Summary of Present Researches of Hyperoxia in Sports Training and Outdoor Activities

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Abstract
The main goal of this overview article is to sum up the available information about the technics of hyperoxia, the possibility of its usage in outdoor activities, its influence on sports performance and recovery between loads. Results have been taken from the relevant reviewed documents published, in full, in scientific magazines and specialist monographies. Articles were expanded by a reference pick ("snow ball" method) of other works written by the same authors and works of cited authors in these articles.
In our study, we are mainly focused on using long-term inhalation of a hyperoxic mixture to replecate the actual condition in outdoor activities (climbing and diving), but we are also focusingon using short-term inhalation of a hyperoxic mixture, which is used more often, primarily in cycling, canoeing and swimming. In this article we are pursuing the usage of hyperoxia for maximum performance.
We have two options on how to provide the hyperoxic environment. Firstly, to use pressurized bottles with more concentrated oxygen, which is good for direct usage. Secondly, to use oxygen concentrators, which separate oxygen from common air. For acute conditions, which can happen in outdoor activities, it is very important to start the inhalation of pure oxygen as soon as possible. Eligible scientific sources are split about the impact in sports training.

Key words:
Hyperoxia, oxygen, emercency, submaximal exercise, mountain sickness, decompression sickness, outdoor activities

Souhrn
Hlavním cílem přehledové studie je shrnout dostupné informace týkající se techniky aplikace hyperoxie, možností jejího využití v outdoorových aktivitách, dále pak jejím vlivem na sportovní výkon a zotavení mezi zátěžemi. Informace byly získány z relevantních recenzovaných dokumentů publikovaných v plném znění ve vědeckých časopisech a odborných monografií. Články byly rozšířeny referenčním výběrem (metoda „sněhové koule“) o další práce stejných autorů a o práce autorů v těchto článcích citovaných.
V naší studii se zabýváme především využitím dlouhodobé inhalace hyperoxické směsi pro překlenutí akutních stavů při outdorových aktivitách (horolezectví, přístrojové potápění), ale i využitím krátkodobé inhalace hyperoxické směsi, která je ve sportovním tréninku, zejména cyklistice, kanoistice i plavání, využívána více než dlouhodobá inhalace hyperoxické směsi. V článku se zabýváme vlivem hyperoxie na úroveň maximálního výkonu, přičemž na základě výzkumů se ukazuje, že tento vliv je minimální.
Pro aplikaci hyperoxické směsi existují v zásadě dvě možnosti a to použití tlakových lahví, které slouží jako zásoba plynu vhodného k přímému použití, či koncentrátorů, které separují kyslík z okolního vzduchu. Při akutních stavech, které mohou nastat v outdoorových aktivitách, je důležité neprodleně zahájit inspiraci čistého kyslíku. V případě sportovního tréninku se dostupné zdroje rozcházejí ve vlivu hyperoxie na sportovní výkon.

Klíčová slova:
Hyperoxie, kyslík, neodkladná lékařská péče, submaximální cvičení, akutní horská nemoc, dekompresní nehoda, outdoorové aktivity

Introduction

Hyperoxia is an increase in the partial pressure of oxygen above the normal values, meaning above 20 kPa (150 mm Hg). Paleček (2001) states that reaching those values of partial oxygen in tissues and blood is not possible via a physiological way. That is why it is necessary to expose the human organism to the inhalation of a gas mixture with an increased partial pressure of oxygen. It can be done in a few ways. Firstly by breathing air with the common concentration of oxygen with an increased partial pressure (e.g.: scuba diving), or secondly by breathing air with an increased concentration of oxygen, or thirdly by a combination of both ways.

Short-term inhalation of hyperoxic mixture is used mainly in the Department of Clinical Medicine as an oxygen therapy (e.g.: spanning acute conditions of a lack of oxygen) (Müller et al., 2008). Last but not least, hyperoxia is used in acute conditions in different outdoor sports, such as mountain climbing or scuba and free diving. In mountain climbing, it is used in the case of acute mountain sickess (AMS), described as a condition in individuals who have ascended too high too quickly, typically above an altitude of 2,500 m Salisbury & Hawley (2011). In scuba/free diving, we use hyperoxia as a treatment for decompression sickness (DCS), which mostly happens due to surfacing from deep water too quickly.

Hyperoxia has been used for a long time in urgent medicine, mostly in treating acute and chronical respirational and circulatory problems (Gosseling et al., 2004). A positive impact has been observed in the inhalation of concentrated oxygen on training load and recovery (Kay, Stannard, & Morton, 2008; Morris, Kearney & Burke, 2000; Pupiš et al., 2010; Sperlich et al., 2011; Suchý, 2012). Training load is perceived as a motion activity, which is causing not only a desired acute change of functional human acitivity, but furthermore, consistent structural and psychosocial changes (Dovalil et al., 2009). However, these changes are not passing off during this motion activity, but after its ceasation in the recovery phase. If the intensity of the sport performance drops under a certain level, the oxidative transformation of lactate into pyruvate takes place in the muscles, which is occurs in mitochondria cells by means of enzymes in the respiratory chain of the cell to produce ATP. In the liver, hepatic glycogen is then resynchronized from the lactate. Both of these transformations are oxidative and their speed depends on the load of oxygen, which is provided by circulatory system. Increasing the intake of oxygen with inhaling a hyperoxic mixture has a positive impact on the regeneration of muscles after training. By inhaling a hyperoxic mixture with an oxygen concentration of 90 -100%, inhaled oxygen uptake is increased by up to 10%, resulting in an increased oxygen supply to the muscles and a decreased heart rate. By that, it is possible to increase training intensity and achieve higher effectivity of sports training (Hollmann & Hettinger, 1980).

An increase of performance with the inhalation of hyperoxic oxygen was observed mainly in actitivities, which lasts 2 to 3 minutes (Haseler, Hogan & Richardson, 1999; Nummela, Hamalainen & Rusko, 2002), but also in ice-hockey players (Suchý, Pupiš & Novotný, 2012). Results of many studies confirmed that the inhalation of concentrated oxygen is possible to accelerate recovery between short-term training loads by increasing the saturation of blood and tissues with oxygen (Suchý, 2012; Pupiš, Babaríková, Brunerová & Suchý, 2011). A reduction in the perceived effort has also been observed (Peeling & Andersson, 2011). On the contrary, performance improvement due to hyperoxia was not demonstrated in the short-term load under submaximal and maximum effort and also in the long-term load (Robbins, Gleeson & Zwillich, 1992).

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Methods

This review article was developed based on expert studies available from the primary databases 'Web of Science and Scopus'. Information was searched by using key words such as: Hyperoxia, Oxygen, Emergency, Submaximal exercise, Mountain sickness, Decompression sickness and Outdoor activities. The data for the review of the technical means used for hyperoxia was drawn from the internet sources Linde Gas (n.d.), Philips Respironics (n.d.) and Kröber Medizintechnik (n.d.).

The selection of primary documents, which were used for the study, was that the full publication had been in a major peer-reviewed scientific journal and/or in an academic monograph. Articles were expanded by a reference pick ("snow ball" method) of other works written by the same authors and works of cited authors in these articles.

Results

The result part of this review study deals with the use of hyperoxia in the treatment of acute conditions in outdoor activities, the health limits of hyperoxia use, the effects of the inhalation of hyperoxic mixture on sport performance and the technical equipment necessary for hyperoxia.

Health limits for the use of hyperoxia

The State Institute for Drug Control (SIDC) warns that the toxicity of oxygen, duringnormobaric inhalation in concentrations exceeding 40 %, is usually possible up to 48 hours. At a concentration from 60 to 70 % up to 24 hours and 100% oxygen up to 6 hours. In hyperbaric inhalation of pure oxygen at a maximum of 3 bar, the treatment dose is limited to 6 hours, with the possibility of repeating up to three times a day. The exception is the CO poisoning therapy in which hyperbaricity is performed until the blood carboxyhemoglobin concentrations are sufficiently diminished. By the inhalation of pure oxygen at a pressure above 3 bar, the patient should be monitored for signs of oxygen overdose such as sinusitis, confusion, convulsions, vision impairment (SIDC, 2016).

Technical equipment for hyperoxia

In order to breathe air with an increased oxygen concentration, devices such as pressure bottles (or oxygen sprays) or facial mask units must be used. Pressure cylinders are designed mainly for the transport and storage of gases. The so-called water volume, typically 1-50 liters, is determined, and they have a maximum fill pressure that is usually 200 bar or 300 bar. For example, 400 liters of gas can fit into a 2 liter bottle with a filling pressure of 200 bar. Due to the high gas pressure, the cylinders are not intended for direct use, but as an oxygen device with a reduction valve (Linde Gas, n.d.) has to be used. Oxygen sprays where oxygen is pressurized to a much lower pressure and are thus designed for direct use, and their components do not have a pressure reducing valve. Their disadvantage is a lower supply of oxygen, typically 5-15 liters and a higher price in proportion to volume. Oxygen devices and oxygen concentrators can be arranged as the aggregates. Oxygen devices use an oxygen supply in a pressure bottle and include a pressure reducing valve that reduces the gas pressure in the bottle to a value suitable for inhalation. The gas flow through the reducing valve is adjustable over a wide range and it is possible to deliver a large amount of gas. Oxygen concentrators can separate oxygen from the ambient air, so they do not need gas in the form of pressure bottles. Typical types are able to achieve approximately 90-95% oxygen concentration at a controllable flow rate of up to 5 liter/min (Philips Respironics, Kröber Medizintechnik, n.d.).

Use of hyperoxia in outdoor activities (emergency states)

Primarily, hyperoxia was used in urgent medicine. Basically, it is the use of normobaric and hyperbaric hyperoxia. Hyperoxicity increases blood saturation and tissues with oxygen, which reduces the venous blood buffer capacity and the binding of CO^2 and CO to hemoglobin. Another important role of hyperoxia is its antibacterial effect. For these reasons, inhaled hyperoxic mixture is used to treat CO poisoning, infection, burns, and severe anemias. Treatment of gas emboli and decompression sickness requires hyperbaric hyperoxia (hyperbaroxia) (Jabor et al., 2008).

According to Salisbury & Hawley (2011), more and more people are taking up alpine tourism. While in 1950-1989 2,631 people reached Himalayan summits, in 1990-2009 it was 9,199 climbers. The authors further state that AMS was the third most common cause of climbers' deaths in 1950-2009 when they attempted to reach Himalayan peaks above 6,000 meters (see Table 1). In the treatment of decompression sickness and AMS, a therapeutic method is used in the form of hyperbaric chamber utilization. In hyperbaroxia, pure oxygen is usually inhaled at a pressure that is 2.5-3 times higher than atmospheric pressure. Therefore, the partial pressure of oxygen in the hyperbaric chamber can be up to 15 times higher than under normal conditions (Czech Society of Hyperbaric and Aerial Medicine, n.d.).

The cause of AMS is not entirely clear. Hultgren (1997) claims that hypoxia increases the blood flow to the brain, to vasodilatation and thus to brain swelling. Berré, Vachiéry, Moraine & Naeije (1999) found that when breathing the hyperoxic mixture, the blood flow to the brain decreases, which has a beneficial effect on the symptoms of acute mountain sickness. This decrease was observed both in climbers who had an increased tolerance to AMS symptoms and in those who had problems with higher altitude. The main symptoms are usually headache, nausea, insomnia, malaise and fatigue. A longer stay at this altitude can lead to the swelling of the lungs, brain swelling and death (Luks, Swenson & Bärtsch, 2017). The most effective treatment of these conditions is, in lighter cases, the normobaric administration of pure oxygen and an accelerated descent to lower altitudes. In the case of pulmonary or cerebral edema, it is advisable to use hyperbaric hyperoxia,

Table 1: Causes of death for all Himalayan peaks in 1950-2009 (Salisbury & Hawley, 2011)

Cause of Death	**Expedition members**		**Hired members**		**Total**	
	Count	**Precentage**	**Count**	**Precentage**	**Count**	**Precentage**
AMS	46	7.6 %	20	8.9 %	66	7.9 %
Exhaustion	18	3.0 %	2	0.9 %	20	2.4 %
Exposure/Frostbite	35	5.8 %	1	0.4 %	36	4.3 %
Fall	237	39.0 %	31	13.8 %	268	32.2 %
Crevasse	15	2.5 %	5	2.2 %	20	2.4 %
Icefall Collapse	2	0.3 %	15	6.7 %	17	2.0 %
Avalanche	175	28.8 %	104	46.4 %	279	33.5 %
Falling Rock/Ice	14	2.3 %	9	4.0 %	23	2.8 %
Disappearance	26	4.3 %	2	0.9 %	28	3.4 %
Illness (non-AMS)	26	4.3 %	15	6.7 %	41	4.9 %
Other	12	2.0 %	12	5.4 %	24	2.9 %
Unknown	2	0.3 %	8	3.6 %	10	1.2 %
Totals	608	100.0 %	224	100.0 %	832	100.0 %
AMS-related	67	11.0 %	18	8.0 %	74	8.9 %
Weather/Storm-related	44	7.2 %	6	2.7 %	50	6.0 %

e.g., using an inflatable hyperbaric chamber while inhaling pure oxygen and a transfer to a medical facility is necessary (Peacock, 1998).

Scuba diving has recently been easily available for laymen and, unlike acute mountain sickness, whose symptoms appear slowly and gradually, a decompression accident can occur almost immediately (e.g. in the case of a rapid emergence). A decompression accident in connection with diving is caused by a rapid drop in the ambient pressure during a rapid submergence which forms bubbles of gas in the blood or tissues. The most serious consequences of a decompression accident are decompression sickness and arterial gas embolization. Decompression illness is caused by the formation of bubbles due to the release of inert gases (primarily nitrogen) dissolved in the blood and a rapid drop in ambient pressure. Microtrugs occur in different parts of the body, which are manifested by fatigue, itching of the skin and abdominal pain. Arterial gas embolization occurs when gas bubbles cause the collapse of the blood circulatory system. When treating a decompression accident, 100% oxygen is given as first aid regardless of the composition of the previous breathing compound during the dive. For more serious symptoms, such as headaches, jointache, dyspnoea, paralysis, hearing impairment, vision, speech or bizarre behavior, it is necessary to place the diver on his back and administer pure oxygen until they are moved to a hyperbaric chamber. The lowest operational pressure in the hyperbaric chamber, wherte the patient should remain at least until the symptoms disappear, is recommended to be 2.8 bar (Novotný & Pácová, 2012).

Howle, Weber, Hada, Vann & Denoble (2017) have retrospectively monitored 3,322 drafts at different depths and different breathing mixtures. They found that in 5.7 % of the dives there was a decompression accident: 89.5 % of these accidents showed light symptoms (skin burns, headache or jointache) and 10.5 % of the symptoms were classified as serious (circulatory problems, serious Neurological symptoms).

The effect of hyperoxia on the training load and the course of recovery between the loads

In their study, Sperlich, Zinner, Hauser, Holmberg & Wegrzyk (2017) reported that the effect of hyperoxia on recreational athletes is likely to be lower than that of possible adaptation changes. It is believed that hyperoxia is of greater significance in top athletes who have already reached their limits in their adaptation.

The results of many studies show that hyperoxia improves performance during both maximal and submaximal loads under a cycloergometer training load (Grataloup et al., 2005; Linnossier et al., 2000; Lovering et al., 2008; Peltonen, Tikkanen, & Russia, 2001; Prieur et al., 2002; Tucker et al., 2007).

Haseler et al. (1999) and Nummela et al. (2002) report that an increased performance with using concentrated oxygen was observed primarily in activities lasting 2 to 3 minutes. Suchý et al. (2012) reported that performance gains also occurred in ice-hockey players in a sports-specific test, the length and course of which simulated one substitution in an ice-hockey match (i.e. about 50 seconds).

Peltonen et al. (2001) reported that inhaling a hyperoxic mixture with an oxygen concentration of 62 % during an all-out test on a rowing ergometer on a 2500 m track has a statistically significant ($p < 0.05$) positive effect on the time during the third 500m Section of the test and increases the mean power throughout the test.

Sperlich et. al. (2011) in his study stated that breathing pure oxygen during a 6-minute pause between five series of 40 swim strokes with maximum effort on a swimming isokinetic treadmill improves maximal performance and mean power during the third, fourth and fifth load intervals.

Robbins et al. (1992) argued that inhalation of 100% oxygen during a four-minute pause between three training loads with a submaximal effort on a running ergometer (the first two five-minute loads, the third load to exhaustion) did not affect the minute ventilation, heart rate, and fatigue perceptions expressed on the Borg scale (Borg, 1982).

Peeling & Andersson (2011), in their article, investigated the effect of hyperoxia on the rate of recovery of oxygen saturation during recurrent recoveries on a kayak ergometer. Probands (5 males and 2 females) underwent a six X three min load with a 2-minute recovery after each load, during which they either inhaled a hyperoxic mixture with 99.5% concentration or a placebo. Prior to testing, the initial oxygen saturation value was measured by a pulse oximeter. The inhalation of the hyperoxic mixture did not affect the average power, frequency of strokes, speed and heart rate. Also, the lactate levels measured 15 seconds before the end of the recovery period were not affected by hyperoxia. The time of the recovery of the oxygen saturation value was significantly reduced, but the subjective perception of recovery quality did not increase with inhaling hyperoxic mixture.

Vanhatalo, Fulford, DiMenna & Jones (2010) in their study investigated the effect of hyperoxia on muscle tissue metabolism and performance dependence on high intensity loading. The objective of the probands was to predict a constant load in single knee-leg extensions at the limit of critical performance (CP), at which a balance in lactate formation and its oxidative conversion back to adenosine triphosphate (ATP) occurred. Spectroscopic magnetic resonance of quadriceps was performed during the test, where the amount of inorganic phosphorus (Pi), ATP-bound phosphorus, intramuscular creatine phosphate (PCr) and phosphodiesters was determined. From the measured values, the pH in the muscle was calculated. At the critical power limit, the probands had the same PCr values (5-10 % of the preloaded value) and pH (~6.65), either with 70 % oxygen or placebo (common air) inhaled during the load. However, when the hyperoxic mixture was inhaled, the critical performance was significantly higher and achieved over a longer period of time compared with placebo inhalation.

Sperlich et al. (2012) dealt with the impact of inhalation of the hyperoxic mixture on the changes of maximal and mean power at the intermittent load with maximum intensity. Ten healthy, trained cyclists performed five 30s of maximum load on a cycloergometer in isokinetic mode (120 rpm), and inhaled pure oxygen or placebo during a six-minute recovery period between the sets. The values of both the maximal and the mean power during the loading did not differ in the case of hyperoxia or normoxia, as did the pH, the concentration of lactate and hydrogen cations in capillary blood. Partial oxygen pressure in the blood and oxygen saturation of the blood increased in hyperoxia. Subjective perceived effort was reduced at the end of the recovery period after the fourth and fifth load cycles.

Discussion

From a technological point of view, the use of inhaled hyperoxic mixture in many sports is limited. Although oxygen inhalation is not on the World Anti-Doping Agency (2017) banned list, it cannot be used in many sporting competitions. It is essential to use the technical equipment to inhale the hyperoxic mixture immediately before or during exercise, which the rules of many sports explicitly prohibit – e.g. in athletic competitions where the competitor cannot bring the technical equipment for hyperoxia to the competition track and field area International Association of Athletics Federations (2017). For this reason, the effect of hyperoxia is investigated primarily in model tests. Many studies also deal with the use of hyperoxia during the recovery from high-intensity exercise to the following exercise performance, with the hyperoxic mixture being administered immediately after the end of the load to accelerate recovery (Nummela et al., 2002; Peeling & Andersson, 2011).

An important limit for the use of hyperoxia in sports is the length of sport performance itself and the intensity of the load. Vanhatalo et al. (2010) and Sperlich et al. (2012) showed that the inspiration of the hyperoxic mixture does not affect the maximum performance level. This is probably due to the fact that the maximum power is dependent on the immediate supply of ATP in the muscles, not on the O_2 delivery system by the circulatory system. On the contrary, some studies (Sperlich et al., 2011; Suchý, 2012) showed that hyperoxia during recovery has a positive impact on the following maximum high intensity performance, which is probably due to the faster conversion of the lactate produced in the previous load to ATP.

There is a limit to the possibility of continuously utilizing hyperoxia during exercise due to its technical difficulty.

In the treatment of acute conditions associated with AMS in mountaineering and scuba/free diving accidents, sources (Peacock, 1998; Novotný & Pácová, 2012; Berré et al., 1999) agree that the most basic option is the rapid initiation of treatment in the form of inhaled hyperoxic mixture, ideally pure oxygen. In the case of heavier AMS manifestations, thuis treatment is important to be supplemented by lowering the affected person to a lower altitude, and in the more severe cases of decompression accidents hyperoxic treatment should be performed hyperbarically.

Dean, Mulkey, Henderson, Potter & Putnam (2004) suggested that chronic or long-term (over 72 hours) exposure to an hyperoxic environment can cause cellular damage, therefore, hyperoxia in sports should be performed under medical supervision. However, short-term hyperoxia in the treatment of acute conditions is not harmful to health, no toxic effects on the brain and the circulation system have been demonstrated (SIDC, 2016).

Unlike hypoxia, exposure of the body to a hyperoxic environment in sports is an artificial improvement in performance. For this reason, inhalation of oxygen-enriched air, whether in sports competitions or training environments, raises ethical concerns. When using hyperoxia during training, it is advisable to closely monitor its possible negative effects on the health of the athlete, especially in hyperoxic training combined with higher altitude stays (Sperlich, Calbet, Boushel & Holmberg, 2016). Conclusions of some research do not confirm the positive effect of hyperoxia on sports performance, and there is insufficient information on whether chronic exposure on the organism of the hyperoxic mixture damages the health of athletes.

In some areas of hyperoxia use there are certain reserves. For example, in sports games such as ice-hockey, handball and floorball, the use of a hyperoxic mixture is offered during the course of a match, as the player, after about 1 minute of the load, goes to the rotation bench where it is possible to inhale air with increased oxygen concentration during the recovery. However hyperoxia is not used commonly in the competition on a larger scale.

Conclusion

The review study summarizes the available knowledge on the technical means of hyperoxia and the use of hyperoxia in outdoor activities and in sports training. There are basically two options for the application of a hyperoxic mixture, namely the use of pressure cylinders which serve as a supply of gas suitable for direct use, or of concentrators which

separate oxygen from the ambient air. In non-laboratory conditions, whether in outdoor activities or in sports training, it is preferable to choose cylinders that do not need electricity for their function.
In the case of hyperoxia in acute conditions in mountaineering and diving, it is important to immediately initiate the inhalation of pure oxygen. For mountaineers in connection with acute mountain sickness, it is important to descend to a lower altitude or to fit into an inflatable hyperbaric chamber that simulates this descent. When treating a decompression accident, it is necessary to deliver pure oxygen as soon as possible, irrespective of the composition of the previous breathing mixture.
In sports training, available resources differ in the effect of hyperoxia on sports performance. In the case of intermittent loading and use of hyperoxia during the recovery period, the positive influence on the mean or maximum performance was demonstrated in swimming (Sperlich et al., 2011). On the contrary performance improvement in a kayak ergometer (Peeling & Andersson, 2011) and on the cycloergometer (Sperlich et al., 2012) has not been demonstrated. In the case of a one-off load, a positive influence on performance was demonstrated in rowing (Peltonen et al., 2001).

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