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APPARATUS

An assessment of the efficiency of the Glostavent® ventilator

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Summary

In parts of the world where supplies of oxygen and electricity are erratic, ventilating patients' lungs can be problematic. Should the electricity supply fail, gas driven ventilators have an advantage as they can continue functioning. However, many are extravagant in their requirement for the driving gas. The Glostavent® ventilator was designed to minimise these requirements. We measured the duration of ventilation achieved by the Glostavent ventilator using an E-size oxygen cylinder at a range of minute volumes, and the inspired oxygen concentration achieved by recycling the driving gas. The period of mechanical ventilation from a single E-size cylinder ranged from 11 h 8 min (SD 4 min) with a minute volume of 7 $l.min^{-1}$ to 18 h 15 min (SD 7 min) with a minute volume of 3 $l.min^{-1}$. The mean fractional inspired oxygen concentration achieved by recycling the driving gas without further inspired oxygen supplementation was 0.33. We conclude that the Glostavent ventilator performs as efficiently and cost effectively as predicted.

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Most mechanical ventilators require electricity as the source of power although gas driven ventilators are also in use, especially when the supply of electricity is unreliable or may fail completely, for example in the developing world. A disadvantage of many gas driven ventilators is the high consumption of gas, which is generally equal to the entire minute volume set for the patient [1]. This is not only expensive but can also create major logistical difficulties, especially in isolated regions where roads may become impassable and transportation difficult. The Oxyvent [2] was introduced in an attempt to overcome this problem by incorporating a Manley Multivent ventilator to reduce the utilisation of oxygen. It was superseded by the Glostavent® (Diamedica Ltd, Devon, UK) which is now marketed for use as an anaesthetic machine or as a mechanical ventilator for use in difficult environments [3].

The Glostavent has three principal components: a draw-over breathing system; an oxygen concentrator; and a gas driven ventilator. It also incorporates an uninterruptible power supply unit (UPS) and a reserve oxygen cylinder. The ventilator (Fig. 1) has been designed to conserve oxygen and works on exactly the same principle as the original Manley Multivent [4]. When electricity is available, the driving gas is supplied by the oxygen concentrator. If, however, the supply of electricity is interrupted and the concentrator ceases to function, the reserve cylinder automatically takes over both as source of pressure to drive the ventilator and of oxygen to supplement the inspired gas mixture. It is in these circumstances, when oxygen from the reserve cylinder is being used as the driving gas, that efficiency becomes of paramount importance and waste must be kept to a minimum. The Glostavent ventilator is a time-cycled, volume-limited pressure generator and has been designed to enable the driving gas to be used to maximum efficiency. Its features are shown in Fig. 2. The manufacturers have estimated that the combined effect of these features is that the volume of driving gas required is approximately one-seventh of the minute volume delivered to the patient [5]. As an additional contribution to efficiency, the oxygen driving the ventilator is recycled by being collected and returned to the breathing circuit to supplement the inspired oxygen concentration (Fig. 3). Although the ventilator entrains air, it is not imperative to measure the concentration of vapours at the patient end as

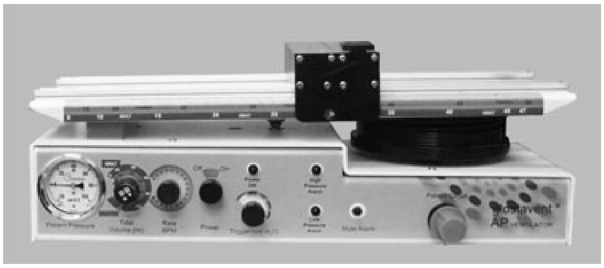

Figure 1 The Glostavent ventilator (photograph supplied by Diamedica Ltd).

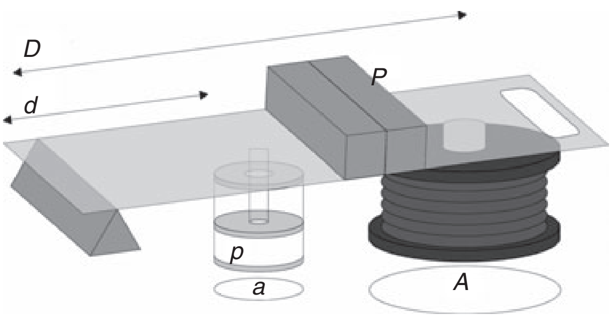

Figure 2 Design of the Glostavent ventilator. A handle is attached at one end to the top of a set of bellows while the other end acts as a fulcrum. A piston drives the handle upwards from below and allows the bellows to expand and fill. The pressure in the piston is then released and an adjustable weight above the handle compresses the bellows and delivers the contents to the patient. Particular design features governing gas usage are: the distance between the fulcrum and the bellows (*D*) is greater than that between the fulcrum and the piston (*d*); the area of the bellows (*A*) is larger than that of the piston (*a*); and the force acting at the piston (*p*) has to be greater than the force generated by the weight (*P*). Together, these ratios have the effect that the volume of drive gas used is one-seventh of the minute volume (diagram supplied by Diamedica Ltd).

the entrainment occurs upstream of the draw-over vaporiser and therefore does not dilute the resulting vapour concentration. Furthermore, the non-rebreathing valve prevents any recycling of expired gas and thus the concentration of inhaled gas equates to that leaving the vaporiser.

Our study had two objectives: to measure the duration of mechanical ventilation achievable by the Glostavent ventilator when an E-size cylinder of oxygen is used as drive gas; and to assess the degree of oxygen supplementation achievable by the recycling of drive gas.

Methods

Following approval from the Research Ethics Committee and the permission of the hospital authorities, the study was performed using a Glostavent anaesthetic machine situated in the theatre recovery unit in a district general hospital. No patients were involved. The recovery room was selected because it is staffed 24 h per day which enabled continuous vigilance throughout the prolonged periods involved. It had the additional advantage of being maintained at a constant temperature of 22 °C.

The breathing outlet from the ventilator was attached to a 2-l reservoir bag representing the lungs. A full E-size oxygen cylinder was used as the source of the driving gas and the ventilator was set to run at tidal volumes of 300, 500 and 700 ml with a respiratory rate of 10 breaths.min^{-1} and a maximum pressure of 25 cmH_2O in each case. These settings were chosen to represent a typical range used in adults. When the oxygen cylinder became exhausted, the bellows on the ventilator ceased to move and the low pressure alarm on the ventilator was activated. The alarm was turned off, the time noted and the duration of the period of ventilation calculated. This exercise was repeated for a total of five readings for each setting of the ventilator and the mean (SD) calculated. For comparison, predicted durations of ventilation were also calculated, assuming the manufacturers' rate of utilisation of oxygen as driving gas noted above, and taking a full E-size cylinder to contain a maximum of 680 l oxygen (although some variation is inevitable during the filling process, the suppliers guarantee the contents to be within 5% of this, i.e. a minimum of 646 l (British Oxygen Corporation, personal communication). In order to allow for this variation in contents, predicted duration of ventilation was also calculated (646 l).

Measurements were also made of the delivered oxygen concentration from samples taken at regular intervals from the inspiratory limb of the breathing system during each test, using a standard anaesthetic gas monitor (S/5; Datex–Ohmeda, Chalfont St Giles, UK).

Results

The ventilator functioned satisfactorily throughout the various periods of the study. The actual and predicted duration of ventilation and the fractional inspired oxygen concentration delivered at each setting are shown in Table 1.

Discussion

The duration of ventilation we measured approximated to the predicted values at 7 and 5 l.min^{-1} although less so at 3 l.min^{-1}, at which minute volume there was also greater variation within the results. These differences are likely to be due, in part, to the design of the ventilator, which gives a 25-ml change in tidal volume per 'click' of the control dial that is not easily discernable to the operator.

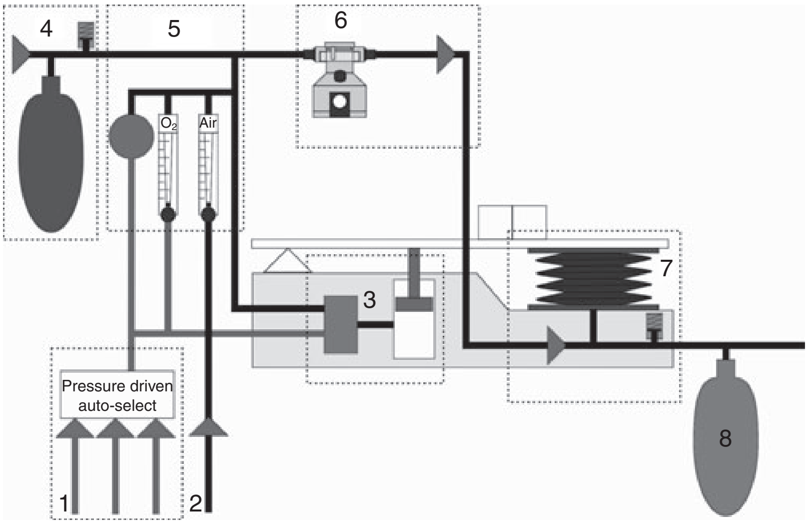

Figure 3 Design of Glostavent ventilator's gas delivery system: 1. Entry of oxygen from the concentrator, back-up cylinder, or external supply; 2. Entry of air from the concentrator; 3. Passage of oxygen through a valve filling the piston and driving the ventilator, from which it passes back through the valve's exhaust port to the patient circuit; 4. Draw-over oxygen conservation circuit comprising reservoir bag, one-way valve and over-pressure valve set at 5 cmH_2O; 5. Control panel with oxygen flush and flowmeters; 6. Draw-over vaporiser incorporating a one-way valve to prevent pumping of the vaporiser; 7. Ventilator bellows with a 60 cmH_2O pressure relief valve; 8. Self-inflating bag; 9. Outlet to non-rebreathing valve (diagram supplied by Diamedica Ltd).

Table 1 Duration of ventilation measured at different minute volumes, predicted duration of ventilation and fractional inspired oxygen concentration (F_IO_2) for the Glostavent ventilator. Values are mean (SD).

	Minute volume		
	3 l.min^{-1}	5 l.min^{-1}	7 l.min^{-1}
Duration of ventilation			
Actual	18 h 15 min (7 min)	14 h 42 min (2 min)	11 h 8 min (4 min)
Predicted			
Cylinder contents 646 l	21 h 42 min	14 h 15 min	10 h 36 min
Cylinder contents 680 l	22 h 51 min	15 h	11 h 10 min
F_IO_2	0.33 (0.009)	0.33 (0.004)	0.34 (0.02)

Clearly this produces a much greater percentage error in a setting of 300 ml than in a setting of 700 ml, and this should be taken into consideration with paediatric patients, or when choosing a low volume ventilation strategy in critical care. Furthermore, at 300 ml tidal volume the reduction in efficiency due to the dead space volume (between the control solenoids and the piston, measuring $\sim$ 5 ml) is more pronounced. This is constant at all settings and therefore this effect is proportionally greater at the lower end of the scale. Finally, the driving gas pressure is pre-set in the factory. In practice, it is set as close as possible to a nominal value of 1.15 bar, but any value above this will tend to reduce the driving gas:minute volume ratio below 1 : 7. These factors, when taken into consideration with the variable contents of the oxygen cylinders when they leave the supplier, mean that a precise calculation of the duration of ventilation is not possible. The study does, however, confirm that the manufacturers' estimate of the driving gas:minute volume ratio is in the order of 1 : 7, both demonstrating that huge savings can be made when this ventilator is used and providing valuable information when long term oxygen requirements are being estimated.

The fractional inspired oxygen concentration achieved by recycling the driving gas was similar at each setting with means of 0.33 (the full range was 0.32–0.37). This is slightly higher than the value of 0.32 that would be expected with a driving gas:minute volume ratio exactly 1 : 7, and this indicates that the ratio may, in practice, be slightly lower. This additional oxygen delivery, which is achieved without additional usage of oxygen, is further testimony to the efficiency of the ventilator and can make a significant contribution to patient safety at no additional cost.

The cost of oxygen cylinders and the method of pricing vary between different parts of the world. In the Gloucestershire Royal Hospital, the cost of rental and filling of an E-size cylinder (including Value Added Tax at 17.5%) is £3.71 (€4.13; US$5.23).[1] In Africa the

[1]All costs and exchange rates as of March 2008.

equivalent costs will vary due to frequent changes in local prices, cost of transport and exchange rates but in Nigeria, as a typical example, a full E-size of cylinder costs £3.15 (€3.5; US$4.44) to purchase (British Oxygen Corporation Gases Nigeria PLC, Lagos, personal communication). Assuming that each cylinder contains the maximum of 680 l then the cost per litre is £0.55 (€0.61; US$0.77) in the UK and £0.46 (€0.51; US$0.64) in Nigeria. The cost in some countries may be much higher since transport plays an important role in the supply of oxygen and fuel is very expensive. In many isolated hospitals with long supply routes and roads that are hazardous or even impassable, the supply of oxygen may cease completely for prolonged periods. Gas driven ventilators assume great importance where electricity supplies are unreliable. Nowhere is this more marked than in the critical care setting where controlled ventilation and supplemental oxygenation may be required continuously for days or weeks at a time. When delivering a tidal volume of 500 ml at a rate of 10 breaths per minute, for example, a standard gas driven ventilator will utilise 7200 l oxygen per 24 h to drive the ventilator. Using the examples above the oxygen required would cost £39.28 (€43.77; US$55.38) per day in the UK and £33.12 (€36.9; US$46.69) per day in Nigeria. With a ventilator that can deliver the same minute volume utilising only one-seventh of the volume of driving gas, the cost of oxygen in the respective examples would be £5.61 (€6.25; US$7.90) and £4.73 (€5.27; US$6.67) per day. Should supplementary oxygen also be required, then the contrast with the standard gas driven ventilator would be further accentuated due to the recycling of the drive gas seen with the Glostavent.

The Glostavent has previously been shown to be safe and effective as an anaesthetic machine capable of delivering great savings in the cost of oxygen [6]. This study confirms the findings of others [7] and shows that it can be even more cost effective in a critical care setting, especially when failures of the electricity supply are commonplace and gas driven ventilators are needed.

Acknowledgements

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