POLISH HYPERBARIC RESEARCH 2(47)2014
Journal of Polish Hyperbaric Medicine and Technology Society

THE EVALUATION OF PHYSICAL FITNESS OF DIVERS WITH REGARD TO VENTILATION PARAMETERS

Tadeusz Doboszyński, Bogdan Łokucijewski

Maritime Medicine Department Military Medical University, Gdynia, Poland

ABSTRACT

On the basis of the data provided by available literature, it is assumed that under normobaric conditions general efficiency of an organism finds its equivalent in the oxygen uptake threshold and is limited by cardiac output, whereas in diving it is limited by ventilation possibilities influenced by the density of a breathing mix.

The objective of the study was to determine the adaptive changes occurring in the respiratory system in relation to effort undertaken under water. The research was carried out in a hyperbaric chamber and participated by 14 divers, 7 with professional training and 7 beginners. The study was based on simple tests used in the evaluation of efficiency of the respiratory system and at the same time the determination of hemodynamic and respiratory changes.

As a result, it was affirmed that an increase in gas density in hyperbaric conditions constitutes the most serious factor limiting the maximal ventilation, and also that training has a positive effect on respiratory efficiency under such conditions. The best differentiating tests proved to be: the maximal exhalation pressure test and the Flack test.

Key words: respiratory efficiency, hyperbaric oxygenation, training, adaptation.

ARTICLE INFO

PolHypRes 2014 Vol. 47 Issue 2 pp. 59 - 68

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

DOI: HTTP://DX.DOI.ORG/10.13006/PHR.47.6
Pages: 14 , figures: 0, tables:5.

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

Publisher
Polish Hyperbaric Medicine and Technology Society

Original article

Originally published in the Journal of Naval Health Service 1973.

Date of approval for print in PolHyp Res.: 2.06.2014 r.

The Navy is an institution assembling the largest group of professionally trained divers in Poland. However, this was not the sole reason for undertaking the above subject matter, as in comparison with other specialists this group is not that numerous. The reason was quite different. The impact of various working conditions provided by the aquatic environment remains in such a sharp contrast with the working conditions on the land that in many cases it is underestimated or improperly understood. For this reason it was our intention to analyse some of the issues associated with the effects of the aquatic environment on divers' efficiency. It should be noted that the discussed issue is of real practical significance despite a considerable lack of information in the available literature.

When undertaking the research in question, we were aware of the difficulty related to finding a satisfactory solution, as in line with the established opinion it seemed quite unlikely that we would obtain a reliable efficiency evaluation, either generally or specifically, on the basis of only several simple indicators or physiological trials.

Even when we take into account the fact that certain adaptive features may develop and be revealed not only during an effective performance of work under water but also during an idle stay in the aquatic environment if it is repeated frequently enough, even at larger depths and therefore under a higher pressure.

A significant role in this regard is played by the following factors: immersion in water, the necessity to use diving apparatus, and the effect of an increased pressure. These three elements impose an unusual burden on the respiratory organs and induce changes in the work of the cardio-vascular system as compared with the conditions present on the surface/in normobaria.

The essential mechanism behind the effect of diving on respiratory functions may be presented on the basis of an impact of immersion on a diver's organism and an increased density of a breathing mix. At the same time it should be emphasised that the influence of immersion on breathing is largely dependent on the type of diving equipment, whereas the density of the breathing mix, in the simplest case being air, is directly related to the diving depth. The effect of each of these two factors on a diver's organism may be depicted as The aforementioned negative pressure will move the balance point above the determined 30% threshold of pulmonary vital capacity. This, on the other hand, will cause breathing to be less energetically efficient, as the most favourable scope falls between 30% and 80% of the said vital capacity (VC). Between these values the slightest effort of the respiratory muscles may evoke the greatest alteration in pulmonary vital capacity. In other words, gas exchange in the said range is the most energy-efficient.

Unfortunately, the breathing bag is rarely placed exactly at the height of the "pressure balance point", similarly as it is in the case of open circuit scuba. In extreme situations when the deviations from the "balance point" exceed 20 cm, the effect is a painfully felt discomfort during breathing.

With positive pressure, i.e. when the "bag or rebreather" is positioned too low, what happens is an unintentional filling of the lungs if the diver counteracts it with an expiratory effort. Under these circumstances the inhalation takes place with a gradual decrease of expiratory effort. This causes respiratory muscles to be forced not only to perform harder work but also to continue it during both breathing phases (instead of a single inhalation phase).

Despite this, the lack of balance and the produced positive pressure in the lungs is less exhausting than the lack of balance in the condition of a negative pressure. (The impact of negative pressure is observed, for instance when swimming with a snorkel) The above information regarding gas exchange in divers takes into account the impact of immersion.

The second factor, differentiating breathing under pressure from that of breathing under normal conditions in normobaria, is an increased density of a breathing mix.

The density of air inhaled by a diver, in accordance with the principle of levelled pressure, is proportionally increased to the depth of diving. Density is significant in defining the nature of gas flow, which may be done on the basis of Reynolds number, where:

$$Re=\frac{p\ v\ R}{\eta}$$

p – density /g cm $^{-3}$ /
v – average flow rate /cm sec $^{-1}$/
R – average flow /cm/
□ - viscosity coefficient /g cm $^{-1}$/.

The experimentally determined so-called critical Reynolds value 2320 determines the type of flow. Below this value the flow is usually laminar, whereas above – turbulent. It is possible for certain deviations to occur in the evaluation due to the important role of the morphology of the respiratory tract.

With regard to air flow evaluation through the respiratory tract we are faced with a particularly interesting problem, as in reality, the bronchial tree possesses a large number of branches, each of which causes a change in the flow's direction. Moreover, particular segments vary with respect to their diameters and lengths.

Finally, the diameter of the respiratory is subject to cyclic changes accompanying the respiratory rhythm. Thus, the above conditions are crucial not only with regard to the geometric issues but also to the dynamics, as the flow is highly differentiated in the section between the trachea and small bronchioles.

For these reasons the Reynolds number indicates varying values at the entire length of the bronchial tree. Already while at rest the air flow in the respiratory tract is in some sections laminar, while in other turbulent.

A classic work by Rohrer (1915) suggested that the ΔP value (the difference between alveolar pressure PA and the pressure at the mouth) in the respiratory tract may be presented as a sum of two components – the laminar and turbulent flow.

$$\Delta P=K_1\underset{\cdot}{V}+K_2\underset{\cdot}{V}^2$$

$K_1\underset{\cdot}{V}$ represents laminar flow in accordance with Hagen-Poiseuille's relation, whereas $K_2\underset{\cdot}{V}^2$ expresses turbulent flow. This description is approximate to Mead's postulate [9]. Therefore, an increased ventilation flow, or hyperventilation, is accompanied with an increased turbulent reaction. In those sections where the rest flow was laminar, during hyperventilation it will become turbulent.

Such phenomena are reflected in the physiology of breathing under water. Breathing with compressed air, following the principle of pressure levelling (in the respiratory tract at ambient pressure) results in an inhalation of air of higher density.

The Reynolds number (which takes this value into account)increases at the entire length of the bronchial tree to the same extent. From the point of view of aerodynamics, breathing at rest at the depth of 40 m corresponds to hyperventilation at the surface, as the flow rate of air may be compared to a flow that is 5 times higher. In other words, normal breathing at the depth of 40 m is associated with an increase in the turbulent reaction to such an extent as it is the case with hyperventilation experienced at the surface.

During turbulent flow the resistance is much higher as compared with laminar flow. For this reason, a growing flow resistance during hyperventilation may lead to the exceeding of the energetic possibilities of the respiratory muscles. Ventilation insufficient to compensate for the needs of an organism is known as hypoventilation. It is believed that in hyperbaric conditions hypoventilation may be induced by at least two factors: an increase in the density of a breathing mix, which was depicted above, and an increased flow rate as a result of an effort-related ventilation.

Consequently, hypoventilation may occur both at a shallow depth during an effort as well as at a greater depth, even when at rest.

In both cases an additional factor which may be conducive to the occurrence of hypoventilation is flow resistance in a diving apparatus.

The after-effects of hypoventilation are those described by traditional clinical medicine: hypercapnia, an increase in cardiac output, arterial pressure and intracranial pressure.

The only absentee is hypoxaemia, which accompanies hypoventilation at the surface, due to the fact that in the air inhaled under pressure oxygen partial pressure is increased.

How, therefore, should we evaluate the possibility of continuing a large physical effort in normobaric and hyperbaric conditions in the light of the above data? It is believed that during an effort made at the surface one of the most significant values determining diver's efficiency, namely oxygen consumption per minute ($^{V}O_2$ max)is limited by cardiovascular factors as well as lactic acid concentration.

In hyperbaric oxygenation, limitation of activity depends to a large extent on the alveolar pressure level CO_2($^{P}ACO_2$) that a diver can tolerate. Also, of great importance is Lanphier's statement [5]that in the situation when the factor limiting the effort is ventilation, it may be maintained over longer periods as it is the case in the limitation caused by cardiovascular factors. According to the above data it is possible to formulate the following theses. Whereas under normobaric conditions general efficiency is reflected by maximal oxygen uptake and limited by the cardiac output, in diving (hyperbaric conditions) it is limited by ventilation possibilities. Gas density increases the resistance in the respiratory tract, while the differences in eupneic and hydrostatic pressures disturb the elastic properties of the lungs-chest system. This leads to an increased level of CO_2 in the alveoli and arteries, thus causing effort reduction.

Based on the above data indicating that during the work performed under water the efficiency level is limited, first of all, by the efficiency of the respiratory system, it was decided to conduct a study on divers aimed at revealing possible adaptive changes in the respiratory system to undertaking an effort under water. At the same time it was determined that the performed tests should be available, so that in the case of proven usefulness they could be recommended for broader application. The study was based on popular tests used in the evaluation of efficiency of the respiratory system and the determination of hemodynamic and respiratory changes.

The subjects of the study were divided into two groups. The first group consisted of diving instructors, most of whom had a professional experience of several years. The second group included trainee divers with 2-months' training and without prior experience in this area. The study was to take into account the VC measurement.

Next, it was decided to determine maximal voluntary ventilation (MVV_{15}), as according to some researchers [5] it is valuable in the assessment of maximal effective ventilation ($\underset{.}{V}_e$ max). However, the determination of maximal breath-holding time was omitted due to little credibility of the obtained data [7] and a decision was made to apply the Flack test as a more objective and particularly valuable method in diver qualification.

METHODOLOGY

Tab. 1

The determined parameters:

Vital capacity /VC/
Due vital capacity /VC/ acc. to Cournand
Maximal expiratory force /P_e max/
Due maximal voluntary ventilation /MVV/ acc. to Baldwin
Flack test
Maximal voluntary ventilation "MVV$_{15}$" with the use of diving apparatus and a "Mors" rebreather
At the pressure of 1 ata
At the pressure of 2 ata
At the pressure of 4 ata
Measurements performed on the basis of height and weight from calculation tables acc. to Cournand's formula [4];
With the use of a precise spring manometer /indication accuracy of 5 mm Hg/;
On the basis of the formula MVV = /86.5-0.552 x age /x body surface/m^2;
40 sec. Breath held at an inhalation at P_3 40 mm Hg with pulse changes evaluation acc. to Flack's table [4];
Volume of exhaled air determined on the basis of pressure drop in the cylinder with compressed air;
Measurement carried out in a pressure chamber
Measurement carried out in a pressure chamber

RESULTS

The physical properties of divers qualified into the instructor group are presented in table 2, whereas the physical properties of the group of trainee divers are in table 2. The average values of maximal voluntary ventilation "MVV$_{15}$" for the "Mors" rebreather measured at the surface and under hyperbaric conditions are shown in table 4. Table 5 contains statistical evaluation of the results of both groups.

Tab. 2.

Physical properties of the group of instructors.

1.	Number of subjects	7
2.	Height /cm/	179-182
3.	Weight /kg/	70-79
4.	Age	26-31
5.	VC /ml/	5400/4500-6100/
6.	VC /ml/ acc. to Cournand's formula	4300/4100-4450/
7.	Δ VC / 5 – 6/ %	+20
8.	$P_e$max /mm Hg/	202/195-210/
9.	Flack test / group /	I
10.	MVV$_{15}$ /1/min/ acc. to Baldwin's formula	136/128-145/

Tab. 3.

Physical properties of the group of trainee divers.

1.	Number of subjects	7
2.	Height /cm/	167-179
3.	Weight /kg/	57-80
4.	Age	20-22
5.	VC /ml/	5000/4200-7000/
6.	VC /ml/ acc. to Cournand's formula	4400/4300-4600/
7.	Δ VC / 5 – 6/ %	+12
8.	$P_e$max /mm Hg/	140/110-170/
9.	Flack test / group /	I-III
10.	MVV$_{15}$ /1/min/ acc. to Baldwin's formula	135/123-150

Tab. 4.

The average values of maximal voluntary ventilation "MVV$_{15}$" for the "Mors" rebreather measured at the surface and in hyperbaric oxygenation.

	Pressure ata	Number of tests	"MVV15" 1/min $\bar{x}$	%	Stand E error
Instructors	1	14	145 ± 18.0	100	4.8
	2	14	88 ± 12.2	61	3.2
	4	14	65 ± 12.0	45	3.1
Trainee divers	1	28	138 ± 9.1	100	3.4
	2	28	87 ± 6.8	63	2.6
	4	28	54 ± 6.9	39	2.6

Tab. 5.

Statistical evaluation of the results.

	Instructors $\bar{x}$	Trainee divers $\bar{x}$	Statistical significance of Student's t-test
Spirometry /ml/	5400	5000	Insignificant differences
"MVV$_{15}$" at 1 ata/1/min	145	138	Insignificant differences
"MVV$_{15}$" at 2 ata/1/min	88	87	Insignificant differences
"MVV$_{15}$" at 4 ata/1/min	65	54	Insignificant differences
$P_e$max /mm Hg/	202	140	Significant differences /6.0 t/
[S1]Flack test /group/	I	I-III	Other classification

DISCUSSION

As it results from table 2, the group of instructors consisting of 7 subjects is characterised by a high vital capacity (VC) reaching 5400 ml, i.e. ca. 20% higher from due capacity calculated according to Cournand's formula. In the opinion of some researchers, such a difference is typical of people actively participating in sports, regardless the type of discipline.

A characteristic value is that of maximal exhalation force P_e expressed in mm Hg, which on average amounts to 202 mm and reveals slight deviations in particular subjects. It is worth noting that the value regarded as correct is estimated at 60 – 100 mm Hg [12]. Another favourable characterisation of the subjects was obtained with the Flack test, which did not indicate disruptions in the pulse of the researched divers under the impact of pulmonary hypertension of 40 mm Hg during breath holding.

The randomly selected group of trainees (having completed 2-months' training) included divers several years younger than the member of the previous group and characterised by a slightly lower body weight. Similarly to the first group, the vital capacity (VC) in this group was higher than that calculated acc. to Cournand's formula. However, the determined difference was smaller and exceeded the value calculated acc. to the formula by 12%. The mean value of maximal exhalation force (P_e max) in this group reached 140 mm Hg, i.e. less than in the instructor group. The result of the Flack test was also less favourable, as not all of the subjects were qualified to the first group. The mean values of maximal voluntary ventilation ("MVV$_{15}$" tab. 4) measured in both groups at the pressure of 1 ata were higher than the values calculated acc. to Baldwin's formula [4] despite their marking with the use of equipment characterised by significant flow resistance. With the consideration of the conditions in which the tests were carried out, the obtained results indicated high efficiency of the respiratory organs in both groups, even though the results achieved with the use of Baldwin's formula were too low.

The measurements performed at an increased pressure of 2 and 4 ata showed significant ventilation reduction with the pressure rise. At 4 ata, maximal voluntary ventilation "MVV$_{15}$" was reduced in the instructor group to 45% of the initial value, whereas in the trainee group to 39%.

Table 5 shows a juxtaposition of the obtained results and statistical evaluation of the significance of differences between both groups, both with regard to spirometry measurements and the "MVV$_{15}$" values, despite the fact that the values obtained by the group of instructors were in all cases higher. The spirometry results of the instructor group do not differ from the values provided in literature with regard to American instructors, in whom the average VC value amounted to 5600 ml [1].

The observed MVV decrease in the function of pressure may be presented as proportional to the square root of the pressure value expressed in ata. This relation was first noted by Cotes and confirmed by Miles, Wood, Maio, Fahri and others [2,8,10,13]. The MVV value determined by these researchers in low-resistance equipment reached ca. 50% of the initial value at the pressure of 4 ata. In the case of our studies conducted with the use of the "Mors" rebreather, the obtained results reached 45% and 39% of the output value. Although such a deviation is not large, it is still necessary to take into account the fact that the reference value for the "Mors" apparatus was lower.

Significant differences, on the other hand, were noted in relation to the values of maximal exhalation force P_e max. Also, different evaluations were obtained in the comparison of Flack test results, as the group of trainees was characterised by a higher diversity of evaluations.

Hence, we might issue a question on how to interpret the observed difference in the mean values of the maximal exhalation pressure in the Flack test and how to explain a lack of difference in the values of "MVV_{15}".

Higher values of maximal exhalation pressure seem to be a sign of an adaptation of chest muscles of diving instructors to the conditions of an impeded ventilation experienced in the course of diving. This is confirmed by the fact of a significant exceeding of the value adopted as a norm, as well as obtaining results that are considerably higher than in the group of trainees.

The differences between both groups in relation to the assessment conducted with the use of the Flack test, with unequivocal evaluation of all divers in the instructor group, seem to be to a large extent an expression of the selection that took place in this group. Since the group of instructors consisted of divers with professional qualifications, who would not be able to obtain valuable results in sport diving even with unidentified disorders of the circulatory system. However, we may not exclude the development of adaptive changes indicating a high level of training of this group.

The lack of statistically significant differences in "MVV_{15}" values appears to stem from several reasons, among which the most important role may be played by test duration. According to Varene, if a measurement is conducted over the period of 4 minutes, and not over 15 sec, the obtained values are considerably lower and characterised by a larger diversification. Zosche, Fritts and Cournand [3,5] observed a drop in maximal ventilation ($\dot{V}_e$max) to 53% of the "MVV_{15}" value during a 15-minute respiratory effort, performed without additional loading of environmental factors (immersion, gas density, equipment resistance). Thus, it cannot be excluded that the results the instructors obtained over a prolonged test period or a further increase of the pressure would manifest greater deviations than the group of trainees.

Unfortunately, at present we are unable to provide concrete arguments in response to this hypothesis. However, what would indicate this possibility are the skills of the instructors in endurance and speed dives as compared to other types of dives. At the same time, an important role is played by another factor, though dependent on the first one, namely the possibility to continue the effort at a high level of alveolar CO_2($^{P}ACO_2$), of which only well-trained and experienced divers are capable. As stated by Lanphier at $^{V}CO_2$= 2.0 1 the effort would be possible to maintain only in the case of a period lasting less than 30 minutes or longer than 60 minutes depending on whether the alveolar $^{P}ACO_2$ amounted to 40 mm Hg or 60 mm Hg [5]. At the same time, this researcher confirmed that an increased tolerance resulted in few problems for experienced divers, rarely stopping their work as a result of an inability to maintain the alveolar CO_2 ($^{P}ACO_2$) at a level of 40 mm Hg, as the decreased tolerance to CO_2 allows them to endure much higher levels.

This, according to some researchers, determines the efficiency in underwater work [5]. It is confirmed with the opinion that general efficiency depends on the efficiency of particular systems, with this relation between extremely complex and thus far impossible to measure.

With regard to the capability to endure high CO_2 levels we must emphasise that it is only possible with the use of air apparatuses, as using oxygen or oxygen-enriched mixes by divers with a reduced sensitivity of chemoreceptors to CO_2 makes them more susceptible to oxygen toxicity than others [6].

The presented material serves to acknowledge the difficulty in establishing the criteria for assessing divers' efficiency and the selection of proper indicators.

CONCLUSIONS

1) The increase in gas density under the impact of an increased pressure constitutes a factor limiting maximal voluntary ventilation in divers, which may be seen as an exponent of ventilation possibilities.

2) However, the ventilation limits resulting from environmental conditions do not induce an identical efficiency decrease in all people.

3) In the evaluation of two groups of varying capabilities the differentiating tests proved to be: the maximal exhalation pressure test and Flack test.

BIBLIOGRAPHY

1. Carey E.M, Schaefer K.E., Alyis H.J.: J.Appl.Physiol. 8,51, 1956.
2. Cotes J.E.: Lung function. Blackwell, Oxford 1968.
3. Comroe H.J.: The lung. Year Book Med.Pub., Chicago 1965.
4. Koziorowski A.: Pulmonary function tests. PZWL, 1964.
5. Lanphier E.H.: in Diving Physiology. Bailiere, London, 1969.
6. Łokucijewski B., Doboszyński T.: Lek.Wojsk. 1972, 9:88.
7. Łokucijewski B., Doboszyński T.: Lek.Wojsk. 1972, 4:377.
8. Maio D.A., Farhi L.E.: J.Appl.Physiol, 1967, 23:687.
9. Mead J.: J.Appl.Physiol, 1963, 18:241.
10. Miles S.: Underwater medicine. Staples Press, London 1966.
11. Paton W.D.: J.Physiol, 1947, 106:119.
12. Sidrowicz W.: An outline of methodology of sport-medicine tests and counselling PZWL, Warsaw 1962.
13. Wood W.B.: Arch.Environ.Health, 1963, 7:47.