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INTRAVASCULAR FREE GAS PHASE DETECTION

ABSTRACT

Doppler ultrasonic detection of intravascular free gas phase is a typical procedure which is useful in studies of decompression. The paper presents an evaluation of this standard technique by using the statistical method.

Keywords:
decompression safety.

INTRODUCTION

In this paper has been validated[1] by Bayesian approach that the Doppler method for intravascular detection of the free gas phase DBM[2] is useful and contributes to enhancement and the safety of diving[3].

DBM is a standard procedure used by several laboratories conducting research on decompression. Its main advantage is the possibility to use it in an actual time.

The simple DBM application[4] is popular in experimental studies of decompression profiles. Described analysis is related to the method and devices used by $DR - DC\ Toronto$[5] [1, 6].

While the measurement technique itself is simple and inexpensive, then its use requires skill and experience. The experimental results can be easily understood

[1] Despite the some researches reservations.
[2] *Doppler Bubble Monitoring*.
[3] Especially during experimental dives.
[4] Ultrasound detection of free gas phase signals are transformed using the electronics into audible beep.
[5] Formerly *Defence and Civil Institute of Environmental Medicine*.

by others subject to the application of standard procedures[6]. $K-M$ code has been used here for signals classification. This code is compared with the classification method presented by Spencer, but $K-M$ code takes into account more factors and allows a more detailed description of signals [1, 6]. These codes are similar to each other, but the results described in any of these methods can be compared only to a certain extent.

Opponents of this approach rightly argue that the symptoms of DCS [7] are not necessarily accompanied by the formation of free gas phase in tissues. This article presents statistical deduction on the basis that those cases are rare and DBM is usable and comparable with other methods of medical diagnosis in the estimation of exposure to decompression stress.

METHOD

From the practical point of view it is rational to apply to any problem all available knowledge on the scrutinised subject especially, when the consequences of decisions are important for: construction, technical or financial decisions and people's safety. Many times such decisions are based on random intuitive knowledge, present engineering experience, medical proficiency or managerial skills. The decision-making process should, however, use different fields of knowledge with a particular account of new trends and discoveries, which can provide a technological as well as logical, economic or scientific advantage. Estimates or historical data necessary in such cases, may be inaccurate, unreliable or totally untrue, therefore so many researchers object to application of such policies for fear of mistakes or because of the well-established penchant for clear inferences. But the practice requires rapid decision-making under uncertainty. Significant progress is supported with science's decision-making, quality control of these decisions, data mining, etc. There are different analytical approaches[8], e.g.: classical, data mining and Bayesian approach — Tab. 1.

The classical approach consists of: defining the problem, the collection of data, analysis of the data accompanied by relevant conclusions which result from identifying unknown model parameters and applying them on the basis of fitting to the data obtained.

[6] Based on earlier studies made by $K.E.Kisman$ and $G.Masurel$, further experiments with the DBM have led to improvement of this method.

[7] Decompression sickness.

[8] Analysis — mental, conceptual isolation and study of the characteristics of components, structures or processes in the systems or processes occurring in them and on this basis to determine the adequacy of the adopted model.

Based on one of the paradigms of physics that there should be integral occurrence in the stochastic behaviour of deterministic systems, this methodology enriched by statistical inference can be applied to the above mentioned methodology. It gives an opportunity to judge the uncertainty of the designation of variables and model parameters on the basis of estimates of uncertainty of measurement results.

Table 1. The approaches used in the data analysis

Approach	Description
Classical	Problem → collecting data → choice of model → analysis → conclusions
Data mining	Problem → collecting data → analysis → choice of model → conclusions
Bayesian	Problem → collecting data → choice of model → choice of distribution → analysis → conclusions

Source: own study.

In the Bayesian approach[9], prior to the collection of experimental data, historical data are analyzed to determine the a $prior$[10] distribution. Based on this preliminary analysis assumptions are formulated to establish probable range of variability of the unknown model parameters. Data obtained by the planned experiment are used to reassessment of these assumptions, which results in determination of the range of variability of independent model parameters based on a $posterior$[11] probability distribution. The confidence intervals of estimated parameters are determined from the verified posterior[12] distributions. From a definition of the conditional probability it follows that:

$$\mathrm{P(A|B)} = \frac{\mathrm{P(A)}}{\mathrm{P(B)}} \cdot \mathrm{P(B|A)}, \qquad (1)$$

where: $P(A) -$ $a\ prior$ probability of an event A, $P(B) -$ probability of the event B, also known as normalization factor in the statistical sense, $P(A|B) - a\ posterior$ conditional probability of an A event, given the event B, $P(B|A) -$ conditional probability of the event B, given the event A.

Equation (1) is called a $Bayes'formula$[13]. The formula (1) defines the relationship between the conditional probability $P(A|B)$ and the inverse conditional

[9] Thomas Bayes, 1702−1961, English mathematician and theologian, gave a model to assess $a\ posterior$ likelihood.

[10] $Prior$ — from Latin: prior, first.

[11] $Posterior$ — from Latin: to the rear, the final.

[12] In this approach the unknown parameters of the model are random variables rather than constant values.

[13] Although it is a fundamental theorem of probability theory, it was as a method of approach forgotten for centuries, at the present time, this theory is gaining importance, the formula determines

probability $P(B|A)$ of the events. The number $P(A)$ is said to be $a\ prior$[14] probability of an event A, $P(B)$ denotes probability of the event B, also known as normalization factor in the statistical sense[15], $P(A|B)$ is called $a\ posterior$ conditional probability of an A event, given the event B , $P(B|A)$ is a conditional probability of the event B, given the event A. In the literature, one can find another versions of Bayes' theorem. If $\forall_{i\neq j}\ A_i \cap A_j = \emptyset\ \wedge\ A_1 \cup A_2 \cup \ldots \cup A_N = \Omega$ and $\forall_{k=1,2..N}\ P(A_k) > 0 \wedge P(B) > 0$, then:

$$\forall_{k=1,2..N}\ P(A_k|B) = \frac{P(A_k)\ P(B|A_k)}{\sum_{i=1}^{N} P(A_i)\ P(B|A_i)}. \tag{2}$$

It follows from equation (2) that $P(A_1) + P(A_2) + \cdots + P(A_N) = 1$,which means that the probability distributions $P(\ A_1),\ P(\ A_2), \ldots, P(A_n)$ form — so called a $prior$ distribution. One can easily notice that $P(A_1|B) + P(A_2|B) + \cdots + P(A_n|B) = 1$, therefore, conditional probabilities $P(A_1|B),\ P(A_2|B), \ldots, P(A_n|B)$ also create distribution called a $posterior$ distribution of events $A_i,\ i = 1,2, \ldots, N$, if an event B occurred. It follows that the formula (1) is a special case of equation (2), where $A_i \equiv A$[16]. Formula (2) is useful for estimating some difficult to define conditional probabilities provided that probability estimates are approved without the reservations by the investigator on the basis of frequency of events or other subjective conditions[17].

The likelihood of symptoms despite the lack of a free gas phase in veins was subject to heated debates by physiologists and practitioners. There is a possibility of forming a free gas phase outside the blood vessels, with simultaneous total absence of this phase or presence only in small amounts in the veins, especially in neurological cases of DCS[18]. From the observations made in the reference centre $DR - DC\ Toronto$ and from PLN experience it follows that there is also considerable potential to confuse the continuous signal with the lack of signal of free gas phase.

The correlation between the signal and the onset of symptoms is not yet well established [2, 3, 4, 8]. Despite these real problems associated with the use of DBM methods to determine the risk of DCS, it will be demonstrated that in practice this method is useful.

Bayesian a posterior probability of mutually exclusive random events $A_1, A_2 \ldots A_n$ (A_i hypothesis), where B the observed event and $a\ priori$ probability of events A_i are equals $P\ (A_i)$.

[14] Called $a\ prior$ because there is no need to have any information about event B.

[15] Normalization factor, which normalizing probability integral function to unity.

[16] Jn $Bayesian\ parametric$ estimation often has been used $Bayes'\ theorem$ for continuous distributions, e.g.: $g(\lambda|x) = \frac{f(x|\lambda)\cdot g(\lambda)}{\int_0^\infty f(x|\lambda)\cdot g(\lambda)\cdot d\lambda}$, where $f(x|\lambda)$ — density function of random variable X with unknown parameter/parameters λ, $g(\lambda)$ — *a priori* distribution function of the parameter λ for observations $X \leftarrow x$, $g(\lambda|x)$ — *a posteriori* distribution function of parameter λ for observations $X \leftarrow x$.

[17] e.g., by estimation by experts.

[18] II and III type of DCS.

From the point of view of applications of this method for detection of free gas phase in the blood vessels it is interesting to estimate the probability $P(DCS|\neg G)$ of occurrence of an event $A:\{DCS\}$ consisting of the obvious symptoms of DCS in spite of event B of lack of free intravascular gas phase detection $B:\{\neg G\}$. For the presented problem situation, an event A was assumed as an event where evident DCS symptoms occur in a diver after completed decompression. As the event B was assumed no signal of intravascular free gas phase was registered, which could suggest the possibility of occurrence of DCS symptoms. With the use of Bayesian approach to this problem it can be written analogously to equation (2): $P(DCS|\neg G) = \frac{P(\neg G|DCS)\,P(DCS)}{P(\neg G|DCS)\cdot P(DCS)+P(\neg G|\neg DCS)\cdot P(\neg DCS)}$.

Approximations necessary to estimate the probabilities can be based on data derived from research at $DR - DC\ Toronto$ — Tab. 2. In order to facilitate their analysis $Veens\ diagram$ can be used, giving the cardinality values for selected events — Tab. 3.

Table 2. The results of measurements of the presence of free gas phase in the blood veins for the 1726 Air and Nitrox exposures and 1508 Heliox exposures carried out in the $DR - DC\ Toronto$

Place	$K - M$ code	Air and Nitrox			Heliox		
		Number of expositions	DCS	$\%DCS$	Number of expositions	DCS	$\%DCS$
Precordial (at rest)	0	1264	7	0,6%	945	6	0,6%
	I	131	0	0,0%	105	2	1,9%
	II	137	8	5,8%	184	1	0,5%
	III	191	25	13,1%	272	22	8,1%
	IV	3	1	33,3%	2	1	50,0%
Precordial (movement)	0	1164	3	0,3%	879	7	0,8%
	I	109	2	1,8%	70	0	0,0%
	II	111	3	2,7%	114	1	0,9%
	III	305	26	8,5%	313	11	3,5%
	IV	37	5	13,5%	132	13	9,8%
Overall[†]	0	819	0	0,0%	623	1	0,2%
	I	287	3	1,0%	214	1	0,5%
	II	183	2	1,1%	187	0	0,0%
	III	365	27	7,4%	347	15	4,3%
	IV	72	9	12,5%	137	15	10,9%
[†]overall, the highest signal, which was observed in the zone of the subclavian vein or precordial zone							

Source: O. S. Eftedal, Ultrasonic detection of decompression induced vascular microbubbles, Trondheim: Norwegian University of Science and Technology Faculty of Medicine Department of Circulation and Medical Imaging, 2007; K. D. Sawatzky, The relationship between intravascular Doppler-detected gas bubbles and decompression sickness after bounce diving in humans, Toronto: York University 1991.

The likelihood of the occurrence of DCS can be for this case estimated as: $P(DCS) \triangleq \frac{n(DCS)}{N} = \frac{41}{1726} \cong 0{,}024$ from observed frequencies given in Tab. 2 and Tab. 3. Estimation of conditional probabilities requires separation between the signals: those suggesting conditions for onset of DCS symptoms and those suggesting the absence of such evidence.

Acceptable safe gradient was taken: $< II +$[19]. Estimation of probability of events involving the absence of a signal[20] designated as dangerous $B: \{\neg G\}$ with a subsequent onset of DCS for Air and Nitrox decompression $A: \{DCS\}$, is: $P(\neg G|DCS) \triangleq \frac{n(\neg G \cap DSC)}{n(DSC)} = \frac{5}{41} \cong 0{,}12$ — Tab. 3. For Heliox dives this value is to $P(\neg G|DCS) \cong 0{,}06$ — Tab. 2. Both values were estimated at very similar, therefore it is justified to calculate one mean value for this probability $(\neg G|DCS) \cong 0{,}09$.

Table 3. Cumulative frequency distribution of DCS and the absence of symptoms $\neg DCS$ for Air and Nitrox decompression and measurements of the occurrence G and lack $\neg G$ of a free gas phase in precordial zone or in the subclavian vein by selecting the larger of the signals

	G	$\neg G$	TOTAL
DCS	36	5	41
$\neg DCS$	401	1284	1685
TOTAL	437	1289	1726

Source: own study.

For the absence of a signal interpreted as a dangerous gradient of the free gas phase $B: \{\neg G\}$ for safe decompression procedure $\neg A: \{\neg DCS\}$, estimation of the probability $P(\neg G|\neg DCS)$ can be based on the same rationale[21].

During measuring of intravascular free gas phase in precordial zone and the subclavian vein[22] for Air and Nitrox decompression, that probability has been estimated as $P(\neg G|\neg DCS) \triangleq \frac{1284}{1685} \cong 0{,}76$ — Tab. 3. For Heliox dives estimated probability was equal to $P(\neg G|\neg DCS) \triangleq \frac{1022}{1476} \cong 0{,}69$. Both values were estimated with a similar DCS risk level therefore it is justified to calculate the mean value: $P(\neg G|\neg DCS) \cong 0{,}72$[23].

[19] Experience has shown that for older divers safety level adopted here $G < II +$ can be tolerated without symptoms, while -for divers under 30 years old it is a real risk.

[20] The larger values for precordial zone and subclavian veins.

[21] *Polish* divers are encouraged to report any symptoms, even at first glance unrelated to hyperbaric exposures, these cases and doubtful DCS cases are always diagnosed for the presence of free gas phase in veins — it never happened yet that the renunciation of medical treatment based on the DBM result has been wrong and caused DCS.

[22] Choosing the larger of the signals.

[23] Adoption of such values seems to be fully justified even when the estimates made by experts are based on their personal beliefs.

Using the same reasoning, it is possible to establish directly from the data[24] presented in Tab. 3 appropriate probability at the level of $P(DCS|\neg G) \triangleq \frac{5}{1289} \cong$ $\cong 0{,}004$ for the case of lack of diagnosis by non-detection of intravascular free gas phase $B:\{\neg G\}$ for Air and Nitrox decompression procedure with the DCS occurrence $A:\{DCS\}$. For Heliox dives estimated value of this probability on the basis of the data contained in Tab. 2 was $P(DCS|\neg G) \triangleq \frac{2}{1024} \cong 0{,}002$. Hence, under the same conditions the mean value of the method error was estimated at $(DCS|\neg G) \cong 0{,}003$. When verifying estimation value of probability $P(DCS|\neg G)$ one can also calculate it from a previously estimated probabilities based on frequencies contained in Tab. 2, according to the formula: $P(DCS|\neg G) = \frac{P(DCS)}{P(\neg G|DCS)\cdot P(DCS)+P(\neg G|\neg DCS)\cdot[1-P(DCS)]} \cdot$ $\cdot P(\neg G|DCS) \cong \frac{0{,}024}{0{,}09\cdot 0{,}024+0{,}72\cdot 0{,}976} \cdot 0{,}09 \cong \cong 0{,}004$, i.e. the results are consistent.

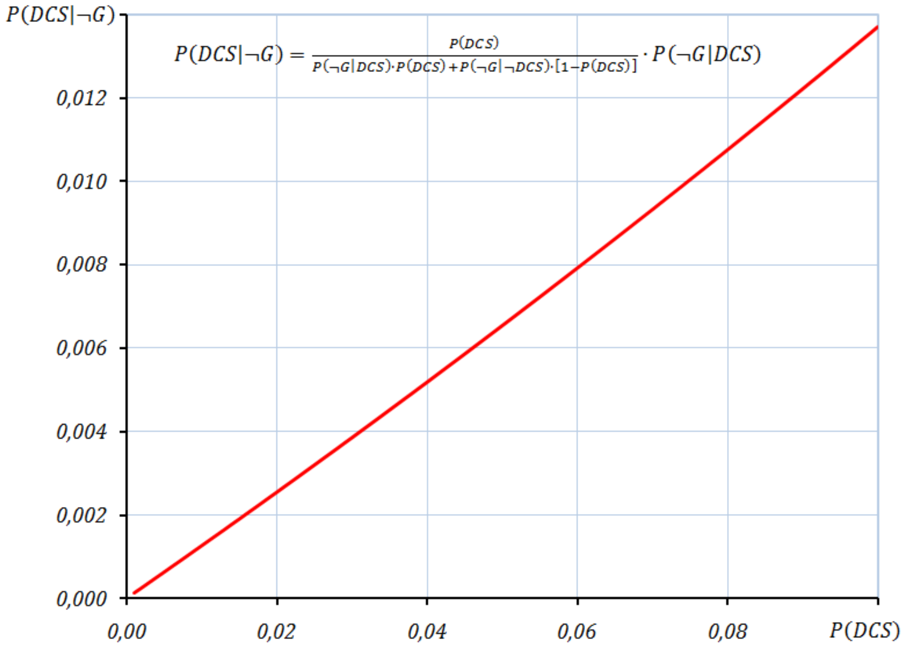

Fig. 1. Probability $P(DCS|\neg G)$ that despite the fact that a free gas phase was not detected during motion or at rest $B:\{\neg G\}$, a diver will have DCS symptoms $A:\{DCS\}$

Source: own study.

[24] Measurements of free gas phase in precordial zone or subclavian veins, and selecting the larger of the signals.

DISCUSSION

In accordance with global trends, PLN assume the tendency to encourage the development of decompression systems, for which the DCS risk is less than 1% [5]. In most cases this is a declaration which fails to be validated due to time or financial constrictions. It is easier to say that DCS risk lies below or above 10%. Hence, for evaluation of experimental dives the adoption of such level of assumption seems to be reasonable: $P(DCS) = 0{,}1$ and for reciprocal event $P(\neg DCS) = 1 - P(DCS) = 0{,}9$.

Table 4. The time span until onset of DCS symptoms from the moment of reaching the surface from 1726 Air and Nitrox dives and from 1508 cases of Heliox dives

Breathing mixture	Type of DCS	Time [min]							Total
		0–30	30–60	60–120	120–180	180–360	360–720	360–1440	
Air and Nitrox	I	18	4	4	1	3	0	2	32
	II	3	0	1	1	0	1	1	7
Heliox	I	18	3	2	2	3	2	2	32

Source: K. D. Sawatzky, The relationship between intravascular Doppler-detected gas bubbles and decompression sickness after bounce diving in humans, Toronto: York University 1991.

Using this assumption one can calculate the probability of an event in which, despite crossing the border for undetected signal originating from intravascular free gas phase during the motion or at rest, the diver will have the symptoms $P(DCS|\neg G) \triangleq \frac{0{,}1}{0{,}09\cdot 0{,}1+0{,}72\cdot 0{,}9}\cdot 0{,}09 \cong 0{,}014 < 1{,}5\%$ — Fig. 1. These results suggest high reliability of diagnostic techniques using DBM enabling to assess the DCS risks during experimental dives.

There is an additional benefit for DBM, related to delay DCS onset after surfacing — Fig. 2 and Tab. 4[25]. These results are entirely consistent with PLN previous observations.

[25] Despite the fact that the data contained in Tab. 2 and Tab. 4 are interrelated, in Tab. 3 is missing two of the cases where it was impossible to determine gap time between surfacing and DCS onset.

CONCLUSIONS

Presented analysis is based on the data from research conducted by $DR - DC\ Toronto$.

DBM method[26] has been used by PLN with success, for many years. Probability $P(DCS|\neg G)$ that despite the fact that a free gas phase was not detected during motion or at rest $B: \{\neg G\}$, a diver will have DCS symptoms A: $\{\text{DCS}\}$ is shown in Fig. 1. The maximum estimated probability was assessed as $P(DCS|\neg G) \triangleq 1{,}5\%$ for DCS probability $\rho(DCS)$ less than $\rho(DCS) \le 10\%$, what confirms the reliability of this method.

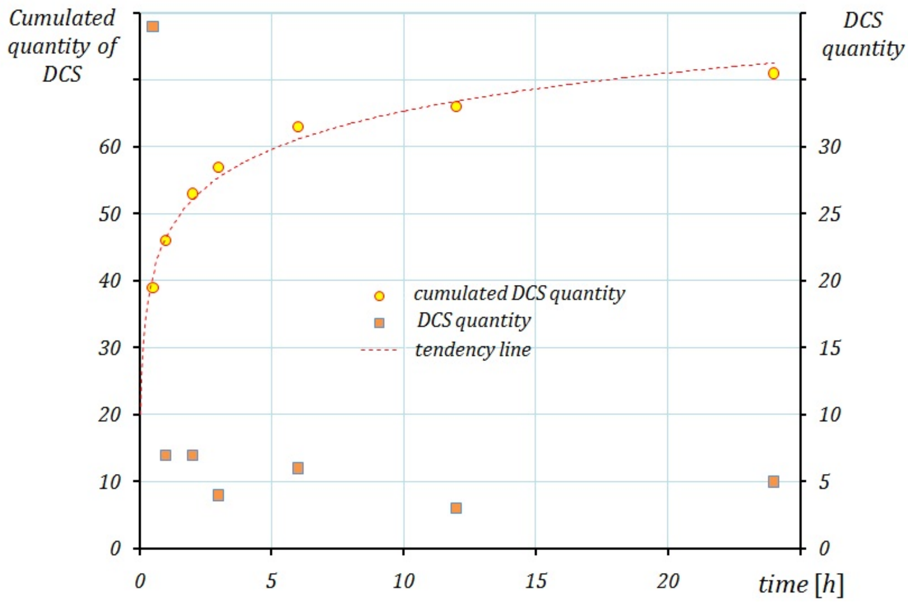

Fig. 2. Time from reaching the surface to DCS symptoms

Source: K. D. Sawatzky, The relationship between intravascular Doppler-detected gas bubbles and decompression sickness after bounce diving in humans, Toronto: York University 1991.

Experience shows that exist differences of interpretation between the DBM technicians, but they are minor and are covered by presented analysis. The high probability of free gas detection makes DBM as a good method for diagnosing DCS risk with a significant lead time [7] — Tab. 4 and Fig. 2.

[26] PLN uses the procedure and equipment recommended by $DR - DC\ Toronto$ [1, 6].

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WYKRYWANIE ŚRÓDNACZYNIOWEJ WOLNEJ FAZY GAZOWEJ

STRESZCZENIE

Dopplerowskie ultradźwiękowe wykrywanie śródnaczyniowej wolnej fazy gazowej stanowi typową użyteczną procedurę stosowaną przy badaniach nad dekompresją. W artykule przedstawiono ocenę statystyczną metody dla przyjętej standardowej procedury detekcyjnej.

Pomimo zgłaszanych zastrzeżeń, metoda dopplerowskiej detekcji śródnaczyniowej wolnej fazy gazowej jest metodą użyteczną i przyczynia się do zwiększenia bezpieczeństwa nurkowania. Jej podstawową zaletą jest możliwość wykorzystania w czasie rzeczywistym.

Dopplerowskie ultradźwiękowe wykrywanie śródnaczyniowej wolnej fazy gazowej jest standardową procedurą wykorzystywaną przez kilka laboratoriów zajmujących się badaniami nad dekompresją. Najczęściej podczas eksperymentalnego badania profili dekompresji stosowane są proste metody polegające na wykrywaniu wolnej fazy gazowej za pomocą odsłuchiwania ultradźwiękowych sygnałów dopplerowskich specjalnie przetworzonych na słyszalny sygnał dźwiękowy. Opisana tutaj analiza odnosi się do metody i urządzeń stosowanych przez DR–DC Toronto. Podobne procedury wykorzystuje się w Centre d'Etudes et de Recherches Techniques Sous-Marines, U.S. Navy Experimental Diving Unit, U.S. Naval Submarine Medical Research Laboratory i U.S. Naval Medical Research Institute.

Podczas gdy sama technika pomiarowa jest prosta i niekosztowna, to jej zastosowanie wymaga umiejętności i doświadczenia. Wyniki badań mogą być łatwo zrozumiałe przez innych pod warunkiem zastosowania standardowych procedur postępowania. Wykorzystywany tutaj kod $K - MK - M$ do klasyfikacji sygnałów jest porównywalny z klasyfikacją przedstawioną przez Spencera, lecz uwzględnia on więcej czynników i umożliwia bardziej szczegółowy opis sygnałów. Kody te są podobne do siebie, jednak wyniki opisane którąkolwiek z tych metod mogą być porównywane tylko w pewnym zakresie.

Przeciwnicy tej metody słusznie zaznaczają, że objawom choroby dekompresyjnej niekoniecznie musi towarzyszyć powstanie wolnej fazy gazowej. W artykule pokazano na podstawie wnioskowania statystycznego, że są to przypadki na tyle rzadkie, aby uznać technikę pomiaru śródnaczyniowej wolnej fazy gazowej jako porównywalną z innymi metodami diagnostyki medycznej przy szacowaniu narażenia na stres dekompresyjny.

Przedstawioną analizę oparto na danych z badań DR–DC Toronto, gdyż w kraju byłoby trudno uzyskać zgodę Komisji Etyki Badań Naukowych na ich przeprowadzenie.

Metoda detekcji dopplerowskiej śródnaczyniowej wolnej fazy gazowej zgodnie z przyjętą procedurą jest od lat stosowana w Akademii Marynarki Wojennej z dobrym rezultatem. Maksymalna oszacowana wartość zagrożenia niewykryciem stwarzającej zagrożenie $DCSDCS$ śródnaczyniowej

wolnej fazy gazowej w funkcji prawdopodobieństwa wystąpienia DCS wynosi $P(DCS|\neg G) \triangleq 1{,}5\%$, co stanowi potwierdzenie wiarygodności tej metody. Z doświadczenia wiadomo, że różnice interpretacyjne pomiędzy technikami dopplerowskimi istnieją, lecz są one nieznaczne i zostały uwzględnione w przeprowadzonej analizie. Oprócz wysokiego prawdopodobieństwa wykrycia i hierarchizacji pod względem stwarzanego zagrożenia możliwością wystąpienia DCS metoda detekcji dopplerowskiej śródnaczyniowej wolnej fazy gazowej daje możliwość diagnozowania tego zagrożenia z istotnym wyprzedzeniem.

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Słowa kluczowe:
bezpieczeństwo dekompresji.