In: Brueggeman P, Pollock NW, eds. Diving for Science 2008.
Proceedings of the American Academy of Underwater Sciences 27th Symposium.Dauphin Island, AL: AAUS; 2008.

Evaluation of Atmospheric Oxygen Concentrators as a Source of Oxygen and Oxygen Rich Mixtures for Treatment of Diving Accident Victims in Remote Areas

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Abstract

The difficulty of obtaining oxygen for the treatment of diving accident victims in remote areas has been a long-standing problem. The normal method for transporting oxygen is in metal high-pressure cylinders. These cannot be carried on airliners, and contain insufficient oxygen for the long-term on-site treatment of diving accident victims or for evacuation to a treatment facility. Oxygen concentrators offer the potential of providing a long duration supply of oxygen in remote areas or aboard ships. These devices selectively remove nitrogen from air, and produce a breathing gas mixture containing up to 95% oxygen. The flow rates, and pressure output of current portable units are insufficient for use with the demand type, or free flow oxygen masks currently used to provide pure oxygen to accident victims. However, when used with oxygen conserving delivery systems, they will provide sufficient flows of oxygen for the on-site administration of up to 90% oxygen, and for the long duration evacuation of diving accident victims, or other patients in need of augmented oxygen. Recently developed PSA units are small, lightweight, and can operate on batteries or 12 volt DC electricity, thus making them practical for use in the field. This study evaluated three different concentrators providing breathing gas to a high efficiency mask and to a semiclosed-circuit rebreather. Significant findings were: 1) High flow rates with lower oxygen content produced higher alveolar oxygen concentrations than low flow rates with high oxygen content, 2) Using the same supply gas, the semiclosed rebreather produced over twice the alveolar oxygen concentrations as did the high efficiency mask, 3) At the same output flow and oxygen concentration a threefold difference in electrical power was measured between different models of concentrators, and 4) One model produced sufficient pressure to conduct in-water recompression to a depth of 20 ft.

Keywords: safety, scuba

Introduction

The difficulty of obtaining oxygen for the treatment of diving accident victims in remote areas has been a long-standing problem for the NOAA Diving Program. The normal method for transporting oxygen is in metal high-pressure cylinders. These cannot be carried on airliners, and contain insufficient oxygen for the long-term on-site treatment of diving accident victims or for evacuation to a treatment facility. Chemical production of oxygen by "oxygen candles" likewise produces insufficient oxygen. Atmospheric oxygen concentrators offer the potential of providing a long duration supply of oxygen in remote areas or aboard ships. These devices concentrate the oxygen in air, and provide a constant supply of low pressure oxygen. They have been successfully used as an oxygen source for the production of divers' oxygen enriched breathing gas (Wells, 1991; Wells and Moroz, 1993; Wells and Moroz, 1994).

PSA oxygen concentrator

The most appropriate type of concentrator for the purposes addressed here are 'pressure swing adsorption' (PSA), units (shown at left). These devices selectively remove nitrogen from air, and produce a breathing gas mixture containing up to 95% oxygen. They are currently used as a replacement for high-pressure oxygen cylinders to provide oxygen-enriched mixtures in the homes of patients who require additional oxygen. These electrically powered devices provide a continuous, slow flow of 95% oxygen. The flow rates, and pressure output of current units are insufficient for use with the demand type, or free flow oxygen masks currently used to provide pure oxygen to accident victims. However, calculations show that when used with oxygen conserving delivery systems, they will provide sufficient flows of oxygen for the on-site administration of up to 90% oxygen, and for the long duration evacuation of diving accident victims, or other patients in need of augmented oxygen. Recently developed PSA units are small, lightweight, and can operate on batteries or 12 volt DC electricity, thus making them practical for use in the field. When used with the oxygen conserving delivery systems identified below, they provide viable methods of providing oxygen for on-site administration and evacuation.

The purpose of this study was to evaluate currently available oxygen concentrators, and oxygen delivery systems, and to provide recommendations to NOAA on the most efficient and cost effective combinations of the systems.

Three PSA oxygen concentrators of different size, weight, and power requirements were evaluated; the Excel, Healthdyne, and Eclipse. Specifications for each of the units are in Table 6 in the Results section below, where these units are discussed.

Two oxygen delivery systems were evaluated. The Hi-OX mask is a partial rebreathing open circuit system and was selected because of its high efficiency relative to similar simple mask systems (Bouak, 2004; Somogy et al., 2002). The design of this mask results in the inspiration of the high oxygen supply gas during the initial portion of the inspiration cycle from a flexible reservoir, and when that is depleted, the latter portion of the inspired gas is made up of surrounding air. The high oxygen mixture thus enters the alveoli first, while the air fills the respiratory dead space. This results in higher alveolar oxygen concentrations than would result if air were mixed with the inspired gas throughout the respiratory cycle.

The closed-circuit diving oxygen rebreather, Minolung, was selected because of its gas-tight design. Since the gas mixture used contained a minimum of 5% nitrogen rather than pure oxygen, it had to be tested in a semiclosed-circuit mode.

The fundamental difference between the above delivery systems is that the resulting alveolar oxygen concentrations at a particular flow/oxygen concentration setting are dependent on the respiratory minute volume, tidal volume, and breathing pattern for the Hi-OX mask, while for the rebreather, alveolar oxygen concentrations depend primarily on the oxygen consumption of the individual and are less dependent on breathing pattern and respiratory minute volume.

Methods

Tests of the volumetric output, oxygen concentration, and power requirements of the oxygen concentrators were accomplished in the same fashion for all three units. Each unit has its own flow indicator. The Excel and Healthdyne have standard 'ball' type flow meters, while the Eclipse has a digital meter. To eliminate differences between the respective individual flow meters, a 'standard' meter was installed in series with output meters and the readings of this meter are those reported here. The gas from the flow meter then passed through a sample cell containing a fast response oxygen sensor attached to a Teledyne oxygen analyzer. The analog output of the analyzer provided input to an A-D converter, and was recorded on a laptop computer equipped with appropriate software to graph the results. The graphs showed when steady state oxygen concentrations were obtained. Power requirements at each of the flow settings were obtained with a wattmeter.

Forced end expiratory oxygen concentration ($FEEO_2$) was used as a measure of alveolar oxygen concentration produced by the various combinations of gas flow rates and oxygen concentrations with the Hi-OX mask. Both $FEEO_2$ and the oxygen concentration of the inspiration 'bag' of the rebreather were recorded. Subjects received brief training in the procedure for obtaining FEEO2. The test procedure consisted of the subject removing the mask and performing a forced exhalation through the gas sampling cell. At the end of the exhalation, the subject placed his fingers over both ports of the cell and held them there for one minute. After approximately 15 sec a stable reading was obtained, and this value was recorded as the $FEEO_2$.

Results

Gas flow and oxygen percentages for the three concentrators are shown in Table 1 and Figure 1. Note that flow rates listed for the Excel and Healthdyne extend beyond the rated values, and beyond the flowmeters on the units, 3 and 5 L/min respectively. The digital flowmeter on the Eclipse limits flow to the rated value of 3 L/min.

Table 1. Flow vs. O_2 concentration

Flowrate L/min	Excel % O_2	Eclipse % O_2	Healthdyne % O_2
1	95.3	94	94.2
1.5		94.6	
2	92.5	96.5	94.2
2.5		96.3	
3	83.5	95.5	93.7
4	70.5		88
5	61.8		73.5
6	55.5		37.2
7	49.8		
8	45.8		

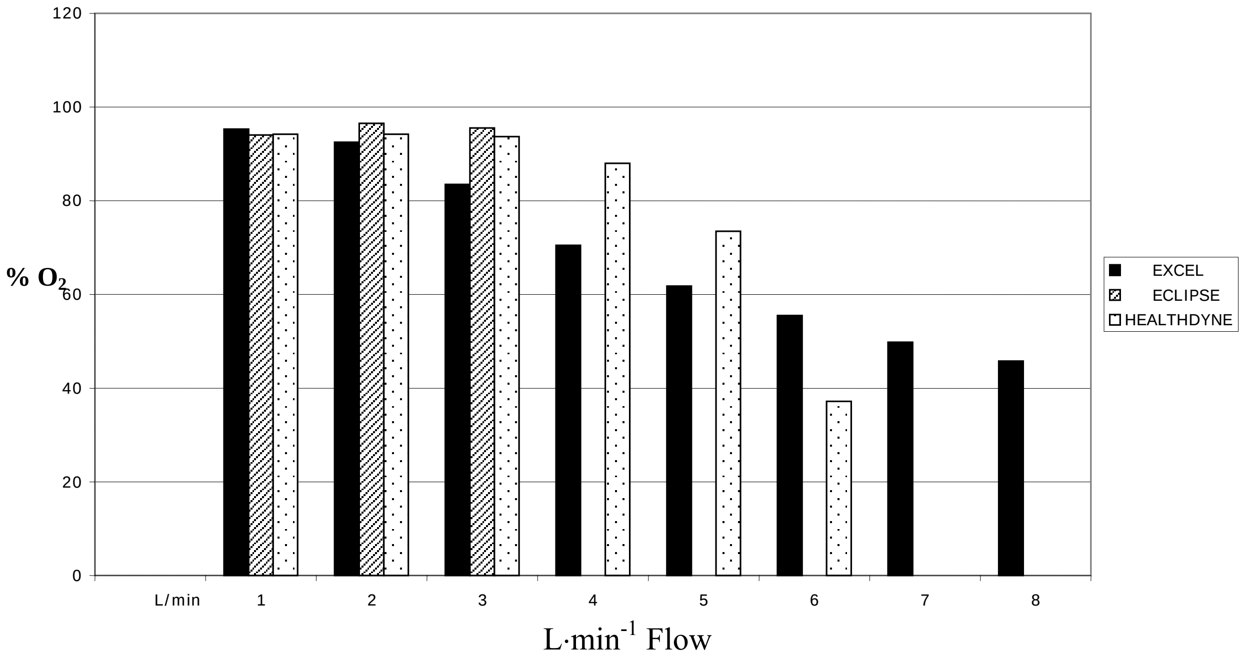

Figure 1. Flow vs. $\%O_2$

Power requirements as a function of gas flow rates are shown in Figure 2 and Table 2. Note that the power consumption for the Excel and Healthdyne is independent of gas flow, while that of the Eclipse is dependent on gas flow.

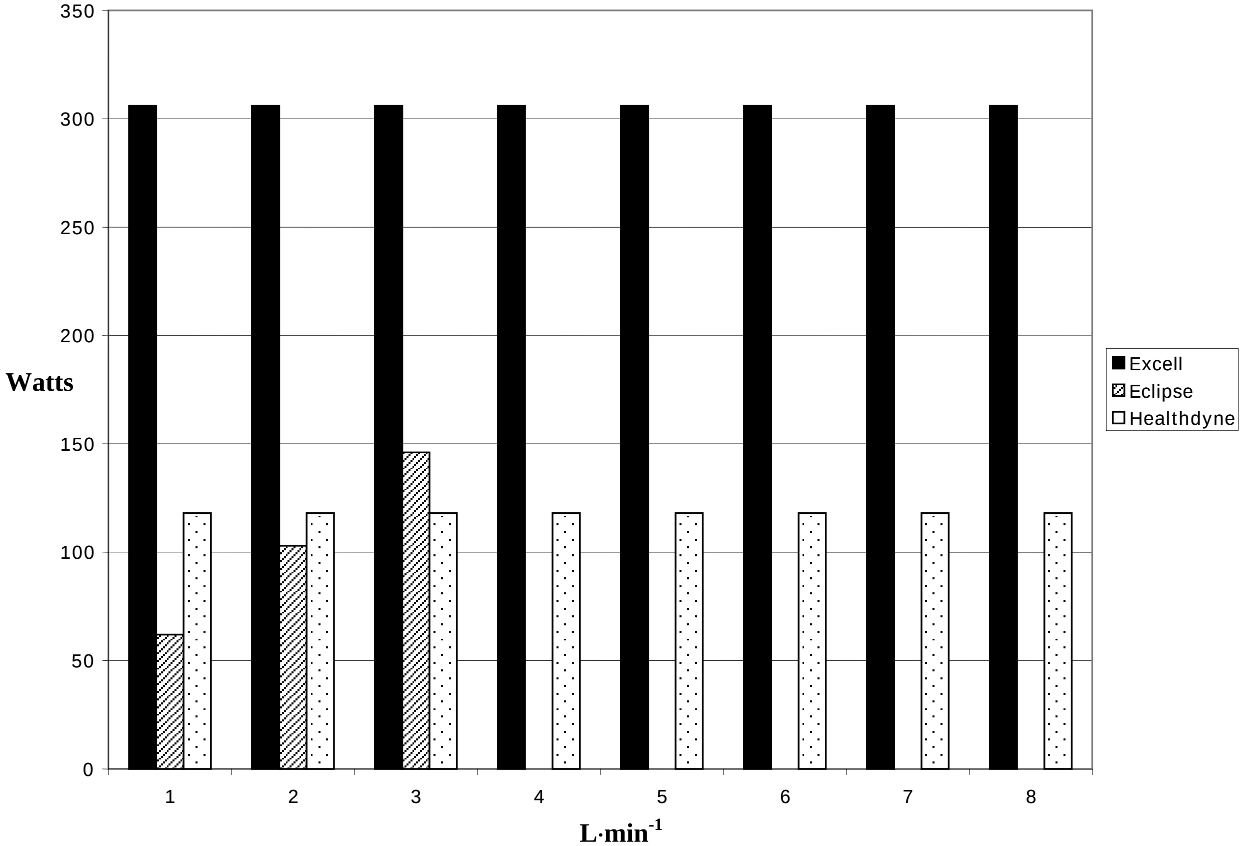

Figure 2. Watts vs. flow

Table 2. Watts vs. flow rates

$L \cdot min^{-1}$	Excell watts	Eclipse watts	Healthdyne watts
1	306	62	118
1.5		76	
2	306	103	118
2.5		116	
3	306	146	118
4	306		118
5	306		118
6	306		118
7	306		118
8	306		118

The $FEEO_2$ values for three subjects using the Hi-OX mask, as a function of gas flow rates and oxygen percentage, are shown in Figure 3 and Table 3 for gas supplied by the Excel concentrator. It is significant that the highest $FEEO_2$ values measured were at high flow rates and low oxygen concentrations, a combination that is not currently used in the administration of supplemental oxygen from oxygen concentrators. These values were obtained at flow rates in significant excess of the rated volumetric output of the concentrator and in excess of the maximum reading of their flow indicators. This observation could have a significant impact on how oxygen concentrators are used in the future.

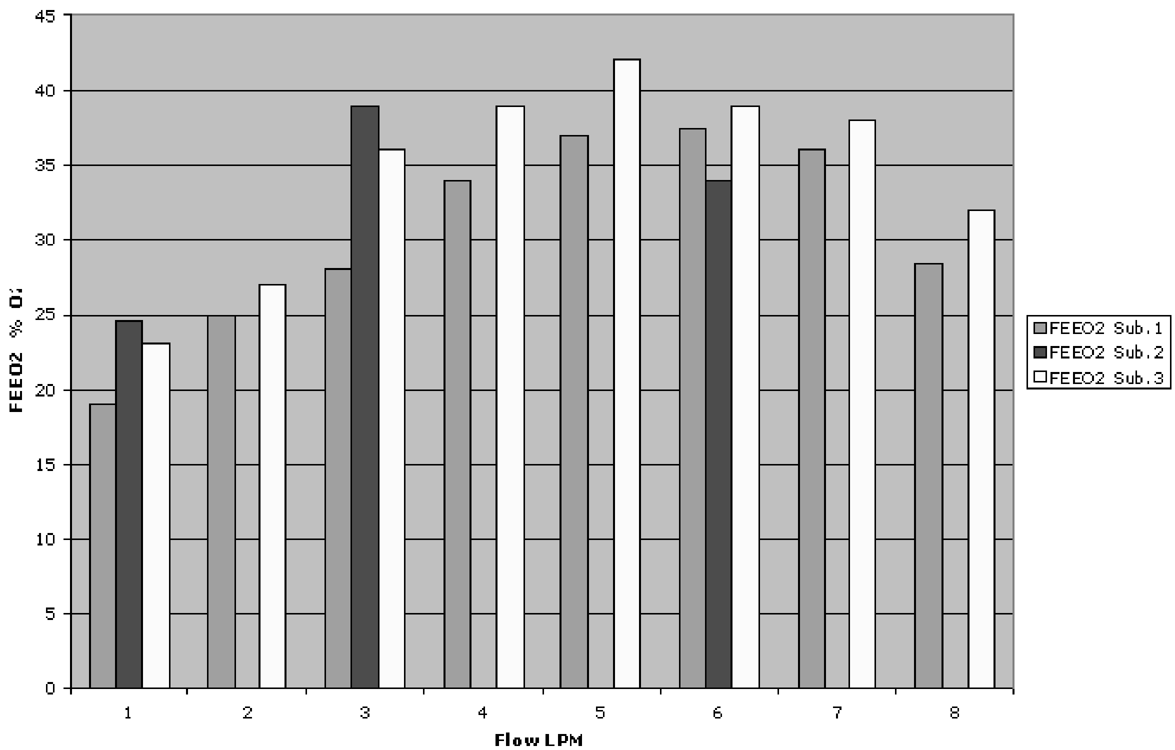

Figure 3. $FEEO_2$ vs. flow

Table 3. $FEEO_2$ vs. O_2 % and flow

L/min	% O_2	$FEEO_2$ Sub.1	$FEEO_2$ Sub.2	$FEEO_2$ Sub.3
1	95.3	19	24.5	23
2	92.5	25		27
3	83.5	28	39	36
4	70.5	34		39
5	61.8	37		42
6	55.5	37.5	34	39
7	49.8	36		38
8	45.8	28.5		32

Table 4 shows the results of the rebreather tests conducted using the Eclipse as an oxygen source. Shown are the supply flow rates and percent O_2, the oxygen % of the inhalation bag, the $FEEO_2$, and the subject. Note that the $FEEO_2$ values listed are all approximately twice those listed in Table 3 for the Hi-OX mask when supplied with a similar gas mixture and flow rates. Table 5 shows data obtained on the same subject on the same day, using the same gas source (Eclipse) when delivered by the Hi-OX mask and rebreather. Again, the rebreather produced twice the $FEEO_2$ of the mask.

Table 4. Rebreather Flow, Bag % O_2, and $FEEO_2$

L/min	Supply % O_2	Bag % O_2	$FEEO_2$	Subject
2	92.5	84	77	1
3	93.5	86.5	79	1
3	93.5	88.5	72.5	2
3	93.5	84.5	73	4

Table 5. $FEEO_2$ Rebreather vs. Hi-OX Mask

L/min	% O_2	$FEEO_2$	Delivery	Subject
3	93.5	37.5	Hi-OX	3
3	93.5	73	Rebreather	3

Table 6 shows the size and weights of the respective units. The Eclipse is the only unit tested that is equipped with a battery. The battery is internal and does not change the size of the case. Weight of the Eclipse is given with and without the battery. The battery is charged in place through the 120 volt AC cord and a 12 volt DC power cord is provided. As is evident from Table 2 the power requirements of the Excell and Healthdyne are small enough for these units to be powered by a 12 volt DC source through a small DC to AC inverter.

Table 6. Unit Dimensions

	Height (in)	Width (in)	Depth (in)	Weight (lb)	Volume (cu in)
Eclipse	18	11.5	7	17.97 with batt. 14.48 w/o batt.	1,449
Excell	18	11.5	11.5	29	2,380
Healthdyne	27	12	18	54.4	5,832

Table 7 shows the relationship between flow settings and output pressure. Note that while the output pressures of the Excell and Healthdyne decrease at higher flow rates, that of the Eclipse increases. Also note from Table 2, that the power requirements of the Excell and Healthdyne are constant at all flow rates while that of the Eclipse increases with increasing flow. This is because the compressor 'speed' of the Excell and Healthdyne is constant at all flow rates, while that of the Eclipse increases with increasing flow. The higher output pressure (9 psig) of the Eclipse offers the potential of using this unit for 'in-water' recompression of divers using a semiclosed-circuit rebreather to a depth of 20 ft.

Table 7. Flow settings vs. output pressure (in psig)

Flow Setting ($L \cdot min^{-1}$)	1	1.5	2	2.5	3	4	5
Eclipse	3	4.5	5.5	9	9		
Excell	2.5		2.5		2.2	2	1.5
Healthdyne	4.2		4.2		4.2	4	4

During a separate study, some day to day variation in the O_2 concentration of the Eclipse was noted. The other units were not used. Careful calibration of the O_2 analyzer showed these variations to be true. The initial tests of all units were conducted at temperatures of 72-78°F. When the Eclipse was used in Key Largo, FL, at temperatures of 92-96°F, a significant decrease in O_2 concentration was measured at the respective flow rates. The unit produced a maximum O_2 concentration of 90%. When the measurements were repeated in an air conditioned space at 73°F the original flow/O_2 values were obtained. This simple observation suggests that the O_2/flow values are dependent on the ambient temperature. While the decrease of approximately 3.5% O_2 for a temperature increase of 20°F is rather small, it may warrant further study. Since the other units tested also work on the PSA basis, known to be temperature sensitive, it is highly probable that their output is also temperature sensitive.

Discussion

1. Using the same high oxygen concentrations and gas flow rates, the rebreather produced twice the forced end expiratory (alveolar) oxygen concentrations as the Hi-OX mask and uniform inspired gas mixtures of 84 - 87 % oxygen.

2. When size, weight, power requirements, and gas output are considered, the Eclipse oxygen concentrator is clearly the most desirable of the units tested for use under remote field conditions.

3. Higher alveolar oxygen concentrations can be achieved with the Hi-OX mask by breathing a high flow (5-6 L/min) gas mixture with low (55%) oxygen content than with a low flow (1-2 L/min) gas mixture with high (93+%) oxygen content. The high flow rates listed above exceed the manufacturer's specifications for the Healthdyne and Excel and similar units. They are 'off scale' on their flowmeters, and are not currently used for oxygen administration. A 'change in procedure,' using the same oxygen concentrators, could result in a significant increase in alveolar oxygen concentration of patients.

4. The Eclipse concentrator provides sufficient pressure, flow, and oxygen concentration to be used for 'in water' recompression, with a semiclosed-circuit rebreather, to a depth of 20 ft.

*Subjects 1 and 4 are the same individual. They are separated by three months in time, a program of physical fitness, and a weight loss of 10 lbs, and thus listed as different subjects.

Acknowledgments

The authors thank subjects David Abbott, Nancy Roche, and Morgan Wells for their time and effort, the NOAA Undersea Research Center of the University of North Carolina, Wilmington for facility support in Key Largo, Florida, and the following manufacturers: Oxlife Inc., Sequal Technologies Inc., and Healthdyne for the loan of the units used in this study.

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