A NEW VALVELESS ALL-PURPOSE VENTILATOR
Clinical Evaluation

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SUMMARY
Preliminary clinical evaluation of a new ventilator, which embodies a new valveless design principle and a circuit which is open to atmosphere, has been performed on adult patients undergoing surgery. Using normal respiratory fresh gas flows (100 ml kg⁻¹ min⁻¹) PaCO₂ and PaO₂ were the same as with a conventional ventilator. High frequency ventilation (HFV) up to 100 b.p.m. caused no statistically significant changes in PaCO₂ and PaO₂. The peak airway pressures were 30% less than with a Manley ventilator and decreased by a further 40% during HFV. PEEP, NEEP, CPAP and IMV were easily applied.

Although the new generation of conventional ventilators are complex and expensive they still lack versatility for general application and are not suitable for high frequency ventilation. As a result, interested clinicians have developed their own high frequency systems (Bohn et al., 1980; Chakrabarti and Sykes, 1980; Sjostrand, 1980) and, consequently, the clinical applications of this technique have been limited and clinical evaluation restricted to a few case reports (Sjostrand, 1980; Rossing et al., 1981; Davey, Lay and Leigh, 1982).

A new valveless all-purpose ventilator has been developed and described in the previous paper (Chakrabarti and Whitwam, 1983). Its circuit is illustrated in figure 1. This paper describes the preliminary evaluation of this ventilator in patients.

PATIENTS AND METHODS
Observations were made on 12 adult patients anaesthized with a thiopentone, opiate, nitrous oxide–oxygen sequence. Pancuronium was administered to produce neuromuscular blockade. All were about to undergo either cardiac or intrahepatic biliary surgery. The patients undergoing cardiac surgery were studied in the anaesthetic room before surgery. Observations on the patients undergoing liver surgery were made during surgery and in the early part of the recovery period. Their ages and weights were in the ranges 30–70 yr and 55–90 kg, respectively. All were in ASA grades I–III. A radial artery and the right internal jugular vein were cannulated and access obtained to peripheral veins for the infusion of fluids. Arterial and central venous pressures, the ECG and heart rate were displayed on an oscilloscope and pen recorder (Roche, Monitor 120). Fe'CO₂ was measured near the patient's airway with a fast response infra-red analyser (Gould Godart MK III). The airway pressure was recorded continuously with a strain gauge and heated stylus recorder (Devices MX2).

A Y-connection was attached to the piped oxygen supply in the operating theatre. One limb was used to supply the Boyle anaesthetic machine, and the other to provide the driving gas for the new ventilator. The patients were ventilated initially on a conventional ventilator (Engstrom Type 300 or Manley) and then transferred to the new machine. A normal ventilation volume (NVV) (100 ml kg⁻¹ min⁻¹) of anaesthetic gas mixture was supplied as the respiratory fresh gas (RFG) throughout the period of mechanical ventilation. The ventilatory gas composition throughout the study was 70% nitrous oxide in oxygen. The respiratory rate for the Engstrom ventilator was set at 12 b.p.m. and for the Manley, having set a fresh gas flow from the anaesthetic machine of 100 ml kg⁻¹ min⁻¹, the tidal volume (VT) was adjusted to give a ventilation frequency of 12 b.p.m.

On transferring to the new ventilator, its rate was set at 12 b.p.m. initially, the same fresh gas flow (100 ml kg⁻¹ min⁻¹) from the anaesthetic machine was maintained and supplied as the RFG, and the jet driving pressure was adjusted to give approximately the same VT and Fe'CO₂. At normal ventilation frequencies the tidal volume was measured using a Wright respirometer, which had previously been
FIG. 1. Ventilator circuit. This ventilator uses a single breathing tube in which the respiratory gas is introduced near the patient's airway, while a jet in a more distal part of the tube (internal volume of one tidal volume or more) drives the respiratory gas into the lungs. J1 = normal driving jet to generate maximum pressure of 3 kPa in the airway; J0 = overdrive jet to generate higher pressures; J2 = PEEP jet; J3 = NEEP jet; RV1 and RV2 = reducing valves; P1 and P2 = pressure gauges; S1 and S2 = switches.

calibrated using a spirometer placed between the endotracheal tube and the fresh gas flow input to measure the expiratory volume. At high ventilation frequencies a pneumatochograph system (Gould Medical) was used which was calibrated with the nitrous oxide–oxygen mixture using a syringe pump.

When the new ventilator was set the effect of the following changes was observed: (1) Doubling the RFG (that is the anaesthetic gas supply from the Boyle machine). (2) Increasing the ventilation frequency in steps up to 200 b.p.m. This was done solely by changing the frequency control. (3) Application of PEEP and NEEP. (4) At the end of the surgical procedure, in the patients undergoing hepatic surgery, and after reversal of the neuromuscular blockade and withdrawal of nitrous oxide, mechanical ventilation was continued at 12 b.p.m. with a decreased VT so that with the return of spontaneous breathing the machine was providing IMV. The effect of the return of spontaneous breathing on the $F_{\text{E}'}CO_2$ was observed. The requirement of RFG during spontaneous respiration, following discontinuation of the artificial ventilation, was determined. After each manoeuvre 15 min was allowed to reach a new steady state.

Where appropriate, statistical analysis was performed using paired t tests and a probability value of less than 5% was accepted as significant.

RESULTS

Changing from a conventional to the new ventilator caused no significant changes in $P_{\text{a}O_2}$ and $P_{\text{a}CO_2}$ (table I).

During normal operation of the ventilator at 12 b.p.m. with a normal ventilation volume, the $F_{\text{E}'}CO_2$ trace showed, in addition to the end-tidal peak, a small increase during the inspiratory phase (fig. 2). Doubling the RFG removed this feature without changing $F_{\text{E}'}CO_2$ (fig. 2). It can also be seen (table I) that there was no significant change in blood-gas tensions when the RFG was doubled.

High frequency ventilation

In a study on six patients undergoing liver surgery the ventilation frequency was increased from 12 to 60 b.p.m. and it can be seen (table I) that there were no statistically significant changes in blood-gas tensions.

In a further study on five patients about to undergo cardiac surgery the effect of ventilation frequencies of 12, 45, 60 and 100 b.p.m. was observed.
TABLE I. Comparison between conventional and new ventilator. Effect of doubling respiratory gas flow and increasing ventilation frequency on $P_{a}O_2$ and $P_{a}CO_2$ (mean ± SD). Observation on six patients undergoing hepatic surgery. n.s. not statistically significant

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Conventional</th>
<th>New</th>
<th>New</th>
<th>New</th>
<th>New</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiratory gas flow</td>
<td></td>
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<tr>
<td>$30% O_2 + 70% N_2O$ (litre min$^{-1}$)</td>
<td>6.76 ± 1.06</td>
<td>6.76 ± 1.06</td>
<td>6.76 ± 1.06</td>
<td>13.80 ± 1.56</td>
<td>6.36 ± 1.26</td>
<td>6.36 ± 1.26</td>
</tr>
<tr>
<td>Driving pressure (p.s.i.)</td>
<td>30–33</td>
<td>30–33</td>
<td>30–33</td>
<td>30–33</td>
<td>30–33</td>
<td>30–33</td>
</tr>
<tr>
<td>Frequency (b.p.m.)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>$P_{a}O_2$ (kPa)</td>
<td>17.19 ± 6.57</td>
<td>17.96 ± 6.73</td>
<td>17.90 n.s. ± 5.46</td>
<td>15.91 ± 4.5</td>
<td>15.81 n.s. ± 5.05</td>
<td></td>
</tr>
<tr>
<td>$P_{a}CO_2$ (kPa)</td>
<td>4.87 ± 0.57</td>
<td>5.14 ± 0.58</td>
<td>4.90 n.s. ± 0.76</td>
<td>5.14 ± 0.76</td>
<td>5.20 n.s. ± 0.95</td>
<td></td>
</tr>
</tbody>
</table>

Again, there were no significant changes in $P_{a}O_2$ and $P_{a}CO_2$ (table II). In addition, the peak airway pressure decreased from 1.62 to 1 kPa, (approximately 40%), during HFV in spite of the development of a PEEP of 0.27 kPa.

In figure 3 the $FE'CO_2$ is displayed at 12 and 60 b.p.m. It can be seen that, on returning from 60 to 12 b.p.m. $FE'CO_2$ returned to control values within three breaths.

**PEEP and NEEP**

PEEP and NEEP can be readily applied with this machine (fig. 4). In one patient who was about to undergo cardiac surgery the ventilation frequency was increased in steps up to 200 b.p.m. (fig. 5). There was a progressive decrease in peak airway pressure and an increase in end-expiratory pressure and the PEEP caused by HFV decreased using the NEEP facility (fig. 5).

**IMV**

During reversal of the effect of the neuromuscular blocking drug, at the end of surgery, the contribution from the ventilator was decreased progressively as spontaneous respiration returned.

During spontaneous respiration the breathing system is a T-piece and the RFG was doubled to maintain a normal $FE'CO_2$. Throughout the transition from artificial to spontaneous respiration, the patients remained quiet, they did not fight the ventilator and when breathing was adequate and chest movement normal the endotracheal tube was removed without any need for a change of breathing system or manual ventilation.

**Peak inflation pressure**

It was found that, using the same tidal volumes,
TABLE II. Effect of frequency of ventilation on respiratory indices and blood-gas tensions (mean ± SD) whilst respiratory fresh gas flow and the driving pressure were maintained constant. The superscript letters (ABCDE) indicate statistically significant differences (P <0.05) between the relevant columns. Observations on five patients undergoing cardiac surgery. *FE'CO₂ was measured after decreasing the respiratory frequency to 15 b.p.m. and taking the value at the third subsequent breath is illustrated in figure 3 (see text) after which the ventilation rate was returned to its previous value (45, 60 or 100).

<table>
<thead>
<tr>
<th>Frequency (b.p.m.)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume (ml)</td>
<td>15</td>
<td>45</td>
<td>60</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>404.0 ± 52.2</td>
<td>292.0 ± 29.49</td>
<td>212.0 ± 8.37</td>
<td>150.0 ± 18.71</td>
<td>406.0 ± 56.439</td>
</tr>
<tr>
<td>Airway pressure (kPa)</td>
<td>1.62 ± 0.21</td>
<td>1.23 ± 0.32</td>
<td>1.12 ± 0.31</td>
<td>1.00 ± 0.36</td>
<td>1.62 ± 0.15</td>
</tr>
<tr>
<td>PEEP (kPa)</td>
<td>0.00 ± 0.06</td>
<td>0.16 ± 0.13</td>
<td>0.27 ± 0.15</td>
<td>0.00 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>End-tidal CO₂ (%) (FE'CO₂)*</td>
<td>4.78 ± 1.18</td>
<td>4.66 ± 1.29</td>
<td>4.64 ± 1.28</td>
<td>4.74 ± 1.30</td>
<td>4.68 ± 1.09</td>
</tr>
<tr>
<td>PaO₂ (kPa)</td>
<td>17.54 ± 3.56</td>
<td>17.58 ± 4.18</td>
<td>17.51 ± 3.27</td>
<td>18.78 ± 4.54</td>
<td>19.41 ± 5.06</td>
</tr>
<tr>
<td>PaCO₂ (kPa)</td>
<td>4.99 ± 0.63</td>
<td>4.78 ± 0.82</td>
<td>4.98 ± 0.78</td>
<td>5.08 ± 0.73</td>
<td>4.88 ± 0.89</td>
</tr>
<tr>
<td>pH (unit)</td>
<td>7.402 ± 0.049</td>
<td>7.422 ± 0.046</td>
<td>7.416 ± 0.051</td>
<td>7.397 ± 0.046</td>
<td>7.433 ± 0.073</td>
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</tbody>
</table>

**FIG. 3.** Carbon dioxide in expired gas at normal (12 b.p.m.) and high (60 b.p.m.) frequencies of ventilation.

**FIG. 4.** Effect of PEEP and NEEP on inflation pressures. Ventilation frequency 12 b.p.m.
with the same \( F_{\text{E}}\text{CO}_2 \), \( P_{\text{aO}_2} \) and \( P_{\text{aCO}_2} \), the peak inflation pressure was approximately 30% less for the new ventilator compared with a Manley (fig. 6).

**DISCUSSION**

This preliminary evaluation of the first prototype of this ventilator reveals that it has the capability to ventilate over a wide range of frequencies and this can be achieved merely by changing the rate control without inducing any statistically significant changes in blood-gas tensions. One advantage of this machine is that, being a pressure generator, the inspiratory flow pattern is similar to a combination of a reverse ramp and a sinusoidal pattern and provides a highly efficient ventilation system (Baker et al., 1982). However, like all pressure generators it is sensitive to changes in compliance. However, this can be overcome by using a simple servo system such that the driving pressure will respond to changes in the volume of ventilation. However, even constant volume ventilators, with conventional circuits, contain large compressible volumes which means that considerable changes in alveolar ventilation may occur in response to changes in pulmonary compliance. Moreover, the measurement of the volume of ventilation may be a poor indicator of the efficiency of ventilation in the presence of abnormal lungs or during HFV. Severinghaus and Stupfel (1957) have shown in the dog that the physiological deadspace decreases when there is a decrease in tidal volume \( (V_T) \) and that the relationship is non-linear.

As yet there has been no comparable study in man on the relationship between \( V_T \) and \( V_D \) and the minimum \( V_D \) in man may be extremely variable (Rossing et al., 1981). Thus, the measurement of \( V_T \) during HFV may give little information about alveolar ventilation. However, it is desirable to continue to monitor the efficacy of ventilation during HFV without resorting to repeated blood-gas analysis.

**FIG. 5.** Top trace: airway pressure at ventilation frequencies from 15 to 100 b.p.m. Bottom trace: airway pressures at 200 b.p.m. showing their decrease by the NEEP facility (Jet J3, fig. 1). On right side, ventilation frequency reduced to 13 b.p.m. without NEEP.

**FIG. 6.** Comparison of the peak inflation pressures with a Manley and the new ventilator at the same ventilation frequency (15 b.p.m.), tidal volume (500 ml) and \( F_{\text{E}}\text{CO}_2 \) (5.5%) in the same patient.
A better approach may be the use of $FE'CO_2$. The relatively slow response time (300 ms) of conventional infra-red carbon dioxide analysers means that, as yet, they have been considered inappropriate during HFV. However, as shown in figure 3, on returning to a lower ventilation frequency (12–30 b.p.m.), which is within the response time of the infra-red carbon dioxide analyser, the true $FE'CO_2$ can be recorded by the third breath. Since with this ventilator the $P_{A0_2}$ and $P_{ACO_2}$ do not change to any significant extent with a change in ventilation frequency, this manoeuvre can be used to sample the efficiency of ventilation when required. Unlike other ventilators with a high frequency capability, this machine uses a low respiratory fresh gas flow from a low pressure source which is not diluted by entrainment. Other high frequency ventilators in which the driving system is separated from the respiratory gas use some form of machine pump (Butler and Bohn, 1979; Bohn et al., 1980) and have obstructions or valves in the breathing system. In the machine described here, because there are no valves and the circuit is open to atmosphere at all times the maximum pressure which can be generated in the breathing system is only that which is required to ventilate the lungs. Using a high ventilation frequency, the peak inflation pressure is lower than at normal frequency. During IMV the patient can breathe at any time and the “fighting” and desynchronization seen with conventional ventilators does not occur. Thus, there is no need for a complex sensing and triggering system to synchronize the ventilator driving system with the patient’s respiration.

Two of the patients, who had low pulmonary compliances (25–30 ml cm H$_2$O$^{-1}$), were ventilated satisfactorily without requiring the use of the “over-drive” jet J0 (fig. 1).

Sterilization is not a problem, as the circuit is either sterilizable or disposable. A bacterial filter on the expiratory limbs acts as a silencer and also ensures bacteria-free expired gases.

REFERENCES


UN NOUVEAU RESPIRATEUR
TOUS USAGES SANS VALVE

Etude Clinique

RESUME
L'étude clinique préliminaire d'une nouveau respirateur constuit sur un principe inédit sans valve et comportant un circuit ouvert à l'air n'a été faite chez des opérés adultes. Avec des débits normaux de gaz respiratoires frais (100 ml kg$^{-1}$ min$^{-1}$), la $P_{ACO_2}$ et la $P_{A0_2}$ étaient les mêmes qu'avec un respirateur conventionnel. La ventilation à haute fréquence (VHF), jusqu’à 1001 p.m., ne modifiait pas de façon statistiquement significative la $P_{ACO_2}$ et la $P_{A0_2}$. Les pressions de crête dans les voies aériennes étaient de 30% inférieures à celles observées avec un respirateur Manley et diminuaient encore de 40% en VHF. La PEEP, NEEP, CPAP et IMV étaient d’utilisation facile.
Bei Erwachsenen wurde während Operationen ein neues Beatmungsgerät mit klappenlosem Design und einem zur Atmosphäre offenen Kreislauf einer vorläufigen klinischen Erprobung unterzogen. Bei normalen respiratorischem Frischgasflow von 100 ml kg⁻¹ min⁻¹ waren PaCO₂ und PaO₂ gleich hoch wie mit konventionellem Beatmungsgerät. Hochfrequente Beatmung (HFV) bis 100 Atemzüge pro Minute führte zu keinen statistisch signifikanten Veränderungen in ACCO₂ und O₂. Die Spitzenbeatmungsdrucke waren um 30% niedriger als beim Manley-Beatmungsgerät, bei HFV sogar um 40%. PEEP, NEEP, CPAP und IMV konnten leicht angewandt werden.

Se llevó a cabo en pacientes adultos sometidos a operaciones una evaluación clínica preliminar de un nuevo ventilador en el cual se incorpora un principio nuevo en su concepto por no tener válvula y estar abierto en la atmósfera. Al usar corrientes de gas respiratorio nuevo (100 ml kg⁻¹ min⁻¹), se comprobó que el PaCO₂ y el PaO₂ eran los mismos que con un ventilador Manley. La ventilación de alta frecuencia (HFV) hasta 100 b.p.m. no causó cambios significativos del PaCO₂ y del PaO₂. Las presiones de pico de las vías respiratorias eran menores en un 30% que con un ventilador Manley y bajaron en un 40% adicional durante la HFV. Se aplicaron con facilidad los PEEP, NEEP, CPAP e IMV.