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Safety and Feasibility Study of A Hyperbaric Infrared Chamber Combining Hyperbaric Oxygen Therapy and Low Temperature Infrared Radiation

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Abstract

Objective: *The aim of both Hyperbaric Oxygen Therapy (HBO) and Low Temperature Infrared Technology (LIT) is to increase oxygen supply to tissues. Combining the two techniques could generate synergistic effects and balance potential detrimental effects of HBO (vasoconstriction) due to vasodilation induced by LIT. Since this combination of HBO and LIT (HBOIR) has never before been tested, the aim of this study was to evaluate the safety and feasibility of HBOIR.*

Methods: *12 healthy subjects completed 6 HBOIR sessions, each lasting 45 minutes with at least 30 minutes of pure oxygen administration at a constant overload pressure of 0.5 bar. Heat was applied via far infrared radiation. Physiological and ambient parameters in the chamber were recorded during the treatment. Mental state was assessed before and after each HBOIR session.*

Results: *There were no adverse effects during or after the HBOIR sessions. We observed significant but not clinically-relevant increases in heart rate, core and skin surface temperature and oxygen saturation. Well-being was not impaired post treatment.*

Conclusion: *HBOIR induces moderate whole body warming accompanied by low cardiovascular exertion. It was demonstrated that HBOIR under an overload pressure of 0.5 bar is safe and well tolerated by the group of healthy subjects.*

Keywords: ***hyperbaric oxygen therapy, low temperature infrared radiation, thermal therapy, core temperature, whole body warming, skin temperature.***

1. Introduction

A major portion of healthcare costs is incurred by chronic disease sufferers [1], such as those with cardiovascular and metabolic disorders, degenerative and inflammatory diseases of the musculoskeletal system as well as diseases of the respiratory system [2]. In many cases, the success of medical treatments is rarely satisfactory, as the treatment

therapy is determined by symptoms rather than causes. In addition, many drugs exhibit numerous side effects, which incur additional costs. Thus, the search for both more cost-effective, cause-oriented and efficient treatment strategies for such diseases together with strategies to prevent disease progression is becoming increasingly important.

The combination of the two well-known and separately approved techniques, Hyperbaric Oxygen Therapy (HBO) and Low temperature Infrared Technology (LIT), potentially provides one such treatment strategy. Both treatments aim to improve oxygen supply to tissues. This is important as one recognized contributing or, at least, aggravating factor leading to chronic disorders is tissue hypoxia and subsequent cellular and metabolic dysfunctions.

HBO has successfully been used as adjunct therapy for a wide range of medical conditions for many years, such as decompression sickness, dysfunction in wound healing, brain injuries, inflammatory diseases and chronic infections [3], [4]. Breathing pure oxygen under hyperbaric conditions leads to an increase in physically dissolved oxygen in plasma as well as an improved oxygen diffusion gradient to tissues. This can lead to reoxygenation of previously hypoxic tissues, e.g. induced by circulatory disturbances or edema, and thus to a restoration of cell function. However, standard pressure chambers require a high capital expenditure and, thus, are restricted to very few specialized institutions.

Thermal therapy is commonly applied in physical medicine and rehabilitation. The effects of mild tissue warming are wide ranging and include, for example, reflex muscle relaxation and pain relief [5], [6], improvement of perfusion and microcirculation [7], [8], amelioration of tissue supply [9] and stabilization of blood pressure regulation [10], [11]. Individual whole-body heat application systems differ in regard to their thermoregulatory and cardiovascular effects. For example, during sauna treatment, heat defense mechanisms are blocked in order to prevent artificial fever, and the quantity of heat delivered through the whole skin surface into the body is not transferred to the periphery. Thus, whole-body warming does not occur during the treatment. However, the heat defense reaction of the skin is generally only little disturbed when heat is applied to only 10-15% of the overall skin surface on the back within the thermoneutral zone (28-37°C ambient temperature) [12]. Therefore, in contrast to sauna treatments, where there is no initial increase in core temperature, treatments within the thermoneutral zone, such as LIT applications, induce a moderate whole-body warming with an immediate small but continuous increase in core temperature in the subfebrile range. However, infrared radiation delivery systems can automatically regulate the heat flux to suit the individual heat capacity of the skin and body (e.g., Sensocare®) so as to avoid chronic or acute thermal damage of the skin [13]. Local heating of the skin (e.g. on the back) under thermoneutral conditions allows maintenance of the central influx of warmed blood without restriction, so that the applied heat can be gradually distributed from the core to the body shell [13]. This procedure allows a discreet and continuous increase in core temperature.

Therefore, combining HBO with LIT could counteract the potential effect of HBO on terminal vessels (i.e., vasoconstriction due to hyperoxia) because the forced heat dissipation of LIT increases peripheral perfusion. In turn, HBO can compensate for the increased oxygen consumption during LIT due to a doubling of the metabolism that results from an elevation of tissue temperature of about 5°C. The synergistic effects of the combined application could also significantly reduce the common HBO application period of about 2.5 hours to less than 60 minutes, and reduce the standard overload pressure of 1.4 bar to 0.5 bar with the same efficacy. Consequently, the lower pressure within the HBOIR chamber together with the lack of need for additional decompression stops, allows for an increase in patient safety (rapid rescue $\leq$ 2 minutes) with no requirement for accompanying personnel in the chamber. To the best of our knowledge, there has been no published study of the effects of combined HBO and LIT treatments to date.

This study is, therefore, the first to assess the safety and feasibility of the combined HBOIR application. The main objective was to identify and investigate any adverse reactions, including patient tolerance and safety at 0.5 bar overload pressure, as well as the practicability of the proposed therapeutic procedures. To this end, we analyzed specific physiological and ambient parameters during 6 HBOIR sessions in a group of healthy volunteers.

2. Materials and Methods

This monocentric, prospective study was carried out on 12 healthy subjects (7 females, 5 males, aged (mean±SD) 32.4±14 years, height 174±8 cm, BMI 23.9±3 kg/m2). Two out of 14 invited subjects were not able to participate due to lack of time. Participants were recruited through online platforms and mailing lists at local Universities and written public notifications in and around the city of Hall in Tirol, Austria. The study was approved by the local ethical Committee of the Medical University of Innsbruck (UN 5232; 329/4.13.331/4.24) and carried out in accordance with the Declaration of Helsinki 1978. The study was also in compliance with the Austrian Standards for clinical investigation of medical devices for human subjects (ÖNORM EN ISO 14155). Written informed consent was obtained by all participants prior to commencing the study.

Inclusion criteria: Only healthy participants between the age of 21 and 70 years who fulfilled the criteria for diving suitability were included in this study.

Exclusion criteria: Participants were excluded due to the presence or inability to exclude any of the following: pregnancy, lactation period; clinically relevant diseases of internal organs such as coronary artery disease, cardiac insufficiency, bronchial asthma or chronic obstructive pulmonary disease; acute allergies, chronic infections, inflammatory diseases or injuries; drug and/or alcohol abuse; participation in a clinical trial within 30 days prior to the start of this study; claustrophobia; acute diseases during the test procedure including simple infections e.g. rhinitis, cough etc.; or lack of compliance or violation of the rules of conduct.

Participants were instructed not to use a solarium or other heat application (e.g. sauna, thermal baths) on the day of treatment. They were also instructed not to dive, fly, or climb to high altitudes (> 2000m) on the previous day, the day of the treatment as well as the following day. Inclusion and exclusion criteria were assessed up to one month before the study during a clinical examination of the subjects that included blood pressure measurements, spirometry and electrocardiogram (ECG). In addition, participants aged 40 years or more had to perform an incremental symptom-limited exercise test on a bicycle ergometer (including ECG). A medical interview was also performed before each HBOIR testing. Calibrated devices were used to determine the body weight (kg) and height (cm) of each subject.

2.1 Study protocol

Participants were initially exposed to one single HBOIR session at an overload pressure of 0.5 bar. Based on their tolerance of the first application, participants were then selected for 5 additional HBOIR sessions with a minimum time interval of 48 hours between each exposure.

Each HBOIR session was performed in a 2000 liter, monoplace hyperbaric chamber equipped with infrared technology (Sensocare® system, Physiotherm, Thaur, Austria) at an overload pressure of 0.5 bar. The chamber was preheated to a thermoneutral ambient temperature of 30°C. Heat was directly applied to the subjects' backs using Sensocare® technology, and a maximum skin temperature was set at 42.5°C in the direct irradiated region in order to avoid thermal skin damage. Participants were seated during treatments, wearing only underpants. Permanent visual and voice contact with the study subjects was maintained throughout the treatment session. Chamber pressure was regulated by a technician under a medical doctor's supervision.

Progressive pressurization was carried out using standardized diving cylinders (15 liters) filled by a 225 bar portable air compressor (Bauer Junior 2, Bauer, Munich, Germany). On reaching an overload pressure of 0.5 bar (after 5-10 min, depending on the individual ability for pressure equalization), the application started for a scheduled period of 45 minutes. After adjustment by the participant (irradiation, heart rate, respiratory rate, blood pressure, subject habituation; *max 15 min*), pure oxygen (100%) was supplied via a facial mask for the remaining application time (minimum 30 min).

After 45 minutes at constant overload pressure of 0.5 bar, the chamber was decompressed. During decompression (2-10 minutes), subjects continued breathing 100% oxygen. The pressurization and decompression profiles were determined according to prior agreement with the participant and regulated by direct contact. Subjects remained in the study center for observation for at least one hour after exiting the chamber.

In case of emergency, or appearance of pre-determined symptoms, the chamber could be decompressed within 2 minutes. The application would also be stopped if other problems occurred during pressurization, including continuous pain in the paranasal sinuses and/or inner ear.

2.2 Physiological parameters

During each HBOIR session, we continuously measured noninvasive systolic and diastolic blood pressure, core temperature (using a rectal probe with a protective cover; P.L. Dahlhausen & Co. GmbH, Cologne, Germany) and oxygen saturation (SpO_2) via a pulse oxymeter (iMEC8, Mindray, Darmstadt, Germany). Heart rate was also continuously recorded using three chest and two waist leads (iMEC8, Mindray). Peripheral skin surface temperature was measured using two probes on each leg, one on the thigh (axial ventral) and the other on the calf (axial dorsal) (Almemo 2890-2 with PT-100 probes, Ahlborn, Holzkirchen, Germany). The irradiated skin on the back of the subjects was visually examined by a physician immediately after exposure, and again after one hour.

2.3 Measurements in the hyperbaric chamber with low temperature infrared technology using the Sensocare® system (HBOIR)

In order to evaluate changes in the climate in the HBOIR chamber, carbon dioxide levels, air humidity and temperature (EE80-5CT3/T04, E&E Electronic, Engerwitzdorf, Austria), air pressure (GMUD MP, Greisinger Electronic GmbH, Regenstauf, Germany) and oxygen concentration (OXY 3690 MP, Greisinger Electronic GmbH) were continuously measured.

2.4 Hyperbaric Infrared Chamber

Pre-heating of the chamber to a thermoneutral temperature (30°C) and regulation of this temperature during the application was performed by means of an infrared heater

(HT-AP 1, CO. Physiotherm, Thaur, Austria) placed at the front of the chamber (HBOIR 2000l, CO. Autotest AG, Lana, Italy). The predetermined maximum working pressure in the chamber was ensured using a pressure limiter (TÜV.SV.10.882.8.D/G.0.31/AZ Armaturen GmbH, Mönchweiler, Germany). Exhaled CO_2 was removed from the chamber through a soda lime cartridge in an active ventilation system (Drägersorb 800 Plus, Dräger Medical GmbH, Lübeck, Germany). During the HBOIR session, O_2 was supplied to the participants at ambient pressure using a demand valve (EASE II, GCE Sabre, Warrington, United Kingdom). The valve was connected to a separate oxygen cylinder outside the chamber that was fitted with a pressure reducer (Medireg O2D DGC KL, GCE Sabre, Warrington, United Kingdom).

2.5 Sensocare® infrared radiator with integrated infrared-temperature sensors

The fully automated Sensocare® system regulates the intensity of the infrared radiator, and thus, the heat input, according to the temperature of the skin on the back. Four infrared temperature sensors are placed directly in the reflector of the infrared heater. Temperature is measured over an area of 60cm² by each sensor every 1 second. The signal is transferred to the control system, which, in turn, automatically regulates radiation intensity in a way that the desired target temperature is reached after 12-15 minutes. The highest temperature recorded by the sensors determines radiation intensity. The precision of the temperature sensor (MLX 90614ESF-DAC, Melexis, Ieper, Belgium) is ± 0.5°C. Depending on the subject's thermoregulatory capability, the infrared system will allow the skin temperature to be exceeded as an inert thermal heating element is used. The system allows an overshoot up to 45.5 °C for a maximum of 3 minutes, which is shown to have no adverse effects [14], [15]. Beyond this, the system immediately switches off.

2.6 Well-being

Two hours before and one hour after the HBOIR application, the subjects were asked to assess their general condition on the basis of the "Basler Befindlichkeitsfragebogen", a multidimensional self-rating system evaluating instant mental state (Cronbachs alpha: 0.88-0.79) [16].

2.7 Data acquisition

Signals from heart rate, blood pressure, heart rate, SpO2 (oxygen saturation of the blood) and core temperature detectors were stored in the monitor's memory (iMEC8) and transferred to a personal computer after each HBOIR session. Skin surface temperature (measured on the back) and radiation data were continuously recorded on a datalogger (Midi Logger GL-800, Shinano-cho, Japan) and automatically transmitted to a personal computer. All data were exported in excel.

2.8 Statistical analysis

Data was analysed using the SPSS statistical software package 20 (IBM, Vienna, Austria). Probability values ≤ 0.05 (two-tailed) were considered as statistically significant. A 2-way analysis of variance (ANOVA) was applied for repeated measurements in order to assess changes induced within a treatment. Data are presented as means ± standard deviation (two-tailed). In case of significant findings, post-hoc analyses were performed using Bonferroni correction for multiple testing. A Kolmogorov-Smirnov test (KS-Test) was applied to estimate the distribution normality of the variables. Values over a period of 5 minutes were averaged for evaluation and descriptive presentation of the data. Blood pressure and core temperature were recorded at a 5 minute interval. In order to evaluate whether SpO_2 levels stayed constantly high, mean values from each application were compared to corresponding baseline levels using a paired t-test. Changes in well-being during the pre- to post-treatment period were analyzed using a paired t-test. Mean skin temperatures of the thighs and calves are reported for the left and right leg, respectively. Differences between baseline and end of treatment (minute 45) thigh and calf skin temperatures were calculated and an unpaired t-test was applied in order to describe these variations in temperature.

3. Results

All participants who performed the first HBOIR treatment (n=12) also completed the other five applications. None of the subjects reported any medical problems and the hyperbaric thermal applications were generally well-tolerated. No adverse effects were observed during or after treatments. No problems were observed in pressure equalization during pressurization of the chamber.

3.1 Physiological data

Baseline and end-of-treatment data for all measured physiological variables over the six treatments (t1, t2, t3, t4, t5 and t6) are presented in *Table 1*.

During t3 and t4 there was a significant increase in mean HR (*Figure 1A*). In contrast, mean systolic (SBP) and diastolic blood pressures (DBP) did not change significantly during the study (*Figures* 1B/1C).

Mean peripheral skin temperatures at the thigh and calves increased significantly during each of the six HBOIR treatments (*Figures* 1D/E). Increase in thigh skin temperature was significantly higher than at the calves in t2 (3.0±1 vs. 2.2±1), t3 (3.3±1 vs. 2.4±1) and t4 (2.7±1 vs. 1.9±1). Likewise, there was a significant rise in mean skin temperature on the back during each treatment. Temperatures exceeding 43.0°C did not last more than 3 minutes, and were always below 43.9 °C *(Figure 1F).* Redness of the skin in the irradiated back region of each

subject was observed but disappeared within one hour after the treatment.

Mean core temperature increased during each treatment but was only statistically significant during t2 and t3. Maximum core temperature did not exceed 38.0°C in any of the study subjects during treatments 1-6.

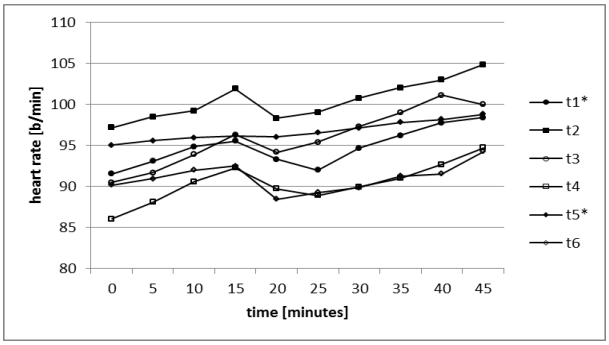
Mean oxygen saturation (SpO_2) significantly increased during pressurization of the chamber (baseline vs. minute 5; p=≤0.01) and again during administration of oxygen (minute 15 vs. minute 20; p=≤0.01; *Figure 1H*). In fact, SpO_2 values remained elevated relative to the baseline value from minute 5 to 45 in all 6 sessions (p≤ 0.01).

Table 1: Changes in physiological parameters from baseline to the end of the HBOIR treatments 1-6.

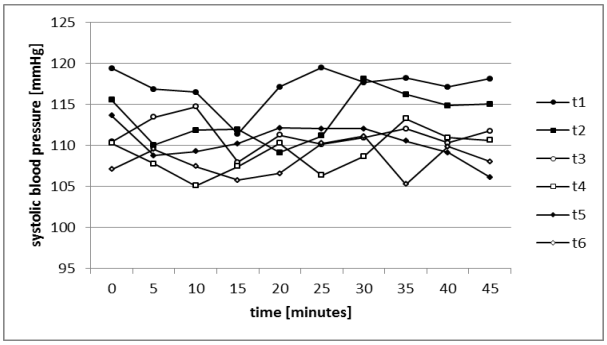
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 6
Heart Rate (b/min)						
Baseline	92 ±13	97±19	90±19	86±13	90±17	90±13
End of treatment	98±12*	105±20	100±16	95±14	100±13*	95±11
Systolic blood pressure (mmHg)						
Baseline	119±11	115±8	111±12	110±11	114±8	107±9
End of treatment	118±11	115±13	112±9	111±11	106±8	108±9
Diastolic blood pressure (mmHg)						
Baseline	75±10	73±5	71±8	69±8	71±8	70±6
End of treatment	73±8	71±5	69±7	66±9	70±10	67±9
Core temperature (C°)						
Baseline	37.3±0.3	37.3±0.6	37.4±0.2	37.3±0.3	37.3±0.3	37.4±0.3
End of treatment	37.5±0.2	37.5±0.5*	37.6±0.1*	37.4±0.2	37.5±0.3	37.5±0.3
Maximum values	37.9	38.0	37.8	37.7	37.9	37.9
Skin temperature (back region) (°C)						
Baseline	35.9±1.7	34.9±1.5	34.8±1.5	34.8±1.6	34.9±1.8	34.6±1.7
End of treatment	42.4±0.2***	42.3±0.4***	42.2±0.5***	42.3±0.4***	42.2±0.5***	42.3±1.3***
Maximum values	43.2	43.9	43.3	43.3	43.2	43.5
Peripheral skin temperature – thigh (°C)						
Baseline	32.6±1.5	32.3±1.5	32.1±1.3	32.2±1.3	32.0±0.8	32.6±1.1
End of treatment	34.9±1.3***	35.3±1.0***	35.4±0.9***	34.9±0.9***	35.4±1.0***	35.0±0.5***
Peripheral skin temperature – calf (°C)						
Baseline	31.6±1.2	31.6±0.9	31.3±1.4	31.5±1.0	31.4±0.7	31.5±0.7
End of treatment	33.4±1.1***	33.8±1.2***	33.6±1.1***	33.5±1.0***	34.1±1.3***	33.3±0.9***
Oxygen saturation (%)						
Baseline	98±0.7	98±0.6	98±0.6	98±0.5	98±0.5	98±0.8
End of treatment	99±0.4***	100±0.3***	100±0.4***	100±0.4***	99±0.4***	100±0.4***
(min-max)	96-100	95-100	94-100	95-100	94-100	95-100

Data are presented as means ± SD. * p-value ≤ 0.05, ** p-value ≤ 0.01, *** p-value ≤ 0.001 for significant changes within one treatment (ANOVA); min-max: minimum and maximum values during one treatment session. N=12.

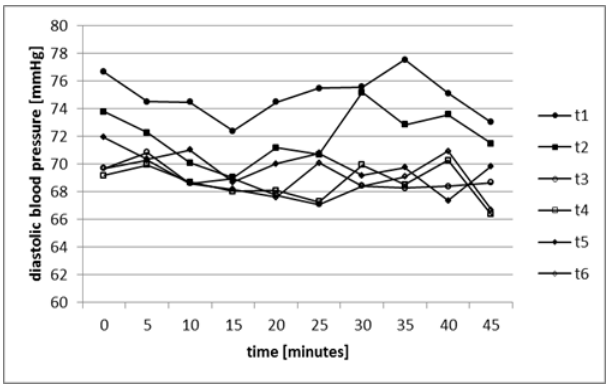
A Mean heart rate



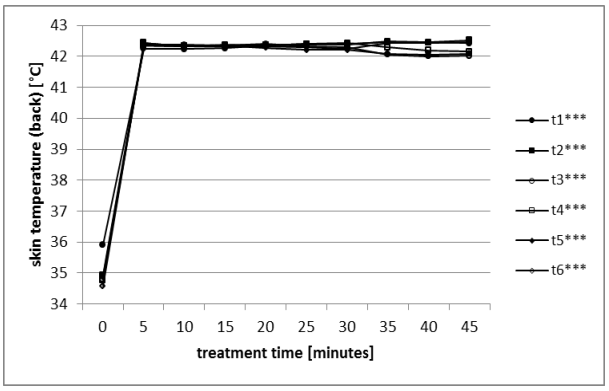
B Mean systolic blood pressure



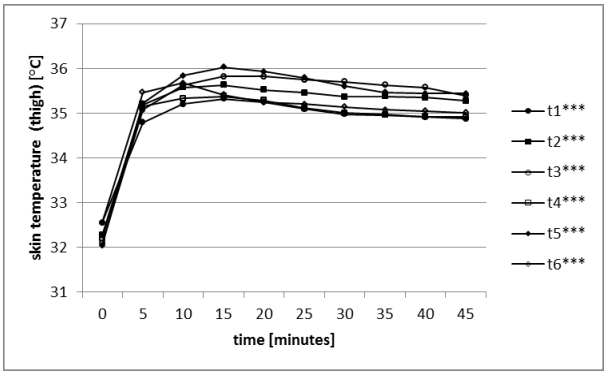
C Mean diastolic blood pressure



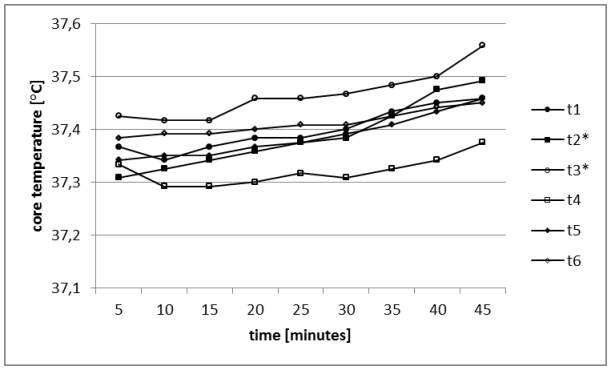
F Mean skin temperature (back)



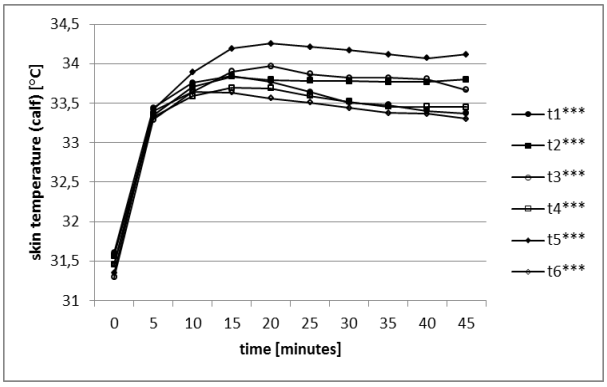
D Mean peripheral skin temperature (thigh)



G Mean core temperature



E Mean peripheral skin temperature (calf)



H Mean oxygen saturation

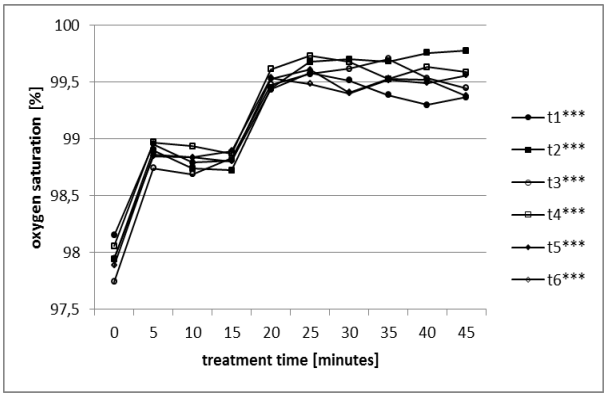


Figure 1*(A-H): Physiological responses during the HBOIR treatments (t) 1-6. Means are calculated over a 5 min period except systolic and diastolic blood pressure (5 minute interval measurement). * P-value ≤ 0.05, *** p-value ≤ 0.001 for significant changes from baseline to the end of treatment. N=12 for each time point.*

3.2 Perceived wellbeing

The scores for perceived well-being did not deteriorate during the course of the treatments. On the contrary, well-being scores significantly increased during t1 (90.4±15 to 98.5±12), t3 (88.6±19 to 96.1±12) and t5 (88.4±19 to 97.9±13).

3.3 Ambient parameters (Chamber)

Ambient parameters in the chamber are presented for the period of time during which the chamber was overpressurized by 0.5 bar (minute 5 to minute 45 for HBOIR sessions 1 to 6) (Table 2; Figure 2).

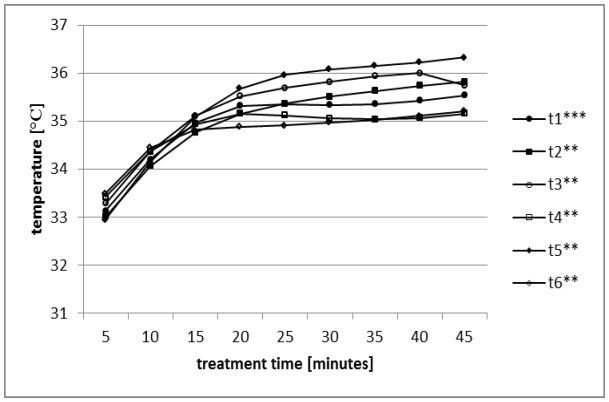
Air temperature in the chamber significantly increased during all treatments (t1: p≤0.001; t2-t6: p≤0.01). Average air temperature was 35.01±1°C. Humidity showed a significant increase (p≤0.001), with an average humidity of 57.1±6 % during all treatments. As expected, there was a significant elevation in oxygen concentration inside the chamber (p≤0.001). Average oxygen concentration during all treatments was 23.3±1 %. After pressurization of the chamber, a slight decrease in pressure was observed during t2 (-2.1 mbar; p≤0.01), t3 (-1.8 mbar; p≤0.05) and t4 (2.7 mbar; p≤0.001). Average chamber pressure during all treatments was 1449.9 ± 4 mbar (0.5bar overload pressure). No significant changes in CO2 were observed. Mean CO2 concentration inside the chamber was 606 ± 242 ppm during all treatment sessions.

Table 2: Changes in ambient chamber parameters

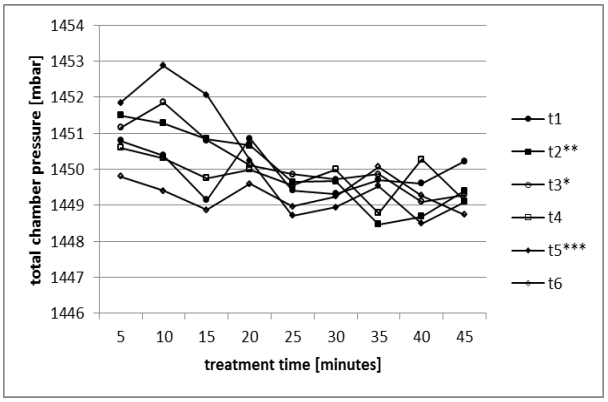
	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 6
Air temperature (°C)						
Start of treatment	33.1±1	33.0±1	33.3±1	33.4±1	33.0±1	33.5±1
End of treatment	35.5±2***	35.8±2**	35.7±2**	35.2±1**	36.3±2**	35.2±1**
Humidity (%)						
Start of treatment	46.3±7	43.7±7	48.5±10	47.4±9	48.1±5	50.7±7
End of treatment	63.0±4***	61.8±4***	64.5±7***	65.9±4***	65.0±4***	66.4±5***
Chamber pressure (mbar)						
Start of treatment	1450.8±1	1451.5±1	1451.1±1	1450.6±2	1451.8±1	1449.8±1
End of treatment	1450.2±1	1449.4±1**	1449.3±1*	1449.1±2	1449.1±1***	1448.7±2
Oxygen concentration (%)						
Start of treatment	21.3±0.8	21.0±0.2	21.4±0.9	21.4±0.8	21.5±1.2	21.5±1.1
End of treatment	26.5±2.4***	25.3±1.0***	25.5±1.4***	25.5±2.1***	25.5±2.0***	24.9±1.2***
Co_2 concentration (ppm)						
Start of treatment	665±118	787±233	679±158	620±138	734±111	591±134
End of treatment	597±181	672±285	633±290	559±196	622±218	538±186

*Values are shown for the time when the chamber was pressurized (minute 5 - minute 45; 1450 mbar). Data are presented as means ± SD. * p-value ≤ 0.05, ** p-value ≤ 0.01, *** p-value ≤ 0.001 for significant changes within one treatment session (ANOVA).*

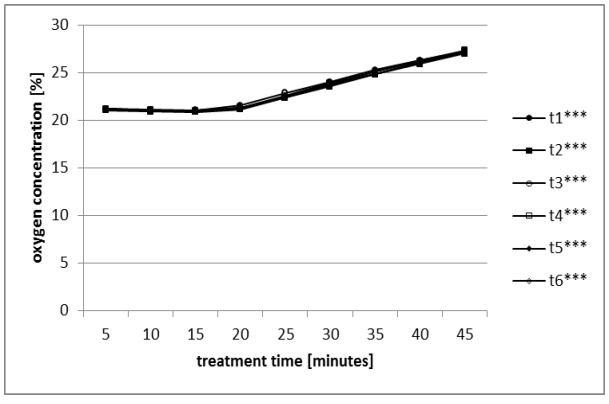
A Temperature



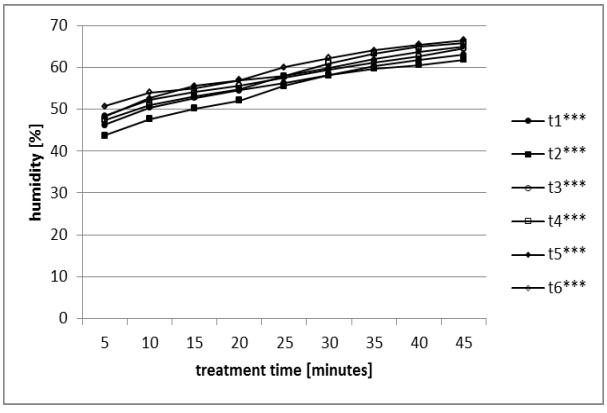
C Chamber pressure



B Oxygen concentration



D Humidity



E CO2 concentration

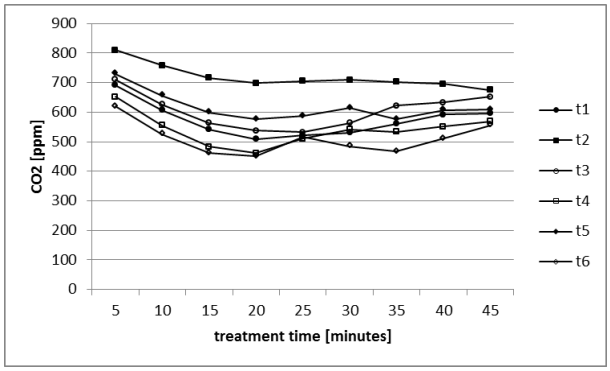


Figure 2 (A-E): *Ambient parameters in the chamber during HBOIR treatments (t) 1-6. Means are calculated over a 5 min period. * p-value ≤ 0.05, ** p-value ≤ 0.01, *** p-value ≤ 0.001 for significant changes from minute 5 to the end of treatment as determined by ANOVA analysis. Data are presented for the period of time when the chamber was pressurized at 0.5 bar. Total chamber pressure is standard atmospheric pressure plus overload pressure.*

4. Discussion

This is the first study to examine the safety and feasibility of a combined application of HBO and LIT in a single hyperbaric chamber. Six treatments were performed on 12 healthy subjects without the appearance of any adverse effects or complications (mentally and physically).

At the end of the HBOIR applications, we observed significant elevations in core temperature to a maximum of +0.2°C. This change was accompanied by increases in mean peripheral skin temperature to a maximum of + 3°C compared to temperatures at study entry. The larger increase in peripheral skin surface temperature at the thigh relative to the calves observed in our study can be explained by a mechanism of temperature regulation: increase in convective heat transfer from the inner body to the periphery [17]. Generally, heat applications can be carried out below, within or above the thermoneutral zone. Sauna treatments (80-100 °C) are usually performed above the thermoneutral zone where more heat is absorbed by the body as can be released as heat cannot be dissipated by conduction, convection or radiation. Moreover, the vapor pressure of the air is higher than that of the skin so the excess heat can also not be released through evaporation. Consequently, blood flow significantly increases in order to reduce thermal strain of the skin. At the same time, blood supply to the inner body initially decreases to prevent an increase in core temperature. This is accompanied by a sharp increase in cardiac output [18]. After an exposure time of 8-15 minutes, reverse blood flow has to be established to compensate for the relative central volume depletion, leading to a rapid increase in core temperature up to 39°C [19], [20]. In contrast, whole-body warming applications (Biosauna or Infrared chambers) at 50-60°C, exert considerably lower cardiovascular strain, and evaporation allows heat dissipation [21]. However, it should be noted that these body-warming applications also do not cause an immediate change in the core temperature and temperature distribution to the body shell is not possible. Heat applications within the thermoneutralzone are used in order to achieve low strain, whole-body warming. Warming of an area of no more than 15% of the overall skin surface, as carried out in our study, allows thermoneutral blood (from 85% of the body surface) to mix with warmed blood (from 15% of the body surface) in the central circulation. In this case, circulation of the small amount of warmed blood to the inner-body is tolerated and heat can be transferred through the blood from the inner body to the body shell, as long as a specific quantity of heat is not exceeded. Thus, cardiovascular strain remains low and the core temperature is able to continuously increase by up to 0.3°C from the onset [13].

Thermal transfer using infrared radiation does not require contact and thus defense reaction of the skin is least affected when compared to other heat application systems. In order to prevent acute (burn) and chronic (erythema ab igne) thermal damage, the intrinsic skin temperature should not exceed 43°C, permanently or repeatedly [22], and heat applications should hinder skin blood flow as little as possible [14], [15]. Heat input should be increased slowly, adapted to the increase in blood circulation. Each 0.9 °C increment in skin temperature cuts tolerance time in half, resulting in a maximum tolerable temperature of ~46 °C over a 45 minute treatment period [15]. As pain response to heat is not a reliable parameter in preventing thermal damage, especially in the presence of sensory disturbances and/or drug intake, heat application systems should register skin temperature in the irradiated region continuously and contactless to ensure automatic regulation of the heat input. The implemented Sensocare® technology fulfills these criteria and allows avoidance of acute or chronic skin damage.

In this study, a significant rise in SpO_2 was observed when oxygen was introduced via the facial mask. Importantly, the elevated SpO_2 values remained constantly high for the rest of each treatment period.

In addition, we found a moderate increase in heart rate, whereas systolic and diastolic blood pressure did not change significantly. In studies of hemodynamic effects, HBO has been reported to provoke a slight augmentation in blood pressure [23], [24]. This observation could be an effect of the combined application of the two techniques (HBO and LIT), with external heat acting as a vasodilatory factor [25], which could potentially compensate for hyperbaric-, hyperoxia-induced increases in blood pressure. According to the study by Cui et al. [18], heat-induced vasodilatation of superficial skin vessels combined with a lack of change in blood pressure can provoke a compensatory increase in heart rate.

Our study demonstrates that HBOIR is technically very realizable, despite the specific challenge of practically combining HBO and LIT. Upon reaching the overload pressure of 0.5 bar, the chamber pressure remained stable during the rest of the treatment. Exhaled CO2 was permanently scrubbed inside the chamber. Consequently, there were no significant changes in mean CO2 concentration values from the beginning to the end of each treatment.

In our study, thermal strain of the skin remains in a very tolerable range. Furthermore, compliance with the skin temperature threshold is confirmed by the disappearance of the reddened skin within two hours of treatment, rendering the implemented automatic radiation system (Sensocare®) safe even under hyperbaric conditions. In addition, we demonstrate that it is possible for healthy subjects to maintain their core temperature in a desired sub-febrile range (≤38°C) using the Sensocare® system in combination with LIT for the scheduled period of 45 minutes even when heat is applied under an overload pressure of 0.5 bar

.5. Conclusion

The combined application of LIT and HBO has successfully been realized, and resulted in a mild whole-body warming, with only moderate cardiovascular strain, without showing any adverse effects or negative impacts on well-being. The results of our study indicate that HBOIR under an overload pressure of 0.5 bar is safe and feasible in a group of healthy subjects. The first step in evaluating the efficacy of the HBOIR system would be to increase the overload pressure to 1.4 bar, thus making HBO and HBOIR comparable. Subsequently, the effect of HBOIR should be evaluated on patients with relevant conditions, such as peripheral vascular disease or rheumatoid arthritis.

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