POLISH HYPERBARIC RESEARCH 3(76)2021
Journal of Polish Hyperbaric Medicine and Technology Society

EVALUATION OF PHYSIOLOGICAL STRESS EXPERIENCED BY DIVERS MAINTAINING AN UPRIGHT POSITION ON THE WATER SURFACE DEPENDING ON THE BUOYANCY CONTROL DEVICE

Aleksandra Żebrowska[1], Piotr Siermontowski[2], Rafał Mikołajczyk[1], Marcin Sikora[1], Olga Łakomy[1]

[1] Department of Physiological and Medical Sciences Academy of Physical Education Katowice, Poland
[2] Department of Underwater Works Technology, Naval Academy Gdynia, Poland

ABSTRACT

The knowledge of physiological reactions enabling a diver increasing the functional reserve in a life-threatening situation is not yet complete. It is suggested that the ability to adapt to prolonged stress experienced by divers maintaining an upright position on the water surface is associated with the diver's individual characteristics and the type of the buoyancy control device. The purpose of this study was to perform a preliminary evaluation of physiological variables in divers wearing two different types of buoyancy control device and floating upright at the surface to determine the level of safety offered by each of them. The physiological variables were measured while participants wearing a classical dive vest and a wing dive vest. The oxygen uptake and heart rate measured after 30 minutes of experiment were significantly greater in participants using wing dive vest than classical dive vest. The results confirm the possibility of using physiological indicators to compare the fatigue and rescue function in divers depending on the buoyancy control device type.

Keywords: diving, buoyancy vest, safety, physical performance.

ARTICLE INFO

PolHypRes 2021 Vol. 76 Issue 3 pp. 35 – 44

ISSN: 1734-7009 **eISSN:** 2084-0535

DOI: 10.2478/phr-2021-0015

Pages: 10, figures: 3, tables: 2

page www of the periodical: www.phr.net.pl

Publisher
Polish Hyperbaric Medicine and Technology Society

Original article

Submission date: 15.05.2021 r.
Acceptance for print: 17.06.2021 r.

INTRODUCTION

The first buoyancy control device (BCD) for scuba divers, which was nicknamed a ‘horse collar’ because of its shape, was developed in the 1980s from the life jackets used by the military aircraft crews. Continued efforts to develop diving equipment led to the construction of BCDs combining the rescue and buoyancy functions with the function of the scuba tank harness. The early models of jackets were attached to the harness, and their next generations were provided with attachments for additional equipment. The BCDs started to be provided with adjustments ensuring their better fit to the diver’s physique. The wing BCD as we know it today was created by removing the buoyancy elements on the front and leaving the horseshoe bladder on the diver’s back.

There are two main types of BCDs that are widely used by divers today: a classical dive vest (CDV) and a wing dive vest (WDV). As well as allowing the diver to control the depth of the dive (i.e., buoyancy) and ascend to the surface, a BCD is also capable of keeping the diver, even an unconscious one, afloat with the head inclined backward to prevent water from entering the airway, thus increasing the odds of survival.

The success of rescue efforts is partly dependent on the ability of a BCD to keep a diver afloat before they are towed to safety, as well as on their condition that depends on the time of exposure to hypoxia, the adequacy of the breathing gas composition, and the reduction in cardiorespiratory capacity [1,2].

As the wing BCD’s centre of buoyancy is located on the diver’s, its primary function is to ensure buoyancy rather than the safety of a floating diver. The outcome of rescue efforts is related to the diver’s functional condition diver that depends on the position in the water, the time of floating, and the protection of the airway from inundation by water. Increasing or decreasing gas pressure in the bladder allows a diver to have zero buoyancy (the buoyant force and the force of gravity have the same value) regardless of the depth of the dive. This feature of the BCD is vital to divers using neoprene wetsuits whose buoyancy decreases with depth because of ambient pressure compressing neoprene gas bubbles. This problem does not occur in the case of divers wearing variable volume suits; however, most divers, especially those who pursue diving as a leisure activity, use neoprene suits.

The range of contemporarily used BCD includes [1]:

- the ‘horse-collar’ vests were developed the earliest and are rarely used nowadays. Because their centre of buoyancy is located above the diver’s chest, their primary purpose is to safe life, the buoyancy control function being secondary,
- the classical dive vests with the centre of buoyancy located at the chest. These vests were designed to offer the same degree of protection and buoyancy control. Their disadvantage is their size, which hinders floating diver’s movements,
- the ‘wing dive vests with the centre of buoyancy (in some models, it is even beyond the divers’ body); their main function is to keep a diver afloat in a safe position.

Most countries in the world, including Poland, have legislation requiring divers to wear a BCD during the dive. As a result, the use of the BCD has become an important module of training programmes for amateur divers developed by all scuba diving federation. However, their main focus is on the buoyancy function and other features of the BCD (attachments for equipment), its rescue function, especially its ability to keep a diver afloat in an upright position on the water surface for an extended period of time, being given little or no attention at all [3].

The primary focus of legislators enacting the diving equipment legislation has been on the diver’s safety, but the evolution of BCD designs seems to increasingly depart from their original rescue function and even, at adverse conditions, put diver’s life and health at greater risk. This observation prompted the authors to conduct a preliminary analysis of the level of safety offered by contemporary BCDs.

As already mentioned in the introduction, the type of the rescue equipment plays a key role in the adaptation of a diver staying afloat for a long time [4]. The most important risk factors related to a prolonged stay in water include impaired cardiovascular adaptation, bradycardia, the slowing of metabolic processes, and hypothermia [4,5]. The knowledge of physiological reactions enabling a diver increasing the functional reserve in a life-threatening situation is not yet complete. It is suggested that the ability to adapt to prolonged respiratory and cardiovascular stress is associated with the diver’s individual characteristics and the type of the BCD worn [6].

Therefore, the purpose of this study was to perform a preliminary evaluation of physiological variables in divers wearing two different types of BCD and floating upright at the surface to determine the level of safety offered by each of them.

MATERIAL AND METHODS

Tests were conducted in an indoor swimming pool at the Physical Education Academy Katowice, in calm water at 26C° under windless conditions. The ambient light was daylight.

The study enrolled 20 male and 14 female recreational swimmers of similar ages (21.7 ± 5.9 years), a body mass of 70.6 ± 14.4 kg, a body height of 174.8 ± 9.6 cm, a BMI of 22.9 ± 3.3, and fat tissue percentage of 15.2 ± 6.4 %. The body composition of the participants was determined using bioelectrical impedance analysis (an InBody570 analyser, Biospace Inc., Seoul, South Korea). Before the tests, participants’ heart rate (HR), blood pressure, resting oxygen uptake, and haemoglobin oxygen saturation ($SatO_2$) were determined and spirometry measurements were performed.

The physiological parameters were measured while participants wearing BCDs were floating vertically with the face above the water. The testing protocol provided for the use of two of BCDs: a classical dive vest (CDV) and a ‘wing’ dive vest (WDS). Which vest was used first was decided randomly and the interval between the first and second test was at least 3 days.

Parameter measurements were performed at four time points: at rest, and then 10, 20, and 30 minutes after the test. Each time, participants’ oxygen uptake (VO_2), the percentage of carbon dioxide in exhaled air (VCO_2), minute ventilation (VE), breathing frequency

(BF), and tidal volume (TV) were recorded. Calculations were made to determine their relative oxygen uptake (VO_2/kg), the metabolic equivalent of task (MET), and the ventilation-perfusion ratio (VE/VO_2).

The effect of physical exercise on participants' respiratory indicators was assessed using an ergospirometer (Ergo2000M, MES software, Poland), and haemoglobin oxygen saturation levels ($SatO_2$) were measured with a pulse oximeter (Konica Minolta PULSOX-300i, Japan). HR values were recorded in an ongoing throughout each test (POLAR H10 HearRate with 3.1.1 version software, Kempele, Finland). Diastolic and systolic blood pressure (DBP and SBP) was measured at rest and after the test with a sphygmomanometer (OMRON M2, Japan).

All participants were advised on the purpose and protocol of the study and gave their written consent to participate in it. The test procedures were conducted as shown in Figure 1.

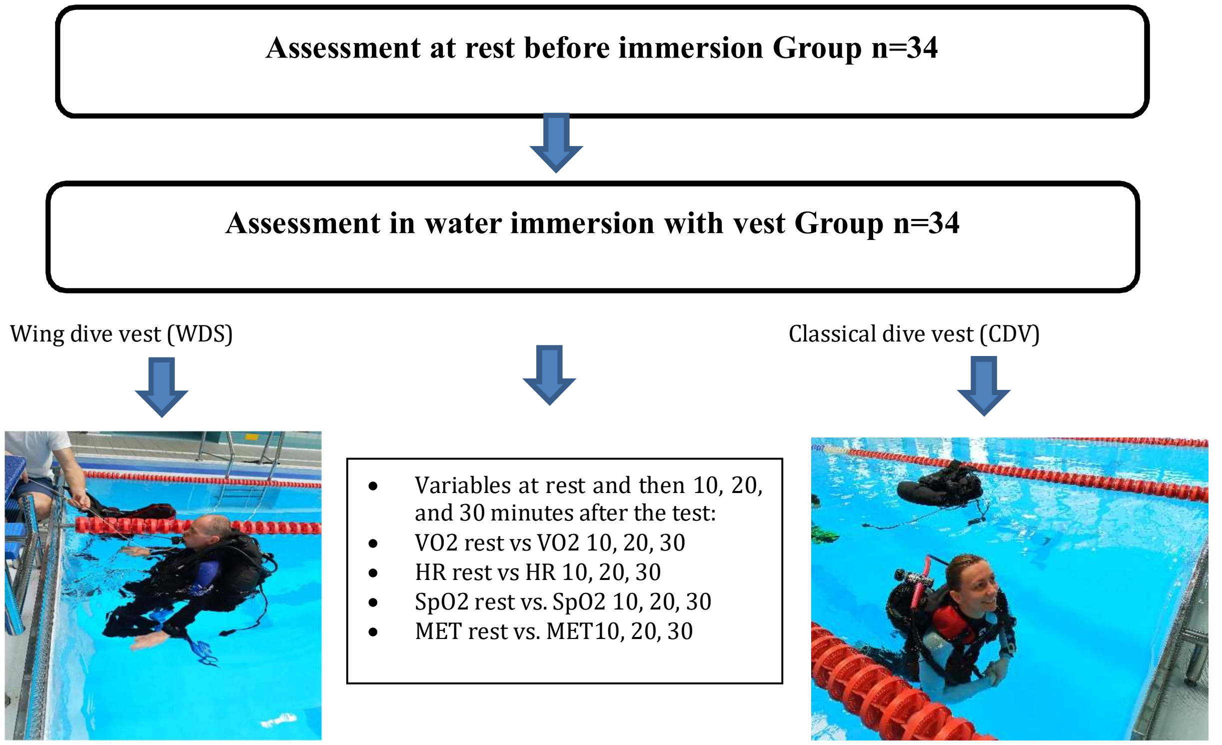

Fig. 1 The test procedures.

The data recorded during the tests were subjected to statistical analysis involving the calculation of basic descriptive statistics (means, standard deviations – SD, standard errors of the mean – SEM, confidence intervals, skewness, and kurtosis). Each parameter's distribution was assessed for normality using the Shapiro-Wilk test. The level of statistical significance was set at $p < 0.05$. The two-way ANOVA was preceded by Levene's test for homogeneity of variance. The effect of the BCD type (CDV vs. WDV) and the test duration (resting values vs. values measured after 10, 20, and 30 minutes) on the analysed indicators and parameters was assessed. The data were processed using the Microsoft Excel spreadsheet (2019) and statistical analysis was performed in Statistica v. 13.3 by StatSoft.

RESULTS

The study participants were similar in anthropometric measurements and the values of all indicators measured at rest were in normal ranges (Tab. 1).

The resting values of the physiological parameters measured at the beginning of the tests in participants wearing a CDV or a WDV and trying to maintain an upright position in the water are summarised in Table 1. The parameters' values recorded 10, 20, and 30 minutes into the test are presented in Table 2 by BCD type. The two-way ANOVA showed a significant effect of the BCD type (CDV vs WDV) on oxygen uptake during the tests ($F=9.80$, $p<0.001$) and significantly greater relative oxygen uptake (VO_2 [ml/min/kg]) after 10, 20, and 30 min in participants wearing the WDV compared with the CDV ($p<0.001$; Table 2). In participants wearing the CDV, significant increases in oxygen uptake ($p<0.001$) from the resting levels were recorded. Similar changes were observed for the respiratory indicators. The effect of the BCD type on VCO_2 and VE levels was significant, in contrast to VE/VO_2. Participants tended to have greater VT and smaller $SatO_2$ when wearing the WDV than when they floated with the CDV. The participants wearing the WDV had significantly lower $SatO_2$ after 30 minutes in water compared with its resting levels ($p<0.05$). The heart rate of participants using the CDVs did not change significantly (p>0.05), but its values recorded in the test with the WDVs were significantly higher at all three time points than at rest (p<0.01) and compared with those obtained for the CDVs after 20 (0.006) and 30 minutes (0.004) (F= 5.38; p<0.01) (Table 2). The SBP and DBP of participants using the CDVs were non-significantly lower than when they wore the WDV.

Tab 1.

The resting values of physiological indicators by BCD type (mean± SD).

Indicator	CDV	WDV	*P*
VO_2 [ml kg^{-1} min^{-1}]	6.8 ± 2.0	6.7 ± 1.5	Ns
VE [l min^{-1}]	16.3 ± 6.6	15.4 ± 4.5	Ns
HR [bpm]	72.0 ± 16.0	71.0 ± 15.0	Ns
SBP [mm Hg]	119.0 ± 13.4	118.0 ± 12.2	Ns
DBP[mm Hg]	78.0 ± 8.1	80.0 ± 8.2	Ns
VE/VO_2 [l]	32.6 ± 6.6	31.4 ± 5.2	Ns
MET	1.9 ± 0.6	1.9 ± 0.4	Ns
$SatO_2$ [%]	97.8 ± 1.3	98.2 ± 0.9	Ns

VO2 – oxygen uptake; VE-minute lung ventilation; HR- heart rate; SDP/DBP –systolic and diastolic blood pressure; MET- the metabolic equivalent of task, SatO2-haemoglobin oxygen saturation; ns- not significant statistically;
P – statistically significantly different between CDV and WDV.

Tab 2.

The values of physiological indicators recorded during the tests by BCD type (mean ± SD).

Indicator	Indicator change recorded after			Effect of the test protocol and time point		Post- hoc		
	10 min	20 min	30 min	F	p	Post-hoc 10’ CDV vs. WDV	Post-hoc 20’ CDV vs. WDV	Post hoc 30’ CDV vs. WDV
VO_2 [ml kg^{-1} min^{-1}]CDV	8.4 ± 2.4	8.1 ± 2.3	8.0 ± 2.5	9.80	0.001	0.000	0.000	0.001
VO_2 [ml kg^{-1} min^{-1}]WDV	11.2 ± 3.9	11.0 ± 3.6	10.8 ± 3.0					
VCO_2 [l min^{-1}]CDV	0.5 ± 0.2	0.5 ± 0.1	0.5 ± 0.1	9.80	0.001	0.000	0.000	0.001
VCO_2 [l min^{-1}]WDV	0.7 ± 0.3	0.7 ± 0.3	0.6 ± 0.2					
VE [l min^{-1}]CDV	17.3 ± 4.9	16.6 ± 4.8	16.3 ± 4.7	8.96	0.001	0.000	0.000	0.019
VE [l min^{-1}]WDV	21.6 ± 7.6	20.8 ± 7.7	20.1 ± 7.1					
HR [bpm]CDV	79.0 ± 17.0	75.0 ± 15.0	73.0 ± 16.0	5.38	0.01	Ns	0.006	0.004
HR [bpm]WDV	88.0 ± 16.0	89.0 ± 17.0	88.0 ± 15.0					
MET CDV	2.4 ± 0.7	2.3 ± 0.7	2.3 ± 0.7	9.89	0.001	0.000	0.000	0.001
MET WDV	3.2 ± 1.1	3.1 ± 1.0	3.0 ± 0.9					
$SatO_2$ [%]CDV	97.8 ± 1.0	98.0 ± 1.2	98.2 ± 1.1	0.2	ns	Ns	Ns	ns
$SatO_2$ [%]WDV	97.8 ± 1.1	97.5 ± 1.3	97.7 ± 1.2					

DISCUSSION

The study aimed to evaluate the degree of cardiorespiratory stress in divers wearing a BCD who try to maintain an upright position in the water for an extended time. Its results show that the divers' physiological response to these circumstances varies depending on whether they wear a classical dive vest or a wing dive vest [1,6]. A major finding of the study was that the demand for oxygen, elimination of CO_2, minute ventilation, and heart rate measured after 30 minutes were significantly greater in participants using WDVs than when they wore CDVs.

A classical dive vest keeps a motionless diver afloat in an upright position with the head inclined backward to prevent water from entering the airway (Figure 2).

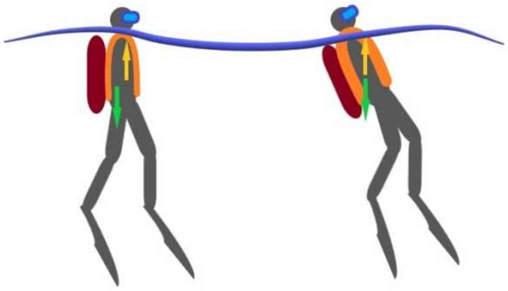

Fig. 2. The effect of buoyancy and gravity in a classic vest.

Such protection is not offered by a wing dive vest, whose centre of buoyancy causes a diver to float with the buttocks uppermost and the face submerged in the water (Figure 3).

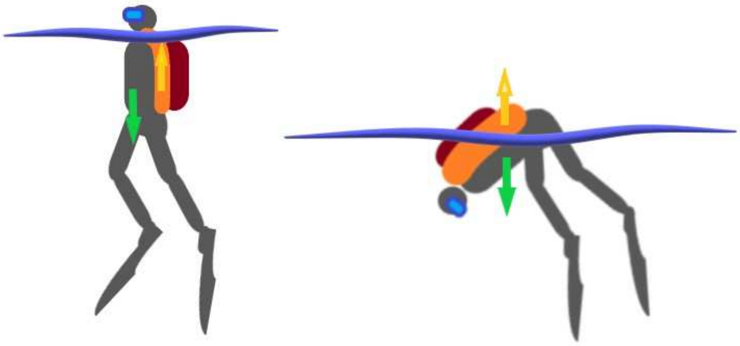

Fig. 3. The effect of buoyancy and gravity in a wing vest.

In order to counteract the position of the body, it is necessary to activate the work of skeletal muscle and adaptive mechanisms increasing oxygen transport to the tissues [7,8].

The results of the tests revealed that the participants' resting heart rate values increased significantly more when they wore the WDVs than when they used the CDVs. The same changes were observed for minute ventilation, MET, and oxygen uptake. However, the haemoglobin oxygen saturation levels measured in participants wearing the WDVs after 30 minutes in water were significantly smaller than at rest.

The relatively small increments in the physiological indicators of participants wearing the CDVs imply that divers who have ascended after a long dive incur a significantly higher physiological cost to stay afloat. The adaptation mechanisms that increase oxygen reserves during free diving and deep diving to protect a diver from an abrupt loss of consciousness are well recognised [2,5,9]. Breathing under limited oxygen supply contributes to lower pulmonary partial oxygen pressure (pO_2), the oxygen content of blood gradually declines, likewise haemoglobin saturation (SpO_2). Chemoreceptor reflexes change blood distribution to protect the brain and heart from hypoxia, which partly attenuates the effect of reduced blood oxygen saturation. Extended apnoea leads to bradycardia and reduces the amount of blood flowing in the muscles, while the activation of pulmonary mechanoreceptors under increased intra-alveolar pressure and pulmonary vessel hypertension initiate defence mechanisms protecting from hypoxia and lung compression. Other major mechanisms enabling physiological adaptation to extended breath-hold time underwater include vasoconstriction improving the hemodynamic parameters, the release of the reserves of oxygen-saturated blood (the diving reflex), and slowed metabolism [5,10].

An underwater dive has an effect on the dynamics of venous return. As peripheral blood flow decreases, more blood circulates in the chest [2]. Changing pressure and availability of O_2 in the respiratory system and faster removal of CO_2 cause are followed by changes in the cardiorespiratory system: blood vessels constrict or dilate, lowering or raising blood pressure, respectively.

The trained divers develop adaptation mechanisms that protect them from hypercapnia associated with breath-holding by improving the use of the available oxygen reserves and slowing down metabolism [11,12]. The extended inhalation of a breathing gas during scuba diving (deep diving) is associated with the occurrence of adverse physiological phenomena and risks related to hyperventilation, oxygen poisoning, and nitrogen narcosis [11].

This experimental study investigating how physiological reactions to floating in an upright position vary depending on the type of a BCD worn by a diver has some limitations. The measurements were taken in participants who did not ascend from a dive and floated in the calm water of constant temperature under windless conditions. Nonetheless, its results confirm the possibility of using physiological indicators to compare cardiorespiratory risk and fatigue in divers depending on the BCD type.

CONCLUSION

1. The wing dive vest does not protect an unconscious diver or one who cannot move their limbs; in other cases, its usability as a rescue device is determined by the diver's physical capacity.

2. The classical dive vest is capable of protecting a diver, even one who is unconscious, for an extended length of time.

3. There is a need for further research with a testing protocol designed to better imitate natural outdoor conditions (a rough water surface, low ambient temperature).

REFERENCES

1. Middleton JR. Evaluation of Commercially Available Buoyancy Compensators. Test Report. Navy Experimental Diving Unit Panama City Fl. 1980;1-80
2. Bosco G, Rizzato A, Moon RE, Camporesi EM. Environmental physiology and diving medicine. Front Psychol, 2018; 9: 72.
3. https://youtu.be/XX4nYoNaJ_g
4. Looney DP, Long ET, Potter AW, Xiaojiang X, Friedl KE, Hoyt RW, Chalmers CR, Buller MJ, Florian JP. Divers risk accelerated fatigue and core temperature rise during fully-immersed exercise in warmer water temperature extremes. Temperature, 2019; 6(2): 150-157, DOI: 10.1080/23328940.2019.1599182
5. Cheung SS, Ainslie PN. Diving and Hyperbaric Physiology. In Advanced Environmental Exercise Physiology. Champaign IL: Human Kinetics 2022; 109-126.
6. Rush T. Test and Evaluation of the Integrated Divers Vest. Test Report. Navy Experimental Diving Unit Panama City Fl. 1994; 11-94.
7. Bain A, Drvis I, Dujic Z, MacLeod D. Physiology of static breath holding in elite apneists. Exp Physiol. 2018; 103: 635-651.
8. Elia A, Wilson OJ, Lees M, Parker PJ, Barlow MJ, Cocks M, O'Hara JP. Skeletal muscle, haematological and splenic volume characteristics of elite breath-hold divers. Eur J Appl Physiol, 2019; 119: 2499–2511.
9. Marlinge M, Coulange M, Fitzpatric R, Delacroix R, Gabarre A, Laine N, Cautela J, Louge P, Boussuges A, Rostain JC, Guieu R, Joulia FC. Physiological stress markers during breath-hold diving and SCUBA diving. Pysiol Rep, 2019; 7(6): e14033.
10. Fernández F, González-Ravé JM, Juárez, D. Breath-hold diving performance factors. J Hum Sport Ex, 2017; 12(3): 582-592.
11. Kjeld T, Stride N, Gudiksen A, Hansen EG, Arendrup HC, Horstmann PF, Zerahn B, Jensen LT, Nordsborg N, Bejder J, Halling JF. Oxygen conserving mitochondrial adaptations in the skeletal muscles of breath hold divers. PLoS One. 2018; 13(9): 0201401. doi: 10.1371/journal.pone.0201401
12. Garbella E, Piarulli A, Fornai E, Pingitore A, Prediletto R. Preliminary observations on the effect of hypoxic and hyperbaric stress on pulmonary gas exchange in breath-hold divers. Diving Hyperb Med. 2011; 41(2): 97–100.

dr hab. med. Piotr Siermontowski, prof. AMW
Katedra Technologii Prac Podwodnych
Akademii Marynarki Wojennej
ul. Śmidowicza 69
81-127 Gdynia
p.siermontowski@amw.gdynia.pl

ORCID - 0000-0003-2557-3561