

## **THE EVALUATION OF THE RISK OF DECOMPRESSION SICKNESS IN DIVERS**

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### **ABSTRACT**

Gas bubbles occurring during the process of decompression create a non-physiological surface which comes into contact with blood platelets and coagulation proteins. The result is activation of blood platelets and contact factors. Accordingly, over 30 years ago Polish researchers began to verify the safety of decompression tables through the evaluation of changes of haemostasis and fibrinolysis.

**Key words:** safety evaluation of decompression tables, decompression sickness, haemostasis and fibrinolysis in risk assessment of decompression sickness.

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## INTRODUCTION

In 1878 Paul Bert worked out the first guidelines regarding the process of decompression [1]. However, even to this day, no decompression tables have been prepared to ensure full certainty regarding divers' safety.

During the process of decompression as well as after its completion, a certain quantity of tolerated symptomless gas bubbles may occur in divers' blood. They do not usually involve pathological symptoms, however after their diameter exceeds that of capillary vessels they cause the production of microemboli, which leads to the development of local hypoxia.

The best known and the most commonly applied criterion of assessing the threat of occurrence of decompression in divers is the lack of symptoms of "the bends". Another assessment criterion consists of Doppler examinations aimed at the detection of microbubbles in divers. It is currently believed that gas microbubbles may be produced in divers after nearly each exposure despite the observance of decompression tables. The occurrence of avascular necrosis in later periods of life is evidence that the Doppler examination and the lack of any symptoms of the bends immediately after diving are insufficient for evaluating the safety of decompression carried out by divers.

A new criterion in assessing the risk of decompression sickness in divers, as well as the safety of decompression tables, may consist in changes in blood coagulation and fibrinolysis appearing during and after decompression. Accordingly, over 30 years ago Polish researchers began to verify the safety of decompression tables through the evaluation of changes in the haemostasis. Gas bubbles occurring during the process of decompression create a non-physiological surface which comes into contact with blood platelets and coagulation proteins. The result is activation of blood platelets and contact factors. The occurrence of certain symptoms of decompression sickness may be caused by the breaking of the barrier of plasma coagulation inhibitors and the occurrence of microemboli.

The "search" for new and more accurate methods of establishing the risk of a decompression incident in divers was commenced abroad only a few years ago. The majority of citations concerned with the Polish method of evaluation of the safety of decompression tables with regard to changes in the coagulation system and fibrinolysis have only begun to appear in foreign literature within the last five years, even though the articles are quoted in some instances as much as ten years after their publication, e.g.:

- article [2] of 1990 *Effect of nitrox saturations upon platelet haemostasis* Bull. Inst. Mar. Trop. Med. 41, 1-4 is quoted twice 2008 (Pontier 2008, 2008), i.e. 18 years after its publication [3, 4].

- article [5] of 2000 *The effect of air and nitrox diving on platelet activation tested by flow cytometry*. Aviat. Space Environ Med. 71: 925-8 is quoted six times: Bosco and others 2001[6], Pontier and others 2008 [3, 4], Kernagis and others 2009 [7], Moon 2009 [8], Bosco and others 2010 [9].

- article (10) of 2001 *Changes in the extrinsic and intrinsic coagulation pathways in humans after decompression following saturation diving*. Blood Coagulation and Fibrinolysis 12, 1- 6 is quoted on six occasions: Poff and others 2007 [11], Hibbs and others 2007 [12]), Pontier and others 2008 [3, 4], Pontier and others 2009 [13], Monaca and others 2014 [14].

Studies on the verification of tables and the assessment of the risk of decompression sickness in divers with the use of selected parameters of haemostasis and fibrinolysis were presented in international on hyperbaric medicine (EUBS – European Undersea Biomedical Society):

- *Plateletal haemostasis - hyperbaric air exposures* [in:] EUBS on diving and hyperbaric medicine (ed. Reinertsen R., Brubakk A., Bolstad G.) 1993, 163- 168 [15].

- *Evaluation of decompression sickness risk in saturated air and nitrox dives judged on the basis of changes in haemostasis* [in:] EUBS on diving and hyperbaric medicine (ed. Mekjavic B., Tipton M., Eiken O.) 1997, 91- 95 [16].

- *Effect of air and trimix diving on selected parameters of haemostasis* [in:] High Pressure Biology and Medicine (ed. Bennett P., Demchenko I., Marquis R.) University of Rochester Press USA, 1998, 234-236 [17].

- *Flow cytometric testing of blood platelets activation in air diving* [in:] EUBS on diving and hyperbaric medicine (ed. Genner M.) 1998, 113-116 [18].

The evaluation of a risk of decompression sickness based on selected haemostasis parameters was presented in two foreign books published in English by the most prominent scientists in underwater medicine: P. Bennett and others 1998 High Pressure Biology and Medicine (University of Rochester Press [17] and H. Ludwig Advances in high pressure bioscience and biotechnology 1999 Springer [19], as well as in the book entitled Decompression sickness risk assessment in divers 2006 Military Institute of Medicine [20].

The level of activation of blood platelets after dives was estimated with the use of flow cytometry. This method allowed the establishment of the proportion of microplatelets and the size of expression of surface molecules engaged in the process of adhesion, aggregation and releasing reaction. After dives – in particular air dives – an increase in the quantity of microplatelets and an intensification of expression of surface molecules, mainly CD61 and CD62P, was observed.

The results of the above research were presented in the following publications: *Flow cytometric testing of blood platelet activation in diving* [in:] *Advances in high pressure bioscience and biotechnology* (ed. H. Ludwig), Springer-Verlag 1999, 565-569 [19], Aviation Space and Environmental Medicine (2000) *The effect of air and nitrox divers on platelet activation tested by flow cytometry*. 71: 925-8 [5], *Activation of platelets and fibrinolysis induced by saturated air dives*. Aviation Space and Environmental Medicine 2010, 81, 6: 585-588 [21].

The obtained results confirm activation of blood platelets in divers subjected to saturated air exposures and operational heliox dives in the Baltic Sea. Particularly strong activation of blood platelets, determined on the basis of an increase in the proportion of blood platelets, indicating the presence of PADGEM molecule (*platelet activation-dependent granule-external membrane protein*), and a growth in the percentage of microplatelets and platelet aggregate, was observed after simulated air dives.

A lesser activation of blood platelets in simulated nitrox and heliox dives, despite divers' exposure to higher pressures, is to be explained with properly conducted decompression not leading to the emergence of microbubbles. The research published in 2010 *Advances in Medical Sciences Trimix instead of air, decreases the effect of short-term hyperbaric exposures on platelet and fibrinolysis* [22] revealed that using trimix as opposed to air in diving up to 60 m had no effect on a decrease in the quantity of blood platelets and significantly limited their activation induced by diving and decompression

The executed studies did not indicate an increase in the concentration of d-dimers, thrombin-antithrombin complexes, fragments of prothrombin 1+2. For the first time, however, the research showed an increased consumption of factor XII and a growth in plasmin-antiplasmin complex, which may suggest the effect of diving on the activation of fibrinolysis (Blood Coagul Fibrin 2001 *Changes in the extrinsic and intrinsic coagulation pathways in humans after decompression following saturation diving 12*, 1– 6 [10]). Clinical reports on the cases of haemorrhages into the eye, brain and spinal cord indicate the necessity to explain the reasons for post-haemorrhagic events occurring after diving.

Further studies, conducted with the objective of preparing a detailed evaluation of fibrinolysis, showed that healthy persons subjected to hyperbaric exposures followed by decompression had statistically significant decreases in the concentration and activity of the inhibitor of tissue plasminogen activator (PAI-1) and the concentration of 2-antiplasmin. However, the research also showed a lack of change in the concentration and activity of t-PA as well as the concentration of thrombin activatable fibrinolysis inhibitor (TAFI) and its proenzyme (Blood Coagul Fibrin 2003 *Diving up to 60 m depth followed by decompression has no effect on proenzyme and total thrombin activatable fibrinolysis inhibitor antigen concentration 14*, 1–3) [23].

The detected changes in the number of blood platelets and PAI-1 level seem to be more a sensitive indicator of changes occurring in people subjected to hyperbaric oxygenation and decompression as compared with Doppler microbubble examination. For these reasons the determination of these parameters raises high expectations with regard to disease occurrence risk assessment in divers and specification of safe conditions for diving and decompression (Polish J Environ Stud 2006 PAP, *PAI-1, platelet count – promising safety parameters of diving 15*, 4B: 130-133) [24].

Moreover, the most recent pilot studies indicate that hyperbaric exposures and decompression cause statistically significant changes in the concentrations of numerous chemical compounds in the blood, including vitamin D metabolites, phospholipids and bile pigments. Further research is recommended with the purpose of defining the importance of the observed changes in relation to divers' health and possibly to apply them in the evaluation of diving safety (J Proteom Res *Metabolomic Approach with LC-MS Reveals Significant Effect of Pressure on Diver's Plasma* 2010, 9 (8): 4131-4137) [25].

The application of the haemostasis method, thus far not considered in the assessment of diving tables around the world, enables interpretation of phenomena taking place during decompression and may constitute a primary element in the determination of the hazard of decompression sickness.

The evaluation of the risk of decompression sickness on the basis of selected haemostasis parameters was presented in numerous magazines:

- *Effect of nitrox saturations upon platelet haemostasis Bull. Inst. Mar. Trop. Med. Gdynia*, 1990, 41, 1-4 [2];
- *Evaluation of the risk of decompression sickness in saturated nitrox diving by examination of haemostasis Bull. Inst. Mar. Trop. Med. Gdynia*, 1995, 46, 1/4, 27-30 [26];
- *Effect of saturated air and nitrox diving on selected parameters of haemostasis Bull. Inst. Mar. Trop. Med. Gdynia*, 1997, 48, 1/4, 75-82 [27];
- *Evaluation of heliox saturated diving on the basis of selected haemostatic parameters Bull. Inst. Marit. Trop. Med.*, 1998, 49, 1/4, 117-121 [28];
- *The effect of air and nitrox divers on platelet activation tested by flow cytometry Aviat. Space Environ Med.* 2000, 71: 925-8 [5];
- *Changes in the extrinsic and intrinsic coagulation pathways in humans after decompression following saturation diving Blood Coagulation and Fibrinolysis*, 2001, 12, 1– 6 [10];
- *Diving up to 60 m depth followed by decompression has no effect on proenzyme and total thrombin activatable fibrinolysis inhibitor antigen concentration. Blood Coagulation and Fibrinolysis*, 2003, 14, 1–3 [23];
- *Assessment of diving risks – based on selected haemostatic parameters Actual Problems of Transport Medicine*, 2005, 1: 80-83 [29];
- *The use of heliox instead of air diminishes the effect of hyperbaric exposures and decompression on blood platelets but not on leukocytes Polish Journal of Environmental Studies*, 2005, 14, I: 95-98 [30];
- *PAP, PAI-1, platelet count – promising safety parameters of diving Polish Journal of Environmental Studies*, 2006, 15, 4B: 130-133 [24];
- *Decreased levels of PAI-1 and alpha2-antiplasmin contribute to enhanced fibrinolytic activity in divers Thrombosis Res.*, 2007 121 [2] : 235-240 [31];
- *Activation of platelets and fibrinolysis induced by saturated air dives. Aviation, Space and Environmental Medicine*, 2010, 81, 6: 585-588 [21];
- *Trimix instead of air, decreases the effect of short-term hyperbaric exposures on platelet and fibrinolysis Advances in Medical Sciences* 2010 [22];
- *The evaluation of the effect of hyperbaric oxygenation on selected fibrinolysis parameters in divers Polish Hyperbaric Research*, 2011, 4, [33], 63-70 [32];
- *Physiological and biochemical conditioning of haemostasis in air hyperbaria* 2011 [33];
- *Selected issues of marine and diving medicine* 2013 [34].

The hyperbaric environment does not remain neutral in relation to the antioxidant system either. Dives performed in accordance with the effective safety standards cause an increased productivity of reactive oxygen forms, which is indicated by a growth in the determined antioxidative enzymes.

The hyperbaric environment contributes to changes within protein structures, thus leading to an increase in the concentration of carbonyl groups occurring after diving.

The occurring oxidative stress seems to have a different effect on men and women, which is reflected by a different type of activity of antioxidative enzymes in researched groups, which was presented in the following articles: *Hyperbaric effect on selected parameters of oxidative stress in diver's blood Pol. J. Environ. Stud.* 2006 Vol. 15, 4B, 96-99 (35), *Analysis of oxidase activity of ceruloplasmin and processes of lipid peroxidation in blood in hyperbaric conditions Pol. J. Environ. Stud.* 2006

## CONCLUSIONS

The application of a risk assessment to decompression sickness in divers, on the basis of changes in the haemostasis that have not been considered in safety evaluations of the decompression tables used around the world, enables a new interpretation of phenomena occurring during decompression.

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