Evaluation of six oxygen concentrators

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ABSTRACT Examples of six oxygen concentrators (DeVO₂, Dom 10, Econo 2, Hudson, Permax, and Roomate) were evaluated over a 9-28 day period to determine (1) the oxygen yield (% O₂) over the flow range 1-4 l min⁻¹; (2) 90% oxygen rise time (90% RT) from a cold start when they were operated at 2 l min⁻¹; (3) accuracy and readability of the flow device; (4) static outlet pressure; (5) major components comprising the product gas (Hudson only); and (6) general characteristics. At an outlet flow of 2 l min⁻¹ the mean % O₂ generated by all models, except the Permax (which was lower, mean (SD) 90.5% (3.1%)), were between 94% and 95% with a range of less than $\pm 0.5\%$. The Dom 10, Econo 2, and Hudson consistently generated higher oxygen concentrations than the other models at flow rates greater than 2 l min⁻¹. The 90% RT was less than 10.5 minutes for all models. Deviations of up to 22% were observed between predicted and measured flow rates in all models except the DeVO₂, Hudson, and Permax. It was possible to set the orifice type flow devices fitted to the Permax and Roomate between indicated flow settings, resulting in cessation of flow. Spectral analysis of the output of one device showed that argon and oxygen were concentrated to similar extents, indicating that the maximal attainable oxygen yield for a molecular sieve concentrator is about 96%.

The results of two controlled studies^{1,2} have clearly shown that the long term administration of oxygen to severely hypoxic patients with chronic obstructive airways disease for at least 15 hours a day can significantly improve life expectancy. The increasing popularity of domiciliary oxygen, and the inconvenience and expense to both patient and community of providing oxygen in cylinders, has encouraged the development of the molecular sieve oxygen concentrator as an alternative source of oxygen for domiciliary use that is reliable and inexpensive.^{3,4} These electrically powered machines provide a constant, readily available supply of oxygen by selectively removing nitrogen from room air.^{5,6}

Most currently available concentrators make use of the properties of a synthetic aluminium silicate belonging to a class of crystalline compounds known as zeolites. The molecular sieve has numerous minute pores linked by channels and is characterised by its huge surface area. The molecular size of a gas and its polarity determine whether it is retained by the sieve material, and this is the mechanism by which the nitrogen and water vapour components of room air are separated from oxygen. A continuous

supply of oxygen is achieved by using two sieve beds in a synchronised adsorption-desorption process. As one sieve adsorbs nitrogen under pressure the other (saturated) sieve is depressurised and purged to remove oxygen. The oxygen enriched air emerging from the sieve bed enters an accumulation tank, where it is available to the patient at a selectable flow rate. The purged nitrogen is released back to the room air.

This study was undertaken to compare the performance, safety, and operation of six molecular sieve oxygen concentrators.

Methods

The six concentrators we evaluated are listed in table 1 with the manufacturers' specifications. Each concentrator was assessed over a period of 9-28 days by the following: (1) A standard electrical examination, including high current earth continuity and a determination of leakage current from the chassis to earth (as detailed in the Australian standard publication No 3200). (2) An analysis of the product gas to determine (i) the percentage of oxygen generated at output flows of 1, 2, 3, and 4 l min⁻¹; (ii) the 90% oxygen rise time (90% RT) from a cold start when the concentrator is operated at an output flow rate of 2 l min⁻¹; (iii) the major

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Table 1 *Manufacturers' specifications*

Model	DeVO ₂	Dom 10	Econo ₂	Hudson 6200	Permax	Roomate
Manufacturer	Devilbiss Co, USA	Rimer—Alco, UK	Mountain Medical Equipment, USA	Ventronics, USA	Dragerwerk, Germany	Cryogenic Associates USA
Power consumption (w)	290	540	390	400	280	330
Safety features*						
Oxygen analyser	No	No	No	Yes†	No	No
Visual alarm(s)	No	Yes	Yes	Yes	Yes	Yes
Power failure alarm	Yes	Yes	Yes	Yes	No	Yes
Alarm test facility	No	No	No	Yes	No	No
Thermal cutout	Yes	Yes	Yes	Yes	No	Yes
Circuit breaker	Yes	Yes	Yes	Yes	No	Yes
Back up O ₂ facility	No	No	Cylinder connection	No	No	No
Bacteria filter	Yes	No	Yes	Yes	External	Yes
Outlet filter†	Yes	External	No	No	No	Yes
Flow device	Rotameter	Rotameter	Rotameter	Rotameter	Orifice	Orifice
Stated flow range (l min ⁻¹)	0-4	0-4	0-7	0-4	0-4	0-4
Oxygen concentration (%) at						
1 l min ⁻¹	95 ± 3	90-92	95 ± 3	96 ± 3	At least 90	96
2 l min ⁻¹	95 ± 3	90-92	95 ± 3	96 ± 3	At least 90	96
3 l min ⁻¹	95 ± 3	90-92	95 ± 3	96 ± 3	At least 80	95
4 l min ⁻¹	88 ± 3	90-92	90 ± 3	86 ± 3	80	92
Outlet pressure (kPa)	66	—	35	70	—	35
Noise levels (dB)	50-52	55	—	53	50	52
Weight (kg)	40	65	52	45.5	35	33
Height-width-depth (cm)	69-48-43	64-43-54	69-46-41	85-42-38	72-30-57	80-43-41

Conversion: SI to traditional units—Gas pressure: 1 kPa = 7.5 mm Hg.

*All models featured sound alarm, time elapsed meter, and inlet filter.

†Refers to filter between sieve beds and outlet.

‡Not fitted to model tested but will be fitted to all units.

components present (Hudson model only); (iv) the accuracy and readability of the flow device; (v) the gas pressure at the outlet when the flow is occluded.

Oxygen concentration (% O₂) was measured by a paramagnetic oxygen analyser (Servomex Controls Ltd, UK), which was known to be linear over the range 0-100%. A two point calibration schedule was followed each hour, oxygen free (99.9%) nitrogen and medical oxygen (assumed to be 100% pure) being used. All analyses were performed on a static gas sample, initially fed into the analysis cell by means of a diaphragm pump. The measurements were made via long delivery hoses supplied or recommended by the manufacturer or agent—7 m for the Roomate and 15 m for all other models. All gas analyses, other than for measurements of 90% RT, were performed at least one hour after the concentrator had been switched on and a 35 minute equilibration period was allowed at each flow setting before gas analysis.

The 90% RT was measured at least 19 hours after the concentrator had last been operated and at a flow of 2 l min⁻¹; it represents the time for the oxygen concentration to reach 90% of its equilibrium value. The major components in the product gas were determined by spectral analysis with a respiratory mass spectrometer (Centronic MGA 200, Centronic, UK).

Flow rates were measured with a rolling seal spirometer (PK Morgan Ltd, UK). All models other than the Roomate and Permax were fitted with a

rotameter type flow meter, which used either a spherical or a cylindrical float to indicate flow. Since the reading positions of the floats were not given in the manuals, the mid points were selected when we were setting flow rates with the spherical float and the top was used with the cylindrical float (Dom 10). All flow measurements were recorded at room temperature (22-23°C) and pressure (753-762 mm Hg). Static pressure at the outlet was measured with a Bourdon gauge of ±1% accuracy by momentarily occluding the output flow.

Results

The concentrators tested had two simple controls, a power switch and a flow control valve (or dial). The only routine maintenance required of the patient was changing (or washing) the inlet filter and ensuring adequate water levels in the humidifier.

All models were fitted with a time elapsed meter and inlet filter; each had some provision for an outlet filter (table 1) and (apart from the Permax) an audible power failure alarm, a circuit breaker, or thermal cutout switch. The DeVO₂ had no visual alarms. Only the Hudson had an external alarm test facility, which enables the 9 volt battery powering the alarms to be checked at will. (Since completion of this study the Hudson concentrator has been fitted with an oxygen sensor that continuously measures the oxygen yield. If the oxygen concentration falls below 70% the sensor illuminates the

Fig 1 Oxygen concentration produced by each concentrator compared with the measured outlet flow rate. Each data point represents the mean (SD) of at least nine measurements made via long delivery hoses. Bars (SD) are not shown where the SD was less than 0.4% O_2 . Ambient conditions: temperature 21.5–22.5°C (mean 22.0), barometric pressure 746–765 (mean 758) mm Hg, relative humidity 46–62% (mean 56%).

“dealer service light,” thus alerting the user to the need to call the service engineer.) The Dom 10 is constructed of fire resistant materials and was the only model to incorporate a ventilation fan to vent the cabinet of possible oxygen immediately before the unit commences operation. The Dom 10 also features a series of light emitting diodes that alert the patient to a possible fault and indicate its probable cause. The Econo 2 has an auxiliary oxygen inlet port for connection to an oxygen cylinder. In the event of power failure the Econo 2 can be switched to the oxygen cylinder if connected.

The Roomate and DeVO₂ were exceptionally quiet in operation compared with the other concen-

trators, even though all the noise levels published by the manufacturers were similar (50–55 dBA). At 4 l min⁻¹ the Dom 10 and Permax produced a high pitched noise that varied in intensity with the adsorption-desorption pressure cycle.

Concentrators designed to be tilted on to two large rear wheels (Econo 2, Hudson, Permax, and Roomate) were easier to move over carpeted areas than those mounted on four small castors (Dom 10 and DeVO₂). If weight is also considered, the Roomate was the most mobile, followed by the Hudson and Permax in that order. Mobility, however, would not be important if the concentrator is in a fixed position in the home. Each concentrator passed the electrical examination for safe use by patients. In the case of the Dom 10, however, earthing was achieved indirectly via a series of connector blocks. This arrangement was considered to be less secure as there is increased risk of incomplete earthing due to loosening of electrical connections.

The oxygen concentration produced varied in a cyclical manner in all models, especially at the higher flow settings. To obtain accurate gas analysis therefore it was necessary to collect and mix six litres of gas in a rebreathing bag before analysis. At the usual therapeutic flow of 2 l min⁻¹ the mean %O₂ generated by models other than the Permax was between 94% and 95% (fig 1), the %O₂ from each varying by less than 0.5% of the mean. At this flow the Permax generated concentrations that were both lower (mean 90.5%) and more variable (87.3–93.6%). At higher flow rates (3 and 4 l min⁻¹) the Dom 10, Econo 2, and Hudson generated the highest concentrations; only the Hudson, however, performed according to the manufacturers' specifications over the flow range studied (1–4 l min⁻¹).

No significant changes in delivered flow or %O₂ were found when short (2 m) and long (7–15 m) delivery tubes were used. Thus in all models the outlet pressure was considered adequate (table 2). At 2 l min⁻¹ the %O₂ produced by each concentrator rose to at least 90% of the equilibrium value within 4.5–10.5 minutes of being switched on (table 2).

Spectral analysis of the gas produced by the Hudson concentrator showed oxygen, argon (3.6%), and nitrogen to be the major components, with oxygen and argon concentrated to approximately equal extents. Carbon dioxide was detected in trace concentrations only.

The accuracy of the flow device fitted to each machine is shown in figure 2. Large deviations between predicted and measured flow rates were found, particularly at low flows, in models other than the DeVO₂, Hudson, and Permax.

Table 2 Static pressure measurements and 90% oxygen rise time

Model	Pressure (kPa)	90% oxygen rise time (min)
DeVO ₂	85–90	9.1
Dom 10	65	6.9
Econo 2	35–40	4.5
Hudson	65	5.6
Permax	35	5.8
Roomate	40–45	10.4

Fig 2 Accuracy of each flow device, shown as the percentage deviation from the flow rate measured with a spirometer. Symbols are the same as those used in figure 1.

Concentrators which had fixed orifices (Roomate and Permax) were judged the easiest for patients to use as readability was excellent and changes in flow rate were made simply by turning a dial. The Roomate incorporated an illuminated panel which clearly displayed the set flow rate at night. In both these models the flow rate could if necessary be preset and the dial removed to prevent tampering by the inquisitive. It was noted, however, that the orifice flow devices could be inadvertently set between indicated flow settings, resulting in cessation of flow.

Of the rotameter type flow devices, the one fitted to the Hudson was judged the easiest to use because it had a clearly graduated and illuminated tube, angled mounting, and quality needle value. The rotameters fitted to the other concentrators were difficult to use for one or more of the following reasons: (1) poor viewing position (Dom 10 and Econo 2); (2) cramped graduations (DeVO₂); (3) unstable float (DeVO₂ and Dom 10).

Discussion

The primary function of an oxygen concentrator is to provide a safe, inexpensive, and reliable source of oxygen at a therapeutically effective concentration and flow rate. They are not designed to provide an accurately defined oxygen concentration as this depends on many variables, such as resistance of the filters and operating voltage and pressure. For home use the concentrator should be durable and simple for patients to operate and maintain. It must also be suitable for operation in the home environment in terms of vibration, noise levels, mobility, and aesthetics. The results of this study indicate that significant differences exist between the models

tested as regards most of these requirements, particularly noise levels, mobility, power consumption, and safety features.

Because these devices are intended for long term use by patients in their homes, the features they possess must ensure their safe operation. The following safety features may be considered desirable:

1 *Electric shock hazard* The device should be electrically safe and insulation, earthing, and leakage current need to conform to individual countries' electrical safety requirements for medical equipment.

2 *Fire hazard* (i) Fire proof construction materials. (ii) Thermal cutout to turn off the unit in the event of overheating. (iii) Mains power circuit breaker in preference to replaceable fuses.

3 *Purity of the gas* (i) Outlet filter to exclude the possibility of sieve material reaching the patient. (ii) Inlet filter(s) for both dust and bacteria.

4 *Correct function* (i) Visual and audible alarms to include indication of (a) power failure and (b) inlet filter blockage/system pressure failure. (ii) Alarm test facility whereby the integrity of the battery powering the alarm can be checked. (iii) Power on-off switch that illuminates when in the on position.

5 *Dosage (and maintenance scheduling)* Time elapsed meter.

Of the six devices tested, only the audible alarm, time elapsed meter, and inlet dust filter were present in each and no concentrator featured the complete list. This lack of uniformity between manufacturers of oxygen concentrators points to the need for a *specific* standard defining minimum requirements for such devices. This is particularly important since the user of an oxygen concentrator is the patient and not a professionally trained operator of medical equipment. The failure of three of the six devices to indicate flow rate to within $\pm 10\%$ of the true value, and the failure of all but one device to fulfill their specifications regarding oxygen concentration produced, also indicates the need for the development of a formal standard.

The similar concentration factors for argon and oxygen of about four (found for the Hudson model) suggest that the maximum concentration of oxygen that can be obtained with a molecular sieve concentrator is about 96%—the remaining 4% consisting largely of argon. This is likely to be true for all the concentrators evaluated because they all use a similar sieve bed material. The ability of a concentrator to concentrate gases other than oxygen (for example, argon) deserves consideration. It is well known that molecular sieve materials are able to retain gases such as carbon monoxide and hydrocarbons and it has not been demonstrated unequivocally that

all atmospheric pollutants are removed. Thus the possibility of creating a physiologically harmful gas mixture by concentrating toxic gases, particularly in heavily polluted areas, has to be considered. In addition, industrial pollution may cause premature exhaustion of the molecular sieve.⁴

The reading position of the rotameter float (top or bottom) can significantly affect the flow rate, so that it should be a requirement for manufacturers clearly to state the correct reading position. We would also recommend that the orifice type flow devices fitted to the Permax and Roomate concentrators should be modified to exclude the possibility of inadvertent occlusion of the outlet flow should the dial be set between indicated flow settings.

All pressures generated were sufficient to allow the use of long delivery tubing without degradation of performance, thus allowing patients access to the oxygen supply without the need to move the concentrator. The use of long delivery tubing, however, greatly increases the possibility of occluding flow. This risk can be reduced by the use of "collapse resistant" tubing or, alternatively, by the construction of a fixed pipeline system from the concentrator to various parts of the patient's house.

The main disadvantage of concentrators compared with cylinders is the possibility of machine failure or power failure. A recent study by Evans *et al*⁴ in the United Kingdom showed that the concentrator can be used for up to 15 hours a day for long periods without the need to supply emergency back up oxygen, provided a stock of spare parts and a standby machine centrally located are readily

available. An alternative to cylinders for standby use is the "Oxyquick" apparatus (Kamiya Tsusan Kaisha Ltd, Tokyo), which is simple to use and produces oxygen by the chemical reaction of sodium carbonate peroxyhydrate and manganic oxide to produce oxygen for about 30 minutes per sachet.

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