Effect of hyperbaric oxygen on oxygen uptake and measurements in the blood and tissues in a normobaric environment

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In recent years some professional and college athletic teams have used hyperbaric oxygen (HBO2) to treat sports injuries, to speed recovery after exercise, and as an ergogenic aid to enhance performance. Because of the importance of oxygen in the aerobic energy system, professional athletes sometimes receive HBO2 before participation in their sport in the belief that subsequent performance will be improved. HBO2 therapy is defined as a medical treatment in which the patient breathes 100% oxygen intermittently while inside a chamber at a pressure greater than 1 atmosphere absolute (ATA). The Undersea and Hyperbaric Medical Society currently approves 13 medical indications for treatment with HBO2.

Physiologists have long debated whether oxygen delivery or use by the skeletal muscles is the limiting factor for VO2MAX. Potential physiological factors limiting VO2MAX include: (a) pulmonary diffusion capacity for O2; (b) maximal cardiac output; (c) the peripheral circulation; (d) the metabolic capacity of skeletal muscle.5 Most physiologists believe that the capacity of the central cardiovascular system to transport oxygen to the tissues is the principal determinant of VO2MAX. This concept has been used to justify HBO2 treatments to enhance the availability of oxygen in an attempt to increase maximal aerobic performance. Also, oxygen stored in the tissues after an HBO2 treatment may be available to working muscles.

Our reasons for this study are the contrary findings in the research literature6 and the observation that the athletic community has used HBO2 before sport performance. Under pressure, oxygen dissolves in all body fluids. For HBO2 to be beneficial, increased oxygen must be stored during the treatment and remain raised on return to a normobaric, normoxic environment. Previous studies have not examined the blood or tissues to determine if these compartments would be additional sources of oxygen available to the mitochondria during maximal exercise. Because of potential misuse by the athletic community, there is a need to establish if there are benefits in using HBO2 as an ergogenic aid. This study examines the ergogenic potential of HBO2. We hypothesised that: (a) venous partial pressure of oxygen (PvO2) and/or transcutaneous oxygen tension (tcPO2) would be unchanged after a single HBO2 treatment in a normobaric environment; (b) VO2MAX would be similar after a single HBO2 treatment in a normobaric environment.

METHODS

Subjects

The subjects were 10 trained (VO2MAX = 57.6 (6.2) ml/kg/min) male volunteers (table 1). They were examined by a doctor and were excluded if contraindications to HBO2 treatment were evident (recent thoracic surgery, repeated ear infections, asthma, cataracts, diabetes, receiving anticonvulsant medication, hereditary spherocytosis, and recent upper respiratory tract infections). All experimental procedures were evaluated and approved by the McGill University Faculty of Medicine institutional review board. Subjects gave written consent to participate after the design and risks of the study had been described to them.

Experimental design

Subjects underwent tests on three non-consecutive days within a two week period. Baseline testing on day 1 included assessment of physical characteristics, tcPO2 during normoxic and hyperoxic breathing, and measurement of VO2MAX. Testing on day 2 included a 90 minute HBO2 treatment followed by a VO2MAX test. The time delay from exiting the hyperbaric chamber to the start of the VO2MAX test was 6.0 (1.0) minutes. On day 3, subjects received a 90 minute HBO2

Abbreviations: HBO2, hyperbaric oxygen; Pvo2, venous partial pressure of oxygen; tcpO2, transcutaneous oxygen tension; Vo2max, maximum oxygen consumption
treatment followed by nine $P_{vO_2}$ samples and $tcPO_2$ measurements for 60 minutes.

**Hyperbaric oxygen protocol**
Figures 1 and 2 illustrate the HBO2 chamber and protocol. The HBO2 treatment was administered in a Sigma Plus monoplace hyperbaric chamber (Perry Baromedical Corporation, Riviera, Florida, USA) under the supervision of a certified chamber operator at the Cleghorn Hyperbaric Laboratory, McGill University. It took about 10 minutes to pressurise the chamber to 2.5 ATA with 95% oxygen. At 25 and 55 minutes into the 90 minute treatment, subjects were given a five minute air break through an oronasal mask to reduce the risk of oxygen toxicity. After 90 minutes, the chamber was decompressed from 2.5 to 1.0 ATA in about eight minutes.

Under normal sea level conditions, barometric pressure is 1 ATA or 760 mm Hg, and oxygen content in the air is 20.9%. In these conditions the $PaO_2$ is 100 mm Hg. During our HBO2 treatment, the combination of increased pressure (2.5 ATA) and increased oxygen concentration (95%) results in additional oxygen dissolved in plasma. During the hyperbaric treatment at these conditions the $PaO_2$ is predicted to be:

$$PaO_2 = \left(\frac{P_{BTTPS} \times FIO_2}{PaCO_2/R}\right)$$

where $P_{BTTPS} =$ pressure at body temperature pressure saturated (mm Hg), $FIO_2 =$ fraction of oxygen in inspired air (%), $PaCO_2 =$ partial pressure of CO2 in arterial blood (mm Hg), and $R =$ respiratory quotient.

**Exercise test procedure**
Before the exercise test, physical characteristics (height, weight, and body composition) were measured. Percentage body fat was estimated from skinfold measurements and the regression equation of Jackson and Pollock.

$VO_2MAX$ was measured on a Quinton Q65 Series 90 treadmill (Quinton Instruments, Seattle, Washington, USA). Subjects began an incremental test at 5 mph (134 m/min) and 5% grade with speed increased by 0.5 mph (13.4 m/min) every minute until volitional exhaustion. Expired gases were collected with $VE$, $VO_2$, and $VCO_2$ averaged every 20 seconds using a SensorMedics 2900 Metabolic Measurement Cart (SensorMedics, Yorba Linda, California, USA). Subjects were verbally encouraged to continue exercising until volitional exhaustion. Criteria for reaching $VO_2MAX$ were attainment of age predicted heart rate maximum, a respiratory exchange ratio of 1.10, or a plateau in $VO_2$ with increased workload. $VO_2MAX$ was calculated by averaging the highest values over one minute. Heart rate was measured using a Polar Accurex Heart Rate Monitor (Polar Electro, Kempele, Finland) and averaged every five seconds. Four minutes after the $VO_2MAX$ test, a finger prick blood sample was taken to determine peak blood lactate concentration. The blood samples were analysed with an Accusport Portable Lactate Analyzer (Behringer Mannheim, Mannheim, Germany).

$tcPO_2$ measurement
tcPO2 was measured at two sites: chest (second intracostal) and leg (mid-thigh over the rectus femoris). The sites were prepared by removal of hair, cleaning with alcohol, and denuding the skin by repeated application and removal of adhesive tape. A calibrated TCM 30 Transcutaneous PO2 Monitoring System (Radiometer, Copenhagen, Denmark) was used to measure $tcPO_2$ continuously. The electrodes were warmed to 45°C as recommended for use in hyperbaric operations. There was a lag of about 10 minutes after application of the electrodes before stable values were achieved. Values were recorded every minute for 60 minutes. The baseline $tcPO_2$ assessment included a 20 minute oxygen challenge in which the subjects breathed 100% oxygen through an oronasal mask from minute 20 to minute 40 to demonstrate their $tcPO_2$ responsiveness to high concentrations of oxygen.

$PvO_2$ measurement
When each subject left the hyperbaric chamber on day 3, a 14 gauge intravenous catheter was inserted into an antecubital vein. The line was kept patent between samples with 5% dextrose solution (IVDSW). Blood samples (3–5 ml) were drawn 3, 5, 10, 15, 20, 30, 40, 50, and 60 minutes after the subject had left the chamber. To ensure blood samples were not contaminated with IVDSW solution, 5 ml blood was drawn and discarded before every blood sample was collected. Samples were immediately aspirated into a
Radiometer ABL5 blood analyser, which was calibrated with known samples provided by the manufacturer. Every 30 minutes, the blood analyser performed a barometric pressure and a 1 point calibration of the PO2 electrode using gas of 19.8% O2. Every two hours the blood analyser performed a 2 point calibration of the PO2 electrode using gases of 0% and 19.8% O2.

With regard to blood sampling, our preference was to obtain arterial PO2 (PaO2) measurements because it is unclear how long PaO2 remains raised after an HBO2 treatment. The ethics institutional review board did not approve arterial sampling for this study, and requested that an intravenous catheter be used to obtain blood samples.

**Statistical analysis**

Paired t tests were used to compare baseline conditions with those after treatment for VO2MAX and peak blood lactate data. A one way repeated measures analysis of variance was used to compare PvO2 data for the two conditions. A two way repeated measures analysis of variance was used to compare tcPO2 data at two sites (chest and leg) and two conditions (baseline and after HBO2). Analysis of variance was followed by post hoc comparisons using Tukey’s HSD (honestly significant difference) test. For all statistical analyses, was set at p<0.05.

**RESULTS**

Table 2 shows the exercise test results. No significant differences were found for VO2MAX or peak blood lactate concentration between the baseline condition and after HBO2 treatment. The mean (SD) VO2MAX values were 57.6 (6.2) and 57.3 (5.8) ml/kg/min in the two conditions. The time from exiting the chamber and initiation of the exercise test was 6.0 (1.0) minute. The HBO2 treatment did not enhance exercise performance, as run times were identical in both conditions (10.1 (1.9) min). Peak lactate concentrations were similar (8.9 (2.8) and 10.0 (1.9) mmol/l) in the two conditions.

Table 3 summarises and fig 3 illustrates the PvO2 results. There was a significant change in PvO2 over time ($F = 6.61; df 8.40; p<0.001$) after the HBO2 treatment, with a lower PO2 value at three minutes than at 5–60 minutes. The tourniquet on the upper arm was in place for about one minute before drawing of the initial blood sample. We attribute the significantly lower PO2 at three minutes to altered blood flow in the arm. The PvO2 data suggest that there was no excess oxygen circulating in the blood after the HBO2 treatment.

Figure 4 summarises the tcPO2 data. In the baseline condition, the start of the oxygen challenge was at 20 minutes. The chest tcPO2 increased from about 80 to 290 mm Hg in about five minutes, and the leg tcPO2 increased from 70 to 230 mm Hg in the same time frame. Upon completion of the oxygen challenge at 40 minutes, both the chest and leg tcPO2 returned to baseline values within three minutes. After the HBO2 treatment, the leg tcPO2 was significantly ($F = 11.93; df 1.18; p = 0.003$) lower than the baseline values, with a difference of 14 mm Hg. In contrast, the chest tcPO2 values were similar at baseline and after HBO2 treatment.

**DISCUSSION**

Intermittent HBO2 treatments have been used to speed recovery of muscle strength after exercise induced injury. Quadriceps muscle soreness was induced by eccentric exercise.13 HBO2 treatments improved recovery of eccentric strength compared with placebo treatments. The effect of a
Effect of hyperbaric oxygen

A single HBO2 treatment at 2.5 ATA for 90 minutes does not raise VO2max in a normobaric, normoxic environment. Transcutaneous tissue and blood PO2 measurements after the HBO2 treatment support the statement that HBO2 does not have ergogenic benefits for the athletic community.

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Take home message

A single HBO2 treatment at 2.5 ATA for 90 minutes does not raise VO2max in a normobaric, normoxic environment. Transcutaneous tissue and blood PO2 measurements after the HBO2 treatment support the statement that HBO2 does not have ergogenic benefits for the athletic community.

In summary, the results of this study show that a single HBO2 treatment at 2.5 ATA for 90 minutes does not raise VO2max in a normobaric, normoxic environment. Oxygen measurements in the venous blood (PO2v) and in the tissues (tPO2) provide new data to support the rationale that HBO2 treatments do not enhance performance. This message needs to be conveyed by doctors and sport scientists to the athletic community. Our findings support the work of Webster et al.,7 McGavock et al., 4 and the Undersea and Hyperbaric Medical Society statement that HBO2 does not have ergogenic properties.

Assess oxygen levels in muscle tissue after the HBO2 treatment. It appears that the excess oxygen that is physically dissolved in plasma during HBO2 is rapidly consumed upon exiting the HBO2 chamber. Upon application of the tPO2 electrode, it takes about 10 minutes to obtain a reliable value as the electrode warms the skin.16 In our study, 10 minutes after exiting the chamber tPO2 values had returned to baseline and leg tPO2 values were lower than baseline. The lower tPO2 values in the leg may be attributed to vasoconstriction. It has been shown both in vivo and in vitro that blood flow is decreased when inspired PO2 increases above 500 mm Hg.24 The vasoconstrictive effect occurs in both arterial and venous vascular beds.25

Cabric et al.6 administered 100% oxygen at 2.8 ATA for 60 minutes. Eighteen female students were randomly divided into three groups (six per group). After the HBO2 treatment, the first group performed a VO2MAX test at 30 minutes, the second at three hours, and the third at six hours. Both VO2MAX and treadmill run time to exhaustion had increased significantly 30 minutes (p < 0.05), 10% at three hours (p < 0.05), and 7% at six hours (non-significant). The improved performance was attributed to oxygen stored within skeletal muscle tissue. It has also been reported that blood lactate levels, VO2, and VCO2 were lower during submaximal exercise in a normobaric environment.14 This study included only two subjects and therefore it is difficult to generalise their findings.

Webster et al.1 questioned the ergogenic effect of HBO2. Their subjects performed three exercise tests on a cycle ergometer. These tests were performed on separate days with the first two exercise tests designed to establish baseline data, and the third test after an HBO2 treatment at 2.0 ATA for 60 minutes. The mean time from exiting the chamber to cycling was 22.5 minutes. No significant differences were found for VO2max, ventilatory threshold, lactate threshold, VEmax, or HRmax for the three tests. Near infrared spectroscopy was used to examine tissue oxygenation of the vastus lateralis muscle at rest, throughout exercise, and during recovery. After the HBO2 treatment, muscle tissue oxygenation during rest and recovery were similar to control values.

McGavock et al.6 examined the acute effects of a single HBO2 treatment on aerobic performance in a normobaric environment. Subjects (n = 12) performed four exercise-HBO2 conditions designated as: (a) control; (b) exercise-non-HBO2; (c) no exercise-HBO2; (d) exercise-HBO2. Exercise was a 90 minute run to produce fatigue. The HBO2 treatments were at 2.5 ATA for 90 minutes. At the end of each condition, aerobic performance was assessed using running economy tests and a VO2MAX test. The time between exiting the chamber and running on the treadmill averaged 40 minutes. Recovery was not enhanced after a single HBO2 treatment nor did it alter submaximal or maximal running performance.

Our findings support the results of Webster et al.1 and McGavock et al.6. Baseline conditions and those after HBO2 were similar for VO2max, treadmill running time, and peak blood lactate, indicating that the single HBO2 treatment was not ergogenic.

tPO2 is a reliable assessment of oxygen available to tissues.18 It is traditionally used to predict if HBO2 treatment will be beneficial for wound healing and to maintain tissue oxygen levels within an appropriate range.21 Chest tPO2 values have been recorded at 1312 (112) mm Hg during a HBO2 treatment at 2.4 ATA.22 In our study, tPO2 was used to

single HBO2 treatment on subsequent exercise performance has also been examined. Kajiser14 compared dynamic forearm exercise under hyperbaric (3.0 ATA) and normobaric conditions. The performance time to exhaustion was increased in three subjects and unchanged in three subjects.

There is evidence that breathing hyperoxic gas during exercise enhances performance.19–21 Using arterial and femoral venous sampling combined with measurement of blood flow, it has been shown that hyperoxia increases VO2max of an exercising leg.15 As it is unclear if HBO2 treatment before exercise alters performance, we examined PvO2, tCP02, and VO2max in a normobaric environment after a single HBO2 treatment. Four studies have investigated maximal aerobic performance in a normobaric environment after HBO2 treatments, with two studies showing positive findings5,6 and two studies reporting no benefits.4,7

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