The influence of high-fat diets on the occurrence of decompression stress after air dives

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ABSTRACT

Introduction: In hyperbaric air exposures, the diver's body is subjected to an increased gas pressure, which simulates a real dive performed in water with the presence of hydrostatic pressure. The hyperbaric effect depends on pressure, its dynamics and exposure time. During compression, physical dissolution of inert gas in body fluids and tissues takes place. The decompression process should result in safe physiological disposal of excess gas from the body. However, despite the correct application of decompression tables we observe cases of decompression sickness. The study aim was to find factors affecting the safety of diving, with a particular emphasis on the diet, which thus far has not been taken into account.

Methods: The study subjects were 56 divers. Before hyperbaric exposure, the following data were collected: age, height and weight; plus each divers filled out a questionnaire about their diet. The data from the questionnaires allowed us to calculate the approximate fat intake with the daily food for each diver. Moreover, blood samples were collected from each diver for analysis of cholesterol and triglycerides. Hyperbaric exposures corresponded to dives conducted to depths of 30 and 60 meters. After exposures each diver was examined via the Doppler method to determine the possible presence of microbubbles in the venous blood.

Results and discussion: Decompression stress was observed in 29 subjects. A high-fat diet has a direct impact on increasing levels of cholesterol and triglycerides in the blood serum. A high-fat diet significantly increases the severity of decompression stress in hyperbaric air exposures and creates a threat of pressure disease.

INTRODUCTION

Despite many years of experience, highly developed techniques and properly used decompression tables, the incidents of decompression sickness (DCS) still occur. What is more, long-term effects of diving are found, especially avascular necrosis of bones as well as neurological disorders [1,2]. There is ongoing research to find other factors that affect divers' safety and health. These factors, underestimated and overlooked in research thus far, may be partly connected with divers' diets.

The main condition that has to be fulfilled in safe diving consists in using the right method of decompression. The amount of diluted gas in tissues is influenced mainly by the depth and the duration of diving. These are the parameters specified in decompression tables. Currently there are no decompression tables that would fully guarantee divers' safety or eliminate the threat of DCS [3]. Despite the application of decompression tables, it is possible that decompression illness will appear. For example, if the most popular U.S. Navy tables are used correctly, the risk of DCS is as high as 3.9% [4]. It is believed that gas microbubbles may be formed after almost every dive.

In spite of the correct usage of decompression tables, in individual cases divers may suffer from the effects of decompression sickness. Studies that use the Doppler method, showed very significant differences in the formation of bubbles among different people who were subjected to hyperbaric exposures of the same type [5,6]. For this reason, while planning the dive or hyperbaric exposure, it is necessary to consider the many factors that may influence the course of decompression.

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Obesity is considered to be a significant risk factor in decompression sickness due to the greater storage of inert gas in tissues that contain fat [1,7,8]. The solubility of nitrogen in fat is 5.3 times higher than that in hydrated tissues. An additional anatomically predisposing factor is the poor vascularity of adipose tissues, which slows down elimination of inert gas in relation to hydrated tissues. It is believed that adiposity increases the statistical risk of decompression sickness [7,8,9]. However, the scientific community has divided opinions in relation to this assertion.

The above calculation does not include fats in the blood – which increase the solubility of inert gases. Till now there have been no studies in this area. Due to the long duration of fat metabolism, the diet that is rich in fats will definitely raise the level of lipids in the blood [10], and therefore increase the amount of dissolved inert gas and thus the probability of decompression stress or DCS. The term “decompression stress” refers to the occurrence of usually asymptomatic gas bubbles (nitrogen) in the blood after a hyperbaric exposure [11].

Not only mechanical actions such as the formation of gas emboli, but also gas bubbles, which are foreign bodies for the organism, can produce different reactions. Bubbles may end up coated with thrombocytes and form a microthrombus that will remain in the circulatory system even after the elimination of bubbles due to the fact that the clot fibrinolysis processes occur more slowly. For this reason, the possibility of microemboli formation, especially in pulmonary circulation, is significant. The greater the number and size of bubbles, the more intense the effect a foreign body will have, with repeated exposures causing an accumulation of consequences. The bubbles coated with a few microclots or the microclots alone are able to obstruct capillaries or precapillaries. If this is a single occurrence, it will give no symptoms and result in no visible pathological changes. However, many microemboli lead to the damage of tissues that are sensitive to hypoxia [12,13,14,15,16].

The most common examination used to evaluate the course of decompression is ultrasound detection of gas microbubbles in the circulating blood [17,18]. On the other hand, not all individuals with microbubbles found in their system go on to develop DCS. Therefore, methods and markers other than the use of ultrasound are needed for assessing an individual’s risk of decompression sickness.

Despite the usage of decompression tables, high incidences of decompression sickness indicate the need to improve them, and, above all, to look for new risk factors that influence the course of decompression. Until now there has been little research carried out into either a divers’ alimentation or the influence of the levels of lipids in the blood serum on decompression [19,20,21].

The aim of the work

The studies conducted were meant to demonstrate the impact of the diet on diving safety. The study focused particularly on divers’ nutritional preferences, with a special focus on the intake of fats and their effects on the levels of cholesterol and triglycerides in the blood serum and the incidence of decompression stress after air hyperbaric exposures. The aim of this study was to demonstrate that an increased intake of fat in the diet significantly increased the risk of decompression stress.

Materials and methods

This research has been conducted within the project “Effects of hyperbaric on human body homeostasis.” The research was approved by the Ethics Committee of Military Medical Institute. The participants expressed a written voluntary consent to participate in research.

Fifty-six men, aged from 20 to 48, with recreational or professional diving qualifications, took part in the hyperbaric exposure and the ensuing study. Exclusion criteria included genetically determined dyslipidemia and diet change three months prior to the exposure.

Divers completed questionnaires concerning their diet, which was used to calculate approximate consumption of fat in their daily food intake. The percentage of the daily fat intake was specified based on surveys in relation to the maximum recommended intake depending on the type of work (according to Polish standards) [22,23]:

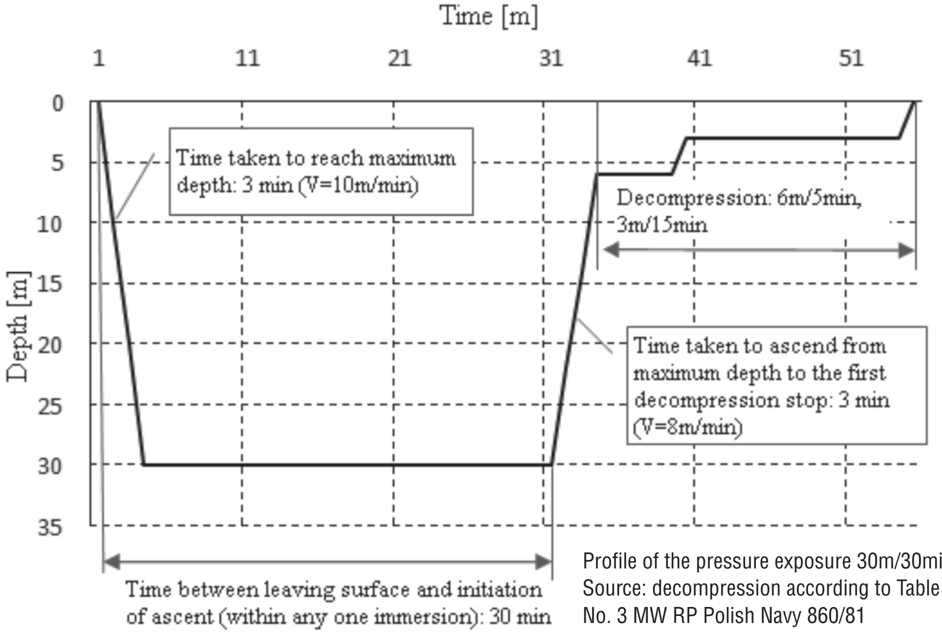
- hard work – 155 grams fat / per day;
- moderate work – 125 grams fat / per day;
- light work – 100 grams fat / per day.

Before each exposure, a vacuum tube containing a clotting activator was used to collect a sample of each diver’s blood from a vein in the arm. These samples were then used to determine the lipid levels.

Tests were performed in a certified analytical medical laboratory. Lipid levels were determined by Roche Modular enzymatic colorimetric analyzer.

After the exposure, a Doppler ultrasound procedure was performed using a SonoSite M-Turbo ultrasound device, with Doppler color scanner. The procedure was performed three times: immediately after exposure, 30 minutes after exposure, 60 minutes after exposure) to

FIGURE 1. Pressure exposure profile



Profile of the pressure exposure 30m/30min.
Source: decompression according to Table
No. 3 MW RP Polish Navy 860/81

determine the possible presence of gas bubbles in the venous blood. Flows in heart valves, subclavian and groin vessels were studied. The research was evaluated in accordance with the Kisman-Masurel scale. Evaluation of the first stage (single gas bubbles) was regarded as the norm. In cases where the presence of numerous gas bubbles was stated (II, III, IV degree), the study was conducted every hour until the gas was sluiced out from the blood. Inert gas washout was carried out by breathing 100% oxygen at atmospheric pressure or at a pressure of 0.6 atmospheres absolute (atm abs) and according to medical procedures used in hyperbaric oxygen therapy.

Exposure to hyperbaric conditions was carried out in a hyperbaric chamber, allowing the creation of comparable conditions for all subjects who took part in the experiment. Exposure parameters such as the breathing mixture (air) used, exercise, ambient temperature and humidity were constantly monitored and recorded. The exposures imitated pressure conditions that appear during 30- and 60-meter dives, *i.e.*, 0.3 and 0.6 MPa respectively: Each diver was exposed to the equivalent of 30 meters' depth and given a 24-hour break before performing a 60-meter dive. Decompression was carried out in accordance with Polish Navy decompression tables [24]. In order to increase the safety factor, doubly restricted profiles were used.

METHODOLOGY

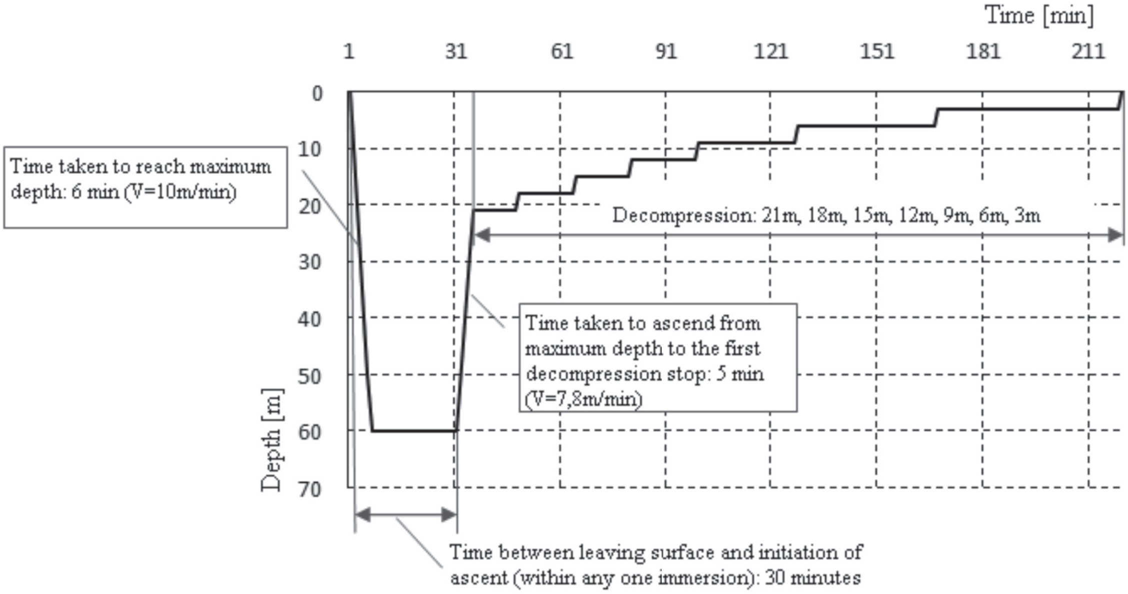
Methodology of the exposure corresponding to the diving depth of 30 meters *(Figure 1)*

After medical qualification, people involved in the experiment were compressed to the pressure of 400 kPa. The divers were divided into groups of four. The time of exposure from beginning of compression to beginning of pressure reduction was 30 minutes, followed by gradual decompression carried out in accordance with the naval decompression tables. During the exposure and the decompression respiratory factor was the air.

Exposure parameters:

- Time taken to reach maximum depth: three minutes (V/descent rate = 10 meters/minute);
- Time between leaving surface and initiation of ascent (within any one immersion): 30 minutes;
- Time taken to ascend from maximum depth to the first decompression stop: depth: three minutes (V = 8 meters/minute);
- Decompression: 6 meters/five minutes, 3 meters/15 minutes.

FIGURE 2. Profile of exposure pressure



Profile of the exposure pressure 60m/30minutes. Source: decompression by Table No. 3 MW RP Polish Navy 860/81.

Exposure methodology corresponding to the diving depth of 60 meters *(Figure 2).*

After medical qualification, individuals involved in the experiment were compressed to the pressure of 700 kPa. As in the exposure to 30 meters' depth, the divers were divided into groups of four, the exposure lasted 30 minutes from the start of the compression until the relief of pressure, and the decompression was performed in accordance with the naval decompression tables. In this experiment, the respiratory factor was also the air.

Exposure parameters:

- Time taken to reach maximum depth: six minutes (V=10 meters/minute);
- Time between leaving surface and initiation of ascent (within any one immersion): 30 minutes;
- Time taken to ascend from maximum depth to the first decompression stop: five minutes (V=7.8 meters/minute);
- Decompression: 21m/12 min.; 18m/15 min.; 15m/16 min.; 12m/19 min.; 9m/28 min.; 6m/40 min.; 3m/52 min.

Analysis of the results

The results were divided into groups depending on occurrence or non-occurrence of decompression stress. In order to examine whether there is a correlation between the occurrence of stress decompression and the following parameters, a preliminary descriptive statistical analysis was conducted *(Table 1)*.

Following the exposure to 400 KPa pressure, no symptoms of decompression stress were observed via the Doppler research methodology in any of the divers. In blood, asymptomatic bubbles of inert gas (nitrogen) were observed; however, they are not always connected with the symptoms of decompression sickness. The presence of inert gas bubbles is not neutral for the human body.

However, in subsequent exposures to the pressure of 700 kPa, the symptoms of decompression stress was observed in 29 of the 56 subjects (minimum second degree in the Kisman-Masurel scale).

The aim of the statistical analysis was to demonstrate whether there is a statistically significant correlation between the occurrence of decompression stress, and the various parameters of concern, such as:

- daily fat intake (RDI);
- total cholesterol level (CHOL);
- triglycerides level (TG);
- body mass index (BMI);
- age of the diver.

The calculated confidence intervals define the range of values in which there is the average value of the parameter with a probability of a 95% confidence level.

TABLE 1. Non-occurrence of the decompression stress group characteristic

STRESS-*NO*			*n*=27		
Variable	*Average*	*Min*	*Max*	*SD*	*Median*
RDI %	91.94	51.00	117.40	18.46	97.30
Chol mg/dl	187.89	136.00	262.00	33.57	184.00
TG mg/dl	153.33	43.00	588.00	111.55	142.00
BMI kg/m^2	24.90	20.50	28.70	1.89	24.90
Age	31.07	20.00	42.00	5.19	32.00

TABLE 2. ***Occurrence of the decompression stress group characteristic***

STRESS-*YES*			*n*=29		
Variable	*Average*	*Min*	*Max*	*SD*	*Median*
RDI %	145.84	105.80	209.60	29.30	139.50
Chol mg/dl	211.38	133.00	303.00	38.65	216.00
TG mg/dl	230.00	57.00	615.00	129.46	208.00
BMI kg/m^2	26.33	20.30	33.20	3.29	25.80
Age	32.79	20.00	48.00	5.81	33.00

Detailed analysis was performed in order to draw more reliable conclusions.

The analyzed data including RDI, CHOL, TG, BMI and divers' age were not distributed normally and therefore, non-parametric tests were applied – specifically the Mann-Whitney U-test against stress variables *(Figures 3, 4)*.

Preliminary analysis

In the group without decompression stress the average value of the RDI was 91.93% ±18.46, while in the group with stress there was an average of 145.84%±29.30 ($p = 8.66 * 10^{-10}$). This allows us to conclude that the difference between the RDI in both groups is statistically significant. Thus, we may say that the higher the value of the daily fat intake, the bigger the probability of occurrence of decompression stress *(Figure 5)*.

In the group of subjects without decompression stress the average cholesterol value was 187.88 mg/dl ± 33.57, while in the group with stress it reached 211.38 mg/dl ± 38.65 (p=0.028) *(Figure 6)*. This allows us to conclude that the difference between the cholesterol values in both groups is statistically significant. This means that the cholesterol value significantly influences the probability of occurrence of decompression stress.

In the group without decompression stress the average triglycerides level reached 153.33 mg/dl ± 111.55, while in the group of people with stress this value amounted to 230.00 mg/dl ± 129.46 (p=0,00602) *(Figure 7)*. This allows us to conclude that the difference between the triglyceride values in both groups is statistically significant. This means that the triglyceride value has a significant influence on the probability of occurrence of decompression stress.

In the group of individuals without decompression stress the average BMI value reached 24.9 kg/m^2 ± 1.89, whereas in the group with stress it amounted to 26.33 kg/m^2 ± 3.29 (p=0.0462) *(Figure 8)*. This allows us to conclude that the difference between the BMI values in both groups is statistically significant. This means that a higher BMI value correlates with the occurrence of decompression stress.

In the group of subject without decompression stress the average age was 31.07 ± 5.19, while in the group with stress the average age was 32.79 ± 5.81 *(Figure 9)*. This allows us to conclude that there is no significant difference between both groups in relation to age. The subjects' age does not influence the occurrence of the decompression stress.

On the basis of these tests, a statistically significant correlation was observed between the occurrence of decompression stress and RDI, CHOL, TG and BMI values. It should be mentioned that despite a statistically significant correlation, decompression stress occurred both in the groups with normal body weight and in those who were overweight, but not among all the overweight individuals. It may suggest that BMI is an overrated risk factor and could indicate new, additional risk factors such as the diver's diet, overall cholesterol and triglyceride levels.

FIGURE 3. Presentation of how decompression stress varies for RDI, CHOL, TG, with SD in error bars

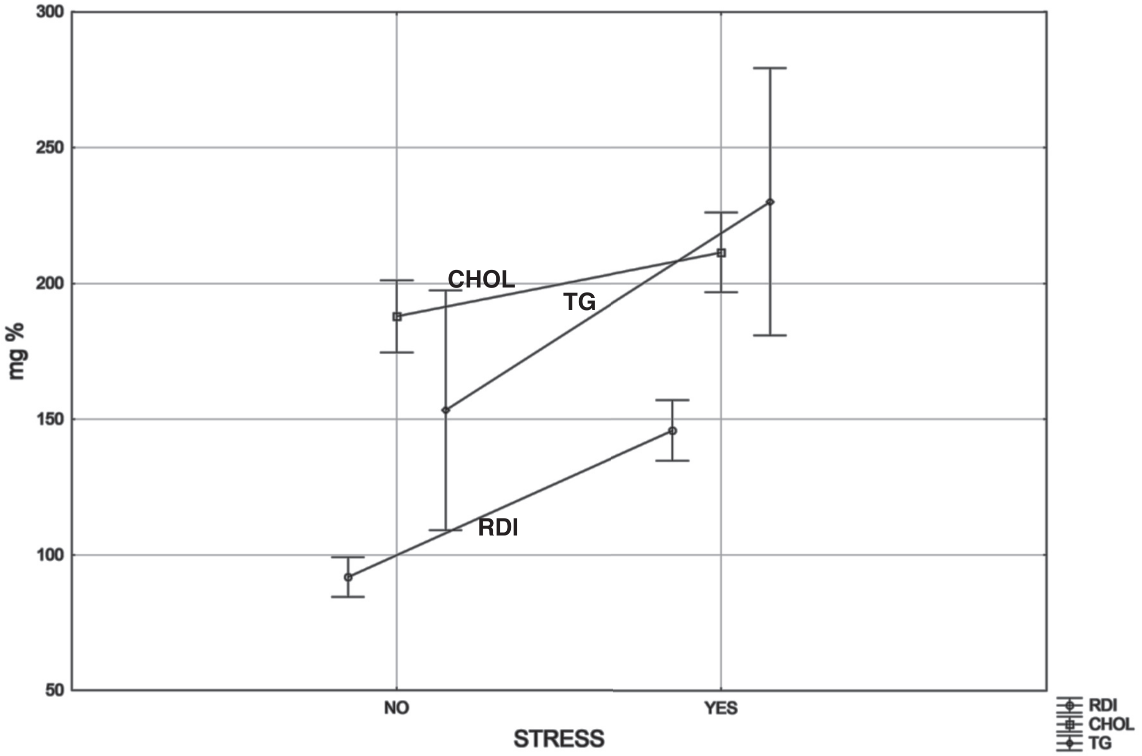


FIGURE 4. Presentation of how decompression stress varies for BMI, age

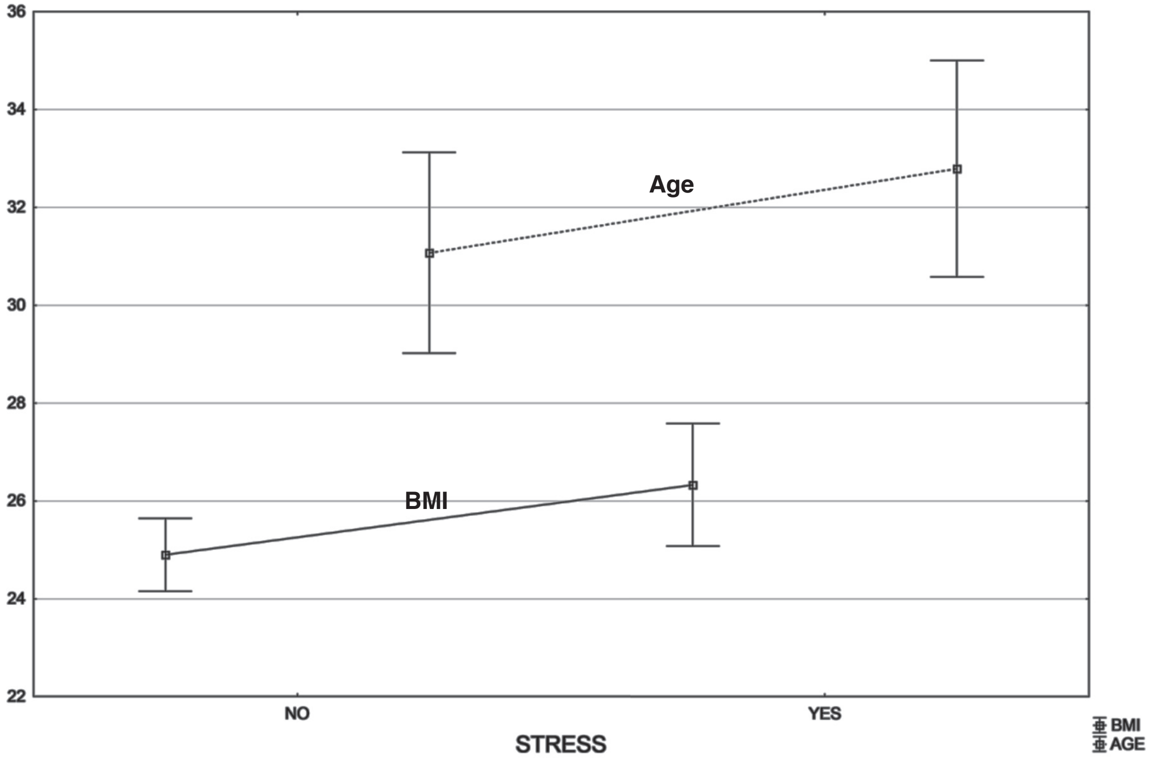


FIGURE 5. Presentation of how decompression stress varies for RDI

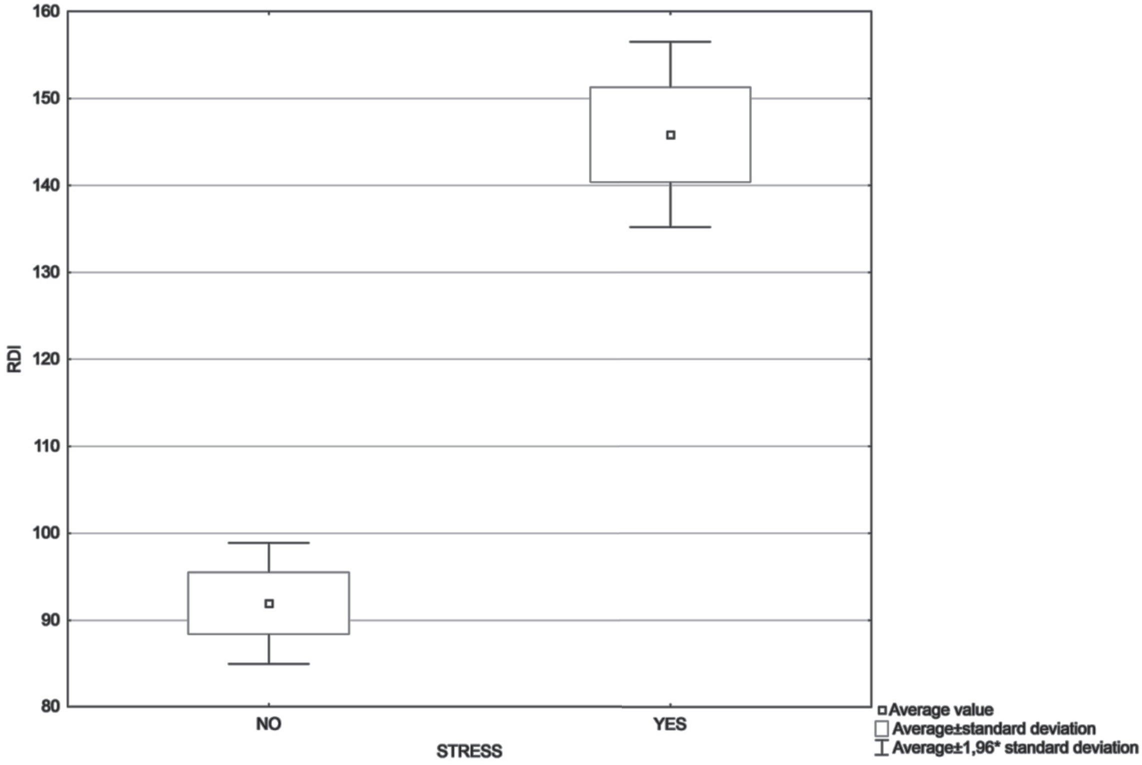


FIGURE 6. Box plot shows how CHOL varies with decompression stress

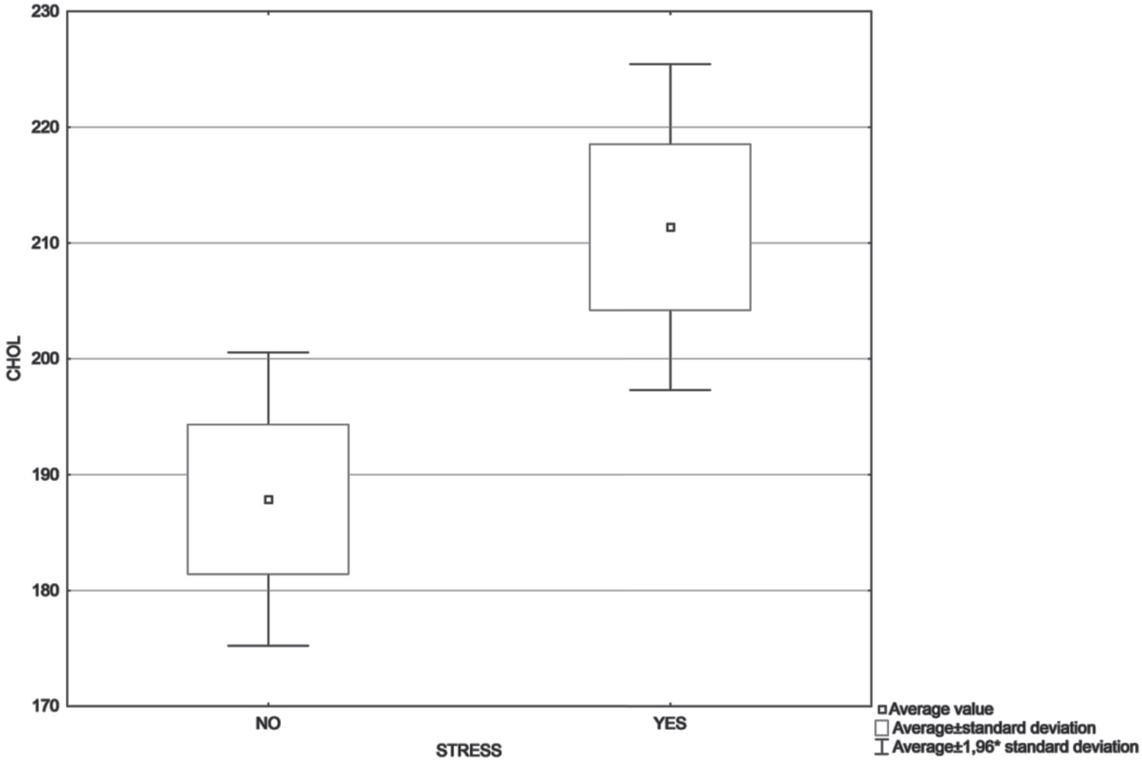


FIGURE 7. Box plot shows how TG varies with decompression stress

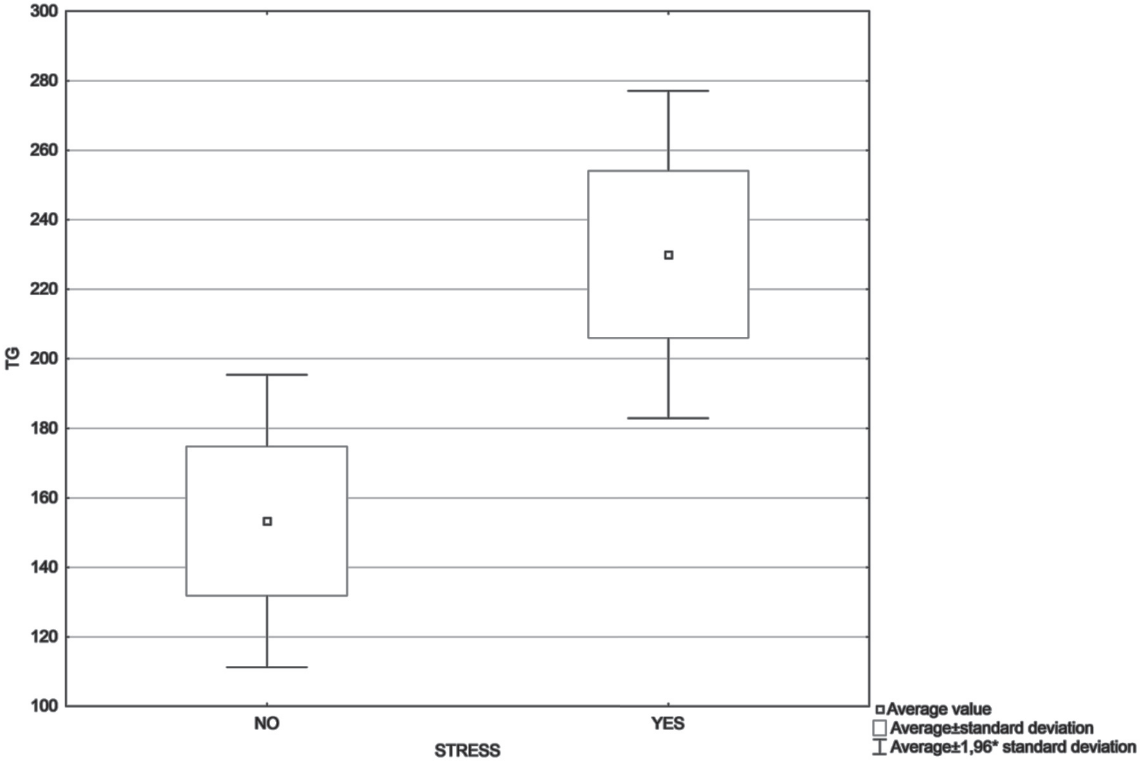


FIGURE 8. Correlation between BMI and decompression stress

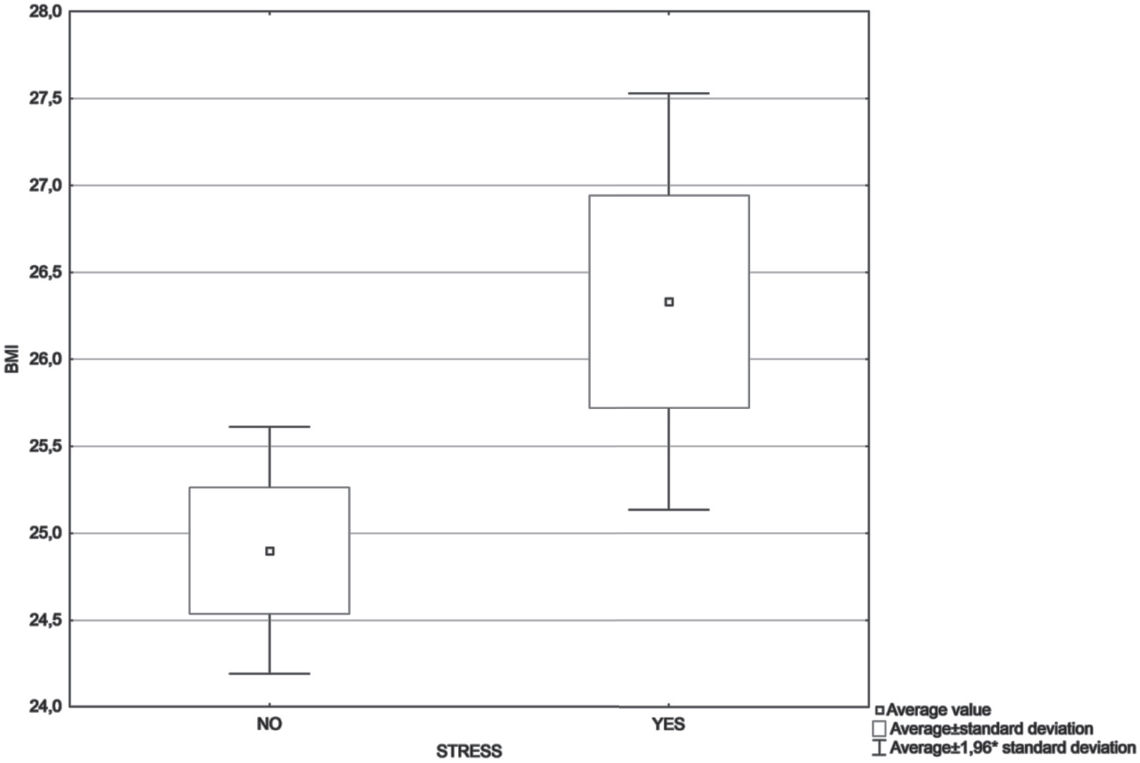
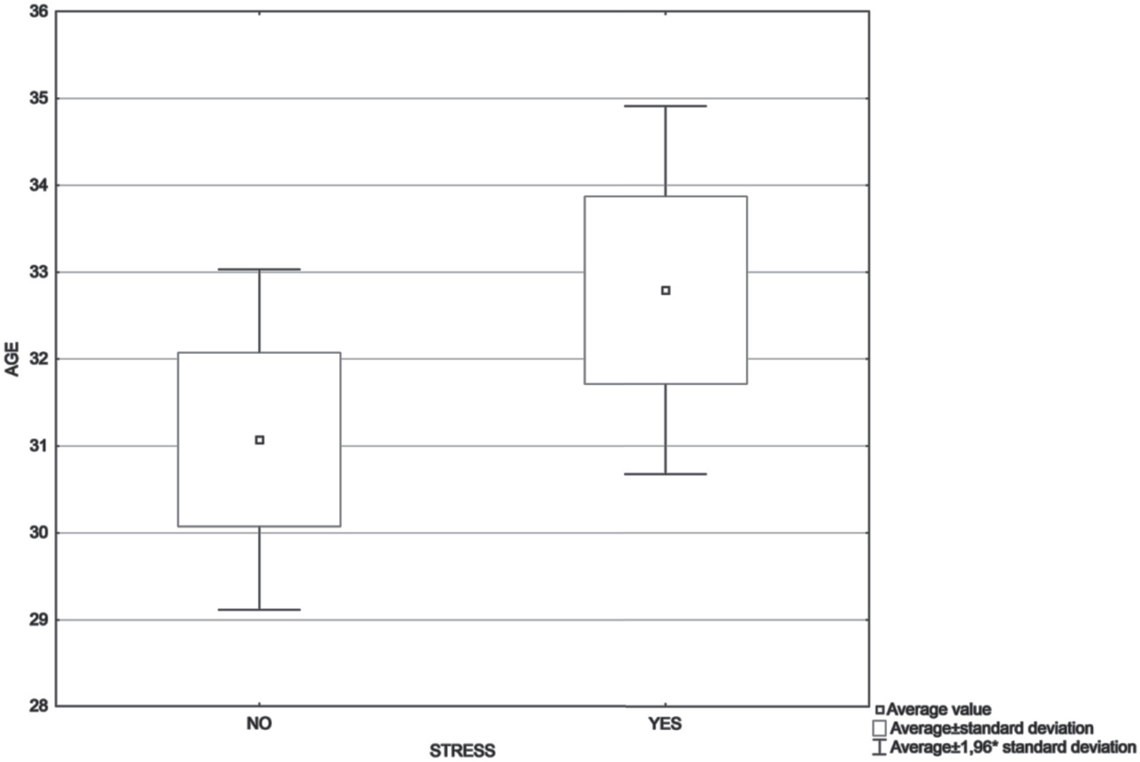


FIGURE 9. Correlation between age and decompression stress



DISCUSSION

As far as decompression is concerned, it was assumed that the main factors contributing to its safety include: divers' fitness level; effort during the dive; physical and physiological condition; breathing mixture used during the dive; age and body mass index. Nowadays, when both professional and sport diving are becoming more popular, there is a huge need to take into account as many factors as possible in considering issues in decompression. Nutrition is not yet among them, but it may have a substantial impact on diving safety.

Since Haldane's time, obesity has been considered a risk factor in diving. In the present study, the course of decompression disorders occurred among divers of regular weight as well as obese ones. Thus, neither the correct energy value of food nor an excessive energy intake in the diet will guarantee coverage of all individual nutritional needs. A common mistake consists in the shift between main energy components, *e.g.*, replacing carbohydrates with fat as a component of a higher energy value. This is due to a misconception in meeting the body's energy needs, particularly in individuals who undertake hard work, such as scuba diving [22]. Therefore, it is necessary to pay attention not only to the overall energy supply, but also to nutrition and balanced diet in terms of its content.

Individuals who are on a high-fat diet – and yet have a correct energy intake with regard to their energy requirements – will not show a tendency to gain weight and, therefore, their BMI will be at a normal level. Only excess in the supply of energy, regardless of the source (carbohydrates or fats), leads to gaining weight. However, an excess of fat in the diet, not always associated with excessive body weight, leads to disturbances in the lipid balance. In particular, higher consumption of animal fats with a lack of vegetable and fish fat intake (which contain unsaturated fatty acids – n-3 series) leads to increased cholesterol and triglyceride levels [25].

In addition, the amount of time taken to metabolize fat when compared with carbohydrates, especially when there is an excess in fat supply, will result in consistently higher postprandial lipid levels in the blood serum. No one dives on an empty stomach. In accordance with safety principles, dives should be performed approximately two hours after a meal, when nutrients have been absorbed into the bloodstream, and fats in the diet have increased the level of lipids in the blood serum. Fat has a direct impact on the increasing volume of inert gases that are dissolved in the blood serum during a hyperbaric exposure, and, in the case of someone who has eaten a fatty meal, normal decompression time consistent with the dive tables may prove to be insufficient for complete desaturation [26].

It is likely that with an increased volume of inert gas in the blood serum, there will be some disturbances in desaturation and a delay in the blood-air transport. The actual mechanism maybe as follows: gas that is dissolved in lipids that are suspended in the blood, according to the differential gradient, first diffuses into the aqueous phase of serum and only afterwards into a light pulmonary vesicle.

From our experience, such a situation will result in at least a greater severity of decompression stress. Therefore, it is important to seek a balanced diet in terms of its composition and energy value, allowing full physical capacity of the organism to be achieved without creating an additional health risk.

The results obtained from the implementation of this project have provided us with new information that may be helpful in identifying risk factors associated with decompression so that safer, more precise programs can be developed. So far there have not been any reports about the influence of diet on safe diving. The research indicates that during the revision of the current decompression tables and the creation of new ones, the level of triglycerides in the serum should be taken into consideration when determining the factors that will restrict decompression regimes. The new additional significant criteria and medical qualifications that result from this research, especially for commercial and business diving, have been highlighted while formulating the principles of a good diet for divers.

CONCLUSIONS

1. High-fat diets have a direct impact on the increasing level of cholesterol and triglycerides in the blood serum. They greatly boost the severity of decompression stress after air hyperbaric exposures and increase the risk of decompression sickness.
2. Creating an adequate diet for divers will have a beneficial impact on the safety of diving.
3. In accordance with this research, body mass index has a smaller impact on the severity of the decompression stress in comparison with excessive fat intake and lipid levels in the blood serum.

The authors report that no conflict of interest exists with this submission. ■

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