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The effect of breath-hold diving on selected adaptive mechanisms in the circulatory-respiratory system in simulated static and dynamic apnoea

Magdalena Solich-Talanda
Department of Physiological and Medical Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland, a.zebrowska@awf.katowice.pl

Robert Mikolajczyk
Department of Physiological and Medical Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland, a.zebrowska@awf.katowice.pl

Robert Roczniok
Department of Sports Theory, The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland, a.zebrowska@awf.katowice.pl

Aleksandra Zebrowska
Department of Physiological and Medical Sciences, The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland, a.zebrowska@awf.katowice.pl

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Abstract

Background: Current research results indicate high adaptation of an organism to long-term apnoea. Breathing techniques allow increasing the volume of the inhaled air and thus prolong the breath-hold time at rest and during physical effort. The purpose of this study was to assess the impact of breath-hold on adaptations of the respiratory and circulatory systems and cardiopulmonary-respiratory reactions at rest and during physical effort in persons practising freediving. Material and methods: The study involved 17 athletes practising breath-hold diving, at the mean age of 38.4 ±8.4 years. Spirometry tests to evaluate static and dynamic lung indicators were conducted. The heart rate (HR), oxygen saturation (SpO2), and the apnoea time in three breath-hold trials were measured: static dry STA-D, static with face immersed in water STA-I and dynamic (DYN-D). Results: The values of spirometry indicators were higher than the normal values at the appropriate peak expiratory flow (91.6 ± 27.2%). A significant effect of breath-hold on the HR was demonstrated in the STA-D test ($W = 0.43$, at $p < 0.05$) and STA-I ($W = 0.51$, at $p < 0.05$). The mean breath-hold time was significantly lower in the dynamic trial DYN-D vs STA-D ($p < 0.001$) and in STA-D Ex vs STA-I ($P < 0.001$). Higher mean values of SpO2 were shown in DYN-D in comparison to STA-D ($p < 0.05$). Conclusions: The results of this study indicate that breath-hold training beneficially affects adaptation of the circulatory system, causing strong bradycardia and lower tolerance in response to prolonged apnoea during physical effort.

Keywords

freediving, spirometry, heart rate, apnoea, exercise

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Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Data Interpretation
E Manuscript Preparation
F Literature Search
G Funds Collection

Magdalena Solich-Talanda[1 ABDF], Rafał Mikołajczyk[1 D], Robert Roczniok[2 C], Aleksandra Żebrowska[1 ADEF]

[1] Department of Physiological and Medical Sciences,
The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland

[2] Department of Sports Theory,
The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland

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Corresponding author: Corresponding author: Aleksandra Zebrowska, Department of Physiological and Medical Sciences, The Jerzy Kukuczka Academy of Physical Education, Mikolowska Street 72 A, 40-065 Katowice, Poland; E-mail: a.zebrowska@awf.katowice.pl ; phone no.: +48608418581.

INTRODUCTION

Freediving is a sports discipline in which athletes compete in various diving events with their breath withheld. The first group of events includes the depth ones: fixed ballast, free immersion, variable ballast and no limits. The second group comprises three pool events in which the athlete has to swim the longest distance underwater using fins or a monofin (dynamics in fins), swim the longest distance underwater without fins (dynamics without fins) or hold their breath under water for as long as possible (statics) [1, 2]. The trends in improving world records in this sport indicate high adaptation of an organism to long-term apnoea [2, 3, 4]. The applied breathing techniques allow increasing the volume of the inhaled air and thus prolong the breath-hold time at rest and during physical effort [5, 6, 7]. Physiological response to regular, repeatable manoeuver of breath-hold in divers relies on increasing lung vital capacity (VC) through greater utilisation of residual volume (RV) and triggering adaptive mechanisms which protect against hypercapnia and hypoxemia developed during apnoea [8, 9, 10, 11].

The evidence-based protective mechanisms in the cardiovascular system that allow few minutes' breath-hold include: cerebral vasodilation due to increased CO_2 levels, increased oxygen dissociation from haemoglobin and the use of oxygen reserves [12, 13, 14]. It has been proven that in well-trained freedivers, an increase in the apnoea time results from a decrease in partial pressure in the lungs, a decrease in blood saturation (SpO_2) [15], a reduction of the heart rate (HR) with a simultaneous increase in the stroke volume (SV) [16, 17, 18]. The described adaptive reactions are defined as a "diving reflex". Increased secretion of adrenal catecholamine, which worsens the spleen effect, is the main response to the diving reflex [18, 19 20]. The function of the diving reflex is to reduce the consumption of oxygen by organs and tissues to ensure adequate supply of oxygen to the brain and the heart [21].

An additional factor that affects the response of the cardiovascular system during breath-hold diving is the immersion of the body in water. As a result of water immersion, there is further centralization of circulation and bradycardia by stimulation of the trigeminal nerve [20, 21, 22].

The above-mentioned mechanisms and adaptive reactions protect against hypoxia and at the same time allow for longer breath-hold in static competition [3, 12] and apnoea tolerance in dynamic tests [10, 13]. Previous studies did not explain what significance the ability to increase ventilation and perfusion in the airways has for the adaptation to static and dynamic breath-hold and whether there are protective mechanisms in the cardiovascular system in trained athletes – representatives of the national team, medallists and finalists of the World Championship in pool freediving.

The aim of the study is to demonstrate the impact of specific breath-hold diving training on cardiopulmonary reactions at rest and during physical effort in trained athletes – representatives of the national team, medallists and finalists of the World Championship in pool freediving.

MATERIAL AND METHODS

SUBJECTS

The study involved 17 athletes (4 women and 13 men) aged 38.4 ±8.4 years. The mean training experience was 8.3 ±7.7 years (Table 1). Figure 1 presents the best results in breath-hold diving without fins (DNF) and with fins (DYN), and Fig. 2

in static breath-hold (STA). Prior to the cardiopulmonary stress tests in the subjects, somatic indicators were evaluated in the study group (Inbody 570, Sweden) and their written consent to participate in the study was obtained. The research project was approved of by University Bioethics Committee for Scientific Research at Jerzy Kukuczka Academy of Physical Education – Opinion No 3/2018 of 19 April 2018.

Table 1. Subjects' characteristics

Variables n=17	Mean, SD
Age (year)	38.4 ± 8.4
Height (cm)	178.6 ± 8.2
Weight (kg)	76.2 ± 12.3
BMI (kg/m2)	24.5 ± 4.1
FFM [kg]	62.3 ± 11.1
Training status (years)	8.3 ± 7.7

BMI – body mass index, FFM – free fat mass

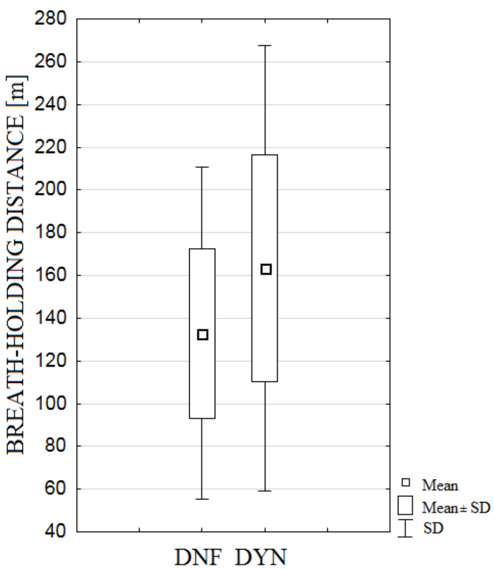

Fig. 1. The best distance in breath-hold diving without fins (DNF) and with fins (DYN)

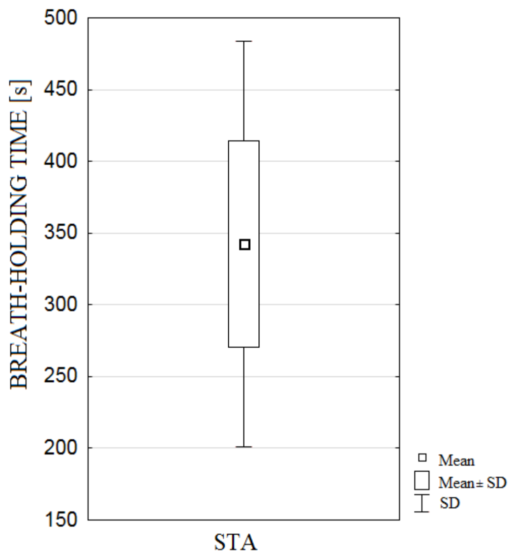

Fig. 2. The best time in the static breath-hold (STA).

RESEARCH PROTOCOL

Spirometry control

In the spirometry test, the following parameters of the lungs were measured: vital capacity (VC), forced vital capacity (FVC), forced expiratory volume in one second of forced vital capacity (FEV1), peak expiratory flow (PEF). The ratio of FEV1/FVC, the maximal expiratory flow (MEF 75%, 50%, 25%) and the maximal voluntary ventilation, (MVV) were calculated. The study was conducted in accordance with recommendations for spirometry tests [23] using a portable spirometer (Pony-FX from the Cosmed company, Italy).

Protocol of the static test and dynamic breath-hold

An assessment of the heart rate (HR) and oxygen saturation in haemoglobin (SpO2) was performed during three trials of breath-hold at room temperature (23oC). Breath-hold tests during effort were conducted in consistence with the previously described test protocol [24]. The static dry apnoea test (static dry, STA-D) was carried out in a sitting position without hyperventilation after calm inhalation (tidal volume, TV). The static breath-hold was repeated under conditions of immersion in water of a temperature of 15°C (static water immersion, STA-I).

In the dynamic dry apnoea test (dynamic dry, DYN-D), the subjects performed a cardiopulmonary stress test on a cycling ergometer (Monark 828E, Sweden) with moderate intensity during which they held their breath. The effort started with 3 minutes of warm-up, after which the load was increased to an individual intensity corresponding to 60% of the maximal oxygen uptake (VO_2max). After obtaining the due intensity and stabilization of the HR, the subjects held their breath. The trial was interrupted when the subject was unable to continue the effort on apnoea.

During the static and dynamic apnoea tests, the HR and SpO_2 were recorded continuously. A MASIMO Rad-5, USA, oximeter was used for the measurements. The results were recorded before the start of each trial, in each subsequent 5th second of the test and immediately on completion of the STA-D, STA-I and DYN-D tests.

STATISTICS

The obtained data were statistically analysed using Statistica v.13.1 (StatSoft, 13.1) software. Descriptive statistics were calculated. The obtained results are shown as mean values (x) and standard deviation (SD). The U Mann Whitney test was applied to compare two independent groups.

The Friedman ANOVA statistics and the Kendall's coefficient of concordance (W) were also used to assess the impact of time on changes in the tested indicators. The significance of differences was specified for the value of $p < 0.05$.

RESULTS

The subjects who participated in the static and dynamic apnoea tests were characterised by similar body composition. The subjects' results in DYN and DNF are shown in Fig. 1. The distance covered with fins was longer than the distance covered without fins (163 ±53 m vs 132 ±39 m; $p < 0.05$). The subjects' best results of the apnoea time during dry static (STA) amounted to 342 ±72 s (Fig. 2).

Table 2. Spirometry variables (means, SD and predicted values)

n = 17	Mean, SD	Pred (%)
FEV_1 (L)	4.3 ±1.3	103.9 ±23.9
FVC (L)	4.8 ±1.4	96.7 ±20.6
VC (L)	6.0 ±1.7	108.8 ±25.4
FEV_1/FVC	89.4 ±6.2	110.5 ±7.7
PEF (L/s)	8.5 ±3.1	91.6 ±27.2
MEF_{75} (L/S)	8.1 ±3.0	101.5 ±31.2
MEF_{50} (L/S)	5.4 ±2.0	100.9 ±31.7
MEF_{25} (L/S)	2.9 ±1.2	114.6 ±39.8
MVV (L/min)	163.2 ±31.5	114.4 ±19.3

FEV1 – forced expiratory volume in one second of forced vital capacity, FVC – forced vital capacity, VC – vital capacity, PEF – peak expiratory flow, MEF25-75 – maximal expiratory flow, MVV – maximal voluntary ventilation.

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The results of the spirometry test are shown in Table 2. The lung vital capacity (VC) was 6.0 ±1.7, which represents 108% of the normal value for the studied group. In the spirometry test, the flow values were higher than the normal ones. The peak expiratory flow (PEF) and the forced vital capacity (FVC) showed slightly lower values than the normal ones (PEF 91.6 ±27.2% vs. FVC 96.7 ±20.6%, respectively).

A significant effect of breath-hold on HR was demonstrated in the STA-D test ($W = 0.43$ for $p < 0.05$) and in STA-I ($W = 0.51$ for $p < 0.05$). Significant differences in the HR decrease were demonstrated between the 20th s and the 95th s, and an increase between the 110th s and the 150th s (for $p < 0.05$) in STA-D. In STA-I, significant differences in the HR were demonstrated throughout the whole apnoea time ($p < 0.05$). There were significant differences in the HR between the STA-D and STA-I tests between the 40th s and the 70th s of the apnoea (Fig. 3).

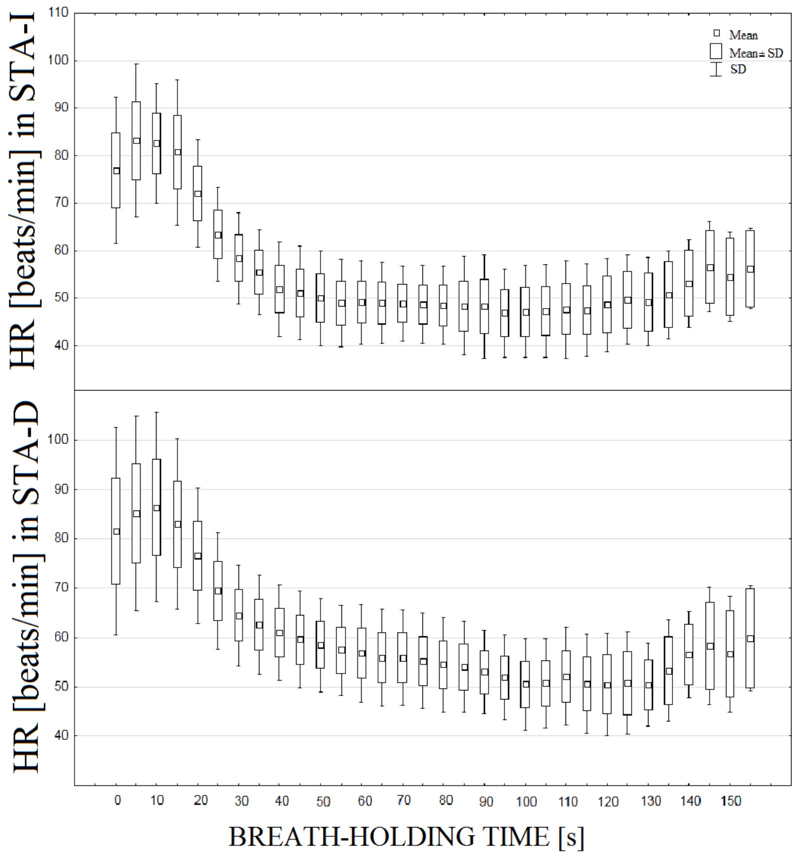

Fig. 3. Heart rate (HR) changes during STA-D and STA-I

There was a significant effect of breath-hold on SpO_2 in the STA-D test ($W = 0.95$ for $p < 0.05$) and in STA-I ($W = 0.95$ for $P < 0.05$). Significant differences in SpO_2 were demonstrated during the entire apnoea time. No significant differences were found between SpO_2 changes in STA-D vs. STA-I trials (Fig. 4).

A significant influence of the apnoea time on the HR changes was found in the DYN-D trial ($W = 0.91$ for $p < 0.05$). Post hoc analysis showed a significant decrease in the HR between the 5th s and the 40th s of breath-hold effort ($p < 0.05$), then the HR levelled off until the end of the test (Fig. 5). The same test showed a significant influence of breath-hold on SpO_2 ($W = 0.91$ for

$p < 0.05$). A reduction of SpO_2 was observed in apnoea during the test until the 50th s, then SpO_2 levelled off till the completion of the stress test ($p < 0.05$) (Fig. 6).

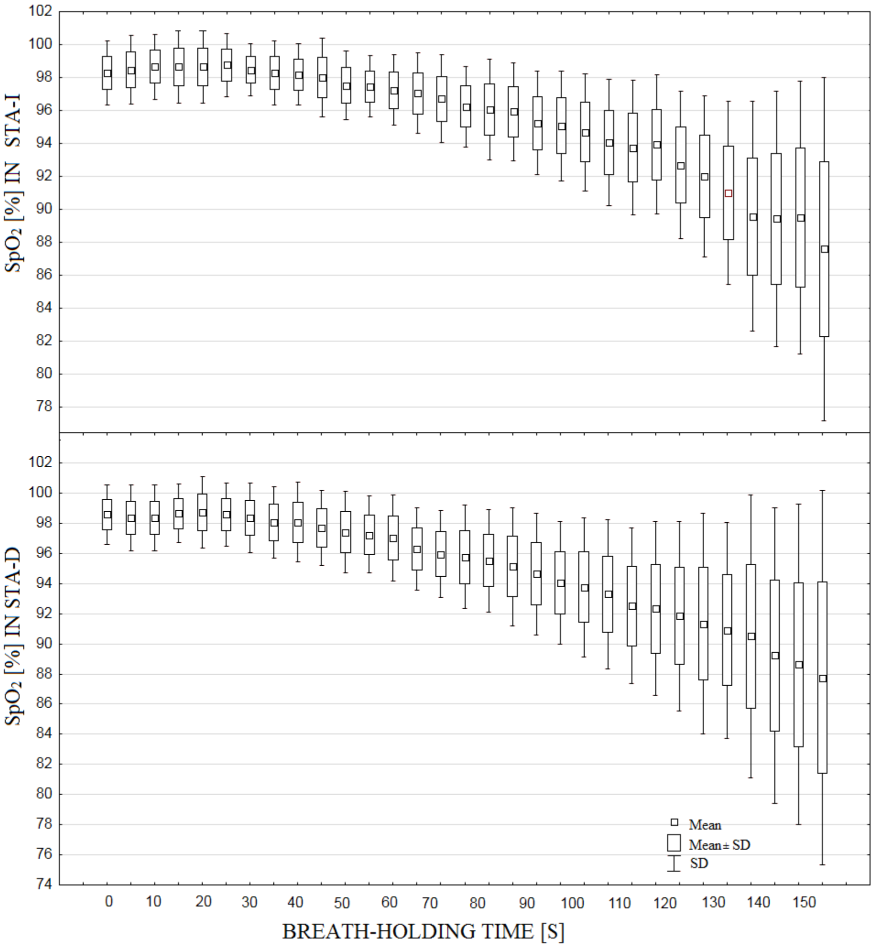

Fig. 4. Oxygen saturation (SpO_2) changes during STA-D and STA-I

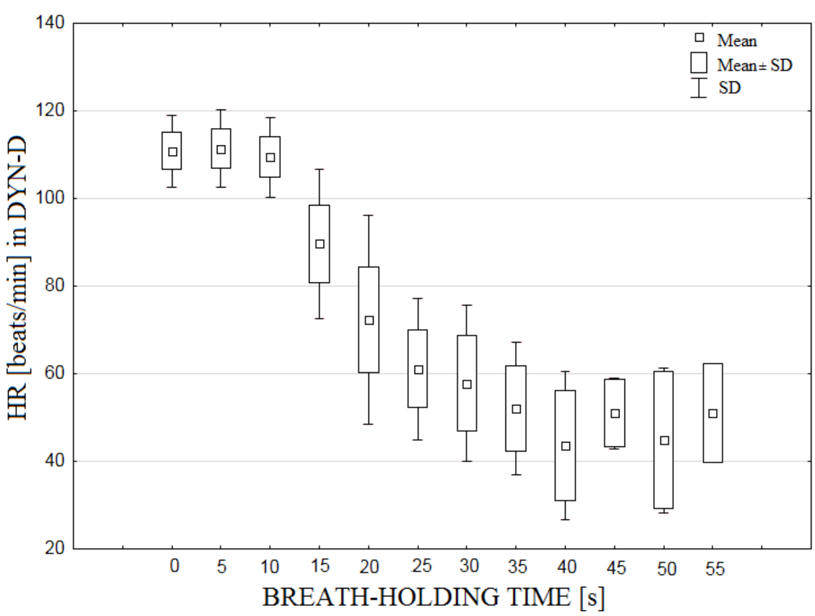

Fig. 5. Heart rate (HR) changes during DYN-D

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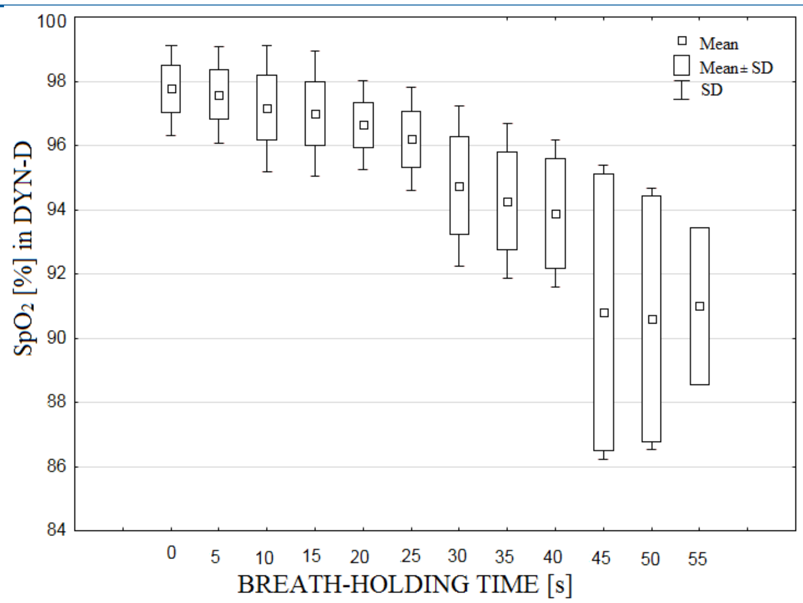

Fig. 6. Oxygen saturation (SpO_2) changes during DYN-D

The mean as well as the minimum and maximum breath-holding time (BHT), heart rate (HR) and oxygen saturation (SpO_2) measured in the performed tests are presented in Table 3. The mean breath-holding time was significantly shorter in DYN-D vs STA-D ($p < 0.001$) and DYN-D vs STA-I ($p < 0.001$). The mean HR did not significantly differ in the test trials; there was a trend of a lower mean HR in DYN-D in comparison to STA-D and STA-I. The lowest heart rate in the DYN-D was 20 bt/min. Higher mean values of SpO_2 were shown in DYN-D as compared to STA-D ($p < 0.05$). Individual lowest values were found in STA-I in comparison to the other tests (STA-D and DYN-D) (Table 3).

Table 3. Breath-holding time (BHT), heart rate (HR) and oxygen saturation (SpO_2) in static dry and static immersion (STA-D, STA-I) and dynamic dry (DYN-D)

Variables	STA-D		STA-I		DYN-D	
	Mean, SD	Min.-Max	Mean, SD	Min.-Max	Mean, SD	Min.-Max
BHT [s]	154.0 ±28.3	115–205	149.0 ±26.3	85–185	42.3 ±15.9***	20–75
HR [bpm]	46.0 ±8.0	32–58	46.0 ±11.0	32–69	43.0 ± 14.0	22–62
SpO_2 [%]	85.9 ±5.6	75–91	89.1 ±7.0	69–95	92.4 ±3.7*	85–98

*Significant differences DYN-D vs. STA-D and STA-I *p<0.05; ***p < 0.05*

DISCUSSION

The study showed a high level of adaptation of the respiratory system to breath-hold training without serious restrictive and obstructive disorders in the lung function. The subjects were characterised by a longer breath-holding time in static tests (STA-D and STA-I) in comparison to the dynamic test (DYN-D). The obtained results correspond to the high scores obtained by the studied competitors in sport events of static (STA 324 ±2 s) and dynamic (DYN 163 ±53 m, DNF 132 ±39 m) diving. Differences in the cardiac function and hypoxia tolerance, which were dependent on the type of the breath-hold trial, are also relevant results of this study. The mean heart rate at the end of STA-D and STA-I was similar. Lower HR was demonstrated during the facial immersion test (STA-I) in comparison to STA-D (Fig. 3). A lower mean HR in

DYN-D occurred with reduced tolerance of the breath-hold time. The obtained results confirm previous studies which demonstrated that apnoea induces adaptation of the cardiovascular and the respiratory systems in various ways in static and dynamic tests [10, 25, 26].

Adaptation of the respiratory system

Spirometry tests in this study showed high values of the lung vital capacity (VC), the forced expiratory volume (FEV) and the maximum expiratory flows (MEF). The obtained results confirm reports from previous research [7] which demonstrated that VC in well-trained competitors can be up to 24% higher than the norm. Seccombe et al. [24] present similar conclusions with reference to breath-hold divers whose VC was 15% higher. Studies confirmed the significant effect of training on increasing the lung VC without significant changes in the total lung capacity (TLC), which is explained by multiple repetitions of a specific breathing technique and increasing the elasticity of the rib cage [6, 7]. The described mechanisms are beneficial to the dynamic indicators of the lung function, as confirmed in this study (Table 2.). Intrapersonal differences were noted in the adaptation of the respiratory system of those engaged in breath-hold diving as well as a tendency to lower values of the expiratory flow and much higher than the expected standards for the results in VC (130%), FEV1 (133%) and PEF (135%) [7, 27]. Earlier studies suggest adverse changes occurring in people practising breath-hold diving which can increase the risk of restrictive or obstructive pulmonary diseases [5, 7]. It should be emphasised that the subjects of this study were characterised by the correct values of FVC, FEV1, and PEF, thus not confirming in our results the increased risk of respiratory disease in persons training freediving.

In the presented results, the respiratory system adaptation during static breath-hold allowed for a long time of apnoea and simultaneously high tolerance of hypoxia. The results of this study seem to confirm previous research on the protective mechanisms in the cardiovascular system which allow a few minutes' breath-hold without risking loss of consciousness [10, 28, 29].

Cardiovascular response to breath-hold

The most important conclusions after the STA-D and STA-I tests may include a significant decrease in the heart rate in the first 20 seconds of breath-hold and maintaining a slow heart rate of approximately 40 bt/min for 2 further minutes of the STA-D and STA-I trials. Bradycardia caused by apnoea and immersion in water was carefully documented in previous studies on divers [3, 9, 11]. Noteworthy is the three-phase course of the HR changes [14, 30, 31]. In the first phase lasting for about 1 min, there is an exponential decrease in the HR, in the second phase a small increase in the HR, and in the third phase gradual slowing down of the heart rate. According to the literature, the third phase is induced by stimulation of arterial chemoreceptors which activate mechanisms reducing oxygen consumption (the oxygen-conserving breaking point) [14, 32]. In consistence with previous reports, we observed a slight acceleration of the HR, followed by a significant reduction and stabilisation of the HR until the 130th second in static breath-hold trials. In this study, no significant effect of immersion in water on the mean values of the analysed variables, i.e. the breath-holding time (BHT) and the HR, was found. There was a slight tendency to a higher value of oxygen saturation in the blood with the same heart rate in STA-I in comparison to STA-D (89.0 vs. 85.9). Our results, unlike those of

Stromme et al. [25], do not confirm the highly significant differences in the HR and SpO_2 between STA-D and STA-I. Such results can be explained by high adaptation of the top freedivers to the local action of the thermal agent. Further research under the conditions of whole body immersion in water would allow for an explanation of the factors inducing the diving reflex among leading freedivers [22, 28, 30].

The conducted research on the influence of chilling the face area on increasing bradycardia confirm the significance of stimulating sensory fibres of the trigeminal nerve, which induces a trigeminal cardiac reflex characterised by strong bradycardia [20]. A reduction of oxygen demand in the body following the increase in the diving reflex and immersion is a very important factor. In the conducted study, saturation amounted to 85.9 ±5.6% at the end of dry static trials (STA-D) and 89.0 ±7.0% with the face immersed in water (STA-I). Similar conclusions were reported in Andersson and Schagatay' study from 1998, in which they showed mean saturation values higher by 1.3% at the end of the trial with face immersed in water [8]. These results were confirmed in subsequent works by that author, indicating SpO_2 higher by 2% [33] and by 4% [9, 13] under the conditions of water immersion. It has been confirmed that differences in the power of the diving reflex may be dependent on differences in the sensitivity of arterial chemoreceptors, vasoconstriction and oxygen consumption by the brain [28, 34]. It should be noted that the intensity of bradycardia determines the magnitude of vasoconstriction in the muscular system, reducing the predisposition to exercising during dynamic breath-hold trials [21, 26, 35, 36, 37].

The dynamic of changes in the cardiovascular parameters associated with the diving reflex in static tests and during physical effort has been described in previous studies [14, 32, 38]. This work presents a DYN-D trial in which the subjects held their breath during effort on a cycling ergometer for about 42.3 ±15.9 seconds. In this trial, a reduction of the heart rate was observed already in the first phase of the test without a stabilization period, and a significantly lower tolerance to apnoea. The minimal values of the HR and SpO_2 (STA-D 32 bt/min, 75%; STA-I 29 bt/min, 82%; and DYN-D 20 bt/min, 85%) achieved by the subjects during each of the breath-hold trials are an important aspect of this study. The cited values indicate a very strong reaction of the cardiovascular system during apnoea confirmed in previous studies in which the lowest recorded value sustained for over 20 s of bradycardia was < 10 bt/min [36].

The results of this study seem to confirm results of previous research on the dynamics of changes in the parameters of the diving reflex during effort which revealed a reduction in the cardiac output, increased blood pressure and total vascular resistance without a period of stabilisation of these parameters [10, 33, 38].

CONCLUSIONS

The results of this study indicate a significant effect of breath-hold training on favourable changes in parameters of static and dynamic functions. Breath-hold training has a beneficial effect on the adaptation of the cardiovascular system, resulting in strong bradycardia and greater tolerance in response to prolonged apnoea in static tests in comparison to physical effort.

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