

Portable ventilators

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Mechanical ventilators used in intensive care units are sophisticated devices. The guiding principle in their design is the provision of optimal lung ventilation. They incorporate precise but sizeable pneumatic components intended to utilize piped gases and mains electricity. However, when transporting patients receiving ventilatory support, these devices are rarely suitable because of their size, weight, requirement of external power, and rate of gas consumption.

Portable ventilators are compact devices designed to provide mechanical ventilation in settings where piped gases and mains electricity are unavailable. Modern engineering has afforded these devices a level of sophistication approaching that of a conventional intensive care ventilator.

Ideally, a portable ventilator, including oxygen and battery supplies, should be lightweight, robust, and able to function in demanding environments with little maintenance. It must use available gas or electrical supplies sparingly. It should be inexpensive, simple to operate, and provide a range of effective ventilatory modes.

General applications

Portable ventilators are used in various situations that place different requirements on their design:

- (i) primary transfer—from an accident scene;
- (ii) secondary transfer—between healthcare facilities (intra- or inter-hospital);
- (iii) domiciliary ventilation;
- (iv) improvised intensive care facilities, for example, military field hospitals, civilian contingency planning

Each application entails differences in the clinical condition of patients, operator experience, and demands of the environment. A single device is unlikely to be ideal for all situations; therefore, a range of ventilators are available. Three of these are considered as examples throughout this review (Table 1). Key practical features of a portable ventilator are the gas and power supplies required and modes of ventilation supported.

Gas supplies

Sufficient oxygen is required to meet the patient's requirements. It may also be used to provide a background rate of gas flow (bias flow) through the breathing circuit, or to control the ventilator cycle itself.

During critical care transportation, oxygen is commonly supplied from gas cylinders. Ambulances carry a pair of code F (1360 litre) or HX (2300 litre) cylinders in the cabin and two small D (340 litre) or CD cylinders (460 litre). Modern CD and HX cylinders have similar dimensions to their counterparts but are filled to 23 000 kPa rather than 13 700 kPa. They include integral four bar pressure regulators and Schraeder outlets.

Ventilators incorporating gas compressors (e.g. LTV-1000) can also utilize various low-pressure oxygen sources to enrich ambient air. Oxygen concentrators can be used if supplying cylinders is problematic, such as in a military field hospital. For aeromedical evacuation, low-pressure liquid oxygen systems can provide three times more gaseous oxygen than a similar sized cylinder.

Gas blending

The ability to control inspired oxygen concentration allows a balance to be struck between the patient's oxygen requirements and gas consumption, and the adverse effects of oxygen. A Venturi within the ventilator can be used to entrain ambient air into a high-pressure oxygen supply. The ventiPAC offers inspired oxygen concentrations of 100 or 45% depending on whether the entrainment port is switched off or on to provide an 'air mix'.¹ The Oxylog 3000 adjusts the entrainment ratio using solenoid valves to provide a continuous range of oxygen concentration.² In the absence of a high-pressure oxygen supply, the LTV-1000 uses a different approach. Oxygen supply pressure is measured and a system of valves blends oxygen proportionally with ambient air into a reservoir chamber for delivery to the patient.³

Key points

A portable ventilator should be lightweight, robust, and able to function in demanding environments with little maintenance.

Most portable ventilators display the oxygen concentrations selected by the operator, and do not measure that delivered by the ventilator.

Portable ventilators may not provide identical support to the ICU machine in use despite apparently similar settings; a trial period should always be allowed before moving the patient.

Portable ventilators that assist spontaneously breathing patients are more complex and generally require microprocessor control.

Alternatives to oxygen cylinders such as oxygen concentrators and liquid oxygen should be considered for prolonged use outside of hospital.

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doi:10.1093/bjaceaccp/mkn039

Continuing Education in Anaesthesia, Critical Care & Pain | Volume 8 Number 6 2008

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Table 1 Operating characteristics of three common portable ventilators

	Power for cycling	Power for inspiratory flow	Internal battery supply	External electrical supply	Gas supply (bar)	Bias flow (litres min ⁻¹)	Cycling requirement
VentiPAC 200D	Pneumatic	Pneumatic	> 1 yr (alarm module only)	N/A	3–6	0	20 ml cycle ⁻¹
LTV-1000	Electric	Electric	1 h	Battery 3, 4, 9 h, 12 V DC, 240 V AC	2.8–5.5 or <0.7	10	0
Oxylog 3000	Electric	Pneumatic	3 h (NiMH) or 4 h (lithium)	10–32 V DC, 240 V AC	2.7–6.0	0.5	0

Crucially, the inspired oxygen concentration displayed by most portable ventilators is that selected by the operator and not a measured value.

Types of portable ventilator

Mechanical ventilation requires energy to drive inspiratory gas flow and run the systems that regulate the respiratory cycle. Portable gas-powered ventilators use pneumatic energy to provide these functions. A microprocessor-controlled ventilator uses electrical power to regulate the respiratory cycle but inspiratory flow may be driven either pneumatically or by an electrical compressor.

Portable gas-powered ventilators

The ventiPAC is a time-cycled flow generator. A high-pressure gas supply drives a mechanical oscillator that controls the respiratory cycle. During inspiration, an adjustable flow restrictor limits the rate of gas delivery from the pressurized supply. Pressurized cylinders are used for most critical care transfers, and exploiting their potential energy in this way is relatively efficient.

The operating controls on the front panel are calibrated under nominal loading conditions. If delivering 100% oxygen, the ventilator will continue to provide reasonably accurate tidal volumes despite conditions of increased airway resistance or reduced lung compliance. However, if ‘air mix’ is selected, the back-pressure imposed on the Venturi in these conditions may result in reduced tidal volumes.⁴ Therefore, it is necessary to monitor the adequacy of ventilation, using end-tidal CO₂ monitoring and, where possible, arterial blood gas sampling.

The flow-generator model enables effective ventilation of patients with severe adult respiratory distress syndrome including those being transferred to specialist centres. However, airway pressures may increase and must be carefully monitored during transport.

The use of pneumatic components to detect inspiratory effort and control the respiratory cycle conveniently allows MRI-compatibility. However, this type of ventilator may not effectively support the patient’s own attempts to breathe. The ventiPAC incorporates a demand valve opened when pressure changes caused by inspiratory effort are transmitted back along the circuit to the ventilator. Fresh gas is provided to the patient but the ventilator provides no additional assistance so the work of breathing is not

reduced. Spontaneous breathing does, however, retard the oscillator controlling the respiratory cycle and may improve synchrony between patient and ventilator.

Microprocessor-controlled ventilators

Technological advances have enabled portable ventilators to replicate most modes of respiratory support. Ventilator software responds to feedback from sensors in the breathing circuit by actuating solenoid valves that regulate gas flow during the respiratory cycle. These valves control flow driven by a high-pressure gas supply in the Oxylog 3000. In contrast, the LTV-1000 uses an internal battery-powered turbine to pressurize gas for the flow control valves. Eliminating the necessity for gas cylinders is particularly liberating for patients ventilated at home who can then travel more easily. However, when used in critical care, battery life can be almost halved when the turbine is required to generate pressure-controlled ventilation with high levels of PEEP.⁵

The LTV-1000 and Oxylog 3000 provide a range of pressure- or volume-controlled modes, allowing them to adapt to changes in lung mechanics or circuit leaks. They also incorporate patient-triggered modes, which are effective at reducing the work of breathing during spontaneous ventilation. This type of ventilation is well tolerated, in general, and increased sedation should not be required for ventilator tolerance alone.

Reductions in the work of breathing are achieved using sensitive triggering and rapid delivery of adequate flow rates of gas during assisted breaths. To achieve this, the LTV-1000 and Oxylog 3000 generate a bias flow through the circuit during expiration. Although this increases gas consumption, it facilitates the use of rapidly responding flow-sensors located close to the patient, and fulfils the patient’s immediate inspiratory requirements. In combination with pressure support modes capable of providing high flow rates, the work of breathing can thus be minimized.⁶

Ventilator performance is affected by design compromises required for portability, such as miniaturized flow-control valves and robust sensors. Data comparing implementation of similar modes of ventilation on different ventilators are limited but duplicating settings from one device to another may not result in equivalent ventilation. Therefore, a trial period on the portable ventilator is advisable before transfer (Box 1).

Box 1 Clinical example of the use of a portable ventilator.

How much oxygen will I need?

Modern ventilators consume gas for purposes other than supplying the patient's minute ventilation. If gas consumption is not displayed by the ventilator, a crude estimate can be made. Provision for patient deterioration should be made when predicting $F_{I_{O_2}}$. The oxygen requirement for transfer includes an additional 50% in case of unforeseen delays.

Gas consumption = (minute ventilation + bias flow) \times $[(F_{I_{O_2}} - 0.2)/0.8]$ + cycling requirement.

A more accurate approximation can be obtained using:

Gas consumption = [minute volume + (bias flow \times [(Ti/Ti + Te)])] \times $[(F_{I_{O_2}} - 0.2)/0.8]$ + cycling requirement.

Transport requirement = Gas consumption \times estimated duration \times 1.5.

What about spare batteries?

Unless an adapter is used to draw power from the vehicle electrics, sufficient batteries should be taken to provide for the journey allowing for possible delays. Turbine-driven ventilators require more power and this must be considered. A means of manual ventilation in case of equipment failure must always be immediately available.

What ventilator mode?

Consider the likely course of the patient's condition, the method of transport and reason for transfer. A recent deterioration, the need to sedate or paralyse the patient indicates controlled mandatory ventilation. For short journeys with a patient largely weaned from ventilatory support, a patient-triggered mode may be preferable. A trial period on the portable ventilator before departure is advisable.

Example

An intubated patient with an extradural haematoma, ventilated with MV = 8 litre min^{-1} requires a 30 min transfer to the regional neurosurgical unit using an Oxylog 3000 with a NiMH battery.

Oxygen (allowing for $F_{I_{O_2}} = 1.0$): O_2 consumption = 8.5 litres min^{-1} , requirement = 380 litres.

Battery: lasts 3 h when fully charged, sufficient for estimated journeys of 2 h.

Mode: intracranial pressure management requires sedation, paralysis and controlled ventilation.

Electrical supplies

Batteries have limited charge capacity and can be cumbersome. To overcome this problem, increasingly energy-dense cells such as nickel cadmium, nickel metal hydride (NiMH), and lithium ion batteries have been developed. Specialist transfer vehicles and some ambulances are fitted with inverters that convert DC from

the vehicle battery to standard 240 V AC supply. Additionally, a 12 V DC supply can be drawn from the cigarette lighter socket in most road vehicles. Adapters are available allowing portable ventilators to utilize both these electrical supplies.

Patient circuits and valves

Breathing circuits incorporating non-rebreathing valves carry inspiratory gas from ventilator to patient, and direct expired air into the atmosphere (Fig. 1). Valves should maintain PEEP but provide low expiratory resistance to prevent gas trapping. Many ventilators use bespoke breathing circuits and valves which, if replaced by poor quality disposable circuits, can cause decreased tidal volume delivery and unstable or excessive PEEP.⁷ Poorly maintained, misassembled, or soiled patient valves are a recurrent cause of inadequate ventilation.

The ventiPAC circuit includes a Laerdel valve onto which a manual PEEP valve can be attached. A pressure manometer within the ventilator displays circuit pressure, but the valve prevents expiratory pressures being measured. Ventilators that incorporate microprocessors use more complex arrangements. Sensors close to the patient detect spontaneous breathing; they provide feedback for the control of ventilation and for monitoring. By measuring differential pressures across a fixed resistance, the sensors allow flow rates to be derived.

The LTV-1000 uses a manually adjustable PEEP valve modified for use within a T-piece. During inspiration, the ventilator closes the valve by pressurizing a control hose alongside the breathing circuit. The Oxylog 3000 cycles between inspiratory and expiratory pressures and a mushroom-shaped diaphragm allows the patient's airway pressure to equilibrate with that in the circuit.

Specialist applications

Aeromedical

The hypobaric (75–85 kPa) environment of the aircraft cabin, pressurized to resemble altitudes between 1500 and 2500 m, has implications for both patient and equipment. Patients with respiratory failure present particular challenges. Maintaining constant alveolar oxygen tension at reduced barometric pressure requires increased inspired oxygen concentration or may necessitate the use of PEEP. If lung function is marginal, positive pressure ventilation may be necessary at cabin pressure in patients requiring only face-mask oxygen at sea level.⁸ Gas within the cuff of tracheal tubes expands and may compromise tracheal mucosal perfusion at cabin pressure. Gas can be partially removed during ascent and replaced during descent, or substituted for saline. Ventilation can also be compromised by gaseous expansion within pneumothoraces, intestines, or the abdominal cavity.

Aviation poses particular problems for medical equipment. Ventilators must be able to withstand engine vibration and be compatible with the electromagnetic environment associated with aircraft systems. Pneumatically cycled ventilators are affected by

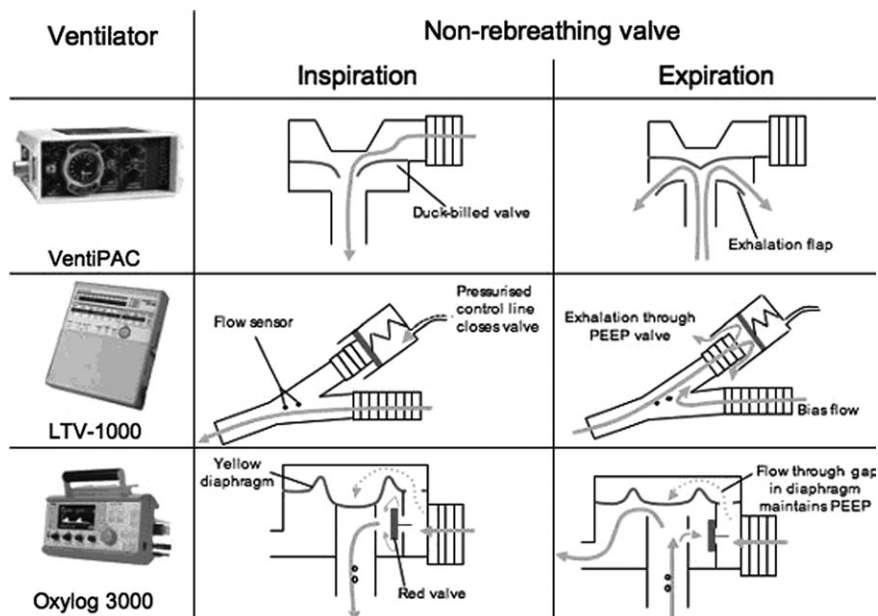


Fig. 1 Non-rebreathing valves within different ventilator breathing circuits.

changes in ambient pressure; generally, a reduced ventilatory frequency is offset by increased tidal volume. Microprocessor-controlled ventilators (e.g. LTV-1000, Oxylog 3000) contain transducers that compensate for changes in ambient pressure, although an increase in oxygen concentration will still be required.

The weight of oxygen cylinders is restrictive in long-range transportation and alternatives including liquid oxygen supplies or oxygen concentrators built into aircraft should be considered. Ventilators with minimal gas consumption are preferable in these circumstances. Furthermore, a circle breathing system can be improvised to enhance conservation of oxygen supplies.⁹

Paediatrics

Paediatric patients require ventilators capable of consistently delivering low tidal volumes at increased ventilatory frequencies. The susceptibility of infants to barotrauma and the use of uncuffed tracheal tubes favour pressure-controlled ventilation. The pneumatic characteristics of the Venturi in the VentiPAC cause it to act as a pressure-generator at flow rates $<0.25 \text{ litre s}^{-1}$ with the ‘air mix’ setting. The VentiPAC, LTV-1000 and Oxylog 3000 can all ventilate infants as small as 5 kg but specialized paediatric ventilators are required beyond this.

Domiciliary ventilation

Domiciliary ventilation is associated with survival benefits in patients with neuromuscular disease and has also been used when chest wall and lung diseases result in respiratory insufficiency.¹⁰ Patients may receive support nocturnally or continuously, provided

invasively by tracheostomy or non-invasively by facemask. The LTV series of ventilators was originally developed for domiciliary ventilation. Supplemental oxygen is usually not required in patients with neuromuscular disease and the ability of these ventilators to operate on battery without compressed gas supply maximizes portability, enabling them to be mounted on electrical wheelchairs.

Non-invasive ventilation

The emergence of non-invasive ventilation without tracheal intubation has inevitably resulted in the requirement to transfer patients undergoing this therapy. Gas leakage from around the mask is often a problem within the critical care environment and slight dislodgement during transport may increase leak and significantly reduce effectiveness. The combination of sophisticated sensors and basal gas flows within the patient circuit allows microprocessor-controlled ventilators to compensate for circuit leaks. There is increasing experience in the use of these ventilators for non-invasive ventilation during the transfer of acutely unwell patients, and domiciliary ventilation in chronic disease. Remember that expiration will still occur through the patient circuit exhalation valve so a non-vented mask is required.

Conclusions

Various portable ventilators are available, driven by demands for equipment suitable for different clinical situations and environments. Their design reflects availability of gas and electrical supplies and the modes of ventilatory support required by the patient population. When transporting critical care patients,

provision for estimated gas and electrical requirements should be made. A ventilatory mode suited to the patient's clinical condition should be selected and trialled before departure.

An appreciation of how different portable ventilators function, preferably supported by comparative data, can help when an organization purchases such equipment. Understanding the strengths and weaknesses of a specific ventilator and breathing circuit may help anticipate and prevent complications during transfer.

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Please see multiple choice questions 4–6