Oxygen Conservation During Long Distance Transport of Ventilated Patients

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Introduction

The Royal Adelaide Hospital Mediflight Retrieval Service in Adelaide, Australia, undertakes several international retrievals/repatriations of critically ill patients each year. Currently the standard management for ventilated patients is continuous mandatory ventilation (CMV), facilitated by sedation with the addition of a nondepolarizing muscle relaxant (NDMR) as appropriate. The ventilator in current use is the Oxylog 1000 (Dräger Medical, Lübeck, Germany), which is the standard ventilator for all in-hospital transfers (eg, for radiological imaging) and also interhospital and roadside-to-hospital transportation. The amount of oxygen that has to be carried during international transfers is considerable. The size and weight of the cylinders have safety and significant cost implications.

Many of the patients transported overseas receive a form of pressure or volume assist/support ventilation, rather than CMV, before the transfer. In addition, they likely have been either lightly sedated or received no sedation at all. Increasing sedation and paralyzing patients, even for relatively short periods, may prolong the time of respiratory weaning. The use of steroid-based NDMRs in critically ill patients with regards to critical care myopathy/neuropathy may be another consideration.

Oxylog 1000 Ventilator

The Oxylog 1000 is a simple, pneumatic driven, time-cycled, volume constant ventilator. Either an adjustable (0-10 cm H_20) or fixed value positive end expiratory pressure (PEEP) valve may be attached to the expiratory valve of the ventilator. The ventilator is gas driven and so does not require an electrical supply or internal battery. With no internal electrical circuit boards, less can go wrong.

For the vast majority of intrastate transfers, oxygen use is not an issue as ample supplies are carried in road ambulances, Royal Flying Doctor Service planes, and rescue helicopters. During long distance transfers, however, the use of oxygen as a driving gas in addition to that delivered to the patient becomes a negative point. When traveling by commercial aircraft, all oxygen required for the journey must be carried in cylinders within the cabin. To safely secure these cylinders requires the use of several seats, which has considerable cost implications.

To address these issues we will first discuss what the oxygen requirements are and how to reduce them. Second, we will present the requirements of a suitable transport ventilator along with a review of those currently available.

Oxygen Requirements

Our initial assessment suggested that the ventilator problems are twofold: approximately 1 L per minute of oxygen is required as the driving gas in addition to that delivered (Dräger datasheet), and there are only 2 options for oxygen concentration: no air mix (100% O_2) and air mix (60% O_2). Oxygen is unnecessarily wasted if patients require less than 60% O_2, which would generally be the case for elective transfers. However, when looked at more closely, only the extra liter per minute to drive the ventilator needs to be considered, for the following reason.

When estimating oxygen requirements for transportation, the worst-case scenario must be taken into account. Although it would be unusual to transfer a patient who required a FiO_2 greater than 0.5, there is always the possibility with any critically ill patient that the oxygen requirement may increase during transfer. This may only be a small increase because of dependent lung atelectasis as a result of sedation and NDMR as occurs in patients during general anes-

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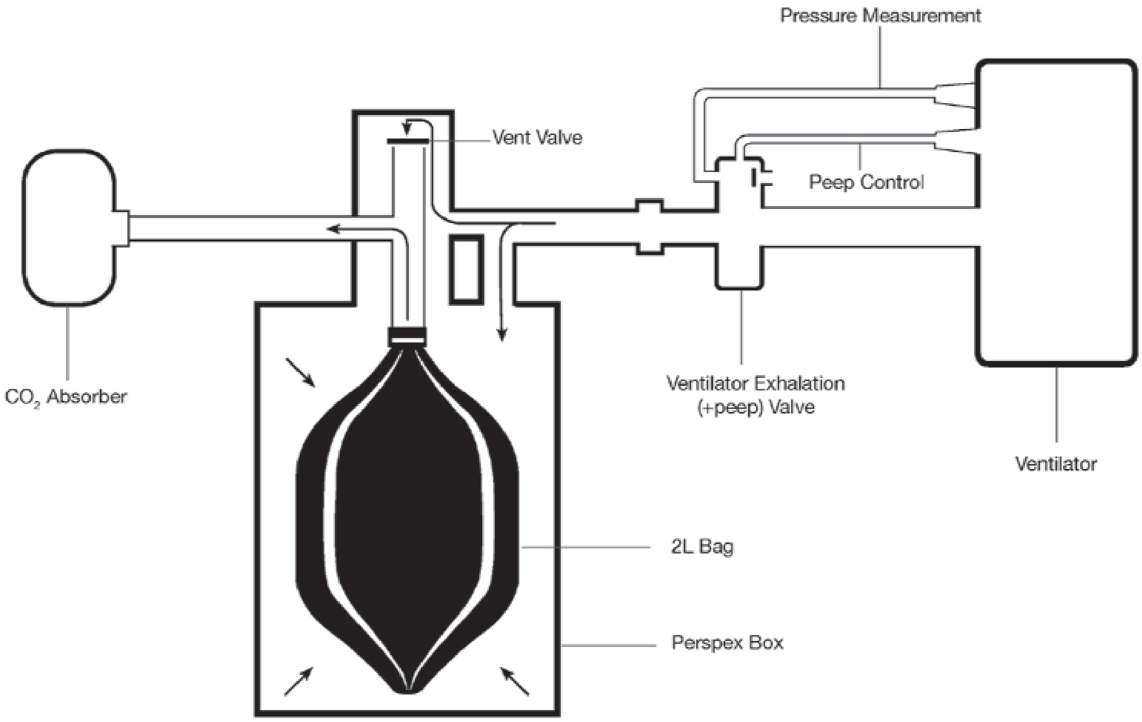

Figure 1. Adelaide Box Transfer Unit

thesia. The possibility of more significant deterioration, however, must be considered (eg, mucus plugging and lobar collapse, pulmonary embolus, or pneumothorax). The ability to deliver up to 100% oxygen to the patient for the whole journey must be allowed for because adverse events may occur at any time during the transfer. A reserve of oxygen should be carried in addition to this to cover delays. Therefore, the minimum "safe" oxygen requirements for a 24-hour transfer with the Oxylog, ventilating with a tidal volume of 700 mL and rate of 10 bpm (ie, MV 7.0 l/min), would be:

7.0+1.0 (incl. driving gas) = 8.0 l/min = 480 l/hr = 11,520 L (almost 8 Australian D size cylinders [standard D size cylinder volumes: Australia = 1500 L, UK = 340 L, US = 420-450 L])

Using a ventilator powered solely by electricity saves approximately 1.0 L per minute immediately. Using the same 24-hour example, an electric ventilator would require 7.0 l/min = 10,080 L (7 D size cylinders). This saves 1 D size cylinder on a 24-hour flight. More significant oxygen conservation can be achieved by adapting the patient circuit so that oxygen is reused.

The perfect example would be a circle circuit as is found in almost all operating theaters in the developed world. These circuits all incorporate some form of a bag in bottle (BIB) system and a unit that absorbs carbon dioxide from the patient's expired gases.

The BIB systems used in modern theaters are all relatively complex, not to mention heavy and invariably directly linked to a built-in, electrically controlled ventilator unit that relies on a 4-bar gas supply (oxygen) to drive it. For transport purposes the requirement is a stand-alone BIB that can be driven by air that is delivered by an electrically powered ventilator. The FiO_2 would be monitored throughout, so the theoretical risk of a leak reducing the concentration of oxygen delivered should always be noticed before patient safety is compromised. In addition, the BIB must be simple in design and easily repairable. It must also be able to either incorporate some form of PEEP valve or be designed in such a way that it allows PEEP generated within the ventilator circuit to be transmitted to the patient circuit.

The Adelaide Box Transfer Unit (Figure 1) appears to fulfill the requirements for a transportable BIB system. Unfortunately this unit is no longer available and does not have therapeutic goods approval.

Modified Circle System (Figure 2)

In an effort to reduce oxygen use without including a BIB, a modified circle system (MCS) has been developed by Pacific Air Ambulance in New Zealand. The MCS consists of the following component parts.

Oxygen "dead space" tubing

In essence this simple addition to the circuit solves the absence of a BIB. The tubing needs to have a volume somewhat

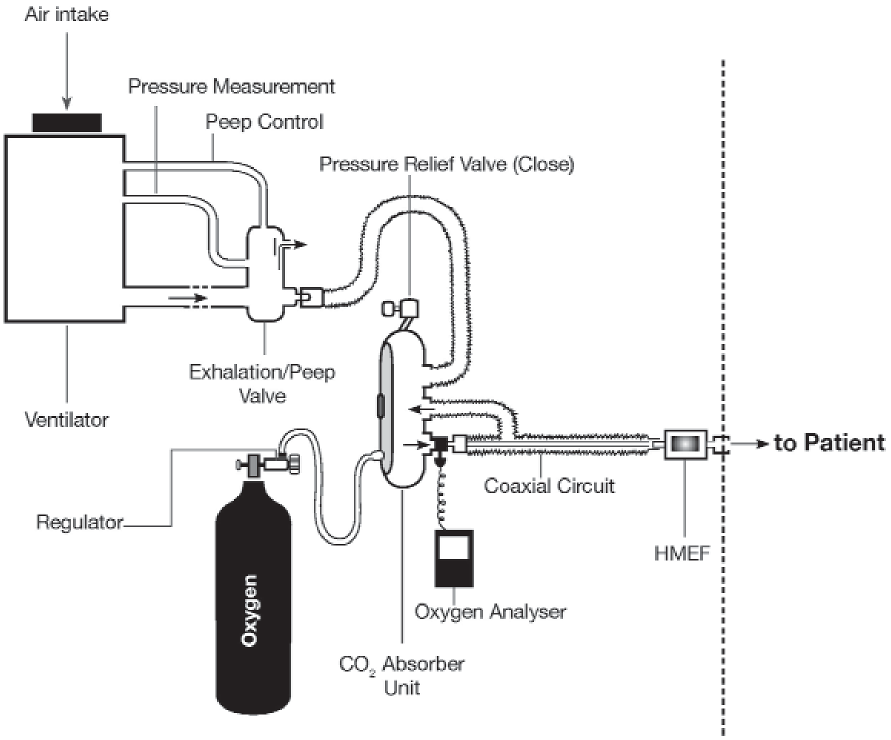

Figure 2. Modified Circle System

greater than the patient's tidal volume. Accepting that a tidal volume greater than 700 mL would be unusual for a ventilated patient, tubing with an internal volume of 1000 mL is adequate. Two standard lengths of anesthetic circuit tubing joined with a total static volume of 1000 mL (tested with water) were used.

Soda lime unit

The components of the soda lime unit (KAB-DNIP, Disposable Circular CO_2 Absorber Medical Developments, Melbourne, Australia) include 2 unidirectional valves, a female port where the oxygen dead space tubing connects, an oxygen inlet nipple, and an adjustable pressure relief valve (designed to attach to a gas scavenging system). The pressure relief valve remains completely closed unless the circle is being flushed with high flow oxygen, in which case the valve should be partially opened to avoid an excessively large tidal volume being delivered to the patient.

The soda lime is required to absorb carbon dioxide from the expired gases. The main constituents are calcium hydroxide (94%) and sodium hydroxide (5%). The following reactions occur:

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O + \text{heat}$$
$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$$

The production of heat and water can help warm and humidify inspired gases. Water, however, may become a problem as a result of excessive "rain out" in the patient circuit, requiring the inclusion of a water trap.

The rate at which soda lime becomes exhausted depends on the capacity of the canister, the size and shape of soda lime beads, the fresh gas flow rate, and the rate of carbon dioxide production. As an estimate, the following calculations can be used:

- Maximum oxygen consumption of 4 mL/kg/min (ie, 300 mL/min for 75 kg patient)
- Typical R/Q quotient of 0.8 gives CO_2 production of 240 mL/min (ie, approximately 15 L/hr).
- Soda lime absorbs around 15 L CO_2/100 g. A container with 400 g of soda lime should last around 4 hours.

Two reusable containers are sufficient. One is refilled while the other is in use. Some airlines may have concerns, however, about the potential spillage of soda lime during refilling. Disposable units may have to be used.

Oxygen supply

Cylinders. In addition to the main cylinder (the size of which will depend on the length of the journey) a small (eg, Aus C size = 440litres), needs to be carried for both transporting the patient between ambulance and aircraft and also for emergency use if the circuit needs to be rapidly flushed with high flow oxygen (because of the 2 different regulators required).

Regulators. Regulators with fixed flow settings are required, rather than a simple gauge or ball flowmeter. Both gauge and ball flowmeters are fairly inaccurate; the latter require a stable upright position and are relatively fragile because of the exposed glass/plastic column.

As a result of the differing requirements of maintenance

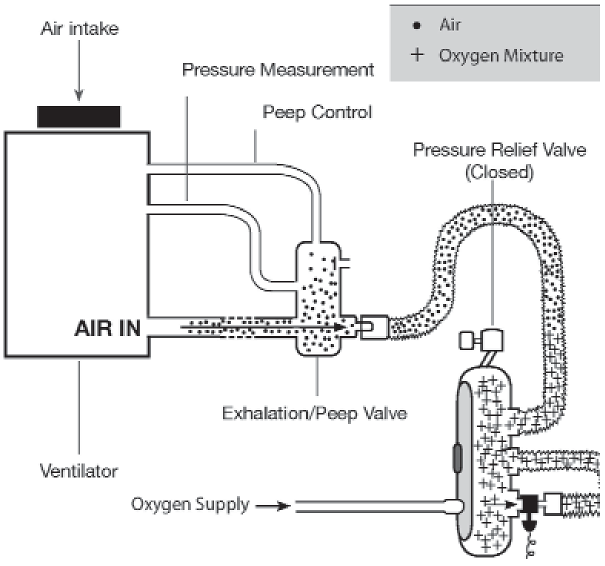

Figure 3. Inhalation

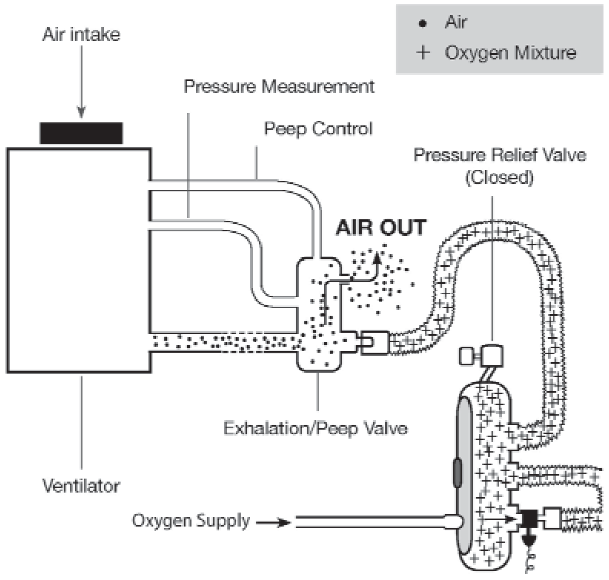

Figure 4. Exhalation

and emergency oxygen flows, 2 regulators may be needed:

a. The maintenance cylinder requires a regulator with flows down to 200 mL/min to maintain optimal efficiency. Higher flows can be used; however, in the patient with a low resting VO_2, a leak must be created by partially opening the CO_2 unit scavenging valve, or the patient's FiO_2 will steadily increase over time.

b. The emergency cylinder needs to be able to deliver high flows so that the FiO_2 can be increased rapidly. Higher flows are also required so that a self-inflating bag (Ambu-bag) can be used to transfer a patient between ambulance and aircraft while the circle circuit is set up on board.

Two possible regulators are low flow (0.03-3 L/min) regulator (Sabre Medical, Aldershot, England) and high flow (1-15 L/min) regulator (British Oxygen Company).

Oxygen concentrators. Oxygen concentrators can provide up to 5 L/min of oxygen, which is more than adequate for the MCS. The major concern would be failure of the power supply to the concentrator or failure of the concentrator itself. There would be no oxygen safety net unless the airline gave agreement to use the onboard emergency supply in this rare event. In addition, the accurate low flows achievable with a regulator are not possible with a concentrator. A leak may need to be introduced into the system to compensate for higher than necessary flows (by opening the CO_2 unit pressure relief valve). Given the oxygen savings achieved with the MCS, the benefits of using an oxygen concentrator are probably outweighed by the possible problems.

Patient circuit

A coaxial circuit (Universal F, King Systems, Medical Developments, Melbourne, Australia) was used to save space and reduce tube entanglement. Alternatively, a standard 2-limb ventilator circuit with a Y-piece can be used.

Oxygen analyzer

Any small portable in-line oxygen analyzer can be used. The Datex Ohmeda 5120 (Louisville, Ky., USA) is the current analyzer used at the Royal Adelaide Hospital. Batteries (C size/LR14) are easily replaceable and last more than 24 hours.

CO_2 monitor

This is standard monitoring equipment. CO_2 measurement is necessary to guide minute ventilation settings because the delivered tidal volume of some ventilators is affected by altitude and a percentage of each volume is lost from expansion in the circuit tubing. In addition, the patient's CO_2 production may vary during the transfer.

CO_2 readings should also be used in combination with the color change of the soda lime granules as a guide to when the CO_2 unit needs changing.

Adjustable pressure relief valve

The requirement for an adjustable pressure relief valve in the circuit is debatable. Because oxygen is entering the circuit at high pressure (albeit at low flows), there is a theoretical risk of barotrauma to the patient. This can occur only if the oxygen dead space tubing is completely occluded somewhere along its length or the patient expiratory limb is occluded. The pressure within the lungs will then steadily increase as oxygen continues to flow (0.5–1.0 L/min) into the circuit with no valve through which to escape, leading to alveolar rupture.

If occlusion of the oxygen dead space tubing occurs, all ventilators should alarm for high pressure. This should alert

Table 1

Comparison of Suitable Electrically Powered Ventilator

	Breas PV 403	**Pulmonetic LTV 1000**	**Newport HT50**	**Uni-Vent 754**	**Puritan Bennett LP 10**
Weight (kg)	5.5	5.7	6.8	5.8	16
Dimensions W x H x D (cm)	35x17.5x26	30x25x8	27x26x20	22x29x11.5	25x37x34
Cost (approx.)	A$12500	A$25000	A$18500	US$8500	A$18000
Company	Breas, Gothenburg, Sweden	Pulmonetic, Colton, Minn	Newport Medical, Newport Beach, Calif	Impact, West Caldwell, NJ	Puritan Bennett, Pleasanton, Calif
Pressure Support	Yes	Yes	Yes	Yes	No
PEEP Internal or External	Max 10 cm H_20 Int or Ext	Max 20 cm H_20 Ext	Max 30 cm H_20 Int	Max 20 cm H_20 Int	Max 10 cm H_20 Ext
Display	LCD	LED	LED and pressure meter	LCD	Pressure meter and dials only
Locked Controls	Yes	Yes	Yes and protective cover	Protective cover	Protective cover only
Operating Temperature (°C)	5 to 35	5 to 40	–18 to 50	–60 to 60	5 to 40
TV Stable at Altitude	No	Yes	Yes	Yes	No
Int. Battery Life -700x10, Norm Lung	14 hrs 20 min	2 hrs	17 hrs	Not tested (av. 3 hrs)	50 min
AC Supply 110-240	Yes	Yes	Yes	Yes	Yes
DC 12V Compatible	Yes	Yes	Yes	Yes	Yes
Hrs From 36 AmpHr Battery	12	12	70	12	10
Pros	• Simple display/ controls • Quietest ventilator •Long battery life	• Designed for transport of critically ill • Used by British Armed Forces and other Australian helicopter retrieval services • Solid yet compact and light • Detects circuit leaks as measures Exp MV • LED screens easily visible in bright and dark light (no protective cover but shock resistant, and if one LED is damaged, remaining screens continue to function) • Basic ventilator settings obvious (although complicated menus can be entered and may be difficult to return from if not familiar)	• Designed in conjunction with Israeli Defense Forces for military/ air medical use • Long battery life • Solid build yet still fairly light • Display/settings are clear and easy to use and protected by fold-down door (which also includes condensed user instructions) • PEEP-controlled internally and solid plastic exhalation valve • I:E ratio constantly displayed	• Designed for transport of critically ill patients • Used by US military and many civilian retrieval services • Compact, sturdy, and light • Protective door over settings	• Solid build • Obvious controls with a protective door and no LED displays to break • Current model for long-term ward ventilation at the RAH

Continued

	Breas PV 403	Pulmonetic LTV 1000	Newport HT50	Uni-Vent 754	Puritan Bennett LP 10
Cons	• Not robust or designed for transport (made for home/long-term ventilation) • Small, dark LCD screen without protective cover • All displays and controls lost if LCD screen damaged • Low pressure alarm sounds only on third breath after disconnection • I:E ratio needs to be calculated or read from Table	• Short internal battery life (although can be attached to pressurized oxygen supply to extend battery life) • PEEP valve brittle and easily damaged by unfamiliar staff	• Does not measure expired minute volume (c.f. LTV 1000)	• LCD display not as clear as LED alternatives • Moderate battery life • Currently no distributor in Australia	• Large and heavy • Very short internal battery life • No pressure support function • I:E ratio needs to be calculated or read from Table

Table 2

Ventilator Battery Test

Lung	Breas PV 403		Newport HT 50		Pulmonetic LTV 1000		Puritan Bennett LP 10	
Normal	Alarm	Stopped	Alarm	Stopped	Alarm	Stopped	Alarm	Stopped
	11 hrs	14 hrs 20 min	12 hrs 35 min	17 hrs	1 hr 20 min	2 hrs	45 min	50 min
Stiff	7 hrs 20 min	10 hrs 50 min	6 hrs 10 min	8 hrs 10 min	1 hr 15 min	1 hr 45 min	35 min	45 min

medical staff and give them enough time to discover the problem and correct it before the patient comes to harm.

The failsafe solution is to place a pressure relief valve at the patient end of the coaxial circuit. A single pressure (eg, 40 cm H_2O) manufactured valve is simplest; a variable valve may be used but must be calibrated and the setting fixed to avoid accidental adjustment.

Water trap

A self-sealing water trap (Siemens-elema, Solna, Sweden) is required to collect excess water within the patient tubing generated by the CO_2 unit. To reduce the chance of collected water accidentally reaching the patient during transport, the trap is best positioned in the expiratory limb of the circuit below patient level.

Oxygen Dead Space Principles

In the perfect setup, the whole system—from the patient, around the circle, and back to the end of the oxygen dead space tubing (where it connects to the ventilator circuit and expiratory valve)—will contain an air/oxygen mix with a constant and fixed FiO_2. The ventilator generates a column of air equal to the required tidal volume. This pushes an equal volume from the dead space tubing into the circle system, and an equal volume from the circle enters the patient's lungs (Figure 3). During expiration the gas is pushed back out of the circle into the dead space tubing, pushing the initial column of air back toward the ventilator. During this time, the ventilator opens the expiratory valve to allow this column of air to be released back into the room, rather than return through the ventilator. At the end of expiration, the original gas within the dead space tubing just reaches the ventilator expiratory valve before the next breath commences (Figure 4).

Although this ideal situation does not occur in reality, the principle holds true. The main reason that oxygen requirements (L/min) are greater than the patient's VO_2 is almost certainly a result of mixing of the air from the ventilator with the air/oxygen mix in the dead space tubing. The gases have fluid properties, and with the force and turbulence generated by the ventilator, mixing will occur. Mixing increases with larger tidal volumes and, to a lesser extent, with increased respiratory rates.

Position of Oxygen Inlet

Oxygen is added to the circuit through the oxygen nipple on the back of the CO_2 unit. The option of adding the oxygen through a T-piece in the inspiratory limb was tried and discounted for the following reasons:

- It makes no difference to the FiO_2 at any given flow rate.
- It takes longer to increase the FiO_2.
- Two additional pieces of equipment are required (T-piece and cap for O_2 inlet).

Controlling the FiO_2

The downside of the circuit is that there is no easy way to dial up a specific FiO_2. The circuit should be set up with a compliant reservoir bag/test lung attached before connecting to the patient. With the ventilator running, the oxygen flow from the cylinder can be adjusted to achieve the required FiO_2. Further fine-tuning may be required as the FiO_2 may drift up or down over time. This fluctuation depends on a combination of the patient's VO_2, tidal volume, respiratory rate, and the oxygen flow rate.

As aforementioned, the FiO_2 may be rapidly increased by attaching the oxygen tubing to the emergency cylinder at 10 L/min. The scavenging valve on the CO_2 unit must be partially opened during flushing to avoid delivering excessively large tidal volumes to the patient. To allow the FiO_2 to decrease, the oxygen supply is simply turned down or off while the oxygen analyzer is closely observed.

Tidal Volumes

Tidal volumes set on the ventilator should be used as a guide and adjustments made in relation to the measured end-tidal CO_2. Several factors will render the set tidal volume inaccurate, including expansion of compliant tubing, additional flow from the oxygen supply (ie, if the oxygen flow rate is increased to improve oxygenation, the tidal volume will need to be decreased slightly to maintain the same CO_2), and altitude effects on ventilator function.

Pressure Alarms

It is important that the ventilator's low pressure alarm should be set high enough to compensate for resistance to flow within the circuit. This ensures that the low pressure alarm will sound if a disconnection occurs. (Similarly the ventilator high pressure alarm may be set slightly higher than normal because the pressure at the patient end of the circuit will be less than that recorded by the ventilator.)

Ventilator Failure

The system design is such that, in the event of ventilator failure, a self-inflating bag can be attached to the circuit in its place and the system will continue to function in the same way. No oxygen supply needs to be attached to the bag, and therefore a reservoir attachment is not needed. A PEEP valve can be fitted to the expiratory valve on the self-inflating bag if required and patient breaths either assisted or controlled as necessary. The only consideration would be avoiding excessive tidal volumes that may increase gas mixing in the dead space tubing.

Changing the CO_2 Unit

When the CO_2 unit requires changing, the safest and easiest method is to connect a self-inflating bag with reservoir (attached to the emergency oxygen cylinder) directly to the tracheal tube mounting catheter through a heat moisture exchange filter.

Suction

Suctioning should be through a closed inline system to reduce oxygen wastage. The circuit FiO_2 inevitably will drop after suctioning; however, standard practice should be to preoxygenate the patient before any suctioning, so this should not be an issue.

Staff Issues

The modified circle requires a period of familiarization, even for an anesthesiologist/respiratory technician who is familiar with circle systems in the operating theatre setting. Color coordinating connections and a condensed aide-memoire may assist in the safe management of the system during transfer by less experienced staff.

Transport Ventilator Requirements

The ventilator should be able to provide a pressure/volume support mode to allow the transfer of patients without additional sedation and muscle relaxation, which is usually necessary with CMV. An electrically powered ventilator that can entrain room air to generate a tidal volume is required for optimal efficiency with the MCS. A pressurized gas supply must not be required. Ideally though, the ventilator should be able to generate a known FiO_2 when connected to an oxygen supply to allow this option for shorter transfers when oxygen conservation is not an issue. (The benefits of simplicity usually outweigh the oxygen-conserving benefits of the system in these situations.) The ventilator should have either an integral PEEP setting or allow an external PEEP valve to be applied to the exhalation valve.

The ideal attributes of the transport ventilator, other than those already mentioned, are:

- Compact, robust, and lightweight
- Easy to understand and use
- Clear display and settings
- Clearly audible and visible alarms
- Display protected from damage
- Settings lockable or protected by cover (to prevent accidental changes)
- Powered by both 12v DC and AC supply with long-lasting internal battery
- Mounting points for securing in aircraft

Ventilator Selection

The initial criteria we used to narrow the search for a suitable ventilator were electrically powered and the ability to generate a tidal volume without an additional pressurized gas supply. Table 1 summarizes each of the ventilators we considered and compares their specifications.

Although each of the 4 ventilators available for bench testing could be powered by both AC and 12v DC supply, the ability to operate from an internal battery for several hours was considered important. As the internal battery life quoted by the respective manufacturers was not derived using a standard test, we decided to perform our own testing. Each ventilator was fully charged (per the manufacturer's instructions) and then set to ventilate the test lung through the modified circle circuit at 2 separate settings:

- Normal lung, 700 mL x 10 bpm (PEEP zero, I:E 1:2)
- Stiff lung, 400 mL x 25 (PEEP 10, I:E 1:2)

Table 2 outlines the results. The performance of batteries can deteriorate over time, and the varying ages of the demonstrator ventilators may have affected the results to some extent. Having said this, the differences were considerable and roughly in proportion to the manufacturers' quoted figures. The Breas 403 and Newport HT50 clearly outperformed the other ventilators in this testing.

Several ventilators currently available fulfill the requirements of the ideal transport ventilator to varying degrees. The frequency of long distance transfers, the availability of aircraft power supply during flight (rather than carrying battery packs), and whether the ventilator will be used for shorter transfers need to be considered. Cost will also enter the equation.

Each critical care service has slightly different factors to consider, so a blanket recommendation is not appropriate. Of the ventilators we tried, the Newport HT 50 appears to best fulfill the criteria.

Conclusion

The Oxylog 1000 requires large amounts of oxygen to be carried when undertaking long distance transfers of ventilated patients. The use of an electrically powered ventilator will reduce these requirements, and several ventilators can be used in this role.

To allow a more substantial reduction in oxygen requirements, a form of circle circuit must be used. An MCS has been described that is relatively cheap and fairly simple to use. This system, in combination with an electrically powered ventilator, allows a large reduction in the safe oxygen requirements when transferring a ventilated patient over long distances.

Several aspects of the MCS require further investigation, including minimum oxygen flow rates to maintain a range of FiO_2, pressure drop across the circuit, and the time required to increase the FiO_2 in an emergency. This discussion will be presented in a separate article.

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