

Evaluation of Oxygen Concentrators and Chemical Oxygen Generators at Altitude and Temperature Extremes

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ABSTRACT Oxygen cylinders are heavy and present a number of hazards, and liquid oxygen is too heavy and cumbersome to be used in far forward environments. Portable oxygen concentrators (POCs) and chemical oxygen generators (COGs) have been proposed as a solution. We evaluated 3 commercially available POCs and 3 COGs in a laboratory setting. Altitude testing was done at sea level and 8,000, 16,000, and 22,000 ft. Temperature extreme testing was performed after storing devices at 60°C and -35°C for 24 hours. Mean FIO₂ decreased after storage at -35°C with Eclipse and iGo POCs and also at the higher volumes after storage at 60°C with the Eclipse. The iGo ceased to operate at 16,000 ft, but the Eclipse and Saros were unaffected by altitude. Oxygen flow, duration of operation, and total oxygen volume varied between COGs and within the same device type. Output decreased after storage at -35°C, but increased at each altitude as compared to sea level. This study showed significant differences in the performance of POCs and COGs after storage at temperature extremes and with the COGs at altitude. Clinicians must understand the performance characteristics of devices in all potential environments.

INTRODUCTION

Supplemental oxygen can be lifesaving in emergency situations, although the burden of providing oxygen during transport and in remote areas is substantial in cost, transport, and materials. Oxygen cylinders are heavy and present a number of potential hazards including fire and projectile risks. Liquid oxygen systems provide a large amount of gas with a smaller foot print but are heavy, exhaust gas over time, and present a burn risk if handled improperly. In addition, the output of both of these oxygen systems is finite and requires refilling, which presents logistical issues in far forward military operations. Simpler, lighter, and longer lasting oxygen delivery systems are needed for military and mass casualty operations. As possible materiel solutions, we evaluated portable oxygen concentrators (POCs) and chemical oxygen generators (COGs) at altitude and temperature extremes. Understanding performance of these devices under deployed conditions is crucial to safe and effective use.

METHODS

We evaluated 3 commercially available POCs (Eclipse 3 and Saros, Chart Sequal Technologies, Ball Ground, Georgia, and iGo, Devillbis Healthcare, Somerset, Pennsylvania) and 3 COGs (O₂PAK, Pacific Precision Products, Irvine, California,

Traumaid-26, HABCO Industries, Glastonbury, Connecticut, and BUDI Oxygen Bag [BOB], Green Dot Systems, Miami, Florida) in a laboratory setting. The devices were evaluated at sea level and at altitudes of 8,000, 16,000, and 22,000 ft corresponding to respective barometric pressures of 760, 565, 412, and 321 mm Hg in a man-rated altitude chamber at Wright-Patterson Air Force Base, Dayton, Ohio. An altitude of 8,000 ft was chosen to represent a simulated cabin altitude during a Critical Care Air Transport Team flight. An altitude of 22,000 ft was chosen to represent the upper limit of crew functionality in the case of aircraft decompression and conditions for Special Operations Forces mission requirements. The devices were also evaluated after storage for 24 hours at temperature extremes of -35°C (-31°F) and 60°C (140°F) in an altitude/environmental chamber at the University of Cincinnati. The devices were allowed to acclimate to room temperature for 30 minutes after placement outside the chamber before measurements were made. Room temperature was 21°C (70°F).

The COG flow output was obtained by attaching the oxygen tubing to the device and to a Fleisch pneumoachograph (Series 4700, Hans Rudolph, Shawnee, Kansas). Measurements of liter flow, total oxygen volume, and duration of operation were measured continuously after activation of the devices until flow ceased. Oxygen concentration was continuously measured with a fast laser diode oxygen analyzer (O₂CAP, Oxigraf, Inc., Mountain View, California) throughout the duration of operation. Surface temperature of the COGs was measured intermittently throughout the duration of operation with a noncontact infrared thermometer (62 Max, Fluke Corporation, Everett, Washington).

Measurements of flow, volume, and fraction of inspired oxygen (FIO₂) were accomplished by attaching oxygen tubing to the outlet of the POCs and to the inlet of an oxygen concentrator tester (Hans Rudolph) and running the device

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in either continuous flow or bolus mode. The concentrator tester has the ability to provide negative pressure to simulate inspiratory effort, which triggers the concentrator to deliver a predetermined bolus of oxygen. Concentrators were tested at 1, 2, and 3 L/min continuous flow and throughout the range of bolus volumes with each device at respiratory rates of 20 and 30 breaths/min, with each bolus setting. Data were recorded every 100 milliseconds with continuous flow mode and breath to breath in bolus mode. Concentrators were allowed 1 minute of stabilization and a minimum of 1 minute of data were collected at each setting.

Flow and volume accuracy was determined by comparing the measured values to the device specifications detailed in the operator's manual of the Eclipse and Saros. The iGo operator's manual did not report an accuracy range for flow and bolus volume, so we used the ranges documented for the other two devices. Reported flow accuracy was $\pm 10\%$ or 200 mL/min, whichever was larger. Bolus volume accuracy was reported as $\pm 15\%$ of the set volume. FIO₂ accuracy range was determined by the documented range in the operator's manual for each device. The reported FIO₂ range was $90\% \pm 3\%$ for the Eclipse, $91\% \pm 3\%$ with the iGo, and $93\% \pm 3\%$ with the Saros. In addition, battery life of the POCs was evaluated at room temperature after charging for 24 hours, using continuous flow at 3 L/min and the highest pulse dose setting at a respiratory rate of 30 bpm. Two devices of each model were evaluated and all tests with each devices was accomplished a minimum of 2 times. Data were continuously recorded to a personal computer for later analysis.

Device Description

Portable Oxygen Concentrators

Figure 1 shows the POCs evaluated in this study. These devices were chosen because each produced the highest commercially available continuous flow output and bolus size. All the devices weighed less than 20 lbs. The Eclipse 3 and iGo can either be carried via handle or placed in a wheeled cart for transport. A harness which attaches to the Saros that includes a shoulder strap provides a hands-free method in which to transport the device. Table I shows the specifications for the concentrators evaluated in this study.

Chemical Oxygen Generators

Current COGs typically contain 1 or more of the following solid compounds: sodium chlorate, sodium perchlorate, potassium superoxide, or peroxide species' sodium percarbonate, or percarbamide peroxide.¹ When combined with a catalyst, the resulting chemical reaction releases oxygen and produces heat. Figure 2 shows the COGs evaluated in this study.

O₂PAK

The main ingredient in the O₂PAK is sodium chlorate in addition to small quantities of disodium peroxide, disodium oxide, mica, magnesium, sodium perchlorate, glass powder, and zinc peroxide. The device is cylindrical, 9.8 inches in height, and 4.0 inches in diameter, weighing 3.0 lbs.² The device is self-contained, sealed, and internally insulated, and is supplied with a nylon cover for further insulation. A pin attached to a wire is pulled to activate the device. Oxygen



FIGURE 1. Oxygen concentrators evaluated in this study.

TABLE I. Concentrator Specifications

	Eclipse 3	Saros	iGo
Size (H × W × D) (in)	19.3 × 12.3 × 7.1	26.8 Length 4.375 Diameter	15 × 11 × 8
Weight With Battery (lbs)	17.4	12.25	19.0
Continuous Flow Settings	0.5–3.0 lpm (0.5 lpm Increments)	1.0–3.0 lpm (1 lpm Increments)	1.0–3.0 lpm (1 lpm Increments)
Pulse Dose Settings	16–96 mL, 128 mL, 16 mL, 196 mL	16–96 mL (16 mL Increments)	14–84 mL (14 mL Increments)
O ₂ Concentration	90% ± 3%	93% ± 3%	91% ± 3%
AC/DC Operation	Yes	Yes	Yes
Battery Life	1.3–5.4 Hours	0.5–1.2 Hours	1.6–5.4 Hours
Storage Temperature (°C)	–20–60	–20–60	–20–60
Operating Temperature (°C)	10–40	0–43	5–40
Altitude Range (ft)	0–13,123	0–18,000	0–13,123

AC, alternate current; DC, direct current; lpm, liters per minute.

begins to flow within seconds of activation. The O₂PAK has a small flow indicator at the end of the outlet tubing where oxygen tubing is attached and also connects to a nasal cannula or simple mask for patient use. The cost of the device is \$675 each.

Traumaid

The main ingredient in the Traumaid is sodium perchlorate with smaller quantities of iron powder, manganese dioxide, and mica. Similar to the O₂PAK, the device is cylindrical, 8.2 inches in height, and 3.5 inches in diameter, weighing 2.3 lbs.³ The device is self-contained, sealed and internally insulated, and may be fitted with an optional nylon cover for additional insulation. The device has 2 pins that must be pulled to initiate the reaction process. Oxygen flow begins seconds after activation. As with the O₂PAK, oxygen tubing is attached from the device outlet to a nasal cannula or simple mask for patient use. The cost of the device is \$895 each.

BUDI Oxygen Bag

The BOB system requires the user to add ingredients to a plastic bag to initiate oxygen production. The reusable bag and chemicals are supplied as a kit. The user places premeasured sodium percarbonate and manganese into the bag, adds 450 mL tap water, swirls the bag to mix, place the top on the bag, and attach oxygen tubing from the outlet in

the top to a nasal cannula or simple mask for use.⁴ Oxygen flow begins several minutes after mixing the chemicals. The top of the device contains desiccant consisting of silica beads to absorb excess moisture as the gas exists the bag. The cost for a single device kit is \$163, and consists of 1 reusable bag and chemicals for 2 separate runs. A refill kit consisting of enough dry chemicals to run 4 reactions costs \$50.

RESULTS

Portable Oxygen Concentrators

The mean FIO₂ with the Eclipse was within the manufacturer stated range during all altitudes and temperatures in continuous flow mode and at all altitudes in bolus mode, but fell to <87% at bolus volumes of 128, 164, and 192 mL at both temperature extremes. Figure 3 shows the ranges and mean FIO₂ with the 192 mL bolus setting at a respiratory rate of 30 at all test conditions. The FIO₂ difference from room temperature was statistically significant (*p* < 0.0001). Delivered FIO₂ was higher at altitude than at sea level especially with the bolus volumes of 64 mL and greater. Using the 2 L/min continuous flow setting, the mean flow was 1.7 L/min at all 3 altitudes, which was slightly below the accuracy range of 1.8 to 2.2 L/min. All continuous flow settings were within the accuracy range at temperature extremes. In bolus mode at the 128 and 160 mL settings at a respiratory



BUDI



Traumaid



O2PAK

FIGURE 2. Chemical oxygen generators evaluated in this study.

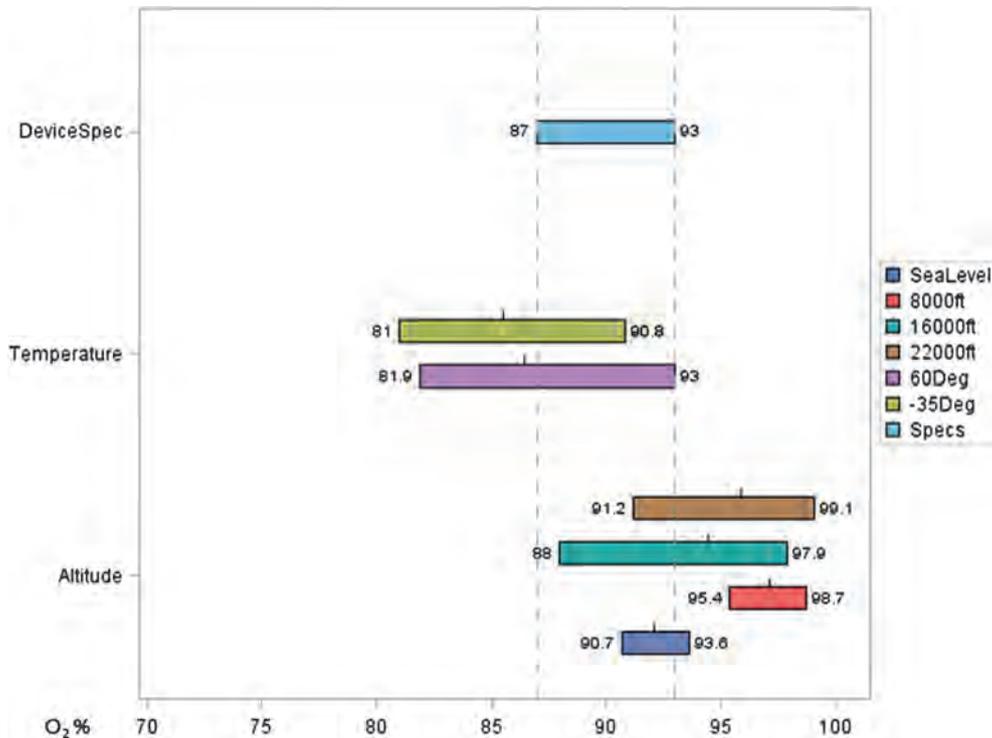


FIGURE 3. Range and mean FIO₂ on the 192 mL bolus setting with the Eclipse at a respiratory rate of 30 during all test conditions.

rate of 30, and 192 mL at respiratory rates of 20 and 30, at all conditions the measured bolus volumes were less than reported accuracy range by 5% to 45%.

The mean FIO₂ with the Saros was within the specified range at all altitudes and temperature extremes in both continuous flow and bolus modes with the exception of 3 L/min continuous flow after storage at -35° (88% ± 3%) and 96 mL bolus modes after storage at both temperature extremes (88% ± 4%). Figure 4 shows the ranges and mean FIO₂ at the 96 mL bolus setting at a respiratory rate of 30 at all test conditions. The differences from room temperature values were not statistically significant (*p* > 0.05). In all continuous flow settings, the Saros liter flows were less than reported accuracy range by 0.1 to 0.2 L/min after storage at -35°C and at all altitudes using the 2 L/min setting and at 16,000 and 22,000 ft using the 1 L/min setting. Flow accuracy was within specifications at sea level and after storage at 60°C. Pulsed dose volumes were 0.1 to 0.4 mL less than stated accuracy at 16,000 and 22,000 ft using the 16 mL setting with respiratory rates of 20 and 30 bpm and after storage at -35°C using the 16 mL setting at a respiratory rate of 20 breaths/minute. All other bolus volumes were within specifications.

The iGo produced a mean FIO₂ that was within the specified range in both continuous flow and bolus modes at sea level and 8,000 ft and after storage at 60°C. At 16,000 ft, the FIO₂ fell to 81% in continuous flow mode and failed to operate in bolus mode. After storage at -35°C, the FIO₂ range was 73% ± 0.3% to 78% ± 9% in continuous flow

mode. The difference from room temperature measurements was statistically significant (*p* < 0.01). Figure 5 shows the range and mean FIO₂ at the 3 L/min continuous flow setting at all test conditions. In continuous flow mode at the 2 L/min setting after storage at 60°C and at the 3 L/min setting after storage at -35°C, measured flow rate was less than specifications by 0.1 and 0.5 L/min, respectively. All bolus modes at sea level, 8,000 ft, and after storage at both temperature extremes were within specified accuracy range.

Battery life varied widely between the concentrators. Table II shows the battery life of each device at the highest pulse dose setting using a respiratory rate of 30 breaths/minute and at the highest continuous flow setting.

One of each of the POCs was rendered inoperable after storage at -35°C. The Eclipse and iGo would start, but the membrane pads to make mode and flow adjustments would not respond and the Saros would not start. These devices were reevaluated after having been at room temperature for 24 hours but the problems remained and were permanent.

Chemical Oxygen Generators

As compared to sea level at room temperature, flow rate, duration of operation, and total volume of oxygen produced varied widely between devices and within the same devices when exposed to temperature extremes and increased altitude. The inter-device variability was greatest with the BOB at all conditions, but this device was least affected by temperature extremes. As compared to room temperature

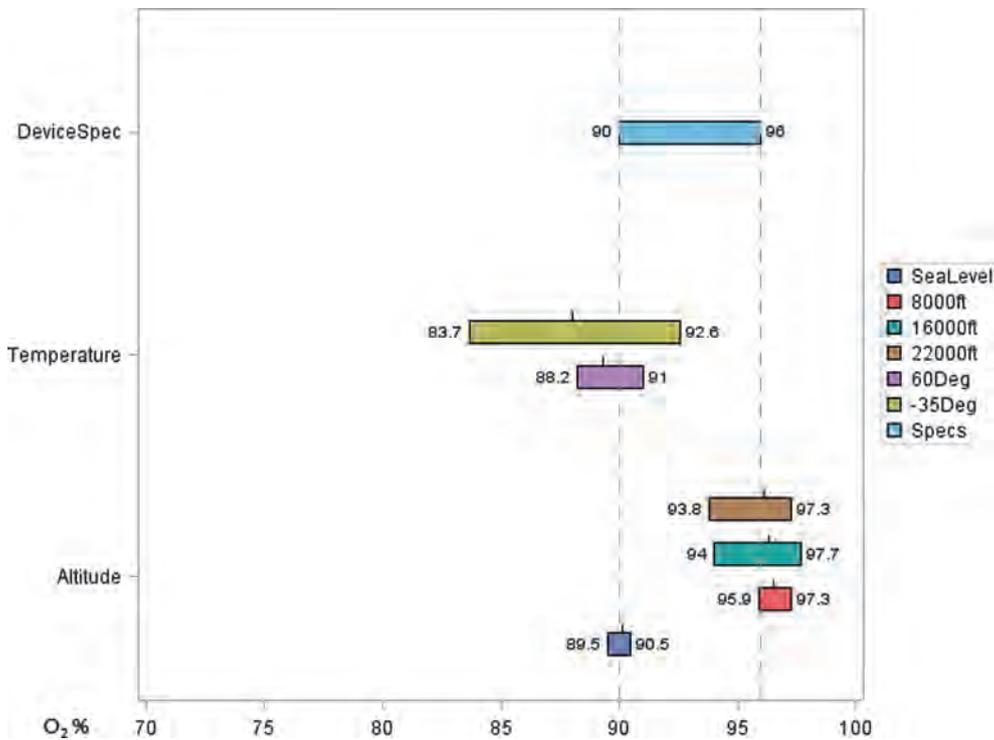


FIGURE 4. Range and mean FIO₂ on the 96 mL bolus setting with the Sacros at a respiratory rate of 30 during all test conditions.

measurements at sea level, mean liter flow and total oxygen volume increased with each increase in altitude with all COGs (Table III). Duration of operation did not markedly change with the O₂PAK and Traumaaid with changes in

altitude and was inconsistent with the BOB. Mean oxygen concentration was 99.9%, 95% confidence interval (CI) (99.87%, 99.94%) with the O₂PAK, 99.9%, 95% CI (99.89%, 99.96%) with the Traumaaid, and 80.9%, 95% CI

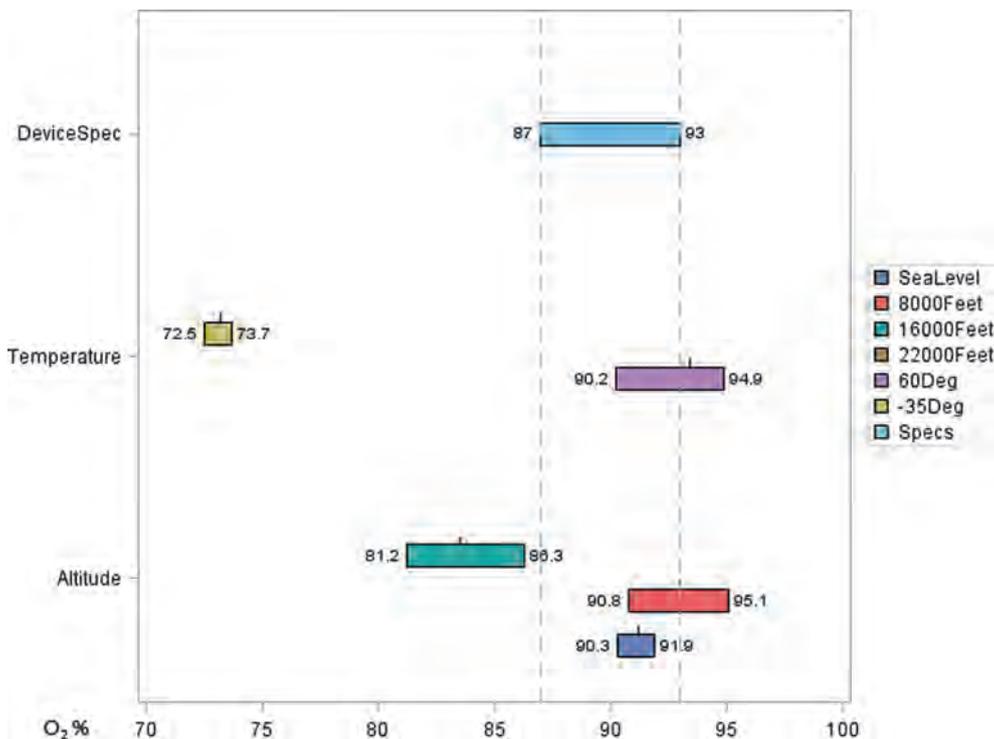


FIGURE 5. Range and mean FIO₂ at the 3 L/min continuous flow setting with the iGo at a respiratory rate of 30 during all test conditions.

TABLE II. Mean Battery Life of Each Concentrator at the Highest Bolus and Continuous Flow Settings

Concentrator	Bolus Setting (mL)	Battery Life (minute ± SD)	Continuous Flow Setting (lpm)	Battery Life (minute ± SD)
Eclipse	192	75.5 ± 0.6	3	76.0 ± 0.8
Saros	96	57.0 ± 4.1	3	34.0 ± 2.2
iGo	84	184.5 ± 0.7	3	108.5 ± 2.1

TABLE III. Mean Liter Flow and Mean Total Oxygen With (% Increase) From Sea Level Measurements With the COGs at Each Altitude

		Sea Level	8,000 ft	16,000 ft	22,000 ft
O ₂ PAK	Liter Flow	6.5	7.6 (17)	10.5 (62)	14.4 (22)
	Volume	181.3	220.5 (22)	301.0 (66)	421.3 (132)
Traumaid	Liter Flow	5.6	5.6 (0)	8.8 (57)	9.9 (77)
	Volume	139.2	152.9 (10)	222.2 (60)	279.6 (101)
BUDI	Liter Flow	0.8	1.8 (125)	3.1 (287)	3.9 (387)
	Volume	23.4	29.9 (28)	55.2 (136)	95.0 (306)

(80.16%, 81.39%) with the BOB. The oxygen concentration measurements started when flow began and continued until flow ceased.

As compared to room temperature measurements, after storage at -35°C mean flow rate was lower with the O₂PAK. The duration of operation was longer, but the total oxygen was not markedly different. The mean flow rate and total oxygen volume was lower with the Traumaid, but the duration of operation was unchanged. The mean flow rate and total oxygen volume was slightly higher with the BOB, but the duration of operation was less.

After storage at 60°C, mean flow rate was higher with the O₂PAK but the total oxygen volume and duration of operation were lower as compared to room temperature measurements. Mean flow rate was higher with the Traumaid,

but total oxygen volume and duration of operation were lower. Mean flow rate was higher with the BOB, total oxygen volume was unchanged, but duration of operation was less. Table IV shows mean flow rate, mean total oxygen volume, and mean duration of the devices at all test conditions.

The highest surface temperature with each device was 172°F with the O₂PAK, 167°F with the Traumaid, and 173°F with the BOB. These temperatures occurred at or near the time oxygen generation ceased.

DISCUSSION

Portable Oxygen Concentrators

Oxygen concentrators were first employed as an alternative for compressed oxygen for use in long-term oxygen therapy

TABLE IV. Mean (±SD) Flow Rate, Total Oxygen Volume, and Duration of Operation at Sea Level at Room Temperature, at Altitude, and After Storage at Temperature Extremes

	Mean Flow (lpm)	Mean O ₂ Volume (L)	Mean Duration (Minute)
O ₂ PAK			
Room Temperature/Sea Level	6.5 ± 2.6	181.3 ± 37.8	27.6 ± 2.3
8,000 ft	7.6 ± 2.7	220.5 ± 6.3	28.9 ± 1.6
16,000 ft	10.5 ± 3.8	301.0 ± 1.4	28.5 ± 0.9
22,000 ft	14.4 ± 5.2	421.3 ± 19.1	29.1 ± 1.8
-35°C	5.5 ± 1.6	188.5 ± 10.6	33.0 ± 2.0
60°C	7.9 ± 2.9	179.2 ± 10.6	22.6 ± 0.6
Traumaid			
Room Temperature/Sea Level	5.6 ± 2.8	139.2 ± 36.2	24.7 ± 0.4
8,000 ft	5.6 ± 3.4	152.9 ± 24.2	27.2 ± 1.6
16,000 ft	8.8 ± 5.6	222.2 ± 7.0	26.9 ± 1.6
22,000 ft	9.9 ± 6.7	279.6 ± 32.1	31.2 ± 1.3
-35°C	3.7 ± 2.6	96.6 ± 30.5	24.0 ± 7.9
60°C	6.5 ± 3.5	122.2 ± 9.4	18.7 ± 0.2
BUDI			
Room Temperature/Sea Level	0.8 ± 1.0	23.4 ± 5.6	28.6 ± 4.3
8,000 ft	1.8 ± 1.5	29.9 ± 5.1	16.6 ± 3.0
16,000 ft	3.1 ± 2.9	55.2 ± 15.7	17.5 ± 2.1
22,000 ft	3.9 ± 3.1	95.0 ± 28.7	20.3 ± 2.7
-35°C	1.5 ± 1.0	36.3 ± 4.5	24.0 ± 3.0
60°C	1.7 ± 1.2	34.2 ± 2.3	19.2 ± 1.2

in the home in the late 1970s. The devices were an attractive alternative because of the ability to supply unlimited oxygen, lower cost, and improved logistics compared to oxygen cylinders. Early concentrators were large and heavy, weighing as much as 143 lbs. Six of these early devices (DevilbissDeVO₂, Rimer-Alco Dom 10, Mountain Medical Econo 2, Ventronics Hudson 6200, Dragerwerk Permax, and Cryogenic Associates Roomate) were evaluated at continuous flows of 1 to 4 liters by Johns et al⁵ and found that all the devices at 1 and 2 L/min produced oxygen concentrations of >90%, but began to fall at 3 L/min with one concentrator. Half of the devices produced oxygen concentrations $\geq 90\%$ at the 4 L/min setting. Gould et al⁶ also conducted a study using three of the same concentrators as Johns (Mountain Medical Econo 2, De Vilbiss DeVO₂, and Cryogenic Associates Roomate) in addition to Mountain Medical Mini 02 and Oxygen Enrichment Company OE-4E, producing similar results. Oxygen concentrators have also shown to be an effective and economical substitute for compressed oxygen cylinders in remote high altitude areas.^{7,8}

Although these early concentrators performed adequately as stationary units in the home, they were too large for ambulatory use, so smaller cylinders were used for this purpose. POCs emerged in 2000 that were smaller, lighter devices with optional battery operation capable of producing up to 3 L/min of continuous flow, making ambulation possible without switching to a cylinder.⁹ Fischer et al¹⁰ conducted a study in an altitude chamber with volunteers having chronic obstructive pulmonary disease using 5 commercially available Federal Aviation Administration-approved POCs (Invacare XPO₂, Invacare, Elyria, Ohio; Freestyle AirSep C., Buffalo, New York; Evergo Philipps Healthcare, Hamburg, Germany; Inogen One Inogen, Goleta, California; Eclipse 3, Sequal, Ball Ground, Georgia) using bolus mode or if not available, continuous flow mode, at a simulated altitude of 2,650 m (8,694 ft). The authors found that each POC was able to provide enough oxygen to the subjects to increase partial pressure of oxygen in arterial blood ≥ 10 mm Hg. POCs have also been evaluated as the oxygen source for chronic obstructive pulmonary disease patients during a 6 minute walk test and were found to be a suitable alternative to portable oxygen cylinders or liquid oxygen for ambulation.^{11,12} Rodriguez et al¹³ recently performed a bench study of using a POC as the primary oxygen source for a portable ventilator that could be used during transport. The study showed that the integrated system was capable of producing an FIO₂ of up to 0.7 during selected settings.

Our study is the first to evaluate the performance of POCs at altitudes above normal commercial airline cabin altitude and after storage at extreme temperatures. With the exception of the Eclipse, the flow rates and bolus volumes were within or slightly less than the reported range. These differences are not clinically significant. The iGo would not operate at the 2 highest test altitudes, which were above the altitude limit stated in the owner's manual. The Eclipse and Saros operated above the operator's manual stated altitude

limit. The POCs are designed to deliver a total volume of 3 L of oxygen/minute, whether in bolus mode or continuous flow mode. In the military setting, especially far forward, mass casualty, and austere environments, pulsed dose technology will provide a higher FIO₂ and is more energy efficient than continuous flow, which would be helpful in those resource-constrained environments. When the combination of respiratory rate and set bolus volume exceeds the 3 L threshold, the Eclipse and Saros mitigate the effect by decreasing the bolus volume, whereas the iGo skips breaths to maintain an acceptable FIO₂. Our study design did not go above the reported maximum respiratory rate for any bolus volume with the Saros and iGo. The maximum bolus volume for these 2 devices was 96 and 84 mL, respectively and was 192 mL with the Eclipse. To maintain an FIO₂ in the specified range, at a respiratory rate of 20 breaths/min with the 192 mL bolus and a respiratory rate of 30 breaths/min with the 128, 160, and 192 mL bolus, the Eclipse decreases the bolus size. This strategy maintained the FIO₂ at sea level/room temperature and all altitudes but not after storage at temperature extremes. The measured FIO₂ range was 83% to 86%, but the bolus volumes were 1% to 13% larger after temperature extreme storage, which may help to explain the lower FIO₂. The storage temperatures may have affected the device's ability to effectively regulate the bolus volume and/or generate the target oxygen concentrations at the higher bolus volume settings. Although the liter flow with the iGo in continuous flow mode after storage at -35°C was within the reported range, the FIO₂ was 15% to 20% lower than at room temperature, demonstrating the effect of extreme cold temperatures on oxygen generation during continuous flow mode. The POCs were tested at altitudes greater than recommended in the operator's manual. While the iGo ceased to operate at 16,000 ft, the Eclipse and Saros operated within specified performance ranges at all study altitudes.

Chemical Oxygen Generators

Chemical oxygen generation is not a new concept. It is the method by which Joseph Priestly discovered oxygen during his work with mercuric oxide. Priestly published his findings in 1775.¹⁴ In 1902, the "Lancet" reported on Kamm's oxygen generator invention for medical use. The device used chlorate cakes and manganese oxide and when heated by a spirit lamp produced approximately 4 cubic ft of oxygen before needing to be replenished with ingredients.¹⁵ More recently there has been interest in employing this technology in areas where providing oxygen in cylinders or in liquid form is logistically difficult or economically prohibitive such as during combat casualty care, disaster situations, and in extreme rural environments in undeveloped countries.

To our knowledge, our study is the first to evaluate COGs at altitude and temperature extremes. Pollock and associates evaluated emOx and SysO₂ COGs at sea level.^{16,17} These devices were similar to the BOB included in our study and

were similar in performance. No other publications of COG evaluations were found. The O₂PAK and Traumaaid were similar in design and function but the O₂PAK produced more oxygen volume because of a higher flow rate and duration of operation at all conditions. After storage at -35°C , the output of these 2 devices decreased, but increased after storage at 60°C as compared to room temperature. Oxygen is produced by an exothermic reaction and the temperature of the device ingredients at time of ignition and throughout operation affects the device output. The total output of the BOB was much less than the O₂PAK and Traumaaid due to a slower reaction. (Fig. 6) Peak flow occurred toward the end of the reaction with the BOB as compared to the beginning of the reaction with the other 2 COGs. Unlike the O₂PAK and Traumaaid, the BOB was unaffected by storage at temperature extremes. The device uses 2 dry granular chemicals which were stored at temperature extremes and uses tap water as a catalyst, which was not stored with the chemicals. This would be the practice during use in the field. The consistent water temperature may have allowed for a reaction that was comparable to the performance at room temperature.

Oxygen volume and flow rate increased with increases in altitude with each device. With the O₂PAK and Traumaaid, the atmospheric pressure impacts the rate of creation and/or expansion of the gas but without change in duration of operation. For a given mass of gas produced, a larger volume will be produced at altitude. Gas is dissolved in a liquid with the BOB and at altitude; Henry's law may explain the increase in oxygen production and flow. Henry's law states that the amount of gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the surface

of the solution. When ambient pressure decreases at altitude, the dissolved oxygen is released in greater quantity and because of the impact of altitude on gas density; a larger volume will be released.

Because of device design and use of dry chemicals to create oxygen, both the O₂PAK and Traumaaid can be operated in any orientation. The devices are small and easy to use, requiring the pulling of 2 pins to activate and start oxygen flow. The BOB is more time consuming to prepare for use. The device requires mixing of 2 dry chemicals with tap water and must be operated in an upright position either sitting on the ground or hanging by the handle due to the use of water as the catalyst, which would spill and/or clog the oxygen outlet. In addition, the cap filled with desiccant through which the oxygen exits the bag is heavy and during operation tends to fall over and crimp the bag, diminishing or ceasing the flow of oxygen. Modifications to positioning of the bag must be made to mitigate this problem. There are safety concerns related to the external temperatures during operation of all 3 COGs. The surface temperature of the devices reached 167 to 173°F, which could easily cause burns if positioned against a patient. Based on the total volume of oxygen produced at sea level, the cost per liter was \$3.73 for the O₂PAK, \$6.44 with the Traumaaid, and \$1.73 with the BOB.

CONCLUSIONS

POCs and COGs have been proposed for use in far forward military operations and in disaster and mass casualty scenarios as alternatives to liquid and pressurized gaseous oxygen systems because of the logistics, weight, and explosive risks

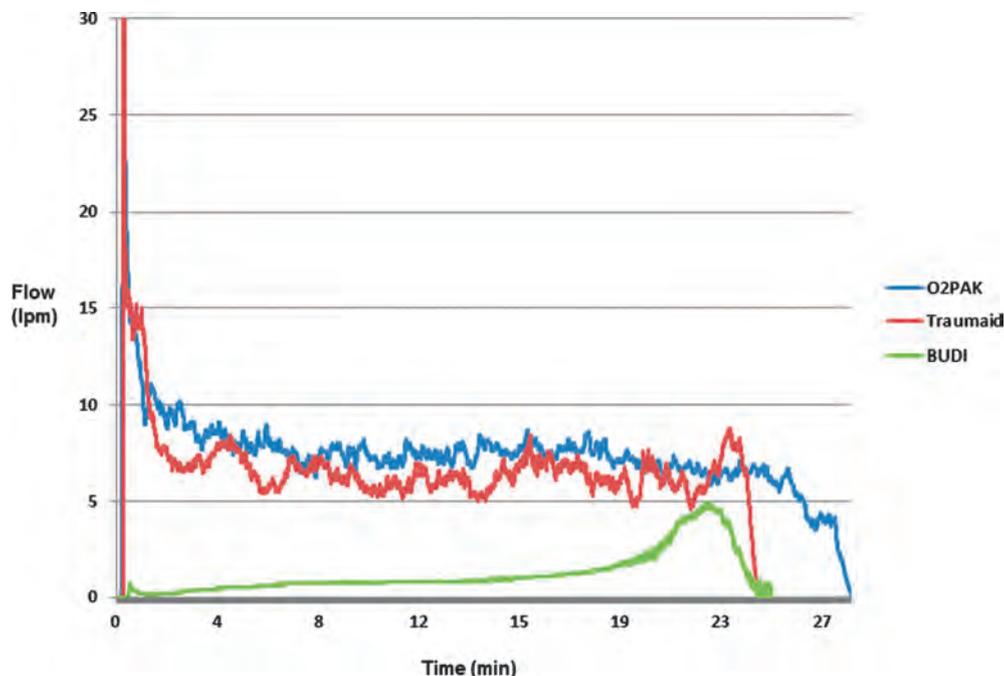


FIGURE 6. Sample run with all 3 chemical oxygen generators showing flow rates and duration of operation.

REFERENCES

inherent in these systems. Although POCs and COGs are not meant to be a 100% solution, in an environment where there is no oxygen available, these systems may be viable alternatives. Although POCs may be used in a clinical environment because of the endless supply of oxygen produced if electrical power is available, COGs exhaust in 30 minutes or less depending on the manufacturer and design and the inability to adjust output, makes the devices unsuitable for continuous clinical care. COGs are more suitable for short missions from point of injury to Role 1 care or for temporary relief of altitude-induced hypoxemia experienced in the Special Forces environment. Because of the limitations of both of these types of devices, alternate oxygen systems such as liquid oxygen or oxygen cylinders should be available when appropriate. The austere environments in which the devices may be deployed may have an effect on performance. Storage at extremely cold temperatures had the greatest negative effect on the performance of the POCs. Allowing additional time for the devices to acclimate to room temperature before start up may improve device performance. POCs should not be operated at altitudes above that stated in the operator's manual.

POCs are an attractive option because of their small size but the output is finite, performance is unpredictable at altitude and temperature extremes, and they may be cost prohibitive to use on a larger scale. The limited flow rate and total oxygen yield with the BOB does not supply an adequate amount of oxygen to be useful in emergency situations and the logistics of maintaining the system is cumbersome. As with the COGs, storage at extremely cold temperatures decreased the output of the O₂PAK and Traumaaid. All the devices tested may benefit from a longer time to acclimate to room temperature before use. Since the intended use of all these devices for military and disaster operations may require that both POCs and COGs be stored and operated in environments that are outside the manufacturer's published thresholds, users must be aware of the limitations of each and mitigated as much as possible.

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