed from 0.25 to 0.43, the percentage increase in minute ventilation was 43.9 ± 4.7. When the I:E ratio was changed from 0.43 to 0.67, the percentage increase in minute ventilation was 13.9 ± 2.6.

Likewise, the increases in driving pressure produced parallel increases in minute ventilation. When the driving pressure was increased from 200 to 300 kPa, minute ventilation increased by 38.8 ± 4.3%, and when it was increased from 300 to 400 kPa, the percentage increase was 28.4 ± 3.6.

Similar minute ventilations can be obtained using different adjustments of the driving pressure and of the I:E ratio (table I); for example, ventilation with a driving pressure of 300 kPa and an I:E ratio of 0.25 provided a minute ventilation identical to that with a driving pressure of 200 kPa and an I:E ratio of 0.43.

Peak airway pressure (fig. 4)

Peak airway pressure decreased only slightly when the rate of ventilation was increased. For example, using a driving pressure of 300 kPa and an I:E ratio of 0.43, peak airway pressures were 11 cm H₂O and 10.2 cm H₂O at ventilation frequencies of 60 and 230 b.p.m., respectively.

Increases in the I:E ratio, on the other hand, induced parallel increases in the peak airway pressure. When the I:E ratio was changed from 0.25 to 0.43, the percentage increase in peak airway pressure was 17.3 ± 4.4, and when it was changed from 0.43 to 0.67, peak airway pressure increased by 11.7 ± 2.1%.

The increases in the driving pressure induced more marked increases in peak airway pressure from 200 to 300 kPa peak airway pressure increased by 72.9 ± 3.6% and from 300 to 400 kPa, peak airway pressure increased by 43.4 ± 2.9%.

Increases in driving pressure Increase in I:E ratio

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</tr>
<tr>
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<td>60 90 110 170 230</td>
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FIG. 4. Changes in peak airway pressure when the driving pressure was increased at each of the three I:E ratios (left column), and when the I:E ratio was increased at each of the three driving pressures (right column).

End-expiratory pressure (fig. 5)

End-expiratory pressure decreased only slightly when the rate of ventilation was increased. For example, using a driving pressure of 300 kPa and an I:E ratio of 0.43, end-expiratory pressures were 11 cm H₂O and 10.2 cm H₂O at ventilation frequencies of 60 and 230 b.p.m., respectively.

Increases in the I:E ratio, on the other hand, induced parallel decreases in the end-expiratory pressure. When the I:E ratio was changed from 0.25 to 0.43, the percentage increase in end-expiratory pressure was 17.3 ± 4.4, and when it was changed from 0.43 to 0.67, peak airway pressure increased by 11.7 ± 2.1%.

The increases in the driving pressure induced more marked decreases in peak airway pressure from 200 to 300 kPa peak airway pressure increased by 72.9 ± 3.6% and from 300 to 400 kPa, peak airway pressure increased by 43.4 ± 2.9%.

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FIG. 5. Changes in end-expiratory airway pressure when the driving pressure was increased at each of the three I:E ratios (left column), and when the I:E ratio was increased at each of the three driving pressures (right column).
**End-expiratory airway pressure (fig. 5)**

End-expiratory airway pressure increased as the rate of ventilation increased. For example, using a driving pressure of 300 kPa and an I:E ratio of 0.43, end-expiratory pressure was 1.35 cm H\textsubscript{2}O at 60 b.p.m. and 2.2 cm H\textsubscript{2}O at 230 b.p.m. A positive end-expiratory pressure was always present whatever the ventilator setting.

The increases in the I:E ratio induced parallel increases in the end-expiratory airway pressure. When the I:E ratio was changed from 0.25 to 0.43, the percentage increase in end-expiratory pressure was 161.4±27.8, and when the ratio was changed from 0.43 to 0.67, the percentage increase was 66.9±15.9.

The increases in driving pressure produced less marked increases in end-expiratory pressure, the percentage increases being 73.6±21.8 and 61.1±16 when the driving pressure was changed from 200 to 300 kPa, and from 300 to 400 kPa, respectively.

**Functional residual capacity (fig. 6)**

Changes in functional residual capacity were similar to those described for end-expiratory pressure.

**DISCUSSION**

High frequency jet ventilation can be used during laryngoscopy (Babinski, Smith and Klain, 1980), bronchoscopy (Vourc'h et al., 1983a), tracheal laser surgery (Vourc'h et al., 1983b), and lung surgery (El-Baz et al., 1982). Its use has been suggested in other areas of anaesthesia (Marquez et al., 1982) and in patients presenting with postoperative respiratory failure (Rouby et al., 1983) or with a bronchopleural fistula (Carlon et al., 1980).

Since jet ventilators cannot provide any indication of the volumes of ventilation, the clinician must try successively different ventilator settings or vary the size or location of the injector. Our data made it possible to obtain approximate values for minute ventilation, airway pressure and the increase in functional residual capacity coincident with various rates of ventilation, I:E ratios and driving pressures. The characteristics of the injector and lung model did not change throughout the study. The latter was adjusted to simulate the usual pattern in patients submitted to endoscopic airway procedures: an increase in airway resistance and a slight increase in compliance.

During high frequency jet ventilation, ventilation is provided by the gases blown by the jet ventilator and by the entrained air. The jet ventilator works like a flow interruptor and a modification of the rate of ventilation should not modify the minute ventilation, although an increase in driving pressure or in I:E ratio should produce an increase in the portion of ventilation attributable to the ventilator. The percentage increase can be predicted.

The relationship between the increase in I:E ratio and the increase in minute ventilation is clear: minute ventilation varies linearly with the increase in inspiratory time. The change from an I:E ratio of 0.25 to one of 0.43 represents a 50\% increase in inspiratory time; this must induce a 50\% increase in the portion of ventilation provided by the ventilator per se. A 33\% increase results from an increase from a ratio of 0.43 to one of 0.67. Our results demonstrated lesser increases in total minute ventilation for each of these modifications; these can be interpreted as being
the result of decreases in the part of ventilation attributable to air entrainment.

Increases in driving pressure and increases in minute ventilation are also related, since the jet injector presents no resistance to the jet (the diameters of the injector and of the solenoid valve are 2.5 mm and 2.2 mm, respectively). An increase in driving pressure from 200 to 300 kPa must induce a 50% increase in the part of the minute ventilation attributable to the ventilator. A 33% increase is provided by an increase in driving pressure from 300 to 400 kPa. Our results demonstrated, once more, a smaller increase in total minute ventilation for each of these modifications; this can also be interpreted as resulting from a decrease in the volume of air entrained.

Changes in end-expiratory pressure and in lung volume are linearly related as we have demonstrated previously (Fischler et al., 1985). Increase in lung volume depends upon the relationship between the inflow and the outflow of gas. The inflow depends on two factors: time of injection (rate of ventilation, I:E ratio) and instantaneous flow (driving pressure). The outflow depends also upon two factors: expiratory time (rate of ventilation, I:E ratio) and the time constant of the respiratory system (airway resistance, total compliance). The latter was constant throughout our study. Hence, an increase in lung volume can be obtained by: increasing the duration of injection (increase in I:E ratio), decreasing the expiratory time (increase in the rate of ventilation), or increasing the instantaneous flow (driving pressure).

Clinical implications

Although the actual mechanisms of gas transport during high frequency jet ventilation are not clear, minute ventilation appears to be the major determinant of carbon dioxide elimination up to a rate of around 200 b.p.m. (Rossel et al., 1981; Slutsky et al., 1981). Accordingly, it would not seem helpful to change the rate of injection, between 60 and 230 b.p.m., since we have reported that minute ventilation is constant within this range. Marked increases in minute ventilation can be obtained by increasing the driving pressure from 200 to 300 kPa or by increasing the I:E ratio from 0.25 to 0.43. Further changes (300 to 400 kPa and 0.43 to 0.67) induced less marked changes in minute ventilation. However, increase in the driving pressure, rather than the I:E ratio, was associated with higher peak airway pressures even when high rates of ventilation were used.

As demonstrated by Rouby and colleagues (1983), the improvement in oxygenation which occurs during high frequency jet ventilation is the result of an increase in lung volume and probably follows the same law as during conventional ventilation: the increase in arterial $P_{\text{aO}_2}$, is related to the increase in end-expiratory pressure and thus in lung volume (Pontoppidan et al., 1977). Such increases in lung volume can, therefore, be achieved in several ways: an increase in the rate of ventilation, an increase in the I:E ratio or an increase in the driving pressure. The beneficial effects of the increases in I:E ratio and in driving pressure have been demonstrated in patients presenting with an acute respiratory failure (Rouby et al., 1983; Benhamou et al., 1984), although Rouby and colleagues (1983) reported no effect on arterial $P_{\text{aO}_2}$ when the rate of ventilation was increased; this was probably attributable to the decreased lung compliance in their patients.

In conclusion, our laboratory study can be used as a guide by which increases in minute ventilation or in lung volume, or both, can be achieved by appropriate adjustments of a high frequency jet ventilator.

REFERENCES


