Trends in competitive freediving accidents

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Abstract
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Introduction: Understanding safety issues in competitive freediving is necessary for taking preventive actions and to minimise the risk for the athletes.
Methods: We analysed occurrence of loss of consciousness (LOC) and pulmonary barotrauma (PBt) in various freediving disciplines in 988 competitions over five years (from 2019 to 2023 inclusive), with 38,789 officially registered performances (starts): 26,403 in pool disciplines and 12,386 in depth disciplines.
Results: Average incident rate in competitive freediving (all cases: LOCs plus PBt, 2019–2023) was 3.43% (1,329 incidents / 38,789 starts). The average incident rate of LOC and PBt within five years were 3.31% and 0.38% respectively for all disciplines. Two disciplines present higher risk for LOC: dynamic without fins (DNF) (mean risk ratio (RR) = 1.48, 95% CI, 1.13 to 1.96, $P < 0.01$) and constant weight without fins (CNF) (mean RR = 2.02, 95% CI, 1.39 to 2.94, $P < 0.001$). The RR for PBt was not higher in any discipline. The overall risk of all types of incidents (LOC plus PBt) was also higher for DNF (mean RR = 1.55, 95% CI, 1.18 to 2.04, $P < 0.01$) and CNF (mean RR = 2.80, 95% CI, 1.70 to 5.04, $P < 0.001$).
Conclusions: The disciplines without fins in the pool (DNF) and at depth (CNF) appear to be the most dangerous in terms of LOC. We may recommend that organisers and safety teams should pay a special attention to no-fin disciplines as most risky for possible LOC.

Introduction

Freediving is an activity that dates back thousands of years. In the last ten years, there is a boom in competitive freediving worldwide. Understanding related safety issues is important, to take preventative measures for minimising the risk for athletes.

The competitions in freediving may be organised in a pool or in the sea. Pool disciplines are static apnoea (STA), dynamic no fins (DNF) and dynamic with fins (DYN). Static apnoea is a holding of breath at the surface of the water without any movement for as long as possible; dynamic apnoea consists of covering the greatest distance horizontally with a monofin (DYN), two fins (bifins) (DYNB) or without fins (DNF) on a single breath of air. Depth disciplines are constant weight no fins (CNF), free immersion (FIM), constant weight with a monofin (CWT) and constant weight with bifins (CWT_B). The objective of the depth disciplines is to descend as deep as possible with constant weight without external assistance, with the exception of FIM which involves descending and ascending pulling a rope by hand. Current freediving records in each discipline are shown on the AIDA International (Association Internationale pour le Développement de l'Apnée) website (https://www.aidainternational.org/).

At the end of a record attempt, on surfacing, a freediver needs to demonstrate cognitive integrity and good physical condition by presenting the 'surface protocol' to judges. An athlete must remove all facial equipment (mask, nose clip), show the 'OK' sign and say 'I am OK', all within 15 sec from surfacing (starting from the emerging athlete's airway being above water). The freediver's airway should remain above the water throughout the whole protocol. If a freediver does not perform the surface protocol appropriately, an attempt is not counted. There are several reasons why the physical and mental condition of an athlete may be compromised at the end of performance. For example, the excellent diving reflex pertinent to high-level freedivers enables them to save their oxygen reserves,[1] but even top sportsmen may find themselves in deep hypoxic situations and may lose consciousness[2] with drop in arterial partial pressure of oxygen (PaO_2) to dramatically low levels.[3,4] Loss of consciousness (LOC) may occur at surface or at depth, but tends to occur commonly near the end of the dive as the freediver nears the surface – referred to as 'shallow-water

blackout'. Despite of understanding that LOC leads to disqualification and willing to escape this scenario, almost 10% of freedivers were disqualified because of LOC at depth competitions between years 1998 and 2004.[5] Freedivers may also suffer from pulmonary barotrauma (PBt) due to the extreme pressure they have to cope with during deep dives.[6] Freedivers with PBt ('lung squeeze') may have a cough and a sensation of chest constriction accompanied with dyspnoea.[7,8] Symptoms of PBt have been reported in up to 25% of freedivers after repeated diving sessions.[9] Repetitive breath-hold diving may increase transpulmonary capillary pressure and this increasing could lead to non-cardiogenic oedema and alveolar haemorrhage.[8] Despite the importance of assessing the risk for the athletes, there are no recent data on freediving incidents observed at competitions. Long-term consequences of freediving injuries and their impact on athletes' health also are limited and are required further investigation in other studies.

The objective of the study was to evaluate the prevalence and risk of freediving-related incidents during competitions and to determine which competitive freediving discipline(s) are at higher risk of incidents. We intend that the results of the study should contribute into assessment of the overall situation with the safety of freediving competitions, and be taken into consideration by coaches, medical teams, organisers of competitions and support the improvement of the competition rules and regulations.

Methods

Data were obtained from open public sources. Approval of the Ethical Committee and the informed consent of subjects was not required. The Medical and Science Committee and the Board of AIDA International provided the authorisation to use the competition data for the purpose of this study.

PARTICIPANTS

Data were collected from the official results of all competitions worldwide organised by AIDA International from 2019 to 2023, inclusive, (https://www.aidainternational.org/). All competitors had a medical certificate allowing them to practice freediving and participate in freediving competitions. A competitor should announce planned performance (time of breath hold, distance, or depth; the official term is 'announced performance') before an attempt. If an athlete does not reach the announced result, penalty points are awarded and the diver is presented with a yellow card by the judge. The announced performance (time of breath hold or distance) may be exceeded in the pool but not in the depth disciplines (the rules prevent that).

GENERAL ASSESSMENT OF ATTEMPT BY JURY

The assessment of a performance by the jury through presenting a card of a different color (white, yellow, or red) doesn't reflect the medical condition of an athlete directly. If an athlete can't complete the surface protocol appropriately, an attempt is not counted (a red card is shown by the judges). Inability to perform the surface protocol which leads to a red card may be connected not only to hypoxia but, for instance, to the lack of competitive experience or to the activities of third parties (for instance, touch of an athlete by safety diver, which is prohibited by the competition rules). A serious deterioration of an athlete's health may lead not only to a failed attempt but to the disqualification from the whole competition. A yellow card typically means that some rules are violated, or the result of the performance is below the announced one. It doesn't reflect the medical condition of an athlete as well. A white card means that all rules and requirements have been met. We considered that the analysis of the jury assessments (cards) could be of interest.

DESIGN

Data were analysed for number of countries where competitions were performed, number of competitions, number of dives, and for success of performance (number of red, yellow and white cards). Frequency of freediving incidents (surface LOC, underwater LOC, pulmonary barotrauma) was analysed in the following pool freediving disciplines: STA, DYN, DYN_B, DNF (pool), and in the following depth freediving disciplines: CWT, CWT_B, CNF and FIM. The decision whether LOC occurred was made by judges who directly observed an athlete after surfacing. The judges were assisted with videotaping of the surfacing, to review any questionable cases. Decisions regarding the occurrence of PBt was made by groups of competition medics who performed the medical examination of an athlete if PBt was suspected.

SAMPLE SIZE

Sample size calculation wasn't performed. All available data were collected from the official results of all competitions organised by AIDA International from 2019 to 2023, inclusive.

STATISTICAL ANALYSIS

Differences in disciplines, type of card, or gender were tested using two- or 3-way ANOVA. For *post-hoc* tests, Scheffé's method with the Bonferroni correction were applied. Underwater LOCs and surface LOCs were analysed in combination and separately. Because of the lack of yearly data on the performances with bifins, data for DYN with a monofin was combined with DYN_B (DYN+B), and CWT with monofin were combined with CWT_B. The relative risk (RR) for the LOCs, PBt and all accidents were calculated by comparing the frequency of accidents for each discipline with the annual pool and depth incidents obtained for each discipline. The RR, its standard error and 95% confidence interval were calculated according to Altman.[10] For RR,

the *P*-value is calculated according to Sheskin.[11] Statistical analyses were performed with SPSS (Version 21.0). The data are presented as means and standard deviation (SD). Differences with *P*-value less than 0.05 were considered significant.

Results

POPULATION

From 2019 to 2023, AIDA International authorised 988 competitions (mean 197, SD 75 competitions per year). The competitions took place in 59 countries, athletes of 116 nationalities participated in these events. In all competitions, there were 38,789 officially registered performances (attempts) in all disciplines (26,403 in pool disciplines and 12,386 in depth disciplines); 23,331 men's starts (60.2%) and 15,458 women's starts (39.8%). All results from all competitions were analysed for the purposes of the study (no missing data).

ALL INCIDENTS

The average incident rate in competitive freediving (all cases: LOCs plus PBt) over five years (from year 2019 to 2023 inclusive) was 3.43% (1,329 incidents in 38,789 starts). Data for each discipline are presented in Table 1.

LOSS OF CONSCIOUSNESS

The average incident rate of LOC (surface plus underwater) over the five year period was 3.31% (1,282 incidents in 38,789 starts) for all disciplines: 3.22% (850 incidents in 26,403 starts) in pool disciplines and 3.49% (432 incidents in 12,386 starts) in depth disciplines. Surface LOC occurred in 2.51% (all disciplines); 3.00% in pool disciplines and 2.01% in depth disciplines. Underwater LOC occurred in 1.91% (all disciplines); 2.44% in pool disciplines and 1.38% in depth disciplines. Loss of consciousness data are presented in Tables 2 and 3. A Pareto chart indicates that CNF and DNF were respectively responsible for 35% and 17% of LOC events (Figure 1).

PULMONARY BAROTRAUMA

The incident rate for PBt is presented in Table 4, with an average occurrence of 0.38% over five years (47 incidents in 12,386 starts). A Pareto chart indicates that CNF was responsible for 58% of PBt (Figure 2).

RISK OF DIFFERENT DISCIPLINES

Two disciplines present higher risk for LOC occurring either underwater or at the surface: DNF (mean RR = 1.48; 95% CI, 1.13 – 1.96; $P < 0.01$) and CNF (mean RR = 2.02;

Table 1

Percentage of attempts resulting in loss of consciousness (LOC) (surface or underwater) or pulmonary barotrauma (PBt) by disciplines; CNF – constant weight without fins; CWT (+ B) – constant weight with a monofin or two fins; DNF – dynamic without fins; DYN (+ B) – dynamic with a monofin or two fins; FIM – free immersion; STA – static apnoea

Discipline	Percent incidents (LOC plus PBt)					
	2019	2020	2021	2022	2023	Total mean
STA	2.45	4.42	3.44	3.69	2.24	3.13
DNF	4.60	5.59	5.46	4.48	5.08	4.85
DYN (+B)	2.82	3.41	3.80	2.51	2.87	2.67
CNF	7.74	4.63	4.42	6.57	9.26	7.82
FIM	2.31	1.64	4.78	3.84	4.10	3.33
CWT (+B)	3.53	0.48	3.22	1.51	3.22	2.36
Total mean	3.89	3.36	4.79	3.70	4.39	3.43

Table 2

Percentage of attempts resulting in surface or underwater loss of consciousness (LOC) incidents in pool disciplines; DNF – dynamic without fins; DYN (+ B) – dynamic with a monofin or two fins; STA – static apnoea

Discipline	Percent incidence of LOC in pool disciplines					
	2019	2020	2021	2022	2023	Total mean
STA	2.40	4.42	3.01	3.63	2.16	3.13
DNF	4.53	5.59	4.90	4.27	4.98	4.85
Dyn (+B)	2.82	3.41	1.88	2.39	2.84	2.67
Total mean	3.25	4.48	3.26	3.43	3.33	3.55

Table 3

Percentage of attempts resulting in surface or underwater loss of consciousness (LOC) incidents in depth disciplines; CNF – constant weight without fins; FIM – free immersion; CWT (+ B) – constant weight with a monofin or two fins

Discipline	Percent incidence of LOC in depth disciplines					
	2019	2020	2021	2022	2023	Total mean
CNF	7.16	2.78	10.09	5.51	8.48	6.80
FIM	2.09	0.98	4.40	3.14	3.61	2.84
CWT (+B)	3.39	0.48	2.94	1.37	2.89	2.21
Total mean	4.21	1.41	5.81	3.34	4.99	3.95

Figure 1

Pareto chart of surface and underwater loss of consciousness (LOC) across freediving disciplines between 2019–2023; CNF – constant weight without fins; CWT (+ B) – constant weight with a monofin or two fins; DNF – dynamic without fins; DYN (+ B) – dynamic with a monofin or two fins; FIM – free immersion; Static – static apnoea

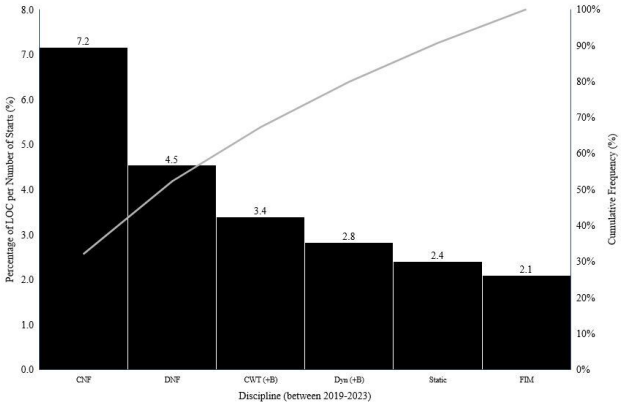


Figure 2

Pareto chart of pulmonary barotrauma (PBt) by freediving disciplines from 2019 to 2023; CNF – constant weight without fins; CWT (+ B) – constant weight with a monofin or two fins; DNF – dynamic without fins; DYN (+ B) – dynamic with a monofin or two fins; FIM – free immersion; Static – static apnoea

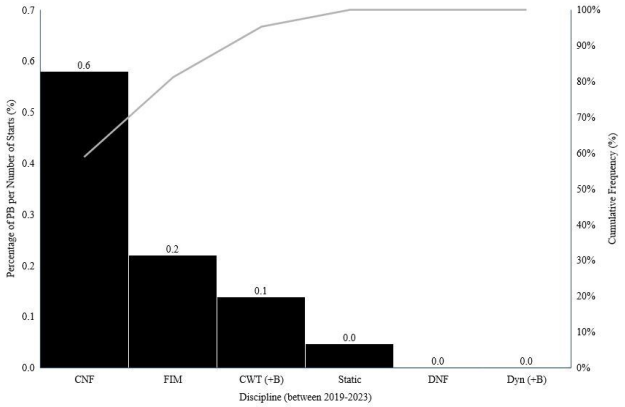


Table 4

Pulmonary barotrauma (PBt) incidents in depth disciplines; CNF – constant weight without fins; CWT (+ B) – constant weight with a monofin or two fins; FIM – free immersion

Discipline	Percent incidence of PBt in depth disciplines					
	2019	2020	2021	2022	2023	Total mean
CNF	0.01	0.02	0.01	0.01	0.01	0.01
FIM	0.22	0.66	0.38	0.70	0.49	0.49
CWT (+B)	0.14	0.00	0.41	0.14	0.28	0.19
Total mean	0.06	0.11	0.13	0.14	0.13	0.38

95% CI, 1.39–2.94; $P < 0.001$). The other disciplines did not present a greater LOC risk. The RR for PBt was not higher whatever the disciplines and years. The overall risk of all types of incidents also remains high for DNF (mean RR = 1.55; 95% CI, 1.18–2.04; $P < 0.01$) and CNF (mean RR = 2.80; 95% CI, 1.70–5.04; $P < 0.001$).

GENERAL ASSESSMENT OF ATTEMPT BY JURY

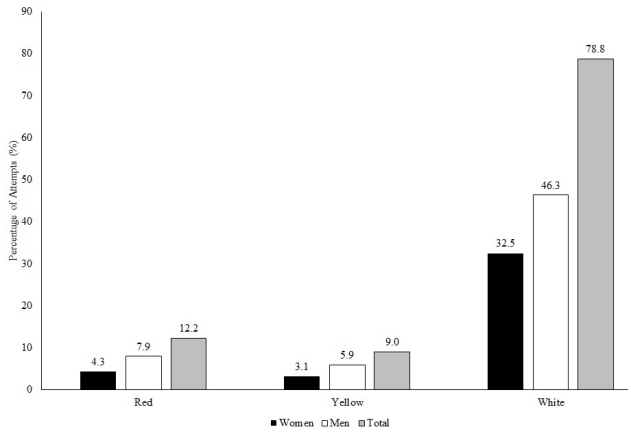
The average percentages of attempts receiving red, yellow, and white cards are shown in Figure 3. Static apnoea has a significantly higher proportion of red and yellow cards than other disciplines (F = 21.33; $P < 0.001$), with fewer cases in women (F= 34.21; $P < 0.05$). Next come CNF and DYN (+B), with no difference between men and for women.

Discussion

These results show that between 2019 to 2023, 1,282 out of 38,789 (3.31%) attempts in international freediving competitions were not counted due to the loss of consciousness or inability to perform the surface protocol

Figure 3

Mean percentage of red, yellow, and white cards issued across freediving disciplines from 2019 to 2023; results are presented by sex (men and women) and combined total; red – disqualified; yellow – rule violations; white – successful performance



through manifestations such as loss of motor control. During the same observational period, PBt occurred after 47 of 12,386 (0.38%) starts. The RRs of LOC were higher in no fin disciplines (DNF and CNF) with no difference for the other disciplines.

To our knowledge, this is the first study of the occurrence of freediving incidents during competitions occurring over an extended period and with the analysis of full set of data obtained from reliable official sources (all competitions under auspices of AIDA International, all disciplines, all incidents). Although we didn't perform direct comparison, it is interesting to note that there are less red and yellow cards in women than in men, especially in STA and CNF. This difference may be explained by different risk-taking between men and women, as anecdotally observed by our team.

If we compare the results of our study with the results of a similar study,[5] our study found a lower incidence of LOC (3.31% vs 9.7–11.1% respectively). That study did not include PBt. The different result for LOC may relate to the difference in sample size (596 in Lindholm's study[5] versus 38,789 in our study). We may conclude that most risky disciplines are those without fins, both in depth disciplines and in the pool. This observation may be speculatively explained on the basis that no-fin disciplines require a greater oxygen consumption due to the recruitment of a greater number of muscle groups. This increased oxygen consumption leads to more rapid desaturation of arterial oxygen.[12] The rapid drop in oxygen levels likely predisposes to syncope and may impair the efficiency of the dive reflex, creating a conflict between oxygen delivery to active muscles and the brain.[13]

There is some evidence that repeated hypoxic events can progressively alter neurocognitive functions. Billaut et al.[14] observed mild executive dysfunction positively correlated with the duration (years) of practicing apnoea. Potkin and Uszler[15] used brain imaging and suggested abnormalities in the brain functions in five elite breath hold divers. In contrast, Doerner et al.[16] found no mid-term morphological changes in the brains of 17 elite freedivers. Other researchers attempted to assess the impact of hypoxia on brain with several brain markers. Liner and Andersson[17] observed high levels of S100B (a serum marker of cerebral ischaemia and brain damage) within five days after a dynamic apnoea attempt ending with LOC, and this observation may suggest long-term negative consequences of severe brain hypoxia in freedivers.[18] Gren et al.[19] showed that the amyloid precursor protein (Tau) associated with neuronal damage or dysfunction, is accumulated in plasma after long static apnoea. In trained freedivers, dynamic cerebral autoregulation is acutely impaired during maximal breath hold attempts.[20] A decrease in cerebral oxidative metabolism and disruption of the blood-brain barrier may also occur.[21–23] Bailey et al,[24] found the persistence of functional-structural destabilisation of the blood-brain barrier (BBB) in elite freedivers periodically exposed to extreme hypoxia. Thus, some evidence indicates that repeated, prolonged apnoeas may lead to minor BBB disruption and neuronal parenchymal damage, increasing the possibility of at least mild neurocognitive sequelae. Thus, a risk to freediver's brain can be hypothesised. Since disciplines without fins appear to present a higher risk than other disciplines, it could be of interest to investigate elite freedivers holding the records in DNF and CNF.

Our study demonstrates the relatively low risk of PBt, and this condition was found to occur only in depth disciplines, not in the pool. It is possible that risk may be underestimated because while clinically significant cases of PBt are recorded, milder cases, when only the athlete is aware of symptoms, often go unnoticed by the event medics. Athletes do not report these symptoms to the physician due to fear of being disqualified from the competitions. The medical consequences after mild or moderate PBt may be important. A suggestion that PBt increases the risk of LOC by limiting oxygenation during ascent should be investigated. Another sign of PBt is haemoptysis after alveolar haemorrhage due to cardiovascular changes that occur during deep apnoea dives. High ambient pressure in depth and exposure to a cold environment increase intrathoracic blood volume and cardiac output, as well as pulmonary capillary pressure. The risk of alveolar haemorrhage is also increased by negative pressure inside the alveoli due to involuntary breathing movements during the late phase of an apnoea dive. Haemoptysis has been self-reported in one-fifth of freedivers.[9] Blood clots which probably arrived from the lower respiratory tract were observed by laryngoscopy in freedivers who dived to a depth of 6 m after complete exhalation to residual volume to simulate thoracic squeeze.[25] Haemoptysis after deep dives may present as a single symptom or occur together with cough and dyspnoea, which are the symptoms of pulmonary oedema.[26,27]

LIMITATION

Unfortunately, we have no access to the full data set by gender and discipline. For this reason, we propose not to include the percentages for men and women separately for each discipline.

Conclusions

The study presents first analysis of five-year prevalence of two important freediving adverse medical events, LOC and PBt, in different freediving disciplines. The disciplines without fins in the pool (DNF) and at depth (CNF) appear to be the most dangerous in terms of LOC. We may recommend that organisers and safety teams should pay a special attention to no fin disciplines as most risky for possible LOC. Athletes should carefully consider announced performance and freediving training technique: movements of the legs and arms should not only be effective, but also as relaxed as possible to minimise oxygen consumption and, most importantly, to prevent sharp reduction of arterial PO_2.

The international freediving federations, AIDA International and CMAS, have competition rules with a section about assessment of the incidents and follow-up actions. The statistics about freediving incidents should be taken in consideration when the competition rules are under periodic revision. If the number of freediving incidents is increasing, the rules should be amended, for instance, to tighten the conditions for further participation of athletes in competitions after serious incidents.

References

1 Elia A, Gennser M, Harlow PS, Lees MJ. Physiology, pathophysiology and (mal)adaptations to chronic apnoeic training: a state-of-the-art review. Eur J Appl Physiol. 2021;121:1543–66. doi: 10.1007/s00421-021-04664-x. PMID: 33791844. PMCID: PMC8144079.

2 Poiret C, Noulhiane M, Clua E, Lemaître F. Breath-hold diving strategies to avoid loss of consciousness: speed is the key factor. Sports Biomech. 2020;23;1–14. doi: 10.1080/14763141.2020.1820073. PMID: 33272108.

3 Bosco G, Paganini M, Rizzato A, Martani L, Garetto G, Lion J, et al. Arterial blood gases in divers at surface after prolonged breath-hold. Eur J Appl Physiol. 2020;120:505–12. doi: 10.1007/s00421-019-04296-2. PMID: 31912227.

4 Scott T, van Waart H, Vrijdag XCE, Mullins D, Mesley P, Mitchell SJ. Arterial blood gas measurements during deep open-water breath-hold dives. J Appl Physiol (1985). 2021;130:1490–5. doi: 10.1152/japplphysiol.00111.2021. PMID: 33830815. PMCID: PMC8354821.

5 Lindholm P. Loss of motor control and/or loss of consciousness during breath-hold competitions. Int J Sports Med. 2007;28:295–9. doi: 10.1055/s-2006-924361. PMID: 17024640.

6 Mijacika T, Dujic Z. Sports-related lung injury during breath-hold diving. Eur Respir Rev. 2016;25(142):506–12. doi: 10.1183/16000617.0052-2016. PMID: 27903671. PMCID: PMC9487548.

7 Tetzlaff K, Swenson ER, Bärtsch P. An update on environment-induced pulmonary edema – "When the lungs leak under water and in thin air". Front Physiol. 2022;13:1007316. doi: 10.3389/fphys.2022.1007316. PMID: 36277204. PMCID: PMC9585243.

8 Tetzlaff K. Pulmonary physiology and medicine of diving. Semin Respir Crit Care Med. 2023;44:705–18. doi: 10.1055/s-0043-1770065. PMID: 37369217.

9 Cialoni D, Sponsiello N, Marabotti C, Marroni A, Pieri M, Maggiorelli F, et al. Prevalence of acute respiratory symptoms in breath-hold divers. Undersea Hyperb Med. 2012;39:837–44. PMID: 22908840.

10 Altman DG. Practical statistics for medical research. New York: Chapman and Hall/CRC; 1990. p. 624. doi: 10.1201/9780429258589.

11 Sheskin DJ. Handbook of parametric and nonparametric statistical procedures. 3rd ed. New York: Chapman and Hall/CRC; 2003. p. 1193. doi: 10.1201/9781420036268.

12 Breskovic T, Uglesic L, Zubin P, Kuch B, Kraljevic J, Zanchi J, et al. Cardiovascular changes during underwater static and dynamic breath-hold dives in trained divers. J Appl Physiol (1985). 2011;111(3):673–8. doi: 10.1152/japplphysiol.00209.2011. PMID: 21719730.

13 Schagatay E. Predicting performance in competitive apnea diving. Part II: dynamic apnoea. Diving Hyperb Med. 2010;40:11–22. PMID: 23111834. [cited 2024 Jun 20]. Available from: https://dhmjournal.com/images/IndividArticles/40March/Schagatay_dhm.40.1.11-22.pdf.

14 Billaut F, Gueit P, Faure S, Costalat G, Lemaître F. Do elite breath-hold divers suffer from mild short-term memory impairments? Appl Physiol Nutr Metab. 2018;43:247–51. doi: 10.1139/apnm-2017-0245. PMID: 29053942.

15 Potkin RT, Uszler JM. Brain function imaging in asymptomatic elite breath-hold divers. In: Breath-hold diving proceedings of the Undersea and Hyperbaric Medicine/Divers Alert Network 2006 June 20–21 Workshop. 2006. p. 135–6.

16 Doerner J, Eichhorn L, Luetkens JA, Lunkenheimer JN, Albers J, Nadal J, et al. Effects of repetitive prolonged breath-hold in elite divers on myocardial fibrosis and cerebral morphology. Eur J Radiol. 2018;103:13–8. doi: 10.1016/j.ejrad.2018.03.020. PMID: 29803378.

17 Andersson JPA, Linér MH, Jönsson H. Increased serum levels of the brain damage marker S100B after apnea in trained breath-hold divers: a study including respiratory and cardiovascular observations. J Appl Physiol (1985). 2009;107(3):809–15. doi: 10.1152/japplphysiol.91434.2008. PMID: 19574501.

18 Marzano LAS, Batista JPT, de Abreu Arruda M, de Freitas Cardoso MG, de Barros JLVM, Moreira JM, et al. Traumatic brain injury biomarkers in pediatric patients: a systematic review. Neurosurg Rev. 2022;45:167–97. doi: 10.1007/s10143-021-01588-0. PMID: 34170424.

19 Gren M, Shahim P, Lautner R, Wilson DH, Andreasson U, Norgren N, et al. Blood biomarkers indicate mild neuroaxonal injury and increased amyloid β production after transient hypoxia during breath-hold diving. Brain Inj. 2016;30:1226–30. doi: 10.1080/02699052.2016.1179792. PMID: 27389622.

20 Cross TJ, Kavanagh JJ, Breskovic T, Johnson BD, Dujic Z. Dynamic cerebral autoregulation is acutely impaired during maximal apnoea in trained divers. Plos One. 2014;9(2):e87598. doi: 10.1371/journal.pone.0087598. PMID: 24498340. PMCID: PMC3911978.

21 Bain AR, Ainslie PN, Hoiland RL, Barak OF, Cavar M, Drvis I, et al. Cerebral oxidative metabolism is decreased

with extreme apnoea in humans; impact of hypercapnia. J Physiol. 2016;594:5317–28. doi: 10.1113/JP272404. PMID: 27256521. PMCID: PMC5023711.

22 Bain AR, Ainslie PN, Hoiland RL, Barak OF, Drvis I, Stembridge M, et al. Competitive apnea and its effect on the human brain: focus on the redox regulation of blood-brain barrier permeability and neuronal-parenchymal integrity. FASEB J. 2018;32:2305–14. doi: 10.1096/fj.201701031R. PMID: 29191963.

23 Elia A, Woods DR, Barlow MJ, Lees MJ, O'Hara JP. Cerebral, cardiac and skeletal muscle stress associated with a series of static and dynamic apnoeas. Scand J Med Sci Sports. 2022;32:233–41. doi: 10.1111/sms.14067. PMID: 34597427.

24 Bailey DM, Bain AR, Hoiland RL, Barak OF, Drvis I, Hirtz C, et al. Hypoxemia increases blood-brain barrier permeability during extreme apnea in humans. J Cereb Blood Flow Metab. 2022;42:1120–35. doi: 10.1177/0271678X221075967. PMID: 35061562. PMCID: PMC9121528.

25 Lindholm P, Ekborn A, Oberg D, Gennser M. Pulmonary edema and hemoptysis after breath-hold diving at residual volume. J Appl Physiol (1985). 2008;104(4):912–7. doi: 10.1152/japplphysiol.01127.2007. PMID: 18202166.

26 Boussuges A, Pinet C, Thomas P, Bergmann E, Sainty JM, Vervloet D. Haemoptysis after breath-hold diving. Eur Respir J. 1999;13:697–9. doi: 10.1183/09031936.99.13369799. PMID: 10232449.

27 Kiyan E, Aktas S, Toklu AS. Hemoptysis provoked by voluntary diaphragmatic contractions in breath-hold divers. Chest. 2001;120:2098–100. doi: 10.1378/chest.120.6.2098. PMID: 11742946.

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