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HEART RATE CHANGES (ΔHR) AND OXYGEN SATURATION IN BLOOD (ΔSAO2) DEPENDENCY IN RELATION TO THE STATIC APNEA DURATION (STA)

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Abstract

In static apnea discipline diver holds the breath in standstill condition. Diving reflex represents a reaction of the body to apnea dive with responses of effectors: bradycardia, peripheral vasoconstriction, splenic contractions. Physiological significance of these body changes implies reduction of oxygen consumption. The main objective of this research is to examine characteristics of connection between heart rate changes (ΔHR) and changes in oxygen saturation in blood (ΔSaO2) during apnea. A group of 15 breath hold divers was examined. Tests were conducted during static apnea, heart rate (HR) was measured as well as oxygen saturation in blood (SaO2). The changes in HR and SaO2 during apnea demonstrated statistically significant correlation. Higher HR values in apnea indicate higher mental tonus during apnea which is followed by higher muscle tonus. The consequence is a greater consumption of O2 and lower values of SaO2min. There is statistically significant correlation between intensity of diving reflex activation and oxygen conserving (less reduction of SaO2).

Keywords: breath hold diving (freediving), diving reflex, apnea

Introduction

Breath hold diving (freediving) is a type of diving, i.e. immersion of the body in the water in apnea condition (holding the breath). It is a sport activity in which the sportsman (diver), diving with only one breath, reaches certain results regarding the length, depth or time of the dive. Freediving is natural (physiological) diving, in contrast to SCUBA (self contained breathing apparatus) and therefore it represents much older type of diving. In freediving, a diver dives within the physiological limits of the body, using only his/her own ways of adaptation.

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The most natural type of diving is repeated dives in short apnea. These are repeated dives within 50-80% of maximum apnea. On the other hand, competitive diving means performing one sub maximum apnea up to 99% of the possibilities, where the limit is represented by tolerance to hypoxemia. The main problem of freediving is hypoxemia (oxygen deprivation while holding the breath). Using various training programmes and combining different training stimuli, one can stimulate different physiological potentials and adaptation mechanisms. Training has a positive effect on higher tolerance to oxygen consumption, tolerance to higher values of CO_2, relaxation of body and mind, increase of breath capacity and quality. Freediving disciplines are static and dynamic apnea, as well as constant weight.

STA (Static Apnea) represents holding breath at a standstill. Divers float on the surface of a pool in the state of complete body and mind relaxation. The time which divers spend holding the breath is measured. The diver wears a diving suit, masks or goggles and noseclip, and possibly gloves and socks. From the mental point of view, this is the most challenging discipline in freediving since the diver is in complete standstill condition on his own. In this discipline the relaxation techniques and mental training are of crucial importance.

Freediving, i.e. apnea represents a combination of factors which have effects on the body:

1) respiratory arrest (holding the breath)

2) O_2 consumption and building up of CO_2 in the body

3) impact of ambient pressure on the diver’s body

Current world record in static apnea (STA) 11 min, 35 sec. (AIDA International 23.02.2011 www.aida-international.org).

Physiological changes in freediving. Apnea means respiratory rest – absence of respiratory activity, i.e. air exchange with the surroundings. As a consequence of metabolic processes in organism, O_2 consumption occurs during apnea, i.e. oxygen saturation in blood and tissue decrease (ΔSaO_2), and CO_2 build up also starts to occur. **Reduction of O2 consumption** means reduced taking O_2 from the lungs, as well as slow O_2 consumption in tissues (Lindholm, 1999). Although respiratory activities stop in apnea, the respiratory process at alveolar membrane, capillary and cell level (all three breathing phases) is still going on continuously. There are two phases of Apnea:

- **fist phase (easy going phase)** – before air urge (diaphragm contraction), high PaO_2, low $PaCO_2$, mostly aerobic phase
- **second phase (struggle phase)** – begins with the diaphragm contractions, the beginning of this phase is determined by high $PaCO_2$, at the end of this phase there is low PaO_2 up to the blackout limit, mostly anaerobic phase.

Changing from the first to the second phase happens at the **physiological breaking point** when subjective feeling of urge to breath appears, which is manifested by involuntary breathing movements, i.e. diaphragm contractions. Physiological breaking point appears at the moment when $PaCO_2$ reaches values which stimulate respiratory centres. However, despite the hypercapnia and involuntary respiratory movements, apnea breaking and breathing can be voluntary postponed (Schagatay, 2001). Training, in other words repeated apneas, develops tolerance to high values of hypercapnia, as well as higher tolerance to hypoxemia (Schagatay, 2009). During apnea, the first phase (easy going phase) takes place within diving aerobic limits. This also applies to short apneas which are stopped before urge for breath (diaphragm contractions) (Schagatay, 2009). Other apneas, which are prolonged after the diaphragm contractions have started, are connected to accumulation of lactate and appearance of oxygen debt. The second apnea phase is anaerobic apnea phase.

There are three factors which determine apnea time limits (Schagatay, 2009): a) organism capacity to store O2, b) tolerance to hypoxemia and/or hypercapnia and c) minimal oxygen consumption VO2min.

a) Organism capacity to store O2 depends on the size and capacity to store O2: TLC (total lung capacity), haemoglobin concentration in blood circulation, amount of myoglobin in muscles and amount of dissolved oxygen in tissues. (Schagatay, 2009)**.**

b) Tolerance to ↓O2/↑CO2. Firstly, the increase of CO2 takes place during apnea, and then the decrease of O2 begins. Apnea training develops high tolerance to hypercapnia (↑CO2). Beginners break apnea as a result of hypercapnia, whereas more experienced freedivers break apnea as a result of hypoxemia. Apnea training improves brain tissue tolerance to low values of O2. Dilatation of brain blood vessels (auto-regulation) and increase of brain perfusion as a consequence of hypercapnia represent significant protective mechanisms. In addition to this, significant acidosis as a result of accumulation of CO2 and lactates appear during apnea. Lactates accumulation occurs in the tissues with weak perfusion, which is the result of peripheral vasoconstriction as a part of diving reflex activation. Furthermore, it has been recorded that freedivers have ability to accumulate double CO2 quantities in their bodies (Schagatay, 2009).

c) Minimal oxygen consumption (VO2min) – VO2min represents minimal oxygen consumption and it is the key physiological factor for determining apnea duration. VO2min is determined by the following physiological characteristics:

- cardiovascular response to the diving reflex
- minimal metabolic consumption RMR (resting metabolic rate – earlier basal metabolism BMR)
- mental activity CMR (cerebral metabolic rate – O2 consumption in brain tissue)
- skeletal muscles relaxation and LBM (lean body mass – O2 consumption in muscle tissue)

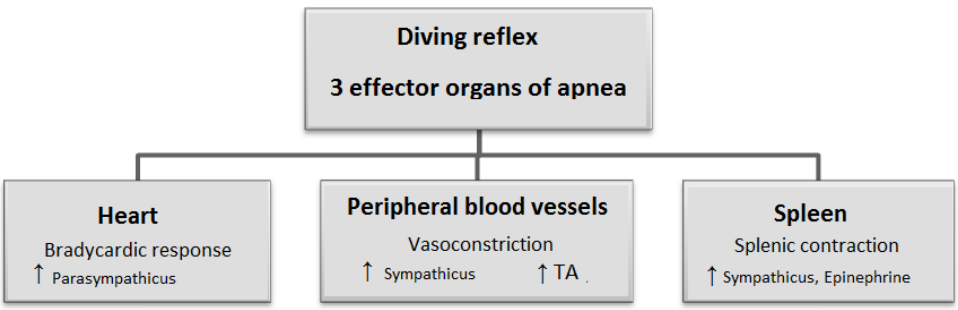
Minimal O2 consumption depends on cardiovascular response to apnea (bradycardia and bloodshift) and anaerobic metabolism capacity. Caloric intake reduction lowers RMR for 17%, as well as CO2 production for 30%. Diet which is rich in glucoses (fats and proteins) has the optimal ratio of O2 consumption /energy production. Relaxation reduces O2 consumption for 32% (Schagatay, 2009). VO2min greatly depends on the diver’s psychological state , i.e. current stress level (mental response to apnea). Relaxation techniques play the key role in freediving training, with three levels of relaxation: body relaxation, breathing relaxation, mental relaxation. Skeletal musculature becomes relaxed and brain functions become synchronised (α state of brain waves) in the state of relaxation. Brain uses 20% of total oxygen consumption, and great deal of the rest of the consumption is consequence of skeletal musculature activity.

The ventilation process, i.e. outer breathing, does not occur during apnea. Although the breathing cannot be seen, the process of breathing continues in organism in three breathing phases (at the alveolar membrane level, blood transport to tissues and organs and on the cell level). During “inner breathing” there is a moment when the level of gases in blood (physiological gases O2, CO2- gases which are included in metabolism) goes beyond physiological limits. Normal organism function (tissues and cells) takes place within physiological scope of O2 and CO2 gas concentration. When the limit is reached, cell and organism functions become disturbed. O2 consumption and CO2 build up occur during apnea. The organism struggles to tolerate oxygen reduction, whereas it better endures increase of CO2. In other words, we are not aware of O2 consumption, but we get the signal to inhale since CO2 has been built up. The receptors in blood vessels and brain record CO2 increase and the urge for air rises.

The relationship between partial pressure of O2 in blood and oxygen saturation in blood is determined by oxyhemoglobin dissociation curve. Oxygen saturation in blood is determined by partial pressure of O2. The plateau of dissociation curve O2 is safety factor in hypoxemia. SaO2 is kept above 90% until partial pressure of O2 does not drop below 60mmHg.

Diving reflex physiology. Diving reflex represents response of the organism to the apnea dive, i.e. holding the breath (Lindholm, 1999). Diving reflex is innate, genetically inscribed model of reactions in organism which is activated when diving (immersion) in the state of apnea. Identical reflex has been discovered in all diving mammals (dolphins, whales, seals). The consequences of diving reflex activation are: bradycardia, peripheral vasoconstriction and splenic contractions. Bradycardia means heart rate reduction, peripheral vasoconstriction means reduction of blood perfusion through peripheral tissues which are resistant to hypoxemia. Physiological importance of these changes in organism means reduction of oxygen consumption (VO2), i.e. storing O2 for the functions of vital organs (Lindholm, 1999). Splenic contractions inject additional blood and haemoglobin in blood circulation which increases blood capacity to transport oxygen. Diving reflex, which represents a series of organism reflex reactions, starts with peripheral vasoconstriction (result of simpaticus actions), and later vagus bradycardia occurs (result of parasimpaticus actions). The initial reaction is peripheral vasocnstriction with hypertension, and HR reduction is, at the beginning, the result of hypertension stimuli to baroreceptors, and later it is the result of hypoxia stimuli to chemoreceptors (Lindholm, 2009). Repeated apnes lead to splenic contraction, as a result of simpaticus activation leading to the increase of haemoglobin concentration in blood circulation (Lindholm, 2009). Past researches showed that there is a correlation between changes of HR values and SaO2 during apnea (Lindholm, 1999).

FIGURE 2
Diving reflex mechanism
Effector organs in apnea: heart, peripheral vascular bed, spleen



The main aim of this research is to examine characteristics of connection between heart rate changes (ΔHR) and changes in oxygen saturation in blood (ΔSaO2) during apnea. Also, we examined the connection between the lower heart rate and reduction of oxygen saturation in blood and apnea duration.

Method

Participants

We used a group of 15 exercising freedivers in our research. The following characteristics were recorded: height, weight, sex, age, heart rate and oxygen saturation in blood in standstill condition. All participants were informed about possible risks and they had made a statement about voluntary participation in this research.

Procedure

Testing was conducted during apnea in the standstill condition (static apnea) in water. Prior to testing, each participant spent 10 minutes practicing relaxation techniques. At the beginning of 8th, 9th and 10th minutes heart rate was recorded in the standstill condition. During the testing, participants performed one sub maximal apnea (almost 99% of the maximum). Heart rate values parameter (HR), oxygen saturation in blood (SaO2) and the time were continuously recorded. The values were recorded every 15 seconds. During the testing, we stayed in contact with participants all the time since we used the means of pre-arranged signals of communication.

Measures

Heart rate values were measured by pulsometer of polar F11 make, which consists of a belt which is placed on the chest with electrodes and transmitter. SaO2 values were measured by digital finger pulse oximeter of Go2 Nonin make, which records changes in values of oxygen saturation in blood at capillary level (point finger). The time was measured by stopwatch. Participants wore a noseclip during apnea due to the obstruction of nostrils, and during the static apnea in the pools they had wet neoprene suits which covered the whole body except face, hands and feet.

Results

General data regarding participants

The sample specimen we used consisted of 15 freedivers who were active competitors and who performed their training practice. The study was conducted in controlled conditions, during the training practice. The divers were in water, they wore wet suits and they performed static apnea. The study comprised 15 divers, competitors on the national level. Sex structure was: 13 men and 2 women. This distribution regarding sex is the result of accidental variation and considering the relatively small number of participants one cannot make a conclusion regarding sex distribution. Considering age structure, majority of divers were in their thirties (11 divers). The youngest diver was 19 years old, and the oldest was 49 years old. One diver was in his forties and two divers were in their fifties.

Characteristics of HR changes in apnea

FIGURE 1.
Distribution of arithmetic means of HR during apnea.
Figure shows distribution of arithmetic means of HR of all divers, for each 15 second interval of measuring.

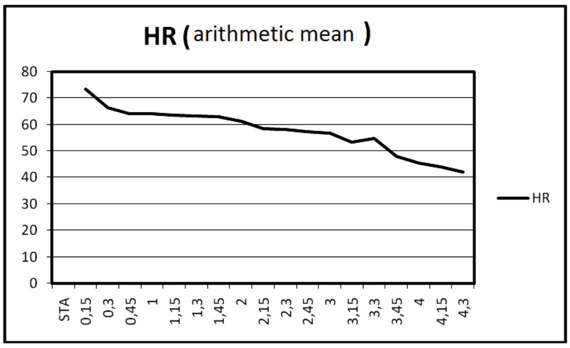
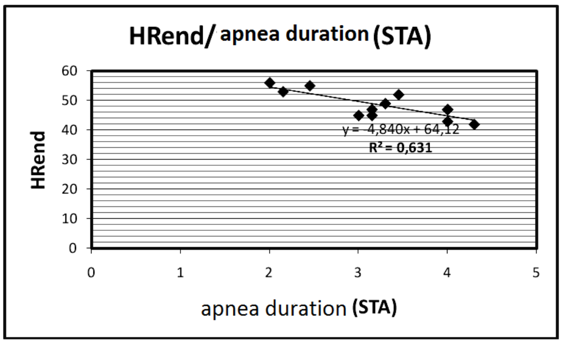


FIGURE 2.
Correlation of HRend values and apnea and apnea duration (STA).
There is statistically significant inversive linear correlation (*R*= - 0,794 for n-2=11 with 95% 0,55).



Characteristics of changes of SaO2 in apnea

FIGURE 3.
Distribution of arithmetic means of SaO2 during apnea.
Figure shows distribution of arithmetic means of SaO2 of all divers, for each 15 second interval of measuring.

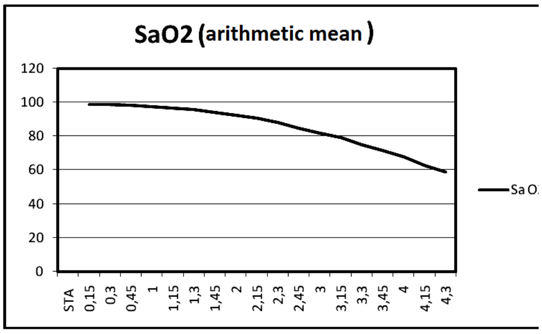
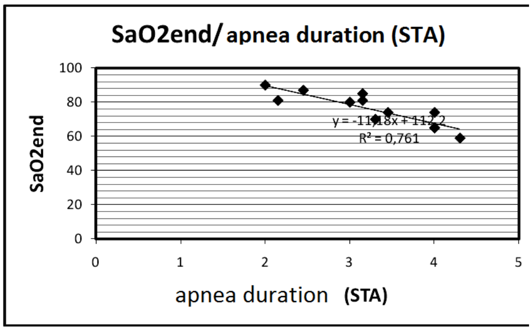
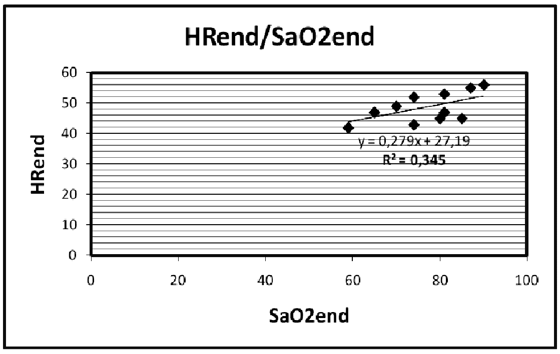


FIGURE 4.
Correlation of SaO2 values and apnea duration (STA).
There is statistically significant inversive linear correlation (*R* = -0,872 for degree of freedom n-2=11 and level of siginificance 5% coeficient is 0,55)



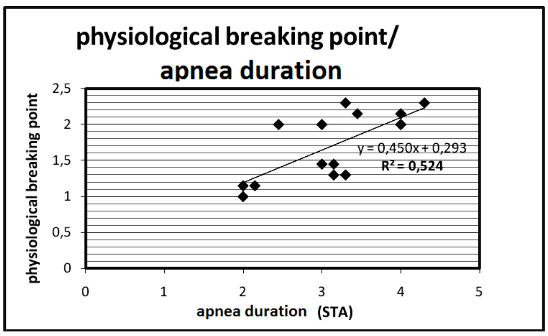
Correlation of HR and SaO2 changes in apnea

FIGURE 5.
Correlation of HR and SaO2 values at the end of apnea.
There is statistically significant linear correlation (*R* = 0,587 coefficient 0,55 for the level of significance of 5% and degree of freedom n-2=11).



Physiological breaking point (urge to breath)

FIGURE 6.
Correlation of apnea duration and the moment of physiological breaking point apnee.
There is linear correlation with statistically significance *R* = 0,723 coefficient 0,514 for level of significance 5% degree of freedom n-2=13.

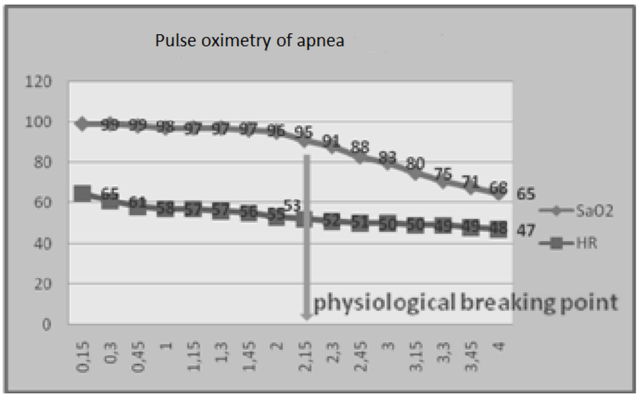


Discussion

It is possible to make apnea profile using the analysis of heart rate values and oxygen saturation in blood. Apnea is divided into two phases, in relation to physiological breaking point (the moment when urge to inhale appears). Apnea profile shows the changes of HR and SaO2 parameters values during apnea. Based on the analysis of apnea profile we gathered the data about physical fitness of the divers, their tolerance to hypoxemia and hypercapnia, psychological state during apnea.

Ideal static apnea profile

At the beginning of apnea, saturation value is high (approximately 100%), heart rate values should be as lower as possible, i.e. ideally between 60-90bpm. A little bit higher heart rate in relation to standstill condition is the result of respiratory response to the preparation for apnea. Heart rate values above 90bmp at the beginning of apnea (especially above 100 bmp) are a negative indicator for apnea duration. It is an indicator either of hyperventilation or psychological anxiety. In the first half of apnea (easy going phase) heart rate slows down to the values of 50-60bpm. This is the result of respiratory rest, i.e. apneustic centre activities. Also, HR reduction in the first apnea phase occurs due to parasimpaticus predomination. SaO2 values in the first phase change a little, and there is a drop above 90%. More significant saturation decrease occurs with the diaphragm contractions (physiological breaking point), which is the second apnea phase (struggle phase). In the second phase HR continues to slow down. HR changes in this phase are the result of parasimpaticus activities and hypoxic response of the brain centres to SaO2 reduction. HR increase in the second apnea phase is the result of inadequate psychological response to urge to inhale (indicator of bad physical condition).



HR changes in relation to apnea duration

Relation between static apnea duration and HRend values show inversive linear connection. Shorter apneas end with higher HR values comparing to apneas which last longer (Figure 1.). The reason for inverse linear correlation of changes of HR values and apnea duration is diving reflex activation which triggers powerful braycardiac response. HR reduction in apnea is progressive as time goes by, although there are some deviations. Shorter apneas with lower values of HR imply good physical condition, deep relaxation and strong diving reflex activation. Contrary to this, longer apneas with HR increase point out to psychological tension, as a negative response to CO2 increase and urge to inhale.

Changes of SaO2 in relation to apnea duration

The relation between static apnea duration and SaO2end values (SaO2 value at the apnea end) shows statistically significant correlation (Figure 3). Apneas which last longer have lower values of the SaO2 and vice versa, shorter apneas end with high values of SaO2. Apnea duration is a variable which directly influences SaO2end values. During apnea the body consumes oxygen so the longer apneas, the greater oxygen consumption. The result is lower SaO2end value.

HR and SaO2 changes in connection to physiological breaking point

Physiological breaking point occurs most commonly in the second minute of apnea, and there is a direct linear correlation between apnea duration and time when the urge to inhale occurs (Figure 6). Change of SaO2 values in the second apnea phase indicates larger decrease of values of oxygen saturation in blood. It can be said that when the physiological breaking point is reached, i.e. during the diaphragm contractions, the oxygen consumption in apnea speeds up. In the second apnea phase, due to the occurrence of urges to inhale, muscle contractions accelerate the oxygen consumption. Also, psychological tension and oxygen consumption in the brain begin to accelerate.

Diving reflex in apnea

Diving reflex gets activated during apnea. We can observe the intensity of the reflex activation by looking at the intesity of HR reduction. During apnea HR reduction is progressive. HR reduction at the beginning of apnea is the consequence of respiratory rest and apneustic centre activities. Quite soon parasimpaticus starts to predominate and the vagus start to influence HR reduction. In the final apnea phase hypoxic stimulus in brain centres prolongates HR reduction. Statistically significant correlation of changes of HR and SaO2 in the second apnea phase has inversive characteristic. Higher HR reduction triggers smaller SaO2 changes. The consequence is conserving oxygen in apnea, which represents physiological justifiction of diving reflex existance (keeping homeostasis in apnea).

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