Validation of hyperbaric oxygen treatment software for use with monoplace chambers.

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J. R. SECHRIST¹, R. A WARRINER III², A. E. WENINGER¹, R. ONG¹

¹Sechrist Industries, Inc., Anaheim, CA 98207, ²Diversified Clinical Services, The Woodlands, TX 77380

Hyperbaric oxygen (HBO₂) therapy is increasingly used in the treatment of a wide variety of medical conditions. However, for monoplace chambers, there is some uncertainty when sufficiently high oxygen concentrations are attained, because most chambers are not instrumented to measure oxygen. To remedy this, Microsoft Excel-based software, HBO₂ Smart Guide, was developed to simulate the atmosphere of monoplace chambers during treatment. Based upon chamber dimensions, patient weight, oxygen purge rates, desired pressurization, and HBO₂ time, the program calculates oxygen concentration, consumption and exposure for each treatment. Software testing was conducted using four different chambers instrumented with an oxygen analyzer. Two purge rate profiles were used: constant, and biphasic (a high initial purge rate was changed to a lower plateau rate when pressurization was reached). Comparison of measured and calculated times to reach 95% oxygen concentration within the chambers demonstrated the software was accurate within 1%. The HBO₂ Smart Guide enables optimum purge profiles to be simulated with resultant potential improvements in HBO₂ treatment efficacy, calculation of effective oxygen exposures (actual time during prescribed treatment during which patient breathes ≥95% oxygen) to enable more accurate comparison of treatment profiles and outcomes, and cost savings in oxygen usage. This software will enable clinicians to provide more consistent HBO₂ treatments.

INTRODUCTION

Hyperbaric oxygen (HBO₂) therapy is based upon the simple concept that by increasing the transport of oxygen to body tissues, the improvement in the partial oxygen pressure of the tissue can be utilized to effect healing in a wide variety of medical conditions (1-3). Some of the more common conditions recognized by the Undersea and Hyperbaric Medical Society (UHMS) (4) for HBO₂ therapy as a primary or adjunctive treatment include CO poisoning (5), necrotizing soft-tissue infections, radiation necrosis, crush injury, compartment syndrome and other acute ischemias, wounds with demonstrated periwound hypoxia, and compromised skin flaps and skin grafts. Besides the direct effect of increasing oxygen tissue concentration, many different biochemical mechanisms have been implicated in HBO₂ treatment, including angiogenesis, stimulation of vascular endothelial growth factor (VEGF), fibroblast replication, collagen synthesis, neovascularization, and epithelialization (6-12).

In order to undergo an HBO₂ treatment, a patient must be placed in a hyperbaric chamber and typically exposed to 2-2.5 atmospheres absolute (ATA) of 100% oxygen (actually 95-100% based upon delivery method for oxygen and impact of air breaks) for a period of 90 to 120 minutes. Most conditions require 5-30 treatments on a daily basis.
In terms of equipment, 2 types are in use: multiplace chambers that are pressurized with air in which several patients usually breathe oxygen through a face mask, and monoplace chambers for a single patient that are pressurized by oxygen. In both cases, air breaks are administered to patients 2-3 times during the HBO₂ session by supplying air through a face mask.

Because multiplace chambers are pressurized with air, the therapeutic oxygen exposure during the HBO₂ session effectively starts when the patient dons the oxygen hood or mask because of the very small wash out volume of the hood or mask. Hoods are commonly used now to overcome problems with mask leakage and incomplete seals which could allow entrainment of air and delivery of less than 100% oxygen. With monoplace chambers there is no analogous situation, since nitrogen in the chamber is displaced by purging with oxygen, even when the desired hyperbaric pressure is reached. This poses the question of when the patient’s optimal (95-100%) oxygen exposure actually begins. While clinical experience suggests that outcomes have been equivalent in a variety of monoplace and multiplace chamber settings, from a clinical research perspective it would be beneficial to know when optimal oxygen exposure begins so that oxygen dosing in multiple and potentially different clinical environments can be identical. If the oxygen concentration in the chamber were known, one could use a benchmark—for example, 95%—and time the session from that point, decompressing the chamber when the requisite time had been achieved. Since the vast majority of monoplace chambers are not instrumented for oxygen measurement, one way around this problem would be to simulate gas conditions within the chamber by utilizing a predictive software program and adjust oxygen flow rates during compression to achieve 95-100% oxygen exposure for the patient utilizing the same compression time.

In this paper, we describe the use of the HBO O₂ Smart Guide, an Excel-based program that is able to calculate hyperbaric oxygen concentrations, given a set of initial conditions. In addition, by integrating the partial oxygen pressure with respect to time, a total oxygen exposure can be calculated, which provides a measure of how much oxygen the patient was exposed to during the HBO₂ session. Such values are currently absent in the HBO₂ treatment literature. We also describe how the program was validated by measuring the oxygen in-chamber, using 4 different monoplace chamber models and employing 2 types of oxygen purge profiles.

METHODS

Software Description

The HBO O₂ Smart Guide is a Microsoft Excel spreadsheet and does not require any special installation. The most important sheet (tab) is the O₂ Dynamics. Input parameters are highlighted at the top left of the spreadsheet in light blue, and include: patient weight, compression rate, decompression rate, compression O₂ purge flow rate, plateau oxygen purge flow rate, plateau pressure, oxygen purge flow rate, hyperbaric pressure, and treatment time. The plateau purge rate is the rate at which oxygen flow can be set after reaching the desired hyperbaric pressure. At the top right of the screen, the diameter and length of the chamber are parameters that must also be entered.

Calculated parameters include total amount of oxygen consumed for the profile selected, and patient exposure with stated units of bar·hr⁻¹. The absolute pressure and partial oxygen pressures are automatically displayed in graphical format below the input/output parameter blocks. Oxygen concentration
profiles can be explored graphically using the Percent O2 2 hours and Percent O2 30 min tabs.

**Software Validation**

Four Sechrist monoplace chambers (models 2800J, 3200, 3300E, 3600E; diameters 28”, 32.5”, 32.5”, and 35.5” respectively), were instrumented with a fast-response oxygen analyzer (model O2T, Oxigraf, Mountain View, CA) sampling from the rear of the chamber (opposite the door) next to the purge outlet, except for model 3200, where it was sampled 6” from the edge of the stretcher, close to the door. The oxygen analyzer was calibrated in accordance with the manufacturer’s instructions. The positive lines of two pressure transducers (model SDX100-D4A, Honeywell, Freeport, IL), were connected to the chamber pressure line and the pneumatic control signal line, with the negative (reference) lines open to the atmosphere.

For each experiment, both the oxygen analyzer and pressure transducer were connected to a multichannel data recorder (Model DASH-8xe, Astro-Med, Inc., West Warwick, RI,), which also recorded the time for each experiment, and the introduction of oxygen (industrial grade, minimum 99.5% oxygen concentration, Lehner & Martin, Inc., Santa Ana, CA). The chamber design, in all cases, introduces the purge flow adjacent to the head (door end) of the chamber. The oxygen analyzer accuracy was ± 0.5%, while the flow meter (purge) accuracy was ± 2% of full scale (10 L/min).

Two different oxygen purge profiles were employed: (a) 400/400 L/min; and (b) 400/80 L/min, in which the first figure represents the initial purge flow rate, and the second figure the plateau flow rate, which was automatically engaged 12 minutes after the start of pressurization. The pressurization rate was 3 PSI/min. For the experiments the chamber was empty—i.e., no stretcher or dummy model representing a patient was present.

Each experiment was carried out 3 times for each model chamber and the time taken to reach a 95% oxygen concentration noted. Using the HBO O2 Smart Guide, and inputting parameters for chamber dimensions, purge flow rate, pressurization rate, and hyperbaric pressure, the theoretical time taken to reach 95% oxygen level in each experiments was also calculated.

**RESULTS**

**Software**

A screenshot of the O2 dynamics tab is shown in Figure 1 (please see page 222 for Figs. 1 and 2). In this case, the example used is a Sechrist 3600E model (35.5” diameter, length 90”), a patient weight of 90 kg, a compression rate of 3 PSI/min, an oxygen purge rate of 400 L/min, and a hyperbaric pressure of 2.5 ATA. The oxygen concentration in the chamber reaches 95% at 13 minutes (Figure 2). This profile includes 7 minutes to reach the desired hyperbaric pressure, another 6 minutes to reach 95% oxygen, a period of 90 minutes at > 95% oxygen, and 7 minutes for decompression, for a total time of 110 minutes of which 90 can be considered treatment time. Total oxygen exposure for a patient would be 4.31 bar·hr⁻¹. However, if the oxygen exposure is calculated only for the 90-minute period during an oxygen concentration > 95%, this is 3.72 bar·hr⁻¹.

Oxygen usage (consumption) for this profile is 43,245 L. However, an alternative profile can be constructed in which the oxygen purge flow of 400 L/min is reduced to 80 L/min 12 minutes after the start of pressurization. While the oxygen exposure for the same 90-minute period in which the oxygen concentration is > 95% is 3.67 bar·hr⁻¹ (1.3% less than the previous example), oxygen consumption (usage) is only 14,552 L, a 66.3% reduction.
Fig. 1. Screen shot of O2 dynamics tab showing input areas (top), oxygen partial pressure curve (top line), and pressure profile (bottom line).

![Fig. 1](http://archive.rubicon-foundation.org)

Fig. 2. Oxygen concentration versus time for a Sechrist 3600E model monoplace hyperbaric chamber, compression rate of 3 PSI/min, oxygen purge rate of 400 L/min, and hyperbaric pressure of 2.5 ATA. Square symbols show time for hyperbaric pressure and 95% oxygen attainment, respectively.

![Fig. 2](http://archive.rubicon-foundation.org)
Software validation

The mean times taken to reach an oxygen level of 95%, recorded from time of initial compression, for the 4 models and different purge profiles were used to calculate the predicted oxygen levels using the software (Table 1). In each case, the comparative error was < 1% (Table 1).

**Table 1.** Mean times and standard deviation (SD), from the start of compression, taken to reach 95% oxygen level with the 4 different chambers using 2 types of purge profiles compared to the predicted oxygen level calculated using the mean times.

<table>
<thead>
<tr>
<th>Chamber Model</th>
<th>Purge flow (L/min)</th>
<th>Observed Mean (min)</th>
<th>SD</th>
<th>Predicted Oxygen level (%)</th>
<th>Comparative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2800J</td>
<td>400</td>
<td>6.03</td>
<td>0.098</td>
<td>94.3</td>
<td>0.74</td>
</tr>
<tr>
<td>3200</td>
<td>400</td>
<td>10.43</td>
<td>0.298</td>
<td>95.7</td>
<td>-0.74</td>
</tr>
<tr>
<td>3300E</td>
<td>400/80</td>
<td>10.30</td>
<td>0.073</td>
<td>95.6</td>
<td>0.63</td>
</tr>
<tr>
<td>3600E</td>
<td>400/80</td>
<td>11.82</td>
<td>0.361</td>
<td>94.1</td>
<td>-0.95</td>
</tr>
</tbody>
</table>

*Initial purge rate/pressure plateau purge rate

**DISCUSSION**

For monoplace hyperbaric chambers, knowing what the oxygen level is after starting the oxygen purge is normally educated guesswork and dependent on many factors: the size of the chamber, the patient size, and the purge profile, as well as the final hyperbaric pressure. If a rule of thumb is used, such as assuming that a 95% oxygen level is reached after 15 minutes, there will be some error in calculating the exposure of the patient to hyperbaric oxygen levels. Although for clinical purposes that error might be relatively small, it must be remembered that most hyperbaric effects are proportional to (a) the partial pressure of the oxygen, and (b) the time that the tissues are exposed to the hyperbaric oxygen (6). In addition, it is desirable to provide the most efficacious, consistent, and cost-effective hyperbaric treatments possible. It should also be noted that certain combinations of chamber size and purge flows can never reach a 95% O₂ concentration. Further, if the purge flow rate is lowered after pressurization is reached, it is important that a reasonable time be selected for pressurization; otherwise it could take a substantial time to reach a concentration of 95% oxygen. The **HBO O₂ Smart Guide** we have developed will help clinicians address those issues.

For monoplace chambers, estimating the oxygen exposure is a complicated exercise. With the software described in this paper, however, it is possible to calculate a total exposure of oxygen at the desired hyperbaric pressure by integrating the partial pressure of oxygen over a period of time. This time can be precisely defined starting with a given level of oxygen—for example, 95%. This ability has 2 advantages: treatments can be programmed to be consistent and the oxygen exposure benchmark can be calculated and compared to calculations using other profiles, other types of monoplace chambers, as well as multiplace chambers. Thus if a patient is exposed to 100% oxygen for 90 minutes at 2.5 ATA (ignoring air breaks) in a multiplace chamber, then the exposure is 3.75 bar·hr⁻¹. Clinicians can then manipulate the input parameters of the program to determine a cost-efficient profile to arrive at approximately the same figure for monoplace practice.

In addition, the program tracks usage (consumption) of oxygen, and it is possible to simulate various purge profiles to determine how much oxygen is consumed from the oxygen source. This might be of minor consideration in the USA, but in other countries, this could assume more importance where oxygen is not so readily available.

In general, different purge flow settings for the pressurization and plateau phases of HBO₂ treatment are more cost efficient when optimized, compared to a single purge flow rate employed throughout the treatment. Savings
of 40-70% in terms oxygen consumption are possible. To ensure accuracy, it is best to employ an electronic unit that will automatically adjust purge flow rates when pressurization has been achieved.

Another use of the HBO O₂ Smart Guide might be its application to clinical trials that involve HBO₂ treatment. For example, it could be used prospectively to create a standardized protocol when different trials are coordinated at different institutions, possibly with different equipment. Further, the software could be used in a retrospective analysis of clinical trials to determine oxygen exposure, and hence find out if substantial differences in oxygen exposure occurred.

Although the software validation study showed a comparative accuracy of ± 1% when the software-calculated times to reach 95% oxygen were compared to experimentally measured times, there are several pertinent factors to consider. First, the chambers did not have stretchers or dummies present to simulate the presence of patients. Under normal operating conditions, it is possible that the presence of a patient could interfere with the gas-mixing dynamics within the monoplace chamber. Second, purge inflow and exhaust outflow for a given chamber are not always identical; purge outflow tends to lag inflow in the beginning of the purge sequence, and exceed inflow when purge rates are reduced. Instant gas mixing does not occur because the chamber is a relatively large volume and a substantial time is taken for a molecule of oxygen to travel the length of the chamber, and because there are small pressure differentials within the chamber. However, based on a second-to-second comparison of theoretically and experimentally derived data, we have no reason to believe that either of these factors is significant. Last, the comparative error figure is approximate, as only 3 trials were carried out for each model chamber/purge profile; a larger number would provide a better estimate of the error.

In summary, use of the HBO O₂ Smart Guide will enable HBO₂ clinicians to optimize the treatment of patients in monoplace chambers, with a concurrent increase in efficiency, treatment efficacy and consistency, while minimizing oxygen consumption.

REFERENCES
