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Context

By its nature, the Industry searches to attain the two main goals: the performance and the safety. Working targets and operational constraints define the level of performance under safety conditions. In commercial diving, underwater construction and tunnelling, the security constraints are particularly important because these activities are associated with numerous risks, a part of which comes from the hyperbaric exposure of workers.

Indeed, the hyperbaric exposure during a dive or the work in a compressed air environment leads to the production of microbubbles in worker's body during the decompression. Under the effect of pressure, body tissues (muscles, fat etc.) are progressively charged with inert gas, generally azote from air or nitrox, which is liberated during the decompression and generates microbubbles. The bubbles grow, penetrate the blood circulation and, in some cases, they can become pathogenic and lead to a decompression sickness accident (DCS).

The bubbles are not synonymous of an accident because the human body possesses the numerous mechanisms for eliminating them: they are filtered out by the lungs and eliminated with the respiration. Nevertheless, a great quantity of bubbles significantly increases the risk of an accident because the bubbles can overpass the lung filter and penetrate the arterial circulation or block the blood vessels, while the bubbles in tissues can grow enough to damage the tissues and/or trigger an inflammatory response.

Bubbles in evaluation of tables and procedures

For more than 30 years, **Defence Research and Development Canada (DRDC, previously DCIEM)**, Institute of Environmental Medicine of the University of Pennsylvania (IFEM) and British Health and Safety Executive (HSE) **have evaluated the level of decompression stress of diving procedures and tables by measuring the circulating bubbles detectable in blood vessels after exposure [1-7].**

Those venous bubbles (VGE) are detected with the Doppler ultrasound (audio detection) or with the echography (imaging) and their number is evaluated on a non-linear scale quantified by grades ranging from 0 (absence of bubbles) to 4 (very numerous bubbles) according to the standard grading systems (Kisman-Masurel [8] or Spencer [9] for audio signals, Eftedal-Brubakk [10] for imaging).

The bubbles grades give an indication of decompression stress because they reflect, at least partially, the quantity of bubbles produced by the organism and their elimination. The numerous studies have shown a strong association between the quantity of bubbles and the risk of DCS [9,11-21]. Even if high bubble grades are a poor predictor of the occurrence of an accident [22], **the absence of VGE is a good safety indicator. For example, within 3234 air, nitrox and heliox dives with 73 DCS analyzed in [18], 66 cases of DCS were associated with grades 3 or 4 (7.2% DCS rate), while only one DCS case was registered for bubble grade 0 (0.07% DCS rate).**

British HSE organized two scientific meetings with working groups on security of industrial diving [6] and compressed air works [7]. These two conferences confirmed the interest of the VGE measurements with Doppler ultrasound in the evaluation of the quality of procedures in laboratory and field conditions. They have concluded that the evaluation must be founded upon the statistics of bubbles production, especially in the beginning of each project and in case of modification of working conditions [7].

Based upon a historical data of bubble measurements and DCS cases for different exposures by combining them with the mathematical modelling tools (bubble growth model [23] and Flook model [24,25]), the following acceptance criteria for procedures in terms of VGE were proposed:

> For under-saturation diving: DRDC fixed experimentally the threshold of 50% of grades 2 or higher to distinguish the acceptable procedures from risky ones [4]. [26] estimated that the threshold of at least 50% of grades 3 or 4 on a given exposure would insure the level of risk below 5%.
> For compressed air works: a criterion of 20% of grade 3 or 4 observed in the whole of workers was proposed as an indicator of procedure necessitating a detailed analysis or an eventual revision [7]. Nevertheless, the authors pointed out that some procedures with good historical statistics of DCS (with few or no accidents reported) could eventually generate up to 60% of grades 1 or 2 and sometimes up to 10 % of grades 3.

Examples of VGE use in evaluation of procedures

The above criteria were used, for example, in [27] for showing that a surface decompression procedure (SurDO2) for a dive to 39.4m for 30 min with moderate work load produced high bubble levels: from Doppler measurements on a sample of divers, the authors have estimated that with 95% probability more than 50% of divers would produce a grade 3 or higher on this exposure. It was suggested to use a longer decompression to insure the sufficient elimination of muscular bubbles for this exposure.

In tunnelling, the air was replaced with the oxygen for decompression (sequence of 20 min oxygen/5 minutes air) with Blackpool table after the series of VGE measurements made by HSE showing a high level of risk associated to the air decompression (median grade 3) and its significant reduction with oxygen (median grade 0) [28]. The Doppler ultra-sound was also used in field conditions to insure the safety after operational modification imposed by the TBM reparation needs during the Western Scheldt Tunnelling Project in Netherlands (sub-saturation exposures were replaced by longer saturation exposures, with the use of Trimix in both situations) [29].

Bayesian approach to the relationship between VGE and DCS

In [30] the authors proposed a Bayesian approach to prediction of DCS risk using the bubbles measurements, having the advantage to combine the previous knowledge of bubbles production and the relationship between VGE and DCS with the results of new bubbles measurements:

« we present a method for estimating DCS risk of a decompression procedure based on observation of intravascular gas bubbles in test subjects and the correspondence between gas bubbles and DCS risk that has been established previously. The method makes use of Bayesian statistics to combine test observations with previous knowledge and assumptions. »

The data of 1726 experimental dives with air and nitrox [18] was used to estimate the DCS risk for each bubble grade. The authors applied the Bayesian computation to estimate the probability of DCS on a given exposure from the bubble measurements in a group of divers on this exposure and the prior for bubbles production extracted from 274 dives from [5]. The advantage of this method is that with a small number of trials (7-15) without DCS one can compare two procedures and get the first estimation of DCS risk. For example, with this method the authors estimated the DCS risk to be 4.6% (95%CI: 1.5%-

7.9%) on a procedure after just 7 exposures without DCS, but with 4 dives within 7 accompanied with a grade 3 or 4. The questionable hypothesis of this method is the conditional independence of DCS risk of exposure given the bubble grades. In other words, one supposed two exposures with the identical VGE statistics have exactly the same DCS risk.

VGE, DCS and exposure parameters

[31] have analysed the data of air and nitrox dives from DRDC database from a different point of view: the authors showed that the prediction of risk of DCS necessitates to take into account both the bubble grades and severity of exposure [32], measured in terms of depth and duration of dive. Moreover, the authors compared the measurements from subclavian area with precordial ones not only from the point of view of agreement of two measures, but also as the indicators of DCS risk, and concluded that subclavian VGE are as good as precordial as DCS risk indicators. This result is in accordance with the observations of [18], even if the subclavian measurements are generally considered as complementary and used to improve the sensitivity of the precordial measures [33].

Long term effects of diving and subclinical VGE

There is growing evidence of long-term effects of subclinical VGE ("silent bubbles"). Several small studies are pointing on endothelial and neuropsychological damages produced by the circulating bubbles.

Several animal and human studies have shown reduced endothelial function after exposure to vascular bubbles [34,35,36], suggesting that this effect may be a central mechanism in the development of serious decompression injury, and possibly also in long-term injury [37]. [38] reported endothelial dysfunction and increased generation of reactive oxygen species (ROS) after successive trimix dives.

In a small number of recreational divers [39] showed an association between the subclinical circulating bubbles with an acute increase of platelets and leukocytes, indicating an activation of reactive system. An acute increase in plasma activity of ACE was also observed in subjects with circulating bubbles [39], that could be a marker of endothelial cell stress and damage. [40] showed an increased arterial pulmonary pressure in divers with post-dive circulating bubbles, the authors hypotized a mechanism of an increase vascular resistances caused by microembolisation.

Cerebral lesions were observed in experienced military divers [41] and white-matter lesions in experienced recreational divers were associated with neuropsychological damages (decrease in short-term memory and higher cognitive function) in [42,43] indicating that repeated hyperbaric exposure increases the risk of white-matter damage.

Conclusion

The literature reviewed here shown the interest of Doppler-detected VGE for the evaluation and the improvement of security in commercial diving and compressed air works. This is the only objective quantifiable measure of decompression stress, which serves to indicate stressful procedures well before the first occurrence of DCS. For more than 30 years the official regulatory and military institutions (HSE, IFEM, DRDC, French Navy) worked on guidelines to the use of bubble measurements for procedures evaluation, with several criteria proposed to insure the safety. Those criteria are still empirical, with the main weak point is that they are based upon VGE statistics, while ignoring the inherent risk associated to the exposure expressed by the exposure parameters.

Azoth Systems integrated this knowledge together with the analysis of data of thousands of exposures to develop a combined approach taking into the account both the intrinsic risk associated with the procedure and the statistics of Doppler-detected venous bubbles.

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