The CompPAC and PortaPAC Portable Ventilators Bench Tests and Field Experience

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SUMMARY: The military and some civilian rescue agencies have a requirement for portable ventilators in the anaesthetic, resuscitation and pre-hospital environment. This paper describes two new portable ventilators specifically designed to satisfy the military requirement for lightweight, robust and versatile equipment which can also be used in a contaminated environment.

Introduction
Portable ventilators are increasingly used by medical and non-medical personnel at the sites of accidents and during transfers to and between hospitals. Among the desirable features of these ventilators are durability, portability and the ability to function in an adverse environment (1). One of the most adverse and variable environments is the modern battlefield; any equipment used by the military must be robust and able to function in the cold of the Arctic and the heat of the desert. The potential use of chemical weapons may result in the requirement to ventilate casualties either from the use of these poisons or as victims of conventional weapons in a contaminated environment. With the growing threat of terrorist organisations using chemical weapons, the ability to ventilate in such a hostile environment is no longer the preserve of the armed forces. Emergency care under field conditions (military or civilian) may also be complicated by the lack of resources and difficulties in resupply, particularly of compressed gases. Using an electrically-powered air-compressor, a pneumatically-powered ventilator can be used as long as the appropriate power supply is available. This, however, necessitates the transport of extra bulky equipment.

In the developing world, a common cause of reversible respiratory-failure is organophosphorous poisoning from insecticides. These patients have the potential to make a full recovery but often require ventilation in facilities where compressed gas and electricity are not reliable.

The anaesthetic ventilator (TCSO - Cape Engineering Ltd, Warwick, England) currently scaled for British Army surgical teams is no longer in production. Hospital squadrons and field hospitals are not scaled for any transport ventilator. Recent experience in former Yugoslavia has shown that these units do need to transfer ventilated patients using their own resources. Therefore the British Army requires a new portable ventilator for anaesthesia and transport.

Two ventilators (CompPAC, PortaPAC - PneuPAC Ltd, Luton, England) have been developed recently. They are small units capable of being driven by a number of power sources, either compressed gas, an internal or external battery, or by mains AC supply via the transformer provided. They were specifically designed for military use, both for casualty transport and resuscitation in the field. They were also intended to be used in field surgical units as an anaesthetic ventilator.

Our aim was to look at the performance of the CompPAC against a standard lung model and assess its use with a draw-over vaporiser (Triservice vaporiser - Penlon, Abingdon, England). In addition, the PortaPAC was assessed, by the second author, as an anaesthetic ventilator under field conditions at Janakpur, Nepal, during a two-week orthopaedic work-camp.

Equipment
The CompPAC (Fig 1a) is a portable automatic ventilator. It weighs 8.5 kg including battery, and has a robust chemically-
hardened housing. It can be driven by an external gas-supply at 280-600 kPa. If the driving gas is oxygen, it will deliver 100% oxygen or 45% in air-in-air mode. Alternatively, it may be powered by an integral compressor, drawing in ambient air through a standard chemical-warfare filter (42.40-99-132-0941 Canister, NBC Respirator). In this case, the lungs will be ventilated with air which can, with supplementary oxygen, be enriched up to 63%. The oxygen is delivered to an auxiliary port at the rear of the unit. The compressor is powered by an external 24/28 volt DC supply or by an internal battery (either lithium which gives eight hours of use or a rechargeable NiCad battery which gives two hours of use).

The rotary control knobs allow the minute volume (MV) ventilation and the frequency to be set independently. The MV control ranges continuously from 4-14 litres per minute (1pm) and the frequency (f) from 10-30 breaths per minute (bpm). An adjustable relief valve protects the patient from high pressures and can be varied between 30 and 80 cm H₂O. An analogue pressure gauge is built into the control panel.

The PortaPAC (Fig 1b) is a simpler unit but with the same principle of operation as the CompPAC, both contain the same pneumatic block and overall design so that conclusions drawn from testing one should apply to the other. The PortaPAC differs in that there is a single control knob for adjustment of minute ventilation between 4.8 and 14 litres per minute, there is no pressure gauge, the output is 45% oxygen when driven by compressed oxygen, but the delivered air cannot be enriched when using the electrically-powered compressor.

The Triservice vaporiser is used widely in draw-over anaesthesia. The Triservice Anaesthetic Apparatus originally employed two such vapourisers in series to deliver halothane and trichloroethylene (2), but more recently a single isolufurane vaporiser has been used as standard (3). Taylor has shown that the performance of the Triservice vaporiser is not altered whether used in draw-over or push-over mode in conjunction with the Cape TC50 (4).

Methods

The performance of the CompPAC was evaluated by comparing a range of set MVs and breathing rates with the volumes actually delivered. Different combinations of lung compliance and airway resistance on a model test lung (constructed by the Nuffield Department of Anaesthetics, Oxford) were used to mimic patients with different lung conditions (5). The MVs used were 4, 8, 12 and 14 lpm, delivered at breathing rates of 10, 13, 20 and 25 bpm using room air as the driving gas. The combinations of compliance and airway resistance on the model lung were: 50 ml/cm H₂O and 5 cm H₂O/1/s; 50 ml/cm H₂O and 20 cm H₂O/1/s; 20 ml/cm H₂O and 5 cm H₂O/1/s; 20 ml/cm H₂O and 20 cm H₂O/1/s. The gas flow signal was measured using a differential-pressure flow transducer (MP45-1-Validyne Engineering Corp., Northridge, CA, USA), connected to a flow amplifier (MC1-1 Validyne Engineering Corp., Northridge, CA, USA). The airway pressure was measured using a strain-gauge pressure transducer (PM131 - Gulton Statham Transducer Inc., Costa Mesa, CA in the US) and the signal was amplified by a strain-gauge amplifier/supplementary reference (Lectromed - Ormed Engineering Limited, Herts, UK). The output voltages and pressure signals were quantified by a calibration/predicted flow rate analyser (RT-200 - Timeter Instrument Limited, St. Louis, MO, USA) using two-point calibrations. The analogue flow and minute gas pressure signals were converted to digital form using a dedicated acquisition card (AT-MIO-16 - National Instruments Corp., Austin, TX, USA) in a personal computer (IBM/Pentium compatible) and continuously displayed on the monitor by a software program developed in the department. Data dependent on each setting were recorded at a sampling rate of 500 Hz for Figures 4a and at least five respiratory cycles and stored on the hard disk. Data collection and analysis was performed on the computer using the play-back function of the software. The average breath duration over the respiratory cycles and the five breaths calculated. Integration using Simpson's rule in Matlab was carried out on the flow signal over the inspiratory duration effect of the tidal volume. Again, the average tidal volume over five breaths was calculated. The MV delivered could then be calculated.

The performance of the CompPAC with the Triservice vaporiser was assessed with the vaporiser placed between the ventilator and the patient non-return valve (Figs 2a + 2b). In this case, the patient valve was connected to a lung ventilator performance analyser (British Oxygen Company, Harlow, England) set to a compliance of 50 ml/cm H₂O and a resistance of 5 cm H₂O/1/s. The fraction of inspired isoflurane was measured at the non-return valve with an agent analyser (Ultima - Datex Instrumentarium, Helsinki, Finland). The temperature of the vaporiser casing was measured with a standard transcutaneous probe. The inspired concentration of isoflurane was recorded at 15 second intervals from time zero, when the vaporiser was turned on to the 1, 2 or 3% setting, and seven minutes. This was repeated with the ventilator set at a frequency of 13 bpm and a MV of 8 or 12 lpm.

Results

Delivered Oxygen Concentration

When the CompPAC is used in its gas-driven mode using oxygen as the driving gas, the oxygen output was 100% and 45%.
in the air-mix mode. If the integral compressor is in use and supplementary oxygen is applied to the auxiliary port at the rear, the output was within +/- 16% of the oxygen concentration predicted by the nomogram on top of the apparatus. By adding a greater flow of oxygen than the suggested 0.5 - 4 litres per minute, a greater concentration of oxygen can be produced, but this is not recommended by the manufacturers.

**Pressure and Flow Delivered**

Flow and pressure waveforms revealed that the CompPAC functions as a constant flow-generator, pressure limited depending on setting of the adjustable relief valve (Fig 3).

Figure 4a shows the delivered tidal volume (TV) as a percentage of that selected at each of the values of MV and frequency studied with normal compliance and resistance. This ratio increases as the set TV decreases, that is at lower MV and higher f, and decreases with increasing MV. Figure 4b shows the effect of reduced compliance. It is found that poor compliance decreases delivered TV but that at a MV of 8 lpm (appropriate for the average serviceman ventilated under field conditions) the delivered TV was within -16 and +14% of predicted values with normal or reduced compliance. Figures 5a and 5b show the equivalent results for the ratio of delivered to predicted minute volume. The ratio of delivered to predicted MV increased as the set MV decreased, while at 8 lpm minute volume, the delivered MV remained within -5 and +15% of predicted in normal and reduced compliance. At 8 lpm the frequency at which breaths were delivered was 12 - 15% higher than set.

When an increased airway resistance of 20 cm H2O/l/s was inserted in the system, even at the lowest frequency of 10 bpm, expiration was not complete prior to the start of the next breath resulting in the gradual development of positive end-expiratory pressure.

**Performance with the Triservice vaporiser**

Figures 6a and 6b show the output of isoflurane against time when the Triservice vaporiser and CompPAC are used in push-over mode. There was a slight over-pressure of vapour generated in the first 15-30 s which rapidly settled to produce a steady output which decreased as the vaporiser cooled. The temperature drop at the 3% setting was from 21.4 to 15.3 C in seven minutes with a MV of 8 lpm and from 20.5 to 14.1 at 12 lpm. At no point was a dangerous or unpredictable level of isoflurane delivered.

**Discussion**

In Nepal, 33 procedures were carried out under general anaesthesia, the majority on children. The versatility of the PortaPAC was proved during frequent power failures when the
tendency to hyperventilate at low set minute and TVs. Thus, pulse-hyperventilation in conditions of poor compliance is in agreement with work of McCluskey and Gwinnutt on the Ventipac.

Recently, service anaesthetists have provided anaesthesia and transport ventilation for children in both Rwanda and Former Yugoslavia. In this situation, it is therefore desirable for a portable ventilator being used in field units to be capable of ventilating quite small patients. CompPAC and PortaPAC are both APVs, mainly for use in children and their range of MV would seem to be in the region of 10-20 cmH2O. The PortaPAC is not being used as a pressure generator for children in whom an uncuffed endotracheal tube would be used. The PortaPAC/CompPAC case can be converted from a volume generating configuration to pressure generating by interposing an APL valve as described above, although this technique is not recommended for inexperienced or inexperienced anaesthetists.

With any automatic ventilator there is a risk of gravitational increasing intrathoracic pressure if there is increased airway pressure, resistance and insufficient time for expiration. This is a potential problem with the PortaPAC as the inspiratory and expiratory time cannot be independently adjusted.

Our study confirms the previous investigators’ conclusion that close monitoring is advisable when portable ventilators are used, especially in children and patients with damaged or disease-won lungs. This should include careful clinical observation and attention to the flow and pressure monitor as well as the use of a measure of ventilation such as arterial or end-tidal carbon dioxide tension, which it is hoped may become more readily available in field units.

The CompPAC has previously been used during anaesthesia under field conditions but only in conjunction with total intravenous anaesthesia. The results of the laboratory study suggest that it could be used safely with the Triservice vapouriser.

Figs 6a & b The CompPAC and Triservice Vaporiser in push over mode: Output of isoflurane against time from turning on the vaporiser. a) Minute Volume 8 l/min. b) Minute Volume 12 l/min.
in push-over mode providing a complete and compact anaesthetic unit allowing simple and rapid adjustment of the depth of anaesthesia. In the manual mode of the Triservice Anaesthetic Apparatus, a self-inflating bag is positioned downstream of the Triservice vaporiser to assist ventilation. If a bag were used during induction of anaesthesia prior to the use of the CompPAC, it is essential to remove the bag before connecting the ventilator upstream of the Triservice Vaporiser. This is because expiration is dependent on the rapid reduction of the pressure in the patient circuit to atmospheric by way of the dump valve in the CompPAC. The presence of the self inflating bag only allowing flow towards the patient, would lead to a build up of pressure in the circuit downstream of the bag.

When there is an electrical supply, the CompPAC has a comprehensive set of alarms. However, when there is no battery or other mains supply in use, there is no warning of disconnection or loss of gas supply. This could be hazardous where there is a high level of background noise or poor lighting unless an independent alarm to indicate any loss of ventilation is used. The manufacturers have, therefore, recommended that the battery is left in place even when not in use as the main power-source.

Conclusion

We have found that the CompPAC compares favourably with other portable ventilators and the accuracy of the delivered volumes lies within acceptable limits when used for adults. As with other ventilators, care is required when used in smaller patients or those with damaged lungs. The use of the APL valve as described allows these units to be used for young children.

The particular characteristics of these ventilators that might make them of interest to the armed forces or disaster relief organisations are their ability to ventilate the lungs with clean filtered air in a contaminated environment, their lack of dependence on one power source, the elimination of the need for any separate gas compressor and the prospect of combining with the Triservice Vaporiser to produce a robust and lightweight anaesthetic apparatus.

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REFERENCES