Measurement of oxygen concentration in delivery systems used for hyperbaric oxygen therapy

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Stephenson RN, Mackenzie I, Watt SJ, Ross JA. Measurement of oxygen concentration in delivery systems used for hyperbaric oxygen therapy. Undersea Hyperbaric Med 1996; 23(3):185–188.—Efficient delivery of oxygen is important during hyperbaric oxygen therapy. We compared two systems in common use, and developed a method to ensure that O₂ delivery was adequate during treatment. The systems were a demand valve system with an oral–nasal mask, and a continuously ventilated hood. Five groups were studied over two different time periods, and a further trial was undertaken to examine inhaled O₂ levels. The results showed that an acceptable Fio₂ could be reliably achieved only with the continuously ventilated hood system or when trained staff supervised their colleagues using the demand system. Inasmuch as the oral–nasal mask system is the standard equipment for the North Sea diving industry, this work shows the importance of ensuring that the correct dose of O₂ is delivered. The study indicates, however, that identification of the problem does not always allow a complete solution, and that a hood-based system is more reliable.

hyperbaric oxygen therapy, ventilated hood, oral–nasal mask, demand valve system

Hyperbaric oxygen (HBO₂) therapy in a multiplace chamber in which two or more people can be compressed; it involves the administration of oxygen either through an oral–nasal mask and demand valve or by a ventilated hood system. Efficient delivery of O₂ is important in therapy for decompression sickness (DCS) and other conditions, for example, carbon monoxide poisoning and necrotizing infections. The aim is to give 100% O₂ at the treatment pressure (1).

Hyperbaric oxygen can be delivered in a multiplace chamber by one of two administration systems. The first is a demand system where an oral–nasal mask is attached to a demand valve. When a patient breathes, the demand valve opens (in response to a minimal change in inspiratory pressure) and O₂ is inspired. Exhaled gas is ducted through an expiratory valve and dumped outside the chamber. Previous work has identified the problems of obtaining an adequate mask fit for this type of equipment (2) and this has also been our experience. The second method is by a continuously ventilated hood system. A neck dam or seal is placed over the patient’s neck and a hood is fitted over the seal. The hood is ventilated with a continuous flow of 100% O₂ through two ports at opposite sides of the hood, and the vented gas is dumped out of the chamber (Fig. 1).

One aim of this study was to compare the concentration of O₂ delivered by these two methods in the context of their clinical application in the hyperbaric medicine unit; another was to develop a method for ensuring that O₂ delivery was adequate during treatment.

METHODS

This study was approved by the Grampian Area Joint Ethics Committee.

To measure hood O₂ levels (Fho₂), a sampling tube was inserted through the front of the hood and positioned on the right side of the subject’s face, on the opposite side of the hood from the fresh gas inlet. Mask O₂ levels (Fmo₂) were measured by sampling via a tube inserted through the front of the mask to lie within the mask dead space. Exhaled O₂ levels (Fco₂) were measured in gas collected from the built-in breathing system O₂ dump in an evacuated 100-liter Douglas bag.

A sample line ducted gas from the face mask or hood through the chamber wall where the flow could be regulated to 0.083 liter · s⁻¹ outside the chamber. Oxygen was analyzed over the first 5 min of O₂ administration (period 1) and during the 15–20 min of administration (period 2). If the Fio₂ fell below 0.8 (as stipulated by Grampian Area Joint Ethics Committee) for patients with DCS (groups A and B), the tender was instructed to improve the fit. Oxy-gen analysis was performed by a paramagnetic O₂ analyzer Taylor Servomex 200, Taylor Servomex Ltd., Crowborough, En-
FIG. 1—High-flow hood administration system for O₂.

A time-weighted average was calculated for the measurement period from an analogue pen recorder trace (Electromed recorder MX216, Ormed Engineering, Welwyn Garden City, England). The choice of these time periods was based on the O₂ cycles of the United States Navy (USN) table 6 (3). They represent the beginning and the end of each cycle of O₂ breathing at 180 kPa (g).

Five groups were studied. Fifteen patients received O₂ by hood during their treatment (group A). During the treatment, both O₂ and carbon dioxide in the hood were measured and hood ventilation adjusted to keep mean carbon dioxide levels below 1 kPa (i.e., 7.5 mmHg). Twelve patients received O₂ using an oral–nasal mask and demand valve (group B). One patient was withdrawn from the group because his inspired O₂ measured in the mask was consistently poor; therefore the delivery system for him was changed from the mask to a hood. All patients were accompanied in the chamber by a nurse tender who adjusted the equipment to obtain the best visual fit. Patients were studied during the first O₂ breathing session of a USN table 6 treatment at 180 kPa (g). Eleven volunteers who were amateur scuba divers received O₂ via the oral–nasal mask and demand valve without a nurse attendant (group C). Eight nurses, trained as hyperbaric attendants, received O₂ by oral–nasal mask without a nurse attendant adjusting the fit (group D), and eight nurses received O₂ by oral–nasal masks and demand valve with a nurse attendant who helped to adjust the mask on a clinical basis; they had no knowledge of the mask O₂ reading (group E). For all non-patient groups there was a research attendant in the chamber and neither the subject nor the nurse tender knew the measured fractional O₂ concentration (FO₂). In all patient groups, neither the tender nor the patient knew the measured FO₂, but this was monitored by the therapist outside the chamber who could alter management if the inspired O₂ fell. Group D consisted of the nurse tenders themselves using the oral–nasal mask systems simulating the situation in normal hyperbaric treatment where the tender is given prophylactic O₂ to prevent DCS. All healthy volunteers were studied at a chamber pressure of 80 kPa (g) to ensure adequate operation of the O₂ dump system while minimizing their pressure exposure.

The mask system used was the Scott built-in breathing system incorporating a demand valve and a dump valve. Mask sizes 2 or 3 were used, as appropriate (Scott Aviation, CA). The hoods were manufactured by Sea Long Medical Systems, Inc., KY.

Twelve of the healthy subjects who had participated in the above study took part in a further trial to examine FeO₂ levels during O₂ administration by face mask and demand valve. FeO₂ was sampled during the first 5—10 min of O₂ breathing as described above and, at the same time, expired gas was collected in 150-liter Douglas bags. To exclude the potential effect of sampling from the mask, expiratory gas was also collected from 10 to 15 min with no concurrent mask sampling. Finally, FeO₂ analysis was performed from 15—20 min to ensure that the mask reading during the 10—15 min period was representative.

Statistical methods: Data were assessed by analysis of variance by ranks (4) using the computer program SPP, a statistics package for personal computers (5), using Scheffe post-hoc, pairwise comparisons where required. Descriptive statistics and regressional analyses were performed using the statistics package Minitab release 10 (Minitab Inc, State College, PA).

RESULTS

In all cases of DCS the treatment was successful. Time-weighted average FeO₂ was reliably over 0.9 in only those people receiving O₂ by hood (Fig 2, Table 1), and levels of O₂ within the hoods were significantly higher than those

![Hoods Fractional O₂ concentrations during periods 1 and 2 for each of the study groups. Chart shows median values, the interquartile range is represented by the box. Whiskers indicate the range of the data within 1.5 times the interquartile range from the median; solid triangle indicates outliers that fall outside this range.](image)
Table 1: Efficiency of Oxygen Administration Systems

<table>
<thead>
<tr>
<th>Group</th>
<th>Patient's Hoods A</th>
<th>Patient's Masks B</th>
<th>Volunteer's Masks C</th>
<th>Nurse's Masks D</th>
<th>Nurse with Tender E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Subject numbers</td>
<td>15</td>
<td>15</td>
<td>12</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$F_mO_2$</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(42%)</td>
<td>(82%)</td>
<td>(36%)</td>
</tr>
<tr>
<td>$&gt;0.8$</td>
<td>(100%)</td>
<td>(100%)</td>
<td>(42%)</td>
<td>(82%)</td>
<td>(36%)</td>
</tr>
</tbody>
</table>

measured in any of the other groups ($P < 0.015$). Thirty liters per minute was the lowest flow of $O_2$ used to control carbon dioxide levels within the hood and usually 40–50 liters·min$^{-1}$ were used. Using oral–nasal masks, however, $F_mO_2$ was reliably more than 0.8 during the second analysis period only for nurses who allowed an attendant to adjust the mask and not when these people adjusted their own masks. The $F_mO_2$ of 0.8 was an arbitrary parameter for the analysis of results. We believe that an inspired $O_2$ level consistently below 0.8 (as stipulated by the regional ethics committee) leads to an inadequate dose of $O_2$ being delivered. The nurses are trained and experienced in mask breathing; it is therefore not surprising that their mask fit was improved compared to the patient group who were unfamiliar with this equipment. Volunteers, who were untrained subjects without supervision, failed as a group to maintain an $F_mO_2$ level of over 0.8. The concentration of $O_2$ measured was higher during the second measurement period ($P < 0.005$) and, as a result, more people achieved an $F_mO_2$ of 0.8 during this second sampling period.

For the group in which mean expired $O_2$ was also analyzed, we found no significant differences in $O_2$ levels obtained by sampling gas from the mask or from the expired gas, either when the two methods were applied together or separately (Fig. 3). It was clear, however, that there was a disparity between the two methods for some subjects. At 5–10 min of $O_2$ breathing, for those subjects in whom $F_mO_2$ was more than 0.8, $F_eO_2$ was also more than 0.8. In the three subjects in whom $F_mO_2$ was less than 0.8, $F_eO_2$ was considerably higher, although still below 0.8 in two subjects and with $F_eO_2$ dropping below 0.8 for the other in 10–15 min (Fig. 3).

**DISCUSSION**

The importance of estimating $F_iO_2$ in HBO delivery systems is clear. A marked difference exists between the use of the oral–nasal mask and demand valve and the ventilated-hood delivery systems, and a measured $F_eO_2$ of more than 0.8 could be reliably achieved only for patients using a hood system (Table 1). $F_mO_2$ was not reliably more than 0.8 in any of the groups using the demand-valve system, except when trained staff supervised their colleagues, even though the masks used were always adjusted to ensure a proper visual fit. The hood system delivers a more reliable high concentration of $O_2$ and may therefore be the preferred $O_2$ administration system.

The aim of HBO therapy is to give 100% $O_2$ as the inhaled gas. Unfortunately there is no simple method to measure inhaled $O_2$ levels in a mask-administered system. In most multiplace hyperbaric chambers in the United Kingdom, a demand-valve system is used and the patient breathes from an oral–nasal mask. It is impractical in emergency cases to fit a completely leak-proof system individually, thus some leakage across the seal of a face mask is likely. Analyzing $O_2$ levels in the face mask of such a system will underestimate inhaled $O_2$ levels because the flow ducted to the analyzer is continuous, whereas inspiration is intermittent. Inspiratory duration at rest, when the mask is flooded with 100% $O_2$, is of shorter duration than exhalation and so analysis of a continuous flow of $O_2$ will be disproportionately influenced by exhaled $O_2$ levels. Exhaled $O_2$ levels are lower than inhaled levels particularly while nitrogen is being excreted, and so this method underestimates inhaled $O_2$ especially at the start of $O_2$ inhalation when the volume of exhaled $N_2$ is greatest. This
pattern is demonstrated by our data, which show that \( O_2 \) levels are lower at the start of an \( O_2 \)-breathing session (Fig. 3) and that exhaled \( O_2 \) levels may be higher than those measured in the mask. The problem of sampling artifact is much less in the hood \( O_2 \) administration system. Although dead-space purging in a mask system is dependent on the respiratory pattern in a demand system, the hood system uses forced ventilation and \( O_2 \) levels are not subject dependent. Fresh gas flow for the hood system used in this study was more than 30 liters \( \cdot \min^{-1} \) under ambient conditions of pressure and temperature. To some extent, therefore, the difference between hood and mask \( O_2 \) levels is methodological rather than real, and to test the degree of this effect we analyzed exhaled \( O_2 \) levels in a group of people with concurrent mask sampling. Although there were no statistically significant differences across the group as a whole, the three subjects with an \( Fm_{O_2} \) of less than 0.8 also had a low \( Fe_{O_2} \) which was sustained through the \( O_2 \) administration period. Low \( Fm_{O_2} \) indicated an \( O_2 \) delivery problem and reinforced concern generated by the data from the larger study group.

The oral–nasal mask demand system is at present standard equipment for the treatment of decompression incidents in multiplace chambers in the United Kingdom and for the prevention of DCS in the North Sea industry. This study shows clearly that it is very important to estimate the inspired \( O_2 \) concentration to ensure that the anticipated dose is delivered. Failure to achieve adequate inspired levels of \( O_2 \) during treatment of DCS may reduce efficiency of the treatment and perhaps increase relapse rate after treatment. Similarly, prophylactic use of \( O_2 \) during standard decompression schedules may also be less effective than expected, and surface-oriented \( O_2 \) decompression schedules may also be unexpectedly risky. A simple and relatively inexpensive way to monitor \( O_2 \) delivery might be to install mask analysis lines within the masks and to measure \( Fm_{O_2} \). The experience of this study, however, indicates that this approach, while allowing identification of the problem, does not allow its complete solution. A hood-based system of \( O_2 \) administration was more reliable.

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REFERENCES