Evaluation of the Pneupac Ventipac portable ventilator: comparison of performance in a mechanical lung and anaesthetized patients

A. MCCLUSKEY AND C. L. GWINNUTT

Summary
The performance of the Pneupac Ventipac portable gas-powered ventilator was evaluated in two stages. The accuracy of delivery of the ventilator was assessed using a mechanical lung model at different combinations of compliance and airway resistance to simulate normal and diseased lungs. The performance of the ventilator was then assessed in 20 anaesthetized patients. The tidal volume delivered by the ventilator in airmix mode (nominal inspiratory oxygen fraction $F_{O_2}$ 0.45) was between $-20$ and $+30\%$ of the preset tidal volume with the mechanical lung model adjusted to normal adult values of compliance and airway resistance. The corresponding value with the ventilator set to deliver 100 % oxygen was between $-22$ and $-7\%$ of the preset tidal volume. The performance of the ventilator decreased when either compliance was reduced or airway resistance was increased in the mechanical lung model; this effect was greater in airmix mode. Delivered tidal volume was between $-19$ and $+12\%$ of the present tidal volume in the group of anaesthetized patients using the ventilator in airmix mode. The ventilator was reliable and simple to use, and performance was within acceptable limits in the anaesthetized patients. However, we recommend that a means of verifying the adequacy of ventilation should always be used when transporting critically ill or anaesthetized patients with any portable ventilator, particularly when lung compliance or airway resistance may be abnormal. (Br. J. Anaesth. 1995; 75: 645–650)

Key words
Equipment, ventilators. Model, lung.

Patients and methods
The PV is a time-cycled, volume-preset, pressure-limited, constant flow generator. It can be driven by either oxygen or air at a pressure of 270–600 kPa. The front panel has six controls and an airway pressure dial. Inspiratory and expiratory times may be adjusted between 0.5–3.0 s and 0.5–6.0 s, respectively. The inspiratory flow may be set over the range 0.1–1.0 litre s$^{-1}$. The remaining three controls determine the nominal $F_{O_2}$ (0.45 or 1.0), ventilatory mode (CMV or Demand) and adjustment of the inspiratory pressure limit. Ventilatory variables ($V_T$, $MV$, 1 : E ratio) are determined by adjusting the inspiratory and expiratory times and inspiratory flow rate independently. Tidal volumes of 50–3000 ml and ventilatory frequencies of 7–60 b.p.m. may be set at different 1 : E ratios. The ventilator allows the patient to breathe freely through the system between mandatory breaths, although SIMV is not available. A PEEP valve adjustable to 20 cm H$_2$O is provided.

The PV was tested in both airmix and 100 % oxygen modes using a mechanical lung model (Biotek Instruments VT-1 Adult Ventilator Tester). Tolerances for the compliance and resistance values were within the limits specified by the International Standards Organization (ISO) model lung. Twelve

EQUIPMENT

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combinations of inspiratory time, expiratory time and inspiratory flow rate were selected to deliver tidal volumes between 375 and 1125 ml (table 1). The PV was evaluated at each tidal volume with the mechanical lung adjusted to each of four different combinations of compliance (C) and airway resistance (R) as follows: (1) normal adult lung during anaesthesia (C = 0.05 litre cm⁻¹ H₂O, R = 5 cm H₂O litre⁻¹ s⁻¹); (2) reduced compliance (C = 0.025 litre cm⁻¹ H₂O); (3) increased airway resistance (R = 20 cm H₂O litre⁻¹ s⁻¹); and (4) combination of both (C = 0.025 litre cm⁻¹ H₂O, R = 20 cm H₂O litre⁻¹ s⁻¹).

The mean tidal volume delivered by the PV was calculated over eight breaths by the angular displacement transducer of the ventilator tester. This had been calibrated previously for the study by the manufacturer to an accuracy of ±3%, confirmed using a volumetric syringe (PK Morgan Ltd) at 300, 400, 600, 800 and 1000 ml. The breath-to-breath variation was also recorded.

P₀₂ delivered by the PV in airmix mode was measured using a Critikon Oxycheck 2000 (calibrated to an accuracy of ±1% at 21% oxygen and ±2% at 100% oxygen) at each of the four settings of compliance and airway resistance, at flow rates of 0.25, 0.5, 0.75 and 1.0 litre s⁻¹. The inspiratory and expiratory times were fixed at 1.5 and 3.0 s, respectively (I : E ratio 1 : 2 ventilatory frequency 13 b.p.m.).

The second part of the investigation was approved by the local Ethics Committee and signed informed consent was obtained. We studied 20 patients aged 16–75 yr, ASA I–III, during elective abdominal surgery requiring mechanical ventilation. Patients with significant pulmonary disease were excluded. Premedication with oral temazepam 10–30 mg was given 1–2 h before operation. Baseline recordings of heart rate, arterial pressure and peripheral oxygen saturation (S₀₂) were recorded on arrival at the anaesthetic room (T₀). Anaesthesia was induced with a rapid i.v. infusion of alfentanil 50 g kg⁻¹ and propofol 1 mg kg⁻¹, and maintained by a continuous infusion of propofol 6–10 mg kg⁻¹ h⁻¹, adjusted according to clinical response, and alfentanil 50 g kg⁻¹ h⁻¹. Tracheal intubation was performed without the use of a neuromuscular blocker. During surgery the lungs of all patients were ventilated for three sequential study periods of 20 min to determine the effect on basic cardiorespiratory physiology of the transition to and from the PV ventilator. A Cape-Waine Mk III anaesthetic ventilator set to a tidal volume of 10 ml kg⁻¹, ventilatory frequency 10 b.p.m., I–E ratio 1 : 2 and P₀₂ 0.45 was used for the initial and final periods. During the second period the patient was attached to the PV ventilator in airmix mode and the lungs ventilated using the same variables. The electrocardiogram, S₀₂, arterial pressure, Peco₂ and peak airway pressure were monitored throughout the procedure and recorded at 10-min intervals (T₁–T₆). Finally, the PV was tested in each patient at 10 different combinations of inspiratory time, expiratory time and inspiratory flow rate to deliver preset tidal volumes between 375 and 1000 ml (table 1). At each setting the delivered tidal volume was measured and averaged over eight breaths using a mechanical Wright respirometer (Ferraris Development and Engineering Co., Ltd). This had been calibrated previously to an error of −2% at a flow of 16 litre min⁻¹ and +5% at 60 litre min⁻¹. As the response of a respirometer is flow-dependent, it was calibrated further by connecting it between the PV and the mechanical lung so that the flow profile during ventilation of the mechanical lung would be similar to that obtained with anaesthetized patients. The respirometer output was compared with that of the angular displacement transducer using the method described by Bland and Altman [5] and then mathematically recalibrated to zero bias with respect to the angular displacement transducer [6].

Statistical analyses were performed using multiple paired t tests with Bonferroni’s correction. P < 0.05 was considered significant.

### Results

The results obtained during ventilation of the mechanical lung with the PV in airmix mode are shown in figure 1(A–D). At normal values of compliance and airway resistance (fig. 1A), the delivered tidal volume was within the range −20 to +30% (mean error −0.2%) of that preset. The delivered tidal volume decreased when either compliance was decreased (fig. 1B) or airway resistance was increased (fig. 1C). When both abnormalities were simulated (fig. 1D), the delivered tidal volume was between −42 and +7% (mean error −21.5%) of that preset. Figure 2(A–D) shows the results obtained during ventilation of the mechanical lung with the PV delivering 100% oxygen. At normal values of compliance and airway resistance, the delivered tidal volume was within the range −22 to −7% (mean error −14.7%) of that preset. When both compliance and airway resistance were abnormal, the delivered tidal volume was between −28 and −15% (mean error −21.9%) of that preset.

The breath-to-breath variation in volumes delivered by the PV was within ±1% in, both modes. The oxygen concentration in airmix mode varied between 51% and 59%.

When the accuracy of the respirometer was

<table>
<thead>
<tr>
<th>Setting No.</th>
<th>Tw (s)</th>
<th>Tw (s)</th>
<th>Flow rate (litre s⁻¹)</th>
<th>I : E ratio</th>
<th>Preset Vₚ (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>1.5</td>
<td>4.0</td>
<td>0.25</td>
<td>1 : 2.7</td>
<td>375</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>4.0</td>
<td>0.25</td>
<td>1 : 2.0</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>3.0</td>
<td>4.0</td>
<td>0.25</td>
<td>1 : 1.3</td>
<td>750</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>4.0</td>
<td>0.50</td>
<td>1 : 4</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>4.0</td>
<td>0.50</td>
<td>1 : 2.7</td>
<td>750</td>
</tr>
<tr>
<td>6</td>
<td>2.0</td>
<td>4.0</td>
<td>0.50</td>
<td>1 : 2</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>4.0</td>
<td>0.75</td>
<td>1 : 8</td>
<td>375</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>4.0</td>
<td>0.75</td>
<td>1 : 4</td>
<td>750</td>
</tr>
<tr>
<td>9*</td>
<td>1.5</td>
<td>4.0</td>
<td>0.75</td>
<td>1 : 2.7</td>
<td>1125</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>4.0</td>
<td>1.0</td>
<td>1 : 8</td>
<td>500</td>
</tr>
<tr>
<td>11</td>
<td>0.75</td>
<td>4.0</td>
<td>1.0</td>
<td>1 : 5.3</td>
<td>750</td>
</tr>
<tr>
<td>12</td>
<td>1.0</td>
<td>4.0</td>
<td>1.0</td>
<td>1 : 4</td>
<td>1000</td>
</tr>
</tbody>
</table>
compared with that of the angular displacement transducer, the respirometer bias was found to be +6.4% with limits of agreement -0.4 to +13.1%.

After correction for the bias, the limits of agreement were within ±6.0% of the output of the angular displacement transducer.
We studied 20 patients, mean age 48.1 (range 25–76) yr, mean weight 66.3 (range 47.5–98.0) kg. Data for the physiological variables monitored are shown in table 2. There were no significant changes in mean arterial pressure, \( S_{0_2} \), or \( F_{E_{CO_2}} \) when the PV was substituted for the Cape-Waine, or when the patient was reconnected to the Cape-Waine. There was a small increase in heart rate on attaching the patients to the PV, although this increased rate did not differ from preinduction values. No arrhythmias were noted.

The performance of the PV in the anaesthetized patients is summarized in figure 3. The mean tidal volumes delivered at each of the dial settings were within \(-19\) and \(+13\%\) (mean error \(-8.6\%\) of the preset value.

### Discussion

Critically ill patients often require artificial ventilation of their lungs during resuscitation, transportation within the hospital for complex investigations or between hospitals for definitive care. Manual ventilation using a self-inflating bag may be associated with irregular tidal volumes, ventilatory frequencies and inflation pressures, and inability to deliver 100 % oxygen [7]. Furthermore, there is the potential for pulmonary barotrauma and the development of respiratory alkalosis caused by over-vigorous ventilation, with associated haemodynamic disturbances [8]. Additionally, the medical attendant is limited in his ability to perform other tasks. Consequently, the use of portable mechanical ventilators has been advocated [9, 10], particularly as their reliability and versatility are increasing. Previous investigations of these ventilators have only assessed performance using mechanical lung models or by monitoring the effect on arterial blood-gas tensions.

In the first part of this study, the PV was tested over a range of tidal volumes (375–1125 ml) and because of the versatility offered by this device, the accuracy of each tidal volume was assessed at up to four different inspiratory flow rates. There are no published standards for the performance limits of portable ventilators against which to compare the PV. We considered performance to be satisfactory if the delivered tidal volume was, within \( \pm 20\% \) of that preset. When compliance and airway resistance values representative of the normal adult lung during anaesthesia were set, ventilator performance was generally satisfactory in both the airmix and 100 % oxygen modes. However, in the airmix mode at the lowest flow rate studied (0.25 litre s\(^{-1}\)), the PV consistently gave a greater than preset tidal volume. When abnormal compliance resistance values were set, there was only a relatively small further reduction in performance with the PV adjusted to deliver 100 % oxygen (fig. 2A–D). In comparison, when abnormal compliance and resistance values were set with the PV in airmix mode, performance decreased significantly, particularly at combinations of tidal volume and inspiratory flow rate associated with a high airway pressure.

The greater variations in performance observed in airmix mode are caused by the effect of back pressure on the air entrainment ratio of the Venturi system and are consistent with previous investigations of portable ventilators [1–3]. Although the PV is nominally a constant flow generator, it has been shown that the flow rate of such ventilators varies inversely with the airway pressure when the Venturi is used [2]. Thus excessive tidal volumes are likely when a low inspiratory flow rate is used and compliance and airway resistance are normal. At higher flow rates, performance is likely to decline, particularly when compliance and airway resistance are abnormal. To overcome the problem of inaccurate delivery, the use of interchangeable injec-
tors for use at different flow rates has been suggested [11].

The reduction in delivered tidal volumes found in situations of reduced compliance and increased airway resistance are not as great as previous findings with some portable ventilators [3]. This is partly because of the presence of an adjustable, rather than fixed, inspiratory pressure relief valve on the PV which can be increased to a maximum of 80 cm H₂O; loss of volume produced by opening of this valve in the presence of a high airway pressure was prevented by setting the relief pressure at its upper limit.

In view of these findings, we agree that it is essential to monitor the adequacy of ventilation when relying on portable, gas-powered ventilators, particularly in patients with altered compliance and airway resistance, and in children, to avoid the possibility of hypoventilation and hyperventilation, respectively [2, 8]. This can be achieved either by attaching a respirometer to the outlet of the non-rebreathing valve, or by arterial blood-gas analysis, or both.

In the second part of the study, patients were anaesthetized using a total i.v. technique as inhalation anaesthesia was not possible using the PV; neuromuscular blockers were not used. This technique was also felt to be more representative of the situation in the intensive care unit and when portable ventilators are used during resuscitation, particularly by non-anaesthetists. The time available during anaesthesia limited the number of variations in tidal volume that could be investigated and prolongation of anaesthesia to further the study was not deemed ethically acceptable. For similar reasons, the ventilator was tested only in airmix mode. Ten combinations of inspiratory time and flow rate were used which were considered to be representative of values likely to be used in adult patients during transportation and resuscitation. In order to prevent unnecessary hyperventilation, the expiratory time was kept constant at 4 s to limit ventilatory frequency.

The overall performance of the PV in the anaesthetized patients was within our predetermined limits of acceptability, being consistently within ± 20 % of the preset values. Excessive tidal volumes again occurred at the lowest flow rate of 0.25 litre s⁻¹. The performance of the PV was in broad agreement with that using the artificial lung set at normal values of compliance and airway resistance. Although the transition from the Cape-Waine to the PV ventilator was not associated with any cardiovascular instability, and indices of ventilation were unchanged in the patients studied, the effect of such a transition in critically ill patients is not known.

The use of a Wright respirometer has been described previously in a clinical evaluation of portable ventilators [8] and we believe that its use is justified in the context of our study. In their original assessment of the respirometer, Nunn and Ezi-Ashi found that its response during different patterns of gas flow was generally accurate to within ± 5 % of the minute volumes recorded by a dry gas meter in the clinically relevant range of 5–10 litre min⁻¹ [12]. In a more recent study [13], the respirometer was found to be accurate to within ± 8 % of the reading obtained using a Tissot-type gasometer as a reference standard over the range of tidal volumes and frequencies used in the present study. The response of the respirometer used in our study was correlated closely with that of the angular displacement transducer (r = 0.995). There was a tendency to readover; mean error (bias) +6.4 % with limits of agreement −0.4–13.1 %. As described previously [6], if the bias is taken to reflect a “calibration error” of the respirometer, it can be corrected mathematically by manipulating the regression equation between the two measurements of tidal volume such that the regression line coincides with the line of identity. Furthermore, a simple recalibration has also been suggested to improve the accuracy of these devices where a fixed error occurs [13].

Following this transformation, the respirometer read accurately to within ± 6 % of the angular displacement transducer. This degree of accuracy was sufficient to detect clinically important failure of the PV to deliver the preset tidal volume. Furthermore, the inter-individual variation in the delivered tidal volume was greater than the accuracy in its measurement. This may have been caused in part by the effect of abdominal surgery on lung compliance. This was an unfortunate aspect of the study which was unavoidable as it was not deemed ethical to test the PV before the start of surgery, thus unduly prolonging the anaesthetic.

In conclusion, the Pneupac Ventipac portable ventilator was reliable and simple to operate. The cardiorespiratory stability in our patients suggests that the dial settings are sufficiently accurate when the ventilator is used in adults with normal lungs. However, in children and in patients with reduced compliance or increased airway resistance, a suitable means of verifying the efficacy of ventilation should be used.

References
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