Effect of Hyperbaric Oxygen on Venous PO_2, Transcutaneous PO_2, and VO_{2max} in a Normobaric Environment

By

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TABLE OF CONTENTS

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ABSTRACT

Purpose: The purpose was to examine venous PO_2, transcutaneous tissue PO_2 ($P_{tc}O_2$), and VO_{2max} in a normobaric environment following a single HBO_2 treatment. **Methods:** Ten moderately trained (VO_{2max} = 57.6 $mL \cdot kg^{-1} \cdot min^{-1}$) males volunteered for the study. Baseline testing included measures of VO_{2max}, $P_{tc}O_2$, and anthropometry. Subjects received two HBO_2 treatments, which consisted of breathing 95% oxygen at 2.5 ATA for 90 min. Following the first HBO_2 treatment (6.0 ± 1.0 min), subjects performed a VO_{2max} test. Following the second HBO_2 treatment, leg and chest $P_{tc}O_2$ and venous PO_2 were monitored for 60 min. **Results:** VO_{2max}, running time, and peak La were not altered ($p<0.05$) post-HBO_2 treatment. Leg $P_{tc}O_2$ was lower ($p<0.05$) and chest $P_{tc}O_2$ was unchanged following the HBO_2 treatment compared to baseline values. Venous PO_2 was lower in the first 3 min post-HBO_2 treatment than subsequent values, but no other differences were found ($p<0.05$). **Conclusion:** The results of this study show that a single HBO_2 treatment at 2.5 ATA for 90 min does not elevate venous PO_2, $P_{tc}O_2$, or VO_{2max} in a normobaric, normoxic environment. **Key words:** MAXIMAL OXYGEN UPTAKE, TRANSCUTANEOUS TISSUE OXYGEN, MAXIMAL EXERCISE, ERGOGENIC AID

RÉSUMÉ

But : Le but de cet étude était de déterminer la PO_2 veineuse, la PO_2 tissulaire transcutané ($P_{tc}O_2$) et le VO_{2max} dans un environement normobarique à la suite d'une exposition hyperoxique, hyperbare (HBO_2). **Méthodes** : Dix hommes modérément entraînés ($VO_{2max} = 57.6\ mL \cdot kg^{-1} \cdot min^{-1}$) se sont portés volontaire pour l'étude. Les tests constituaient en la mesure de VO_{2max}, de $P_{tc}O_2$, et de l'antropométrie. Les sujets ont reçu deux traitements de HBO_2 consistant à respirer 95% d'oxygène à 2,5 A pour une durée de 90 minutes. À la suite du premier traitement de HBO_2, les sujets ont subi un test de VO_{2max}. À la suite du deuxième traitement de HBO_2, les résultats du $P_{tc}O_2$ et du PO_2 veineux pour les jambes et la poitrine ont été enregistrés pendant 60 minutes. **Résultats** : Suivant le taitement de HBO_2, le VO_{2max}, le temps de course, et le « peak » AL n'ont pas été altérés ($p<0,05$). Aussi, le $P_{tc}O_2$ pour les jambes a diminué alors qu'il est resté le même pour la poitrine. Finalement, le PO_2 veineux a diminué seulement dans les 3 premières minutes suivant le traitement de HBO_2 mais aucune autre difference a été enregistré ($p<0,05$). **Conclusion**: Les résultats de cet étude démontrent qu'un seul traitement de HBO_2 dans un environement norborarique et normoxique à 2,5 A et pour une durée de 90 minutes n'élève pas le PO_2 veineux, le $P_{tc}O_2$, ou le VO_{2max}. **Mots clés** : OXYGÈNE MAXIMALE REÇUE, TISSUE DÒXYGÈNE TRANSCUTANÉS, EXCERCICE MAXIMAL, AIDE ERGOGÉNIQUE.

INTRODUCTION

Hyperbaric oxygen (HBO_2) therapy is a relatively new area of research in medicine and physiology. Hyperbaric chambers were originally introduced in the 1930s as a means of treating decompression sickness. Use has since expanded into the field of hyperbaric medicine. The Undersea & Hyperbaric Medical Society (UHMS) currently approves 13 medical indications for treatment with HBO_2 (9). HBO_2 therapy is a medical treatment in which the patient breathes 100% oxygen intermittently while inside a chamber at a pressure greater than 1 atmosphere absolute (ATA) (9).

In recent years some professional and college athletic teams have used HBO_2 therapy to treat sports injuries, to speed recovery after exercise, and as an ergogenic aid to enhance performance. Due to the importance of oxygen in the aerobic energy system, professional athletes sometimes receive HBO_2 before participation in their sport in the belief that subsequent performance will be improved (18).

Physiologists have long debated whether oxygen delivery or utilization by the skeletal muscles is the limiting factor for VO_{2max}. Potential physiological factors limiting VO_{2max} include: 1) pulmonary diffusion capacity for O_2, 2) maximal cardiac output, 3) the peripheral circulation, and 4) the metabolic capacity of skeletal muscle (21). According to Rowell (21), most physiologists believe that the capacity of the central cardiovascular system to transport oxygen to the tissues is the principle determinant of VO_{2max}. This concept has been used to justify HBO_2 treatments to enhance the availability of oxygen in an attempt to increase maximal aerobic performance. Also, oxygen stored in the tissues following an HBO_2 treatment may be available to working muscles.

There is evidence that breathing hyperoxic gas during exercise enhances performance (1, 4, 6, 14, 16, 19, 26). Using arterial and femoral venous sampling combined with measurement of blood flow, it has been shown that hyperoxia increases maximal VO_2 of an exercising leg (14). However, it is unclear if HBO_2 treatments prior to exercise alter performance.

Contradictory findings have been reported regarding the effect of a single HBO_2 treatment on aerobic performance. Kaijser (12) 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. A small number of investigations have examined the effect of HBO_2 on recovery from exercise. Intermittent exposures to HBO_2 have been used to treat delayed onset muscle soreness in the quadriceps that had been induced by eccentric exercise (23). HBO_2 treatments improved recovery of eccentric strength compared to placebo treatments. HBO_2 has also been used following 90-min runs at 75 - 80% of VO_{2max} (15). A single HBO_2 treatment did not enhance recovery. Regarding HBO_2 as an ergogenic aid to performance, two studies have reported positive findings (2, 3) and two studies have reported no benefits (15, 24).

Due to potential misuse by the athletic community, there is a need to establish if there are benefits in using HBO_2 as an ergogenic aid. Unwarranted use of HBO_2 therapy not only wastes hyperbaric resources but also poses some risks to the patients. This study examines the ergogenic potential of HBO_2. The purpose was to examine venous PO_2, transcutaneous tissue PO_2 ($P_{tc}O_2$), and VO_{2max} in a normobaric environment following a single HBO_2 treatment.

METHODS

Subjects

The subjects were ten trained (VO_{2max} = 57.6 ± 6.2 mL · kg^{-1} · min^{-1}) male volunteers. Subject characteristics are described in Table 1. Subjects were examined by a physician and were excluded if contraindications to HBO_2 treatment were evident (recent thoracic surgery, repeated ear infections, asthma, cataracts, diabetes, receiving anti-convulsant 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 informed 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, $P_{tc}O_2$ during normoxic and hyperoxic breathing, and measurement of VO_{2max}. Testing on day 2 included a 90-minute HBO_2 treatment followed by a VO_{2max} test. The time delay from exiting the hyperbaric chamber to the start of the VO_{2max} test was 6.0 ± 1.0 min. On day 3. subjects received a 90-minute HBO_2 treatment followed by nine venous PO_2 samples and $P_{tc}O_2$ measurements for 60 min.

Hyperbaric Oxygen Protocol

Figures 1 and 2 illustrate the HBO_2 chamber and protocol. The HBO_2 treatment was administered in a Sigma Plus monoplace hyperbaric chamber (Perry Baromedical Corporation, Riviera, FL) under the supervision of a certified chamber operator at the

Cleghorn Hyperbaric Laboratory, McGill University. It took approximately 10 min to pressurize the chamber to 2.5 ATA with 95% oxygen. At 25 and 55 min into the 90-min treatment, subjects were given a 5-min air break through an oronasal mask to reduce the risk of oxygen toxicity. After 90 min, the chamber was decompressed from 2.5 to 1.0 ATA in approximately eight minutes.

Exercise Test Procedure

Prior to the exercise test, physical characteristics (height, weight, and body composition) were measured. Percent body fat was estimated from skinfold measurements and the regression equation of Jackson and Pollock (11).

VO_{2max} was measured on a Quinton Q65 Series 90 treadmill (Quinton Instruments, Seattle, WA). Subjects began an incremental test at 5 mph (134 $m \cdot min^{-1}$) and 5% grade with speed increased by 0.5 mph (13.4 $m \cdot min^{-1}$) every minute until volitional exhaustion. Expired gases were collected with V_E, VO_2, and VCO_2 averaged every 20 s using a SensorMedics 2900 Metabolic Measurement Cart (SensorMedics, Yorka Linda, CA). Subjects were verbally encouraged to continue exercising until volitional exhaustion. Criteria for reaching VO_{2max} were attainment of age-predicted HR_{max}, an RER value of ≥ 1.10, or a plateau in VO_2 with increased workload. VO_{2max} was calculated by averaging the highest values over 1 minute. Heart rate was measured using a Polar Accurex Heart Rate Monitor (Polar Electro, Kempele, Finland) and averaged every 5 s. Four minutes following the VO_{2max} test a finger prick blood sample was taken to determine peak blood lactate (La) concentration. The blood samples were analyzed with an Accusport Portable Lactate Analyzer (Behringer Mannheim, Mannheim, Germany).

$P_{tc}O_2$ Measurement

$P_{tc}O_2$ 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 (22). A calibrated TCM 30 Transcutaneous PO_2 Monitoring System (Radiometer, Copenhagen, Denmark) was used to measure $P_{tc}O_2$ continuously. The electrodes were warmed to 45° C as recommended for use in hyperbaric operations (10, 20). There was a lag of approximately 10 min following application of the electrodes before stable values were achieved. Values were recorded every minute for 60 min. The baseline $P_{tc}O_2$ assessment included a 20-minute oxygen challenge in which the subjects breathed 100% oxygen through an oronasal mask from minute 20 to minute 40. The purpose of the oxygen challenge was to demonstrate the subjects' $P_{tc}O_2$ responsiveness to breathing 100% oxygen.

Venous PO_2 Measurement

Upon exiting the hyperbaric chamber on day 3, a 14-gauge intravenous (IV) catheter was inserted in an antecubital vein. The IV line was kept patent between samples with 5% dextrose solution (IVD5W). Blood samples (3 – 5 mL) were drawn 3, 5, 10, 15, 20, 30, 40, 50, and 60 min after exiting the chamber. To ensure blood samples were not contaminated with IVD5W solution, 5 mL of blood were drawn and discarded before every blood sample was collected. Samples were immediately aspirated into a Radiometer ABL5 blood analyzer (Radiometer, Copenhagen, Denmark), which was calibrated with known samples provided by the manufacturer. Every 30 min the blood analyzer performed a barometric pressure and a 1-point calibration of the PO_2 electrode

using gas of 19.8% O_2. Every two hours the blood analyzer performed a 2-point calibration of the PO_2 electrode using gases of 0% and 19.8% O_2.

With regard to blood sampling our preference was to obtain arterial PO_2 measurements since it is unclear how long P_aO_2 remains elevated following an HBO_2 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 and post-HBO_2 conditions for VO_{2max} and peak La data. A one-way repeated measures ANOVA was used to compare venous PO_2 data from the baseline and post-HBO_2 conditions. A two-way repeated measures ANOVA was used to compare $P_{tc}O_2$ data at two sites (chest and leg) and two conditions (baseline and post-HBO_2). ANOVAs were followed by post hoc comparisons using Tukey's HSD (honestly significant difference) test. For all statistical analyses, α was set at $p<0.05$.

RESULTS

The exercise test results are shown in Table 2. No significant differences ($p<0.05$) were found for VO_{2max} or peak La between the baseline and post-HBO_2 conditions. The mean VO_{2max} values were 57.6 ± 6.2 and 57.3 ± 5.8 mL $\cdot$ kg^{-1} $\cdot$ min^{-1} in the two conditions. The time from exiting the chamber and initiation of the exercise test was 6.0 $\pm$ 1.0 min. The HBO_2 treatment did not enhance exercise performance, as run times were identical in both conditions (10.1 $\pm$ 1.9 min). Peak La values were similar (8.9 ± 2.8 and 10.0 ± 1.9 mmol $\cdot$ L^{-1}) in the baseline and post-HBO_2 conditions.

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 P_aO_2 is 100 mm Hg. During our HBO_2 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 P_aO_2 is predicted to be:

$$P_aO_2 = \{(P_{BTPS} * F_iO_2) - (P_aCO_2 / R)\}$$

$$P_aO_2 = \{[(2.5 \text{ ATA} * 760) - 47 \text{ mm Hg}] * 0.95\} - (40 \text{ mm Hg} / 0.82)$$

$$P_aO_2 = 1853 - 49 = 1804 \text{ mm Hg}$$

where P_{BTPS} = Pressure at body temperature pressure saturated (mm Hg)

F_iO_2 = Fraction of oxygen in inspired air (%)

P_aCO_2 = Partial pressure of CO_2 in arterial blood (mm Hg)

R = Respiratory quotient

The venous PO_2 results are summarized in Table 3 and illustrated in Figure 3. The only significant ($p<0.05$) difference in venous PO_2 following the HBO_2 treatment was a lower PO_2 value at 3 min compared to the values from 5 to 60 min. The tourniquet on the upper arm was in place for about one minute prior to drawing of the initial blood sample. We attribute the significantly lower PO_2 at 3 min to altered blood flow in the arm. The venous PO_2 data suggest that there was no excess oxygen circulating in the blood following the HBO_2 treatment.

The $P_{tc}O_2$ data are summarized in Figure 4. In the baseline condition, the start of the oxygen challenge was at 20 min. The chest $P_{tc}O_2$ increased from approximately 80 to 290 mm Hg in about 5 min while the leg $P_{tc}O_2$ increased from 70 to 230 mm Hg in the same time frame. Upon completion of the oxygen challenge at 40 min, both the chest and

leg $P_{tc}O_2$ returned to baseline values within 3 min. Following the HBO_2 treatment, the leg $P_{tc}O_2$ was significantly ($p<0.05$) lower than the baseline values. In contrast, the chest $P_{tc}O_2$ values were similar in the baseline and post-HBO_2 conditions.

DISCUSSION

The purpose of this study was to examine venous PO_2, $P_{tc}O_2$, and VO_{2max} in a normobaric environment following a single HBO_2 treatment. Four studies have investigated maximal aerobic performance in a normobaric environment following HBO_2 treatments with two studies showing positive results and two studies showing no benefits.

Cabric et al. (3) administered 100% oxygen at 2.8 ATA for 60 minutes. Eighteen female students were randomly divided into three groups (n=6 per group). Following the HBO_2 treatment, the first group performed a VO_{2max} test at 30 min, the second at 3 h, and the third at 6 h. Both VO_{2max} and treadmill run time to exhaustion increased significantly at 30 min and 3 h post-treatment. Following the HBO_2 treatment, VO_{2max} increased by 15% at 30 min ($p<0.05$), 10% at 3 h ($p<0.05$), and 7% at 6 h (non-significant). The improved performance was attributed to oxygen stored within skeletal muscle tissue. It has also been reported that blood lactate levels, VO_2, and VCO_2 were lower during submaximal exercise in a normobaric environment following HBO_2 (2). This study included only two subjects and therefore it is difficult to generalize their findings.

Webster et al. (24) questioned the ergogenic effect of HBO_2. 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 following an HBO_2 treatment at 2.0 ATA for 60 minutes. The mean time from

exiting the chamber to cycling was 22.5 min. No significant differences were found for VO_{2max}, ventilatory threshold, lactate threshold, V_{Emax}, or HR_{max} 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. Following the HBO_2 treatment, muscle tissue oxygenation during rest and recovery were similar to control values.

McGavock et al. (15) examined the acute effects of a single HBO_2 treatment on aerobic performance in a normobaric environment. Subjects (n=12) performed four exercise-HBO_2 conditions designated as: 1) control, 2) exercise-non HBO_2, 3) no exercise-HBO_2, and 4) exercise-HBO_2. Exercise was a 90-min run in order to produce fatigue. The HBO_2 treatments were at 2.5 ATA for 90 min. At the end of each condition, aerobic performance was assessed using running economy tests and a VO_{2max} test. The time between exiting the chamber and running on the treadmill averaged 40 min. Recovery was not enhanced following a single HBO_2 treatment nor did it alter submaximal or maximal running performance.

Our findings support the results of Webster et al. (24) and McGavock et al. (15). Baseline and post-HBO_2 conditions were similar for VO_{2max}, treadmill running time, and peak La indicating that the single HBO_2 treatment was not ergogenic.

Measurement of $P_{tc}O_2$ is a direct assessment of oxygen available to tissues (22). $P_{tc}O_2$ is traditionally used to predict if HBO_2 therapy will be beneficial for wound healing and to maintain tissue oxygen values within an appropriate range (27). Chest $P_{tc}O_2$ values have been recorded at 1,312 ± 112 mm Hg during a HBO_2 treatment at 2.4 ATA (5). In our study, $P_{tc}O_2$ was used to assess oxygen levels in muscle tissue following the HBO_2 treatment. It appears that the excess oxygen that is physically dissolved in plasma during

HBO_2 is rapidly consumed upon exiting the HBO_2 chamber. Upon application of the $P_{tc}O_2$ electrode, it takes ~10 minutes to obtain a reliable value as the electrode warms the skin (22). In our study, 10 minutes after exiting the chamber $P_{tc}O_2$ values had returned to baseline while leg $P_{tc}O_2$ values were lower than baseline. The lower $P_{tc}O_2$ 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 PO_2 increases above 500 mm Hg (17). The vasoconstrictive effect occurs in both arterial and venous vascular beds (7).

Sheffield (22) presents normal values for blood and tissue O_2 measured by blood gas analyzer, mass spectrometer, tissue tonometer, implanted polarographic electrode, and $P_{tc}O_2$ at pressures of 1.0 to 3.0 ATA. Normal mean values for venous PO_2 range from 36 - 40 mm Hg (8, 25). Between 10 and 60 min post-HBO_2, our venous PO_2 data ranged from 31.7 to 38.7 mm Hg indicating that there was no excess oxygen circulating in the blood. Banister et al. (2) previously examined P_aO_2 and P_aCO_2 following an HBO_2 treatment in two subjects. The P_aO_2 and P_aCO_2 were unchanged following the HBO_2 treatment. The time from the end of treatment to drawing blood samples was not stated. Our venous PO_2 and $P_{tc}O_2$ data indicate that plasma and tissue oxygen levels are not elevated post-HBO_2. Tissue auto-regulation reduces O_2 levels upon return to a normobaric, normoxic environment (13).

In summary, the results of this study show that a single HBO_2 treatment at 2.5 ATA for 90 min does not elevate venous PO_2, $P_{tc}O_2$, or VO_{2max} in a normobaric, normoxic environment. Our findings support the work of Webster et al. (24), McGavock et al. (15), and the Undersea & Hyperbaric Medical Society statement that HBO_2 does not have ergogenic properties.

REFERENCES

1. Adams, R. P., and H. G. Welch. Oxygen uptake, acid-base status, and performance with varied inspired oxygen fractions. *J Appl Physiol* 49:863-868, 1980.
2. Banister, E. W., J. E. Taunton, T. Patrick, P. Oforsagd, and W. R. Duncan. Effect of oxygen at high pressure at rest and during severe exercise. *Respir Physiol* 10:74-84, 1970.
3. Cabric, M., R. Medved, P. Denoble, M. Zivkovic, and H. Kovacevic. Effect of hyperbaric oxygenation on maximal aerobic performance in a normobaric environment. *J Sports Med Phys Fitness* 31:362-366, 1991.
4. Cunningham, D. A. Effects of breathing high concentrations of oxygen on treadmill performance. *Res Q* 37:491-494, 1966.
5. Dooley, J., G. King, and B. Slade. Establishment of reference pressure of transcutaneous oxygen for the comparative evaluation of problem wounds. *Undersea Hyper Med* 24:235-244, 1997.
6. Ekblom, B., R. Huot, E. M. Stein, and A. T. Thorstensson. Effect of changes in arterial oxygen content on circulation and physical performance. *J Appl Physiol* 39:71-75, 1975.
7. Fife, C. E., and E. M. Camporesi. Physiologic effects of hyperbaric hyperoxia. *Prob Respir Care* 4:142-149, 1991.
8. Guyton, A. C., and J. E. Hall. *Textbook of Medical Physiology (9th Ed)*. Philadelphia, PA: W. B. Saunders Company, 1996, pp. 513-523.
9. Hampson, N. B. (Ed.) *Hyperbaric Oxygen Therapy: 1999 Committee Report*. Kensington, MD: Undersea & Hyperbaric Medical Society, 1999, pp. 1-74.

10. Huch, A., R. Huch, G. Hollmann, T. Hockerts, H. P. Keller, D. Seiler, J. Sadzek, and D. W. Lubbers. Transcutaneous PO_2 of volunteers during hyperbaric oxygenation. *Biotelemtr* 4:88-100, 1977.

11. Jackson. A. S. and M. L. Pollock. Generalized equations for predicting body density of men. *Br J Nutr* 40:497-504,1978.

12. Kaijser, L. Physical exercise under hyperbaric oxygen pressure. *Life Sci* 8:929-934, 1969.

13. Kelly, D. L., K. R. Lassiter. A. Vongsvivut, and J. M. Smith. Effects of hyperbaric oxygenation and tissue oxygen studies in experimental paraplegia. *J Neurosurg* 36:425-429, 1972.

14. Knight. D. R., W. Schaffartzik, D. C. Poole, M. C. Hogan, D. E. Bebout, and P. D. Wagner. Effects of hyperoxia on maximal leg O_2 supply and utilization in men. *J Appl Physiol* 75:2586-2594, 1993.

15. McGavock, J. M., J. L. Lecomte, J. S. Delaney, V. J. Lacroix, P. Hardy, and D. L. Montgomery. Effects of hyperbaric oxygen on aerobic performance in a normobaric environment. *Undersea Hyper Med* 26:219-224, 1999.

16. Nielson, H. B., P. Madsen, L. B. Svendsen, R. C. Roach, and N. H. Secher. The influence of P_aO_2, pH and S_aO_2 on maximal oxygen uptake. *Acta Physiol Scand* 164:89-97, 1998.

17. Plewes, J. L., L. E. Farhi. Peripheral circulatory responses to acute hyperoxia. *Undersea Biomed Res* 10:123-129, 1983.

18. Potera C. Healing under pressure. *Physician Sportsmed* 23(11):46-47, 1995.

19. Richardson, R. S., B. Grassi, T. P. Gavin, L. J. Haseler, K. Tagore, J. Roca, and P. D. Wagner. Evidence of O_2 supply-dependent VO_{2max} in the exercise-trained human quadriceps. *J Appl Physiol* 86:1048-1053, 1999.

20. Robertson, P. W. and B. B. Hart. Assessment of tissue oxygenation. *Respir Care Clin N Am* 5:221-263, 1999.

21. Rowell, L. B. *Human Circulation: Regulation during Physical Stress*. New York, NY: Oxford University Press, 1986, pp. 243-246.

22. Sheffield. P. J. Measuring tissue oxygen tension: a review. *Undersea Hyper Med* 25:179-188, 1998.

23. Staples, J. R., D. B. Clement, J. E. Taunton, and D. C. McKenzie. Effects of hyperbaric oxygen on a human model of injury. *Am J Sports Med* 27:600-605, 1999.

24. Webster. A. L., D. G. Syrotuik, G. J. Bell, R. L. Jones, Y. Bhambhani, and M. Young. Exercise after acute hyperbaric oxygenation: Is there an ergogenic effect? *Undersea Hyper Med* 25:153-159, 1998.

25. Wells, C. H., J. E. Goodpasture, D. J. Horrigan, and G. B. Hart. Tissue gas measurements during hyperbaric oxygen exposure. In: G. Smith (Ed.) Proceedings of the sixth International Congress on Hyperbaric Medicine. Aberdeen, Scotland: Aberdeen University Press, 1977, pp. 118-124.

26. Wilson, G. D., and H. G. Welch. Effects of hyperoxic gas mixtures on exercise tolerance in man. *Med Sci Sports* 7:48-52, 1975.

27. Van der Kleij, A. J., R. Kooyman, and D. J. Bakker. Clinical value of transcutaneous PO_2 assessment during hyperbaric oxygen therapy. In: *Oxygen Transport to Tissue*

XVIII. E. M. Nemoto, and J. C. LaManna (Eds.) New York, NY: Plenum Press, 1997, pp. 113-120.

Table 1. Physical characteristics of the subjects (n=10).

Variables	Mean ± SD	Range
Age (yrs)	25.7 ± 5.5	20 – 38
Height (cm)	179.7 ± 7.5	165.0 – 194.9
Weight (kg)	76.4 ± 4.1	70.9 – 82.3
Fatness (%)	10.2 ± 2.0	5.5 – 17.4
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	57.6 ± 6.2	47.5 – 67.1

Table 2. Physiological responses during exercise tests (mean ± SD).

Variables	Baseline	Post-HBO_2
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	57.6 ± 6.2	57.3 ± 5.8
VO_{2max} ($L \cdot min^{-1}$)	4.38 ± 0.5	4.38 ± 0.5
Run Time (min)	10.1 ± 1.9	10.1 ± 1.9
HR_{max} ($beats \cdot min^{-1}$)	191 ± 10.3	189 ± 11.3
La_{max} ($mmol \cdot L^{-1}$)	8.9 ± 2.8	10.0 ± 1.9

Table 3. Venous PO_2 following HBO_2 (mean ± SD).

Time (min)	PO_2 (mm Hg)
3	18.0 ± 4.3 *
5	31.3 ± 7.9
10	37.1 ± 10.6
15	36.3 ± 6.8
20	37.3 ± 9.1
30	37.0 ± 10.2
40	36.8 ± 9.6
50	38.7 ± 15.6
60	31.7 ± 9.4

* Significantly different compared to other readings ($p<0.05$).

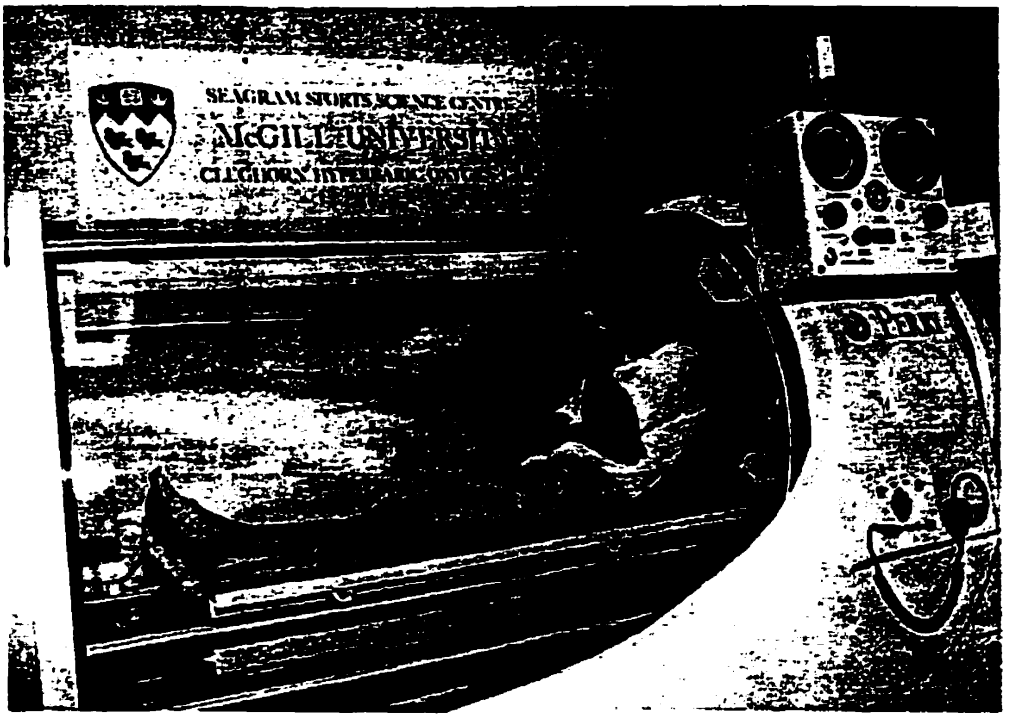
Legends for Figures 1 – 4.

Figure 1. HBO_2 Monoplace Chamber.

Figure 2. HBO_2 Protocol.

Figure 3. Venous PO_2 vs. Time.
* $p<0.05$ compared to all other values.

Figure 4. Chest and Leg $P_{tc}O_2$ During the Baseline and Post-HBO_2 Conditions vs. Time.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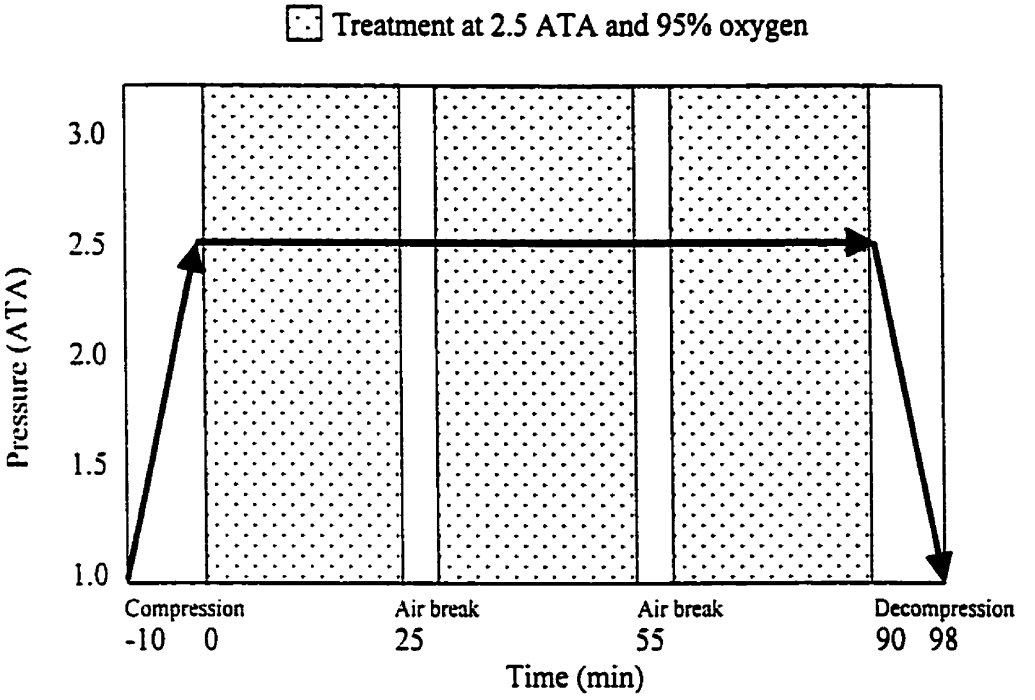
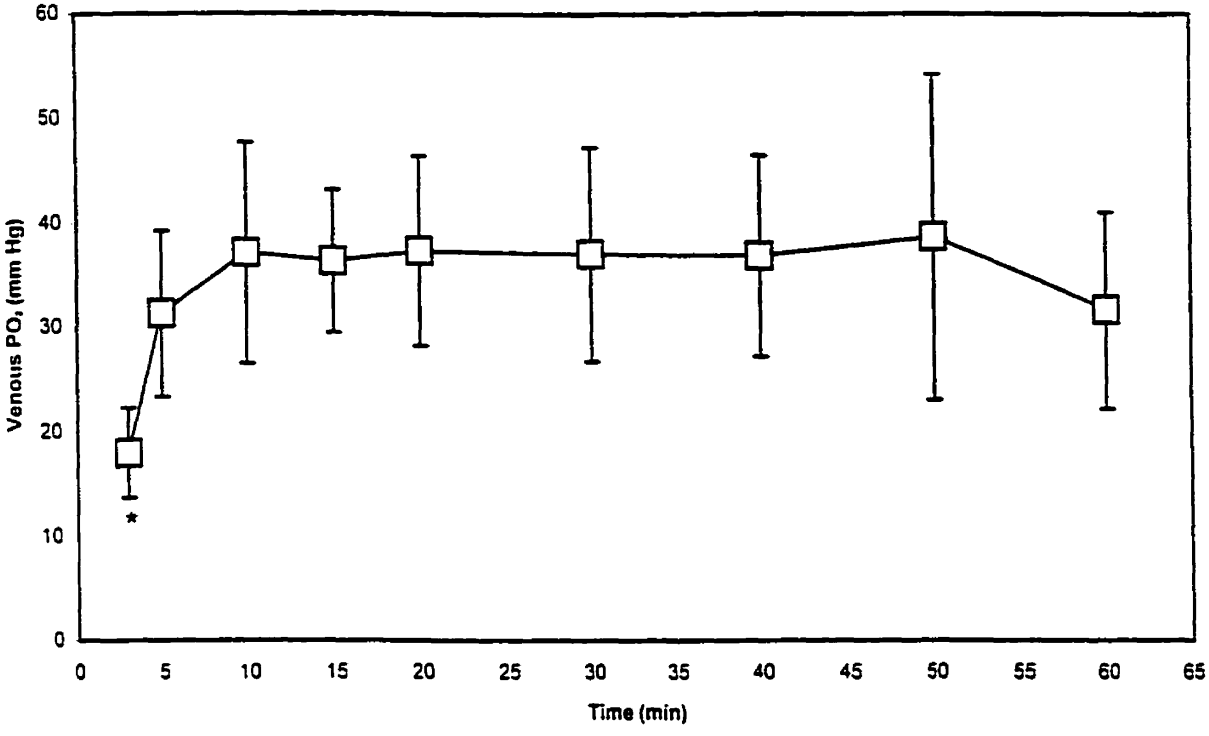
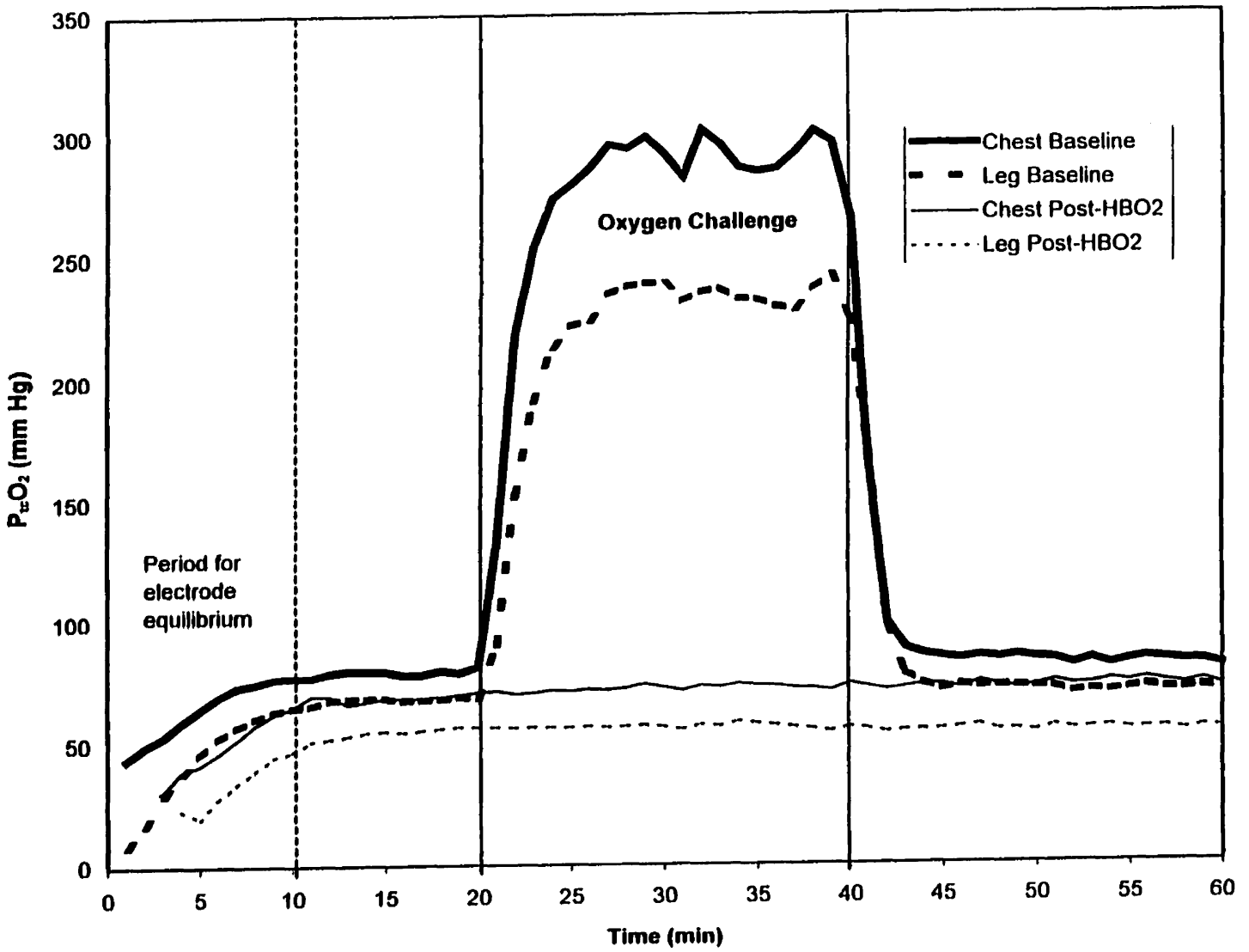

Treatment at 2.5 ATA and 95% oxygen
Pressure (ATA)
3.0
2.5
2.0
1.5
1.0
Compression
-10
0
Air break
25
Air break
55
Decompression
90
98
Time (min)


60
50
40
30
20
10
0
Venous PO_2 (mm Hg)
*
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time (min)


350
300
250
200
150
100
50
0
$P_{tc}O_2$ (mm Hg)
0
5
10
15
20
25
30
35
40
45
50
55
60
Time (min)
Period for electrode equilibrium
Oxygen Challenge
Chest Baseline
Leg Baseline
Chest Post-HBO2
Leg Post-HBO2

APPENDIX A

INTRODUCTION

Hyperbaric oxygen (HBO_2) therapy is a relatively new area of research in medicine and physiology. Hyperbaric chambers were originally introduced in the 1930s as a means of safely decompressing divers suffering from decompression sickness. Use has since expanded into the field of hyperbaric medicine. The Undersea & Hyperbaric Medical Society (UHMS) currently approves 13 medical conditions for HBO_2 treatment (Hampson, 1999).

Hyperbaric oxygen is a medical treatment in which the patient breathes 95 – 100% oxygen at a pressure greater than 1 atmosphere absolute (ATA). In recent years some professional and college athletic teams have used HBO_2 therapy not only to treat sports injuries, but also to speed recovery after exercise and as an ergogenic aid to enhance performance. Because of the importance of oxygen in the aerobic energy system, these athletes have associated HBO_2 treatments with enhanced performance. Contradictory findings have been reported in the research literature regarding the effect of a single HBO_2 treatment on aerobic performance. A small number of research investigations have examined the effect of HBO_2 on recovery from exercise with positive results by Staples (1999), while McGavock et al. (1999) found that a single HBO_2 treatment at 2.5 ATA did not enhance recovery from exercise. Regarding HBO_2 as an ergogenic aid, two studies have reported positive findings (Banister et al., 1970; Cabric et al.. 1991) and two studies have reported no benefits of HBO_2 treatments (McGavock et al., 1999; Webster et al., 1998).

It is difficult to rationalize how prior HBO_2 enhances performance. Cabric et al. (1991) suggested that oxygen might be stored within muscle tissue as an explanation for

the improved performance in their study. It has been shown, however, that tissue auto-regulation reduces oxygen levels upon return to a normobaric normoxic environment (Kelly et al., 1972).

Nature and Scope of the Problem

Oxygen availability to the skeletal muscles is of paramount importance to aerobic performance. Two factors have commonly been isolated as limiting aerobic performance: oxygen delivery to the skeletal muscles and oxygen utilization by the muscles. It is possible, therefore, that if oxygen availability were increased, maximal aerobic performance could be increased.

With use of HBO_2, the oxygen content of the blood can be increased through an increase in the partial pressure of oxygen (PO_2) in plasma. Thus more oxygen is delivered to the skeletal muscles during an HBO_2 treatment. The use of HBO_2 as an ergogenic aid to performance depends on a sustained increase in oxygen availability in the muscles following treatment.

By measuring both venous plasma PO_2 and transcutaneous tissue PO_2 ($P_{tc}O_2$), it is possible to determine how long any increase in oxygen availability is present following an HBO_2 treatment.

Significance of the Problem

There have been a large number of investigations examining the effects of increased oxygen inspiration on aerobic performance (Cunningham, 1963, Ekblom et al., 1975, Wilson et al., 1975, Adams and Welch, 1980, Welch, 1982, Knight et al., 1993,

Nielson et al., 1998, Richardson et al., 1999). There have been a number of investigations on the possibility of changed aerobic performance as a result of HBO_2 therapy (Banister et al., 1970; Kaijser, 1969; Cabric et al., 1991; Webster et al., 1998; McGavock et al., 1999). These studies have been inconclusive on the issue, and a case can still be made for an ergogenic effect following HBO_2 therapy.

Statement of the Problem

The purpose of this study is to examine venous PO_2, transcutaneous tissue PO_2 ($P_{tc}O_2$), and VO_{2max} in a normobaric environment following a single hyperbaric oxygen treatment. The study is designed to answer three questions. Does a single HBO_2 treatment at 2.5 ATA for 90 minutes: 1) elevate venous PO_2; 2) elevate $P_{tc}O_2$; and 3) elevate VO_{2max}, in a normobaric normoxic environment. The following hypotheses were proposed:

1. Following a single HBO_2 treatment, venous PO_2 will return to normal values within 60 minutes.
2. There will be no significant increase in performance (VO_{2max}) following an HBO_2 treatment.
3. $P_{tc}O_2$ will be elevated following an HBO_2 treatment and will return to normal values within 60 minutes following the HBO_2 treatment.

Operational Definitions and Abbreviations

HBO_2 - hyperbaric oxygen is defined as breathing 95 – 100 % oxygen at a pressure greater than 1 atmosphere absolute

ATA	- atmosphere absolute: a measure of the barometric pressure (1 ATA = 760 mm Hg)
VO_{2max}	- a measure of the maximal oxygen consumption of a subject, measured in $mL \cdot kg^{-1} \cdot min^{-1}$
PO_2	- partial pressure of oxygen
P_aO_2	- partial pressure of oxygen in the arteries
P_aCO_2	- partial pressure of carbon dioxide in the arteries
P_AO_2	- partial pressure of oxygen in the alveoli
$P_{tc}O_2$	- partial pressure of oxygen in the tissue measured with a transcutaneous monitor
S_aO_2	- arterial oxygen saturation of hemoglobin
C_aO_2	- blood oxygen content
F_IO_2	- inspired oxygen content
Peak La	- the blood lactate concentration taken after 4 minutes of recovery following completion of a VO_{2max} test

Limitations

This study has a number of limitations:

1. Due to the nature of the equipment available, it was not possible to measure venous blood PO_2 while in the hyperbaric chamber. There was a minimal time delay in obtaining the venous blood samples after decompressing the chamber.
2. Blood lactate analysis was only possible at the end of the VO_2max test. In order to measure blood lactates during the test, the test would have to be discontinuous. This

means that only maximal lactate can be compared pre- and post-treatment rather than comparing lactate values at various work levels.

3. Due to the nature of the transcutaneous monitor, there was a delay of approximately 10 minutes following HBO_2 treatment to obtain the first measurement of tissue PO_2.

Delimitations

It was necessary to delimit this investigation in a number of ways:

1. The study was limited to male subjects. This allowed the use of one test protocol for comparison of VO_2max values. Males were chosen over females due to the nature of subjects available to the investigators.
2. Subjects were between 20 and 38 years of age.

APPENDIX B

REVIEW OF LITERATURE

Introduction

Hyperbaric oxygen (HBO_2) therapy is the condition of breathing 95-100% oxygen in a chamber at higher than sea level pressure (> 1 atmosphere absolute, ATA). Generally, pressurization should be 1.4 ATA or higher to have a therapeutic effect. (Hampson, 1999). HBO_2 therapy was originally introduced in the 1930s as a means to safely decompress divers and treat decompression sickness. Presently, The Undersea and Hyperbaric Medical Society (UHMS) has approved HBO_2 for the following 13 uses (Hampson, 1999):

1. Air or gas embolism
2. Carbon monoxide poisoning
3. Clostridial myositis and myonecrosis
4. Crush injury, compartment syndrome and other acute traumatic ischemias
5. Decompression sickness
6. Enhancement of healing in selected problem wounds
7. Exceptional blood loss (anemia)
8. Intracranial abscess
9. Necrotizing soft tissue infections
10. Osteomyelitis
11. Delayed radiation injury
12. Skin grafts and flaps
13. Thermal burns

The majority of studies in the literature involving HBO_2 concern patients with these conditions. The use of HBO_2 in sports circles has generally been limited to injury

healing. Although the effectiveness of HBO_2 as a treatment for sports injuries remains somewhat inconclusive (Borromeo et al., 1997; Staples et al., 1999), it is a common practice among many collegiate and professional sports teams to treat a wide range of soft tissue injuries with HBO_2 therapy. Use of HBO_2 as an ergogenic aid comprises a very small component of the literature, but a few studies have been done (Kaijser, 1969, Banister et al., 1970, Cabric et al., 1991, Webster et al., 1998, and McGavock et al., 1999).

Since most of the research on HBO_2 involves injuries and medical conditions, the majority of studies concerning HBO_2 and in vivo oxygen measurement deal with tissue oxygenation around a wound site, rather than arterial blood oxygenation. This review examines the principles of HBO_2 regarding the assessment of blood gases, the assessment of tissue oxygenation through transcutaneous monitoring, and the issue of HBO_2 use in sports as an ergogenic aid.

Blood Gas Physiology and Blood Gas Analysis

Principles of HBO_2 and Blood Gas Physiology

Oxygen transport in the blood occurs in one of two ways: attached to hemoglobin (Hb) or dissolved in the plasma. Under normal conditions, 97% of blood oxygen content is bound to hemoglobin while only 3% is dissolved in the plasma. Blood oxygen content (C_aO_2) is calculated by:

C_aO_2 = (Hemoglobin oxygen content) + (dissolved oxygen content)

$C_aO_2 = (1.34 \times Hb \times S_aO_2) + (0.003 \times P_aO_2)$

C_aO_2 = {(1.34 mL O_2 / g Hb x 15 g / 100 mL blood) x 0.98}

+ (0.003 mL O_2 / mm Hg x 100 mm Hg)

C_aO_2 = 19.7 mL O_2 / 100 mL blood + 0.3 mL O_2 / 100 mL blood

= 20.0 mL of O_2 / 100 mL blood

where: Hb = Hemoglobin concentration (15 g / 100 mL blood)

S_aO_2 = arterial O_2 saturation of hemoglobin (98%)

P_aO_2 = partial pressure of oxygen in arterial blood (100 mm Hg)

1.34 = volume (mL) of oxygen bound to 1g of hemoglobin

Gases dissolve according to Henry's law: 'the quantity of a gas that can dissolve in a fluid is equal to the product of the gas partial pressure and the solubility coefficient.' The solubility coefficient for oxygen is 0.00003 mL O_2 / mL blood / mm Hg. Therefore the dissolved oxygen content of blood is (0.003 mL O_2 / 100 mL blood x P_aO_2). In arterial blood, P_aO_2 is 100 mm Hg, so the dissolved oxygen content is 0.3 mL O_2 / 100 mL blood.

Under normal sea level conditions, the oxygen content of air is 20.93% and the barometric pressure is 760 mm Hg. The partial pressure of oxygen in ambient air is therefore 160 mm Hg. The partial pressure of oxygen in arterial blood (P_aO_2) is 100 mm Hg. With hemoglobin concentration of 15 g / 100 mL blood, the oxygen content of arterial blood under normobaric conditions is 20 mL O_2 / 100 mL blood.

During HBO_2 therapy, barometric pressure may reach 3 atmospheres absolute (ATA) or 2280 mm Hg. The inspired air in the chamber typically contains 95 – 100% oxygen. Under these conditions, the partial pressure of oxygen in the chamber is 2160

mm Hg. This combination of increased pressure and oxygen results in more dissolved oxygen in the plasma. P_aO_2 is calculated by:

$P_aO_2 = \{(P_{BTPS} \text{ X } F_iO_2) - (P_aCO_2 / R)\}$

$P_aO_2 = [\{(3 \text{ ATA x } 760) - 47 \text{ mm Hg}\} \text{ x } 0.95] - (40 \text{ mm Hg} / 0.82)$

$P_aO_2 = 2121 - 49 = 2072$ mm Hg

where: P_{BTPS} = Pressure at body temperature pressure saturated

F_IO_2 = fraction of oxygen in inspired air

P_aCO_2 = partial pressure of CO_2 in arterial blood (mm Hg)

R = respiratory exchange ratio at rest

Direct measures of arterial PO_2 at 2.0 and 3.5 ATA have been found to be 1356 and 2448 m Hg respectively (Clark and Lambertson, 1971). Interpolation of these data to 2.5 ATA yields a value of 1720 mm Hg.

Under these hyperbaric conditions, the dissolved oxygen content is increased 20 fold from 0.3 to 6.2 mL / 100 mL blood and oxygen content of the blood is increased from 20.0 to 25.9 mL O_2 / 100 mL blood:

$C_aO_2 = (1.34 \text{ mL } O_2 / \text{g Hb}) \text{ x } (15 \text{ g} / 100 \text{ mL blood}) + (0.003 \text{ x } 2072 \text{ mm Hg})$

$C_aO_2 = 19.7 + 6.2 = 25.9$ mL of O_2 / 100 mL blood

The significance of increased oxygen dissolved in the plasma has been shown experimentally in animals whose entire blood volume has been replaced with Ringer's lactate (Boerema et al., 1960). These animals can survive in an HBO_2 environment based solely on the oxygen dissolved in the solution (with no hemoglobin).

As a result of the increase in P_aO_2 during a HBO_2 treatment, the hemoglobin is still fully saturated with oxygen on the venous side (Hammarlund, 1999). Paradoxically, the increase in oxygen saturation on the venous side may be the cause of complications from oxygen toxicity during HBO_2 therapy. As a result of the oxygen-saturated hemoglobin in the venous blood, carbon dioxide cannot easily bind to hemoglobin for removal from the tissues.

PO_2 at the end-capillary level drives oxygen diffusion to the cell and mitochondria (Robertson and Hart. 1999). End-capillary PO_2 depends on cardiac output, perfusion, and arterial oxygen content. Data obtained from arterial blood gas analysis (P_aO_2) provide information on pulmonary gas exchange. HBO_2 therapy causes an increase in P_aO_2.

It is the increase in dissolved oxygen that provides the interest in HBO_2 as an ergogenic aid. Depending on the time frame with which the P_aO_2 returns to normal, it is hypothesized that the elevated oxygen level in the blood and tissues may enhance aerobic performance.

Blood Gas Analysis

Blood gas analyzers are instruments capable of measuring blood parameters such as P_aO_2, P_aCO_2, and pH. The P_aO_2 electrode is a polarographic device that measures oxygen tension through a chemical process that generates electric currents (oxidation-reduction reactions). Williams (1998) provides normal adult values for P_aO_2 and oxygen saturation (Table 2.1).

Table 2.1: Adult values for P_aO_2 and oxygen saturation.

	P_aO_2 (kPa)	P_aO_2 (mm Hg)	S_aO_2 (%)
Normal	13 (> 10.7)	98 (> 80)	97 (95 - 100)
Hypoxemia	< 10.7	< 80	< 95
Mild hypoxemia	8 - 10.5	60 - 79	90 - 94
Moderate hypoxemia	5.3 - 7.9	40 - 59	75 - 89
Severe hypoxemia	< 5.3	< 40	< 75

According to Weaver and Howe (1992) a blood gas analyzer, such as the Radiometer ABL330, can be used to accurately measure P_aO_2 in subjects receiving HBO_2. In this study 10 subjects received HBO_2 conditions of 100% oxygen and up to 2.9 ATA. The subjects had a catheter placed in the brachial artery (inserted through the radial artery) to allow monitoring of P_aO_2. Results showed that the values for P_aO_2 correlated strongly with the calculated alveolar oxygen tension (P_AO_2) ($r = 0.97$). The authors concluded that the P_aO_2 of normal subjects exposed to HBO_2 could be accurately measured at atmospheric pressure with this particular automated blood gas analyzer.

Beaulieu et al. (1999) examined the stability of PO_2 in fresh blood samples. In this study, whole blood samples were obtained from patients and stored either on ice (124 samples) or at room temperature of 22°C (64 samples). Initial measurement of blood gas parameters (PO_2, PCO_2, and pH) was taken within 30 minutes of sampling. Blood gas parameters were measured again at 15, 30, and 60 minutes after the initial measurements for the samples stored at 22°C, and at 30, 60, and 120 minutes for the samples stored on ice. It was found that PO_2 decreased significantly ($p < 0.001$) over time in the samples stored at 22°C, and increased significantly ($p \leq 0.005$) for the samples stored on ice. The changes in PO_2 were also much greater for the samples stored at 22°C than for those on

ice. The authors concluded that blood gas parameters are more stable when the samples are stored on ice than at room temperature.

Transcutaneous PO_2 and Oximetry

Assessment of tissue oxygen tension is a means of determining the amount of oxygen present in the tissue. HBO_2 therapy produces a higher level of tissue oxygenation than normal conditions and, therefore, tissue PO_2 assessment is an important part of HBO_2 therapy. In this study, the purpose of assessing tissue PO_2 was to determine how quickly levels returned to normal, and the similarity of tissue PO_2 to arterial blood PO_2 following HBO_2 therapy. Methods presently used to assess tissue oxygenation are mass spectroscopy, tissue tonometry, blood gas analysis, invasive polarographic electrodes, and transcutaneous oximetry.

Transcutaneous oximetry, which was the method of tissue oxygen assessment used in this study, was developed as a non-invasive method to measure tissue oxygen tension by Huch et al. (1972). It is used as a tool to predict candidates for HBO_2, to identify the presence of hypoxia in wounded tissues, to predict the response to hyperoxia, and to determine when HBO_2 therapy is complete (Sheffield, 1998). Transcutaneous oximetry is frequently used to assess tissue oxygenation because it is a non-invasive and relatively simple method (van der Kleij, 1997).

According to Robertson and Hart (1999), Clark built the first electrochemical sensor that allowed measurement of PO_2 in the blood in 1954. The Clark electrode is composed of a platinum or gold cathode and a silver anode in an electrolyte solution (potassium chloride). A constant polarizing electric current of 600 to 800 mV is applied

to the cathode. An oxygen permeable but water impermeable membrane separates the electrodes from the tissue (human skin). Oxygen diffuses into the Clark electrode and generates an electric current proportional to PO_2 as it is reduced. To measure $P_{tc}O_2$, Huch et al. (1972) modified a Clark electrode with a heating element and thermistor to maintain a set temperature of 42°C – 45°C. The electrode is attached to the skin with a fixation ring filled with saline. Heating the electrode causes dilation of the capillaries, opening of skin pores, a decrease in oxygen solubility, and shifts the oxyhemoglobin curve to the right allowing oxygen to be released from hemoglobin more easily.

Sheffield (1998) has reviewed the measurement of tissue oxygen levels. According to this article, transcutaneous oximetry was originally developed for use in pediatrics, and is now commonly used in plastic surgery, vascular surgery, anesthesiology, orthopedics, and hyperbaric medicine.

One of the major uses of transcutaneous oximetry is in wound healing. Studies of ischemic wounds have revealed that many problem wounds (non-healing wounds) are severely hypoxic, and that HBO_2 enhances oxygenation to normal levels. Six specific findings were summarized (Sheffield 1998):

1. Problem wounds have low PO_2.
2. Wounds respond to oxygen.
3. Wound PO_2 has minute to minute variability.
4. HBO_2 elevates wound PO_2.
5. Multiple HBO_2 exposures increase wound response.
6. Irradiated tissue responds to HBO_2 like a wound.

HBO_2 increases wound healing by increasing tissue oxygenation.

Sheffield (1998) states that measurement of tissue PO_2 provides a direct assessment of the oxygen available to the tissues, and the most common use of $P_{tc}O_2$ measurement is for medical purposes. Tissue oximetry has gained importance in three areas: 1) determining candidate patients for HBO_2; 2) in predicting non-responders to HBO_2; and 3) to choose amputation sites.

Transcutaneous tissue PO_2 ($P_{tc}O_2$) values above 30 – 40 mm Hg are generally required for wound healing. According to a study by Wyss et al. (1984), patients with leg and foot $P_{tc}O_2$ values below 20 mm Hg were significantly more likely to have ulcers, pain, and amputation than those with values above 20 mm Hg. Matos and Nunez (1994) concluded that transcutaneous oxygen measurement was the best method available to determine the need for HBO_2.

In addition to wound treatment, transcutaneous oxygen measurement can be used to assess the level of tissue oxygenation during or following HBO_2 in healthy subjects. Sheffield and Workman (1983) reported the first known $P_{tc}O_2$ data recorded under hyperbaric conditions. Values above 1,000 mm Hg were recorded in both healthy subjects and patients. A normal value for $P_{tc}O_2$ cannot be specified due to variations in arterial PO_2, type of tissue, inter-capillary distance, and cellular metabolic rate. In normobaric conditions, ideal arterial PO_2 is typically 100 mm Hg with $P_{tc}O_2$ ranging from 49 – 69 mm Hg. Under HBO_2 conditions (100% O_2 and 2.4 ATA), arterial PO_2 increases to 1,700 mm Hg with $P_{tc}O_2$ ranging from 919 – 1,350 mm Hg (Sheffield, 1998).

Transcutaneous oximetry requires careful planning to ensure reproducibility. According to Sheffield (1998) the following factors must be considered prior to collection of $P_{tc}O_2$ data:

1. The method of assessment: The researcher must decide which, and how many sites to assess.
2. Selection of the monitor: Several manufacturers make sensors that can be used in the assessment of $P_{tc}O_2$.
3. Calibration of the monitor: Calibrations and corrections for ambient temperature and pressure must be made prior to collection.
4. Selection of sensor temperature: Changes in skin temperature cause physiological changes (opening of pores, dilation of capillaries, increased skin perfusion, and release of oxygen from hemoglobin) that will create changes in the assessment that do not necessarily reflect a true change in the tissue PO_2.
5. Standardized site of measurement: There should be a standard approach to positioning the sensor.
6. Site preparation for electrode placement: The site should be shaved, clean, and stripped of dead skin. The site should not overlie a bony prominence or superficial vessels.

It appears that when these factors are considered, there is a close correlation between arterial PO_2 measured invasively and $P_{tc}O_2$. Huch et al. (1977) measured the arterial PO_2 and $P_{tc}O_2$ of 7 subjects while exposed to HBO_2 conditions. They found that calculated chamber PO_2 correlated well with arterial PO_2 ($r = 0.98$), and also with $P_{tc}O_2$ ($r = 0.97$).

Exercise Performance & HBO_2: An Ergogenic Aid

Aerobic performance is limited by the ability to consume oxygen. By definition, maximal aerobic performance (VO_{2max}) is a measure of oxygen consumption. There are two limits to oxygen consumption : delivery of oxygen to the tissues (central factors), and use of oxygen by the tissues (peripheral factors). This is summarized by the Fick equation for oxygen consumption :

VO_2 = (Heart Rate x Stroke Volume) x (a – vO_2difference) (Wilmore and Costill, 1994).

where : heart rate and stroke volume = central factors

a – vO_2difference = peripheral factors.

The following evidence indicates that central factors of oxygen delivery can limit maximal oxygen uptake. In this case, an increase in oxygen delivery to the tissues through increased PO_2 in the blood could lead to increased performance.

According to Astrand and Rodahl (1977), one of the limits to aerobic performance is the ability of the body to deliver fuel and oxygen to the working muscle fibre. When exercise workload increases, the active tissues require more oxygen. As a result, endurance abilities depend on the ability of the circulatory system to deliver oxygen to the tissues (Wilmore and Costill, 1994). Richardson et al. (1999) attempted to answer the question of whether maximal exercise is dependant on oxygen supply. Seven trained subjects performed knee extension exercises while breathing three different oxygen concentrations (12%, 21%, and 100%). It was found that maximal oxygen delivery, maximal work rate, and VO_2 all increased with the inspired oxygen concentrations

($p < 0.05$). The authors concluded that, in isolated knee extension exercise, muscle VO_{2max} is not limited by mitochondrial metabolic rate but by oxygen supply.

In a study by Nielson et al. (1998), eleven trained male subjects exercised (Concept II rowing ergometer) at different intensities while breathing ambient air and 30% oxygen. It was found that VO_{2max} was increased by 11% while breathing 30% oxygen. Other maximal exercise measures (pH, lactate, and heart rate) were not changed with increased inspired oxygen content (F_IO_2). Adams and Welch (1980) performed a study in which six male subjects (18 – 28 years) rode a bicycle ergometer to exhaustion breathing F_IO_2 of 0.17, 0.21, and 0.60. There was a significant ($p < 0.05$) increase in performance in the hyperoxic condition compared to the normoxic. VO_{2max}, however, showed no significant ($p < 0.05$) change in either the hyperoxic or hypoxic conditions compared to the normoxic condition. In a study of 12 male subjects (21 – 36 years) Knight et al. (1993) showed a significant ($p < 0.05$) increase in leg VO_{2max} when working on a cycle ergometer in a hyperoxia ($F_IO_2 = 1.0$) environment when compared to a normoxic ($F_IO_2 = 0.21$) environment.

While evidence in the literature indicates that central factors can limit performance, peripheral factors can also act as a limit. In this case increased oxygen delivery to the tissues does not aid aerobic performance.

There is evidence in the literature that breathing an increased fraction of oxygen (F_IO_2) can result in increased aerobic performance (Richardson et al., 1999; Nielson et al.. 1998). The cases of breathing increased F_IO_2 under hyperbaric conditions during exercise and before exercise remain less clear. Kaijser (1970) concluded that breathing oxygen at 3 ATA did not significantly increase maximal aerobic work performance.

Twelve young (18 – 25 years) male subjects performed 5 minutes of exercise at a submaximal load followed by 10 minutes of rest and then worked to exhaustion while breathing oxygen at 3 ATA or while breathing air at 1 ATA.

Welch (1982) reviewed the difference between performance changes due to hyperoxia and due to hyperbaric oxygenation. Welch (1982) defined hyperoxia as the condition in which the inspired oxygen pressure is greater than that of sea level, but at a pressure not more than 1 ATA. Hyperbaric oxygenation is the condition produced by breathing gas in which the partial pressure of oxygen is greater that that of 100% oxygen at sea level. Welch (1982) demonstrated that the effects on performance are different for hyperoxic and hyperbaric oxygenation conditions. An increase in ambient pressure (of up to 6 ATA) decreases performance (while under pressure), while an increase in F_IO_2 increases performance. Welch (1982) suggested 5 possible mechanisms for increased performance with hyperoxia:

1. *Maximal oxygen uptake.* An increase in VO_{2max} with hyperoxia should not be expected to exceed 5 – 6%. Higher values than this are likely the result of measurement error (mixing chamber vs Douglas Bag).
2. *Cardiovascular adjustments during hyperoxia.* There is no evidence of a difference in cardiac output or maximal heart rate during hyperoxia. There is some evidence, however, of a reduction in blood flow to the active muscle. It is not clear that oxygen availability is increased during hyperoxia.
3. *Metabolic responses.* It has been shown that blood lactate concentration is decreased during exercise with hypoxia. There is also some evidence of a shift toward increasing fat oxidation as a fuel in this condition.

4. *Pulmonary ventilation.* Pulmonary ventilation is reduced during moderate to severe exercise with hyperoxia, and there is a greater effect with higher F_IO_2.
5. *Acid-base changes.* Arterial hydrogen ion concentration [H^+] can be changed during exercise in hypoxic and hyperoxic conditions as a result of both respiratory and metabolic responses.

The previous evidence of changes due to hyperoxic conditions are relevant for HBO_2 therapy. An increase in performance might be possible through the use of HBO_2 if the PO_2 in the blood remains elevated following treatment. The use of HBO_2 as a successful ergogenic aid would involve a treatment followed by increased aerobic performance in a normobaric, normoxic environment. It is hypothesized that HBO_2, which results in increased arterial blood oxygen content, may lead to increased aerobic performance through an increase in oxygen delivery. It has also been proposed that HBO_2 therapy may result in a decreased lactate formation during subsequent exercise (Kaijser, 1969, and Banister et al., 1970), allowing a subject to perform at a higher exercise intensity.

The literature on HBO_2 therapy as an ergogenic aid is inconclusive. In a study by Kaijser (1969) six male subjects performed dynamic forearm exercise with a hand ergometer under normal conditions and under HBO_2 conditions of 100% oxygen and 3 ATA. The subjects worked at 3 work intensities (the highest being a supramaximal intensity), while arterial and venous blood was sampled for PO_2, PCO_2, pH, lactate and pyruvate concentrations. Performance times for the submaximal exercise were increased for 3 subjects under HBO_2 conditions, but unchanged for 3 subjects. There was no significant difference in the average performance time. Maximal oxygen uptake in active

muscles was not increased when arterial oxygen content was increased. There was a significantly ($p < 0.01$) lower lactate concentration for exercise at 100% of VO_{2max} under HBO_2 than under normal conditions.

Banister et al. (1970) studied 2 subjects performing severe exercise under normal and HBO_2 conditions. Lactate levels in venous blood were lower, for the same exercise, in HBO_2 than in normal conditions. This effect was also evident during exercise in normal conditions following HBO_2.

Subjects in a study by Cabric et al. (1991) showed significantly ($p<0.05$) higher VO_{2max}, and were capable of sustaining higher exertion following HBO_2 therapy than during baseline tests. Eighteen female physical education students performed a discontinuous maximal treadmill test prior to HBO_2 therapy. The treatment consisted of 60 minutes breathing 100% oxygen in a multiplace chamber with the pressure at 2.8 ATA. Three groups of six subjects performed the same treadmill tests 30 minutes, 3 hours, and 6 hours post-treatment. Significantly ($p < 0.05$) higher values were obtained for VO_{2max} and exertion intensity (as measured by treadmill velocity) for tests performed 30 minutes and 3 hours post-treatment. However, there was no control group in this study.

Two recent studies, however, show no changes in submaximal or maximal performance following HBO_2. In a study by Webster et al. (1998), twelve cyclists underwent two baseline maximal Monark cycle ergometer tests ten and four days, respectively, before HBO_2 therapy. A third maximal test was performed as soon as possible post-treatment. Treatment consisted of 100% oxygen at 2 ATA in a monoplace chamber for 60 minutes. No significant ($p < 0.05$) differences were shown for VO_{2max},

ventilatory threshold, lactate threshold, maximal ventilation or maximal heart rates. McGavock et al. (1999) showed similar findings. Six male and six female subjects underwent a baseline test of running economy and maximal oxygen uptake. Each subject underwent four conditions, two of which involved HBO_2 therapy followed by running economy and VO_{2max} tests. There were no significant differences in running economy or VO_{2max} between the two conditions involving HBO_2 therapy and the baseline condition. There was, however, a 40-minute delay between HBO_2 therapy and exercise testing due to neuropsychological testing.

After reviewing the literature concerning HBO_2 and ergogenic effects during aerobic performance, it is clear that aerobic performance can be enhanced by oxygen in some conditions. It is not clear, however, whether hyperbaric oxygenation enhances aerobic performance in a normobaric environment.

APPENDIX C

CONCLUSIONS

Cabric et al. (1991) demonstrated an increase in performance following a single HBO_2 treatment. Webster et al. (1998) and McGavock et al. (1999) showed no such increase in performance following HBO_2.

With the exception of the value at 3 min post-HBO_2, there was no significant difference ($p<0.05$) between venous PO_2 values during the 60 min post-HBO_2. There was a significant difference ($p<0.05$) between baseline and post-HBO_2 $P_{tc}O_2$ data in the leg but not in the chest. For both the venous PO_2 data and the $P_{tc}O_2$ data, the only significant differences were lower values, which indicates that no excess oxygen was available to the muscle after the HBO_2 treatment. No significant difference ($p<0.05$) was found between baseline and post-HBO_2 VO_{2max}, running time, and peak La. This indicates that the HBO_2 treatment had no ergogenic effect on performance.

In conclusion, the results of this study show that a single HBO_2 treatment at 2.5 ATA for 90 min does not elevate venous PO_2, $P_{tc}O_2$, or VO_{2max} in a normobaric, normoxic environment. The results support the findings by Webster et al. (1998) and McGavock et al. (1999) that there is no ergogenic effect on performance following a single HBO_2 treatment.

APPENDIX D

REFERENCES

Adams, R. P., and H. G. Welch. Oxygen uptake, acid-base status, and performance with varied inspired oxygen fractions. *J Appl Physiol* 49(5):863-868, 1980.

Astrand, P. O., and K. Rodahl. Textbook of work physiology: physiological bases of exercise (2nd Ed.) New York, NY: McGraw – Hill, 1977 pp. 451.

Banister, E. W., J. E. Taunton , T. Patrick, P. Oforsagd, and W. R. Duncan. Effect of oxygen at high pressure at rest and during severe exercise. *Respir Physiol* 10:74-84, 1970.

Beaulieu, M., Y. Lapointe, and B. Vinet. Stability of PO_2, PCO_2, and pH in fresh samples stored in plastic syringe with low heparin in relation to various blood-gas and hematological parameters. *Clin Biochem* 32(2):101-107, 1999.

Boerema, R., N. G. Meyne, and W. K. Brummerlkamp. Life without blood: a study of high atmospheric pressure and hypothermia on dilution of blood. *J Cardiovasc Surg* 1:161-164. 1960.

Borromeo, C. N., J. L. Ryan, P. A. Marchetto, R. Peterson, and A. A. Bove. Hyperbaric oxygen therapy for acute ankle sprains. *Am J Sports Med* 25(5):619-625, 1997.

Cabric, M., R. Medved, P. Denoble, M. Zivkovic, and H. Kovacevic. Effect of hyperbaric oxygenation on maximal aerobic performance in a normobaric environment. *J Sports Med Phys Fitness* 31:362-366, 1991.

Clark, J. M., and C.J. Lambertsen. Alveolar-arterial O_2 differences in man at 0.2, 1.0, 2.0, and 3.5 Ata inspired PO_2. *J Appl Physiol* 50(5):753-763, 1971.

Cunningham, D. A. Effects of breathing high concentrations of oxygen on treadmill performance. *Res Q* 37:491-494, 1966.

Ekblom, B., R. Huot, E. M. Stein, and A. T. Thorstensson. Effect of changes in arterial oxygen content on circulation and physical performance. *J Appl Physiol* 39:71-75, 1975.

Hammarlund, C. The physiological effects of hyperbaric oxygenation. In: *Hyperbaric Medicine Practice* (2nd ed.). E. P. Kindwall, and H. T. Whelan. Flagstaff, AZ: Best Publishing Company, 1999, pp. 39.

Hampson, N.B. (ed.). *Hyperbaric Oxygen Therapy: 1999 Committee Report.* Kensington, MD: Undersea and Hyperbaric Medical Society, 1999, pp. 1-74.

Huch, A., R. Huch, G. Hollmann, T. Hockerts, H. P. Keller, D. Seiler, J. Sadzek, and D. W. Lubbers. Transcutaneous PO_2 of volunteers during hyperbaric oxygenation. *Biotelemtr* 4(2):88-100, 1977.

Huch, R., D. W. Lubbers, and A. Huch. Quantitative continuous measurements of partial oxygen on the skin of adults and newborn babies. *Pflueg Arch* 337:185-198, 1972.

Kaijser. L. Physical exercise under hyperbaric oxygen pressure. *Life Sci* 8(1):929-934, 1969.

Kaijser. L. Limiting factors for aerobic muscle performance. Chapter IV: Adaptation to exercise during oxygen breathing to 3 atmospheres. In *Acta Physiol Scand* (suppl.) 346:29-58. 1970.

Kelly, D. L., K. R. Lassiter, A. Vongsvivut, and J. M. Smith. Effects of hyperbaric oxygenation and tissue oxygen studies in experimental paraplegia. *J Neurosurg* 36:425-429. 1972.

Knight, D. R., W. Schaffartzik, D. C. Poole, M. C. Hogan, D. E. Bebout, and P. D. Wagner. Effects of hyperoxia on maximal leg O_2 supply and utilization in men. *J Appl Physiol* 75(6):2586-2594, 1993.

Matos, L. A., and A. A. Nunez. Enhancement of healing in selected problem wounds. In: *Hyperbaric Medicine Practice*. E. P. Kindwall (ed.). Flagstaff, AZ: Best Publishing Company, 1994, pp. 589-612.

McGavock. J. M., J. L. Lecomte, J. S. Delaney, V. J. Lacroix, P. Hardy, and D. L. Montgomery. Effects of hyperbaric oxygen on aerobic performance in a normobaric environment. *Undersea Hyper Med* 26(4):219-224, 1999.

Nielson. H. B., P. Madsen, L. B. Svendsen, R. C. Roach, and N. H. Secher. The influence of P_aO_2, pH, and S_aO_2 on maximal oxygen uptake. *Acta Physiol Scand* 164:89-97. 1998.

Richardson, R. S., B. Grassi, T. P. Gavin, L. J. Haseler, K. Tagore, J. Roca, and P.D. Wagner. Evidence of O_2 supply-dependant VO_{2max} in the exercise-trained human quadriceps. *J Appl Physiol* 86(3):1048-1053, 1999.

Robertson. P. W. and B. B. Hart. Assessment of tissue oxygenation. *Respir Care Clin N Am* 5(2):221-263, 1999.

Sheffield. P. J. Measuring tissue oxygen tension: a review. *Undersea Hyper Med* 25(3):179 – 188. 1998.

Sheffield, P. J., and W. T. Workman. Transcutaneous tissue oxygen monitoring in patients undergoing hyperbaric oxygen therapy. In : *Continuous Transcutaneous Blood Gas Monitoring*. R. Huch, and A. Huch. (Eds.) New York, NY: Marcel Dekker, 1983, pp. 655-660.

Staples, J. R., D. B. Clement, J. E. Taunton, and D. C. McKenzie. Effects of hyperbaric oxygen on a human model of injury. *Am J Sports Med* 27(5):600-605, 1999.

Van der Kleij, A. J., R. Kooyman, and D. J. Bakker. Clinical value of transcutaneous PO_2 assessment during hyperbaric oxygen therapy. In: *Oxygen Transport to Tissue XVIII*. E. M. Nemoto, and J. C. LaManna (Eds.) New York, NY: Plenum Press, 1997, pp. 113-120.

Weaver, L. K., and S. Howe. Normobaric measurement of arterial oxygen tension in subjects exposed to hyperbaric oxygen. *Chest* 102(4):1175-1181, 1992.

Webster, A. L., D. G. Syrotuik, G. J. Bell, R. L. Jones, Y. Bhambhani, and M. Young. Exercise after acute hyperbaric oxygenation: Is there an ergogenic effect? *Undersea Hyper Med* 25(3):153-159, 1998.

Welch, H. G. Hyperoxia and human performance: a brief review. *Med Sci Sports Exerc* 14(4):253-262, 1982.

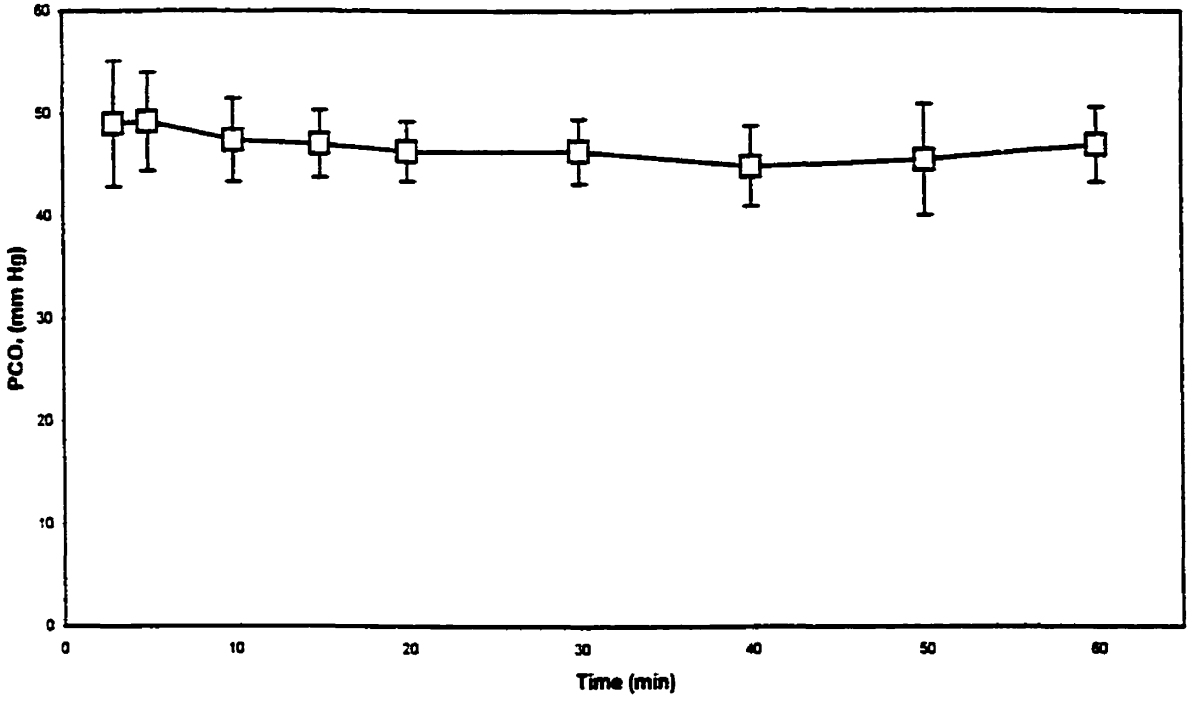
Williams, A. J. ABC of oxygen: Assessing and interpreting arterial blood gases and acid-base balance. *Br Med J* 317:1213-1215, 1998.

Wilmore, J.H., D. L. Costill. *Physiology of Sport and Exercise*. Champaign, IL: Human Kinetics, 1994, pp. 217-238.

Wyss, C. R., F. A. Matsen III, C. W. Simmons, and E. M. Burgess. Transcutaneous oxygen measurements on limbs of diabetic and nondiabetic patients with peripheral vascular disease. *Surg* 95:339-346, 1984.

APPENDIX E

POST-HBO_2 PCO_2 VS. TIME


60
50
40
30
20
10
0
PCO2 (mm Hg)
0
10
20
30
40
50
60
Time (min)

APPENDIX F

ETHICS APPROVAL

McGill

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December 14, 1999

Dr. David Montgomery
Physical Education
475 Pine Avenue West
Montreal, Quebec

Dear Dr. Montgomery,

The research proposal A00-M75-99 entitled **"Effect of Hyperbaric Oxygen on Plasma PO_2 , Transcutaneous PO_2, and VO_2 max in a Normobaric Environment"** as amended in your letter of November 30, 1999 was further reviewed by the Institutional Review Board, Faculty of Medicine at its meeting of December 13, 1999.

The responses and changes were found to be acceptable and we are pleased to inform you that approval for the study, amended November 30, 1999 so **that blood samples be obtained only by an intravenous catheter,** and revised consent document (November 30, 1999) was provided on December 14, 1999, valid until December 2000. The original certification of approval (executed) has been enclosed.

It is the responsibility of the investigator to assure that the approved research protocol and consent form is deposited with the Research Ethics Board of each hospital where patient recruitment or study data will be collected.

We ask you to take note that review of all research involving human subjects is required on an annual basis in accord with the date of initial approval. Should any modification to the study or unanticipated development occur prior to the next review, please advise IRB promptly.

Yours sincerely,

J. Lawrence Hutchison, M.D.
Chair
Institutional Review Board

cc: A12-M75-99

McGill

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CERTIFICATION OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

The Faculty of Medicine Institutional Review Board consisting of:

LAWRENCE HUTCHISON, MD	SHARI BAUM, PHD
PIERRE DESCHAMPS, BCL, LSCR	PATRICIA DOBKIN, PHD
HAROLD FRANK, MD	CELESTE JOHNSTON, DED, RN
ABBY LIPPMAN, PHD	WILSON MILLER, PHD, MD
LUCILLE PANET-RAYMOND	MICHAEL THIRLWELL, MD
SALLY TINGLEY	WARREN WOODWORTH

has examined the research project **A12-M75-99** entitled **"Effect of Hyperbaric Oxygen on Plasma PO_2, Transcutaneous PO_2, and VO_2 max in a Normobaric Environment"**

as proposed by: Dr. David Montgomery (Applicant) to _____ (Granting Agency, if any)

and consider the experimental procedures to be acceptable on ethical grounds for research involving human subjects.

December 14, 1999
Date

Chair, IRB

Dean of Faculty

Institutional Review Board Assurance Number: M-1458

McGill Faculty of Medicine
Institutional Review Board
-Initial Review-

Principal Investigator: Dr. David Montgomery Department/Institution: Physical Education

Tel: 398-4184 ext. 0558 Fax: 398-4186 E-mail: davidlm@glen-net.com

Mailing Address: 475 Pine Ave. West, Montreal, Quebec, H2W 1S4

IRB Review Number: A00-M75-99 Study Number (if applicable):

Title of Research Proposal: Effect of Hyperbaric Oxygen on Plasma PO_2, Transcutaneous PO_2, and VO_{2max} in a Normobaric Environment.

STUDY DESCRIPTION (PLEASE INDICATE ALL THAT APPLY)

Is the research intervention Biomedical?: Yes Behavioural?: _____ Other?:

Is the research clinical?: No Phase I, II, III or IV?: _____ Epidemiological?: _____ Other?:

Does the study involve randomization?: No Control Group?: No Placebo Control?: No

Study scope is international or national: _____ Quebec multicentre: _____ McGill based: Yes

Projected McGill Hospital participation (if applicable): JGH: ____ MCH: _____ MGH: ___ MNH/MNI: ___ RVH: ___

SMH: _____ Other:

STUDY POPULATION (PLEASE INDICATE YES, NO, N/A OR EXPLAIN)

Number of subjects to be enrolled at McGill: 10 Will subjects be recruited from the general population?: Yes

Will the study population be hospitalized?: No Will the study involve recruiting minor subjects?: No

Are the study subjects members of a specialized group (incompetent or legally restricted)?: No

Will the research require written informed consent?: Yes Will the research require specimen collection?: Yes

Will the research require a self-administered questionnaire?: No Interviewer questionnaire?: No

Will the research require recruitment advertisement?: No Subject remuneration?: No

STUDY SUPPORT (PLEASE INDICATE YES, NO, N/A OR EXPLAIN)

Please identify financial support: Granting Agency: _____ Industrial Sponsor:

Cooperative Group: _____ Non-Funded: Yes Other:

Has the research study received regulatory approval from HPB?: N/A FDA: N/A MSSS: N/A

Has the research study been submitted to ethics review elsewhere? Yes If yes, where?: Faculty of Education

APPENDIX G

SUBJECT INFORMATION AND CONSENT FORM

Effect of Hyperbaric Oxygen on Plasma PO_2, Transcutaneous PO_2, and VO_{2max} in a Normobaric Environment

Co-Investigators: DL Montgomery, JS Delaney, VJ Lacroix, ANH Hodges

Introduction

Hyperbaric oxygen (HBO_2) is a medical treatment in which the patient or subject breathes 95 – 100% oxygen at pressures greater than 1 atmosphere absolute (ATA). In recent years some professional and college athletic teams have used HBO_2 therapy not only to treat sports injuries, but also to speed recovery after exercise and as an ergogenic aid to enhance performance. Because of the importance of oxygen in the aerobic energy system, these athletes have associated HBO_2 treatments with enhanced performance.

Contradictory findings have been reported in the research literature regarding the effect of a single HBO_2 treatment on aerobic performance. A small number of research investigations have examined the effect of HBO_2 on recovery from exercise with positive results by Staples (1999). In contrast McGavock et al. (1999) found that a single HBO_2 treatment at 2.5 ATA did not enhance the speed of recovery from exercise. As an ergogenic aid two studies have reported positive findings (Banister et al., 1970; Cabric et al., 1991) and two studies have reported no benefits from HBO_2 treatments (McGavock et al., 1999; Webster et al., 1998). The time lapse from exiting the hyperbaric chamber to performance of the exercise challenge has varied among these studies and may account for the disparate findings.

It is difficult to rationalize how prior HBO_2 enhances performance. Cabric et al. (1991) suggested that oxygen might be stored within muscle tissue as an explanation for the improved performance in their study. However, it has been shown in dogs that tissue auto-regulation reduces oxygen levels upon return to a normobaric normoxic environment (Kelly et al., 1972).

The purpose of this study is to examine plasma PO_2, transcutaneous tissue PO_2, and VO_{2max} in a normobaric environment following a single hyperbaric oxygen treatment. The study is designed to answer three questions. Does a single HBO_2 treatment at 2.5 ATA for 90 minutes: 1) elevate plasma PO_2; 2) elevate transcutaneous tissue PO_2; and 3) elevate VO_{2max}, in a normobaric normoxic environment?

Subjects

Inclusion Criteria Subjects for this study will be male university students with high aerobic fitness (VO_{2max} greater than 50 $mL \cdot kg^{-1} \cdot min^{-1}$) between 19 and 39 years of age. Students with an interest in hyperbaric oxygen and aerobic endurance will be asked to volunteer for this study. A total of 10 subjects will be participating in this study.

Exclusion Criteria Each subject will receive a medical examination by the hyperbaric oxygen physicians (Dr. Scott Delaney or Dr. Vincent Lacroix). The purpose of this examination will be to identify contraindications for HBO_2 therapy. The following contraindications would exclude a subject:

Recent thoracic surgery
Repeated ear infections
Asthma
Cataracts
Diabetes
Receiving anti-convulsant medication

Hereditary spherocytosis
Recent upper respiratory tract infection
Positive response on an Allen test

Since arterial blood samples will be drawn from the radial artery, the physician will evaluate the arterial supply to the hand by performing an Allen test on each subject. This test is useful to assure the patency of the ulnar artery before puncturing the radial artery for blood samples. If the ulnar artery is patent, the palm flushes within about 3 to 5 seconds. Persisting pallor indicates occlusion of the ulnar artery or its distal branches and would exclude the subject from participation in this study.

Each subject will perform the following tests at the Seagram Sports Science Centre of McGill University: 1) one VO_{2max} test to assess baseline aerobic fitness; 2) a second VO_{2max} test conducted immediately after exit from the HBO_2 chamber to assess the ergogenic effect of an HBO_2 treatment; 3) venous PO_2 assessments following an HBO_2 treatment; 4) baseline transcutaneous tissue PO_2 assessments; and 5) transcutaneous tissue PO_2 assessments following an HBO_2 treatment.

The time commitment for each subject will be 9 hours spread over three sessions.

Day	**Time**	**Tests**
1	2 h	baseline transcutaneous PO_2 measures and VO_{2max} test
2	3 h	HBO_2 treatment followed by VO_{2max} test
3	4 h	HBO_2 treatment followed by blood gas and transcutaneous PO_2 measures

Procedures

VO_{2max} Test (2 tests) The subjects will perform a VO_{2max} test on day 1 as a baseline measure, and on day 2 following a HBO_2 treatment. The VO_{2max} test is a standard laboratory assessment of aerobic fitness. The test will be performed on a running treadmill. The initial speed of the treadmill will be 5 mph (134 $m \cdot min^{-1}$) and will increase by 0.5 mph (13.4 $m \cdot min^{-1}$) every minute until volitional fatigue. The grade of the treadmill will remain constant at 5%. This test is comparable to a short, high intensity workout and will last approximately 10 minutes. Verbal encouragement will be provided during the test. Heart rate and VO_2 will be monitored continuously throughout the test. Metabolic measurements will be made from analysis of expired air. Following each VO_{2max} test, one finger prick blood sample will be taken to determine blood lactate concentration. This process is a standard laboratory technique.

Hyperbaric Oxygen Treatment (2 treatments) There will be two treatments in the hyperbaric oxygen chamber on days 2 and 3. During treatments, subjects watch videos. The HBO_2 treatment will be approximately 105 minutes in duration and will consist of a compression period of 7 – 10 minutes, a treatment period of 90 minutes, and a decompression period of 5 – 7 minutes. During the treatments, the chamber will be compressed to 2.5 atmospheres absolute (ATA) and the subject will breathe 95% oxygen.

Under normal sea level conditions, barometric pressure is 1 ATA or 760 mm Hg. The oxygen content in the air is 20.9%. In these conditions, the partial pressure of oxygen in arterial blood (P_aO_2) is 100 mm Hg. During the HBO_2 treatment at 2.5 ATA and 95% oxygen concentration in the chamber, the P_aO_2 is approximately 1600 mm Hg.

Venous Blood Gas Analysis Immediately upon exit from the hyperbaric chamber on day 3, the physician will clean an area on the subject's wrist and insert a catheter into the antecubital vein. Blood samples (3 - 5 mL) will be drawn every ten minutes until normal venous PO_2 values are obtained. This may occur after 1 or 2 samples. A maximum of 6 samples will be drawn. The subject will remain in a seated position for these measurements.

Transcutaneous Tissue Oxygen Measurement (1 test). This is a non-invasive test that measures the oxygen content in the tissues immediately below the skin. Upon exiting from the hyperbaric chamber on day 3, tissue oxygen concentration will be measured at 2 sites (rectus femoris and brachioradialis) by placing two electrodes on the skin over these muscles. Any hair on the skin will be shaved at the electrode sites. The electrodes will be warmed to 45°C to dilate the vasculature. Measurements will be continuous for one hour during the same time period that the blood samples are being collected. The subjects will be in a seated position for these measurements.

Data Analysis

This study is designed to answer three questions. Does a single HBO_2 treatment at 2.5 ATA for 90 minutes: 1) elevate plasma PO_2; 2) elevate transcutaneous tissue PO_2; and 3) elevate VO_{2max}, in a normobaric normoxic environment? One-way analyses of variance (ANOVA) will be used to examine plasma PO_2 and transcutaneous tissue PO_2 data. T-tests will be used to analyze VO_{2max} and blood lactate data.

References

Banister, E. W., J. E. Taunton, T. Patrick, P. Oforsagd, and W. R. Duncan. Effect of oxygen at high pressure at rest and during severe exercise. *Respir Physiol* 10:74-84, 1970.

Cabric, M., R. Medved, P. Denoble, M. Zivkovic, and H. Kovacevic. Effect of hyperbaric oxygenation on maximal aerobic performance in a normobaric environment. *J Sports Med Phys Fitness* 31:362-366, 1991.

Kelly, D. L., K. R. Lassiter, A. Vongsvivut, and J. M. Smith. Effects of hyperbaric oxygenation and tissue oxygen studies in experimental paraplegia. *J Neurosurg* 36:425-429, 1972.

McGavock, J. M., J. L. Lecomte, J. S. Delaney, V. J. Lacroix, P. Hardy, and D. L. Montgomery. Effects of hyperbaric oxygen on aerobic performance in a normobaric environment. *Undersea Hyper Med* 26(4):219-224, 1999.

Staples, J. R., D. B. Clement, J. E. Taunton, and D. C. McKenzie. Effects of hyperbaric oxygen on a human model of injury. *Am J Sports Med* 27(5):600-605, 1999.

Webster, A. L., D. G. Syrotuik, G. J. Bell, R. L. Jones, Y. Bhambhani, and M. Young. Exercise after acute hyperbaric oxygenation: Is there an ergogenic effect? *Undersea Hyper Med* 25:153-159, 1998.

Subject Consent Form

Effect of Hyperbaric Oxygen on Plasma PO_2, Transcutaneous PO_2, and VO_{2max} in a Normobaric Environment

Co-Investigators: DL Montgomery, JS Delaney, VJ Lacroix, ANH Hodges

1.0 Introduction

Hyperbaric oxygen (HBO_2) therapy is a medical treatment in which the patient breathes 95 – 100% oxygen at pressures greater than 1 atmosphere absolute (ATA). Because of the importance of oxygen in the aerobic energy system, some athletes have used HBO_2 as an ergogenic aid to enhance aerobic performance and to speed recovery following exercise. Contradictory findings have been reported in the research literature regarding the effect of a single HBO_2 treatment on aerobic performance.

The purpose of this study is to examine plasma oxygen pressure (PO_2), transcutaneous tissue oxygen pressure (PO_2), and VO_{2max} in a normobaric environment following a single hyperbaric oxygen treatment.

2.0 Study Procedures

Subjects for this study will be university student-athletes between 19 and 39 years of age with high aerobic fitness (VO_{2max} greater than 50 $mL \cdot kg^{-1} \cdot min^{-1}$). You have been asked to participate in this study because of your interest in hyperbaric oxygen and aerobic endurance. A total of 10 subjects will be participating in this study.

This study will take place at the Seagram Sports Science Centre of McGill University. As a volunteer participant in this study, your time commitment will be 9 hours spread over three sessions as follows:

Day	Time	Tests
1	2 h	baseline transcutaneous PO_2 measures and VO_{2max} test
2	3 h	HBO_2 treatment followed by VO_{2max} test
3	4 h	HBO_2 treatment followed by blood gas and transcutaneous PO_2 measures

VO_{2max} Test (2 tests). You will perform a VO_{2max} test on day 1 as a baseline measure, and on day 2 following a HBO_2 treatment. The VO_{2max} test is a standard laboratory assessment of aerobic fitness. The test will be performed on a running treadmill. The initial speed of the treadmill will be 5 mph (134 $m \cdot min^{-1}$) and will increase by 0.5 mph (13.4 $m \cdot min^{-1}$) every minute until volitional fatigue. The grade of the treadmill will remain constant at 5%. This test is comparable to a short, high intensity workout and will last approximately 10 minutes. Verbal encouragement will be provided during the test. Metabolic measurements will be obtained from analysis of expired air. The expired air will be collected from a mouthpiece that is connected via a tube to the metabolic cart as you run on the treadmill. Following each VO_{2max} test, one finger prick blood sample will be taken to determine blood lactate concentration. This process is a standard laboratory technique.

Hyperbaric Oxygen Treatment (2 treatments) You will receive two treatments in the hyperbaric oxygen chamber on days 2 and 3. The HBO_2 treatment will be approximately 105 minutes in duration and will consist of a compression period of 7 – 10 minutes, a treatment period of 90 minutes, and a decompression period of 5 – 7 minutes. During the treatments, the chamber will be compressed to 2.5 atmospheres and you will be breathing 95% oxygen. During treatments you can watch videos. The hyperbaric technician will remind you of various techniques that can be used to equalize pressure during the treatment.

Venous Blood Gas Analysis Immediately upon exit from the hyperbaric chamber on day 3, the physician will clean an area on your wrist and insert a catheter into the antecubital vein. Blood samples (3 - 5 mL) will be drawn every ten minutes until normal venous PO_2 values are obtained. This may occur after 1 or 2 samples. A maximum of 6 samples will be drawn. You will remain in a seated position for these measurements.

Transcutaneous Tissue Oxygen Measurement (1 test). This is a non-invasive test that measures the oxygen content in the tissues immediately below the skin. Upon exiting from the hyperbaric chamber on day 3, tissue oxygen concentration will be measured at 2 sites (mid-thigh and forearm) by placing two electrodes on the skin. The electrodes are about the size of a quarter. Any hair on the skin will be shaved at the electrode sites. The electrodes will be warmed to 45°C. Measurements will be continuous for one hour during the same time period that the blood samples are being collected. You will be in a seated position for these measurements.

3.0 Benefits and Risks

3.1 In this study the benefits to you are minimal. You will receive two maximal treadmill tests that will provide information on your aerobic fitness. The typical charge for a VO_{2max} test in the Seagram Sports Science Centre is $150. You will experience two hyperbaric oxygen treatments. The ergogenic benefits of these HBO_2 treatments may be minimal.

3.2 The risks associated with HBO_2 treatment are rare. They include the following:

Barotrauma: This is the most common side effect of hyperbaric oxygen therapy. This refers to injury or discomfort to the ears due to increased pressure. If the ears are not properly cleared, the eardrum could bruise. Reducing the chamber pressure or stopping the treatment usually corrects the discomfort. Pressure changes in the chamber are normally felt in the ears. The following techniques can be used to clear the ears:

- Swallowing
- Yawning
- Chewing
- Blowing out through your nose while pinching the nostrils

Pneumothorax: It is important that you do not hold your breath during the time the pressure is being decreased in the chamber (at the end of the treatment). Air is expanded during this time and if you hold your breath, it is possible to rupture your lung with air entering the chest cavity. This is very rare and is easily avoided by breathing normally during decompression.

Sinus Trauma: Congested sinuses can cause pain while the chamber is being compressed or decompressed. Reducing the chamber pressure usually relieves the pain. It is important that you inform the physician of any symptoms of congested sinuses prior to treatment so problems can be avoided.

Airway Irritation: This is the very rare case of oxygen causing an airway irritation. The symptom is a dry hacking cough. Should this occur the HBO_2 physician would evaluate you and make a decision as to how the problem will be addressed.

Stomach Distension: If you swallow large amounts of air during the treatment, it will expand when the pressure is decreased. This may cause vomiting or pain in the abdomen. It can be avoided by breathing normally and avoiding carbonated beverages before treatment.

Oxygen Toxicity: Some patients are more sensitive to oxygen than others. Symptoms may include the following:

Visual	- tunnel vision, loss of clear vision
Ears	- ringing or knocking in the ears, and distortion of normal sounds
Nausea	- the urge to vomit
Twitching	- twitching around the eyes and lips
Irritability	- apprehension, fidgeting, or disorientation
Dizziness	- vertigo (sensation of room revolving)
Dyspnea	- shortness of breath

To reduce the risk of oxygen toxicity, two 5-minute air breaks will be administered during the HBO_2 treatment.

Alcohol: Since alcohol consumption may lower the threshold for oxygen toxicity, you are asked to refrain from drinking alcohol within 24 hours on each of the 3 days that you will be tested.

Medication: Any medication you take should be discussed with the physician during the medical examination to determine any contraindications to HBO_2 treatment.

Claustrophobia: Some people experience anxiety due to being enclosed in a confined space. The sidewalls of the hyperbaric chamber are a clear acrylic material that permits you to watch videos during treatment. If there is any concern of claustrophobia, this should be discussed with the HBO_2 physician or technician before entering the chamber.

3.3 The risks associated with a VO_{2max} test are minimal, especially to individuals familiar with running on a treadmill. The final 2 – 3 minutes of the test require a maximal effort similar to what you would experience during a high intensity exercise session. The end point of the test is volitional fatigue.

3.4 The risks associated with a venous catheter to obtain blood samples are: 1) discomfort associated with needle puncture; 2) risk of infection; 3) complications due to venous puncture which include bleeding and local bruising.

4.0 Withdrawal From The Study

The hyperbaric physician will perform a medical examination prior to the HBO_2 treatment. The physician may exclude a participant from the study for the following reasons:

- Recent thoracic surgery
- Repeated ear infections
- Asthma
- Cataracts
- Diabetes
- Receiving anti-convulsant medication
- Hereditary spherocytosis
- Recent upper respiratory tract infection

It is important that you understand your participation in this study is voluntary and you have the right to withdraw from this study at any time and for any reason.

5.0 Costs

There are no costs to you for the HBO_2 treatments, VO_{2max} tests or the laboratory tests (blood gas analysis and transcutaneous tissue oxygen measurements)

6.0 Compensation

After the data have been collected, you will be presented with a copy of your laboratory test results. A member of the research team will meet with you to discuss the results of your tests and to answer your questions.

7.0 Rights of the Subjects

Your participation in this study is voluntary and unrelated to any courses in the Department of Physical Education. You have the right to withdraw from this study at any time and for any reason. You have the right to ask questions at any time, and you have the right to a copy of the data collected on you during this study.

8.0 Confidentiality

Information gained by the examining physician will remain confidential. The examining physician will inform the researchers only whether or not you are clear to participate in the study. Data collected during the study will be stored in a locked filing cabinet and access will be limited to the researchers. A labeling system will be used to

identify each subject in this study by number only, and the names of the subjects will be kept locked in the filing cabinet. In future publications and other references to the study, results will be presented without mention of names or any other information that could provide the identity of any subject.

9.0 Contact

If an adverse event should occur, the HBO_2 physicians Dr. Vincent Lacroix or Dr. Scott Delaney should be contacted. They can be reached at (514) 398-7007 between 8:00 A.M. and 5:00 P.M. and in an emergency can be paged at the following numbers 988-5092 (Dr. Lacroix) or 423-8455 (Dr. Delaney).

If you have any questions regarding your rights, do not hesitate to speak with the investigators of this study:

Dr. David Montgomery (Room 335 at the McGill Sports Complex, telephone 398-4184 ext. 0558)

Dr. Vincent Lacroix (McGill Sports Medicine Clinic, telephone 398-7007)

Dr. Scott Delaney (McGill Sports Medicine Clinic, telephone 398-7007)

INFORMED CONSENT

Title of Study:

Effect of Hyperbaric Oxygen on Plasma PO_2, Transcutaneous PO_2, and VO_{2max} in a Normobaric Environment.

Investigators:

David Montgomery, Ph.D. Seagram Sports Science Centre
McGill University Tel: 398-4184 ext. 0558
Scott Delaney, M.D. McGill Sport Medicine Clinic Tel: 398-7007
Vincent Lacroix, M.D. McGill Sport Medicine Clinic Tel: 398-7007
Alastair Hodges, Graduate Student, McGill University

The purpose of the study, the procedures to be used, the benefits and risks associated with my participation in this study, as well as the confidentiality of the data that will be collected during the study have been explained to me.

I have had the opportunity to ask questions concerning different aspects of the study and my questions have been answered to my satisfaction.

I, the undersigned, voluntarily accept participation in this study. I am aware that I am free to withdraw from the study at any time and for any reason without penalty.

I acknowledge that I have received a signed copy of this consent form.

Name of subject	Signature	Date
Name of witness	Signature	Date
Name of researcher	Signature	Date

APPENDIX H

CONTRIBUTION OF CO-AUTHORS IN

THE RESEARCH ARTICLE

Alastair Hodges

Responsible for recruiting of subjects, data collection, and data analysis. Prepared the final manuscript.

Scott Delaney & Vincent Lacroix

Physicians responsible for supervision of HBO_2 treatments, inserting of venous catheter. and drawing of blood samples. Edited the final manuscript.

Jackie Lecomte

Administered the HBO_2 treatments. Edited the final manuscript.

David Montgomery

Thesis supervisor, assisted with writing of research article.