Decompression sickness in surface decompression breathing air instead of oxygen

Jan Risberg[1], Helle Midtgaard[2]

[1] *NUI, Bergen, Norway*
[2] *Oslo University Hospital, Oslo, Norway*

Corresponding author: *Dr Jan Risberg. NUI, Gravdalsveien 245, 5165 Laksevåg, Bergen, Norway*
jri@nui.no

Keywords
Decompression illness; Decompression tables; Diving tables; Incidents; Occupational diving

Abstract

(Risberg J, Midtgaard H. Decompression sickness in surface decompression breathing air instead of oxygen. Diving and Hyperbaric Medicine. 2024 30 September;54(3):242–248. doi: 10.28920/dhm54.3.242-248. PMID: 39288932.)
We report an unusual decompression sickness (DCS) incident in a commercial diving project. Eleven divers completed 91 dives to 23.5–36.2 m with bottom times ranging 23–67 min. The divers were breathing compressed air while immersed. Decompression was planned as surface decompression in a deck decompression chamber breathing oxygen typically for 15–30 min. Due to a technical error the divers breathed air rather than oxygen during the surface decompression procedure. Two divers suffered DCS. Both were recompressed on site with the same error resulting in them breathing compressed air rather than oxygen. One of them experienced a severe relapse with cardiovascular decompensation following recompression treatment. While DCS was expected due to the erroneous decompression procedures, it is noteworthy that only two incidents occurred during 91 dives with surface decompression breathing air instead of oxygen. Accounting for this error, the median omitted decompression time was 17 min (range 0–26 min) according to the Bühlmann ZHL-16C algorithm. These observations suggest that moderate omission of decompression time has a relatively small effect on DCS incidence rate. The other nine divers were interviewed in the weeks following completion of the project. None of them reported symptoms at the time, but five divers reported having experienced minor symptoms compatible with mild DCS during the project which was not reported until later.

Introduction

Decompression sickness (DCS) is a known complication of diving.[1] The likelihood of contracting DCS is reduced by adherence to recognised decompression tables, but the possibility can never be eliminated. Most surface-oriented diving is planned to allow uninterrupted ascent to surface ('no-decompression diving') or by staged in-water decompression stops at defined depths. An alternative approach to traditional in-water staged decompression stops is to shorten or completely remove the staged in-water decompression stops and rather recompress the diver immediately after surfacing in a deck decompression chamber. The divers will breathe oxygen through tight fitting masks integrated with the built-in-breathing-system (BIBS) of the deck decompression chamber. The benefits of surface decompression with oxygen ($SurDO_2$) include shortened in-water decompression time, avoidance of sea swell and thermal comfort during decompression. Oxygen breathing in the deck decompression chamber allows a shorter decompression time compared to air breathing conventionally used in in-water staged decompression. Surface decompression on oxygen has been suspected to cause a high DCS incidence.[2] However, probabilistic modelling suggests that dives planned according to the US Navy Diving Manual[3] may be completed with DCS probability in the same order as in-water air decompression, and with the above advantages.[4]

We report two cases of treated DCS caused by the incorrect administration of breathing gas (air instead of oxygen) during surface decompression. While we would expect a high DCS probability due to this error ('deserved DCS'), we discuss the fact that many other dives were completed uneventfully in spite of the same procedural error.

The SI unit for pressure is Pa, but decompression tables by convention use meters of seawater (msw) whether referencing to diver's ambient pressure immersed or in the dry environment. For this reason, we have retained the use of msw in this report (10 msw approximately = 100 kPa).

Case reports

The protocol for this work was presented to the Norwegian regional ethics committee west (REC west) for a submission assessment. REC west concluded that no formal ethical review was required. Both divers have read the contents of the manuscript before they gave their written permission to share the contents in public.

BACKGROUND

The commercial dives took place spring 2023 in the harbor of a Norwegian city. The diving company had been awarded a contract to extract oil from a sunken vessel. The wreck was located at a depth of approximately 30–35 msw. The objective of the diving project was to identify the locations of the bulkheads, clean areas using water jets, drill holes in the hull and connect flexible pipes to allow the extraction of the oil. The wreck had a significant list, and the divers could usually stand on the draught or on the sea bottom under the keel and work at fixed water depths. Divers' depth and bottom time were monitored electronically. Diving was done from a small diving support vessel equipped with a deck decompression chamber.

A total of 101 dives were completed of which 91 were $SurDO_2$ dives and 10 were no-decompression dives or conventional staged in-water decompression dives. All dives were planned with compressed air as breathing gas and the $SurDO_2$ decompressions followed nationally approved decompression tables (Norwegian Diving and Treatment Tables).[5] The Norwegian Diving and Treatment Tables $SurDO_2$ dives are slightly modified (metric converted) versions of the US Navy (USN) Diving Manual Rev 7 $SurDO_2$ tables.[3] None of the $SurDO_2$ dives called for staged in-water decompression stops preceding chamber recompression. The procedures instruct the diver to ascend at 10 $msw{\cdot}min^{-1}$ to surface, undress and move into the deck decompression chamber and then immediately start breathing oxygen by BIBS. The diver should be recompressed to 15 msw (253 kPa) within a 5 min surface interval. The first 15 min of oxygen breathing takes place at a chamber depth of 15 msw, followed by oxygen breathing at 12 msw. The diver should breathe chamber air for 5 min following every 30 min of BIBS oxygen breathing to reduce oxygen toxicity. Decompression from 15 or 12 msw to surface pressure is at 10 $msw{\cdot}min^{-1}$.

Due to human error, stored compressed air rather than oxygen was connected to the BIBS system. For a period of 17 days 91 dives were completed with surface decompression breathing air rather than oxygen on BIBS until this error was discovered and corrected.

PREDICTING OMITTED DECOMPRESSION WHEN BREATHING AIR DURING $SURDO_2$

To illustrate the expected consequence of erroneously breathing compressed air rather than oxygen on BIBS during surface decompression, the optimal method would be to apply a probabilistic DCS model such as those developed by the USN.[6] However, such models were not available for us, so we decided to illustrate the extent of omitted decompression using the Bühlmann ZHL-16C model. For this purpose, we used the 'DecoPlanner' software version 4.6.5 (GUE, High Springs, FL) to calculate the required decompression for the entire procedure conducted breathing air. The software was provided such input data for each of the 91 surface decompression dives:

- Breathing gas air (FO_2 = 21%).
- Bühlmann algorithm, ZHL-16C, 100-100 gradient factors.
- Descent rate (compression) 18 $msw{\cdot}min^{-1}$, and ascent rate (decompression) 10 $msw{\cdot}min^{-1}$.
- Bottom time and depth as relevant for the specific dive.
- Ascent to 6 msw, isopressure for 4 min.
- Recompression to 15 msw.
- Air breathing at 15 and 12 msw as relevant for the specific dive.

It should be noted that the 'surface interval' was placed at 6 msw rather than surface which would have been correct based on the actual profile. The reason is that the software would not allow further diving or decompression calculation if any shallower stop than 6 msw was programmed after finished bottom time.

Following the data input, the software was requested to 'plan dive' and provided output as a recommended time of decompression at 3 msw. We will use the term 'Bühlmann-recommended decompression' for the time at 3 msw recommended by DecoPlanner and 'omitted decompression' for the discrepancy between the recommended time and the actual time spent decompressing.

Case descriptions

Two DCS incidents occurred during this diving project.

CASE ONE

The first affected a 48-year-old man, previously healthy with approximately 1,000 dives in his occupational diving career. The incident occurred on the fourth day of this project and his third day of diving. He had been diving a shallow no-decompression dive two days earlier and an uneventful dive to 27.9 msw for 42 min with surface decompression the preceding day without any symptoms. On the day of the incident, he was diving to 28 msw for 55 min. He was recompressed to 15 msw in the deck decompression chamber and followed a 45 min BIBS-schedule. Approximately 1 h after finishing surface decompression he experienced distorted vision, described as flickering, chest discomfort and left upper extremity paraesthesiae. He subsequently developed what was described by the supervisor as a mottling discoloration of the skin on the upper thorax and both upper extremities. He was recompressed therapeutically in the deck decompression chamber approximately 1 h 40 min after finishing surface decompression. The treatment table (Norwegian Diving and Treatment Tables[5] Table 6) is a slightly modified version of the US Navy Treatment Table 6.[3] He experienced immediate improvement of symptoms during recompression and remaining skin discoloration and symptoms disappeared during the initial part of recompression treatment. Due to the erroneously connected compressed-air gas cylinder, he was breathing compressed air rather than oxygen through the BIBS during surface decompression as well as recompression treatment.

He was transported to Oslo University Hospital. Approximately 35 min after finishing treatment, and shortly before hospital arrival, he suffered visual disturbances (shimmering lights), loss of power and intense pain in right upper arm and relapse of the skin rash. On arrival at the hospital, he reported worsening discomfort, severe abdominal pain, photophobia, nausea, hypaesthesia in his upper extremity and some reduction of power in right upper extremity. However, neurological examination was normal, but a reticular blueish discoloration of chest and shoulder skin was evident as was a non-pitting edema in right upper arm. He needed analgesia for his abdominal pain.

He was provided hyperbaric oxygen treatment (HBOT) and experienced immediate relief of most symptoms during the treatment. Abdominal pain persisted for some time after he finished treatment, but a repeated neurological examination did not reveal any abnormal findings. He developed hypotension and haemoconcentration and was admitted to the intensive care unit for intravenous rehydration. He received a total of four HBOT sessions at the hospital before he was released. He suffered some minor discomfort in his right lower arm and right shoulder for a short time after treatment but was in a normal state when interviewed eight months following the event.

CASE TWO

The second incident occurred with a 35-year-old previously healthy man with approximately ten years of experience in occupational diving and some 300 dives. He had never experienced DCS. This event occurred on the 18th day of diving as dive number 100 in the diving project. He had completed 10 dives preceding the incident, nine of these with surface decompression. He was diving to 28 msw for 50 min and was obliged to complete 30 min of oxygen breathing during surface decompression. He experienced the first symptoms approximately 1 h after completing surface decompression. He complained of a rash, feeling of heat and itching in the skin of his left shoulder area. He was recompressed on site according to Norwegian Diving and Treatment Tables Table 6 and experienced immediate relief of itching during recompression and a gradual regress of the rash during the initial part of the treatment. Shortly before the planned decompression from 9 msw to surface pressure, it was realised that he had been breathing compressed air rather than oxygen on the BIBS and the treatment table was prolonged with two additional 25-min oxygen breathing periods at 3 msw. He remained asymptomatic. When examined at the hospital immediately following treatment no abnormalities were found and he has remained well since.

UNEVENTFUL DIVES AND DIVERS NOT TREATED FOR DCS

As mentioned earlier, eleven divers participated in this diving project with a total of 101 man-dives. The two divers suffering DCS completed 14 of these dives. The other nine divers completed 79 uneventful dives with surface decompression in addition to eight no-decompression and staged in-water decompression dives. The 91 surface decompression dives were completed to depths ranging 23.5–36.2 msw and bottom time ranging 23–67 min. Three, eighty-five and one man-dives were completed uneventfully with inadvertent compressed-air BIBS-breathing of 15, 30 and 45 min respectively during what was assumed to be $SURDO_2$. As described above, one dive with 30 min and one dive with 45 min inadvertent air breathing during surface decompression caused DCS (Figure 1).

As seen from Figure 1 many dives were completed to a depth of approximately 28 msw for a bottom time of approximately 50 min. This profile would call for 15 + 15 min of oxygen breathing at 15 and 12 msw according to the Norwegian Diving and Treatment Tables.[5] When air breathing through the BIBS an additional 20 min of decompression time should be added at 3 msw according to the DecoPlanner implementation of the Bühlmann algorithm. Figure 2 shows the difference between the 28 msw/50 min profile as it was dived in this project and how it compares to a recommended profile in DecoPlanner.

When all surface decompression profiles were analysed with DecoPlanner, the median omitted decompression time was 17 min (range 0-26 min, IQR 7 min).

The nine divers not treated for DCS were offered a consultation and medical examination with a diving physician on project day 21 (four days following the last DCS). Four of the divers accepted the offer, none of them exhibited abnormal clinical findings. In addition, they were all interviewed by the company diving physician by telephone in the weeks following the incidents. None of the other divers had raised any complaints following their dives, but when requested in the aftermath for symptoms they reported complaints as detailed in Table 1.

Discussion

Decompression sickness is a recognised occupational illness of diving.[1] The incidence rates per 100,000 dives have been reported to range 4–10 in recreational diving,[1] 0 to 100 in occupational diving[7] and 13 in military diving.[8] A study of 1980's North Sea offshore diving reports a much higher incidence for $SurDO_2$ dives with high inert gas load compared to no-decompression dives.[2] This observation is in agreement with statistical analysis (probabilistic models) of the decompression tables used at the time.[9]

Figure 1

Diving depth and bottom time for 97 dives in a diving project; no-decompression (NoDC) and in-water decompression dives (IWDC) and dives stipulated to include 15, 30 or 45 min of O_2 breathing on BIBS during assumed surface decompression on oxygen are presented with different symbols. Four additional NoDC dives to depths < 6 msw or bottom time < 10 min are excluded to allow better resolution. The two dives with decompression sickness (DCS) are indicated with red crosses

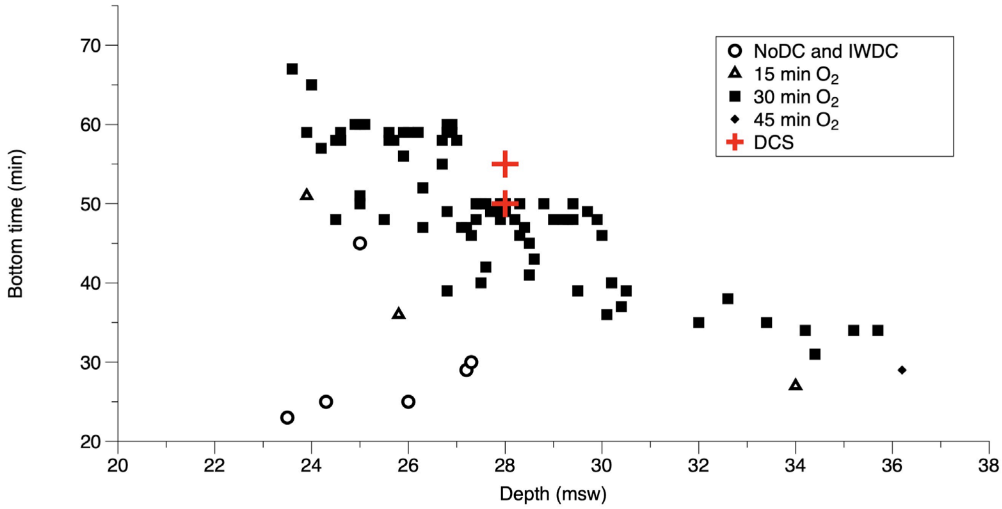
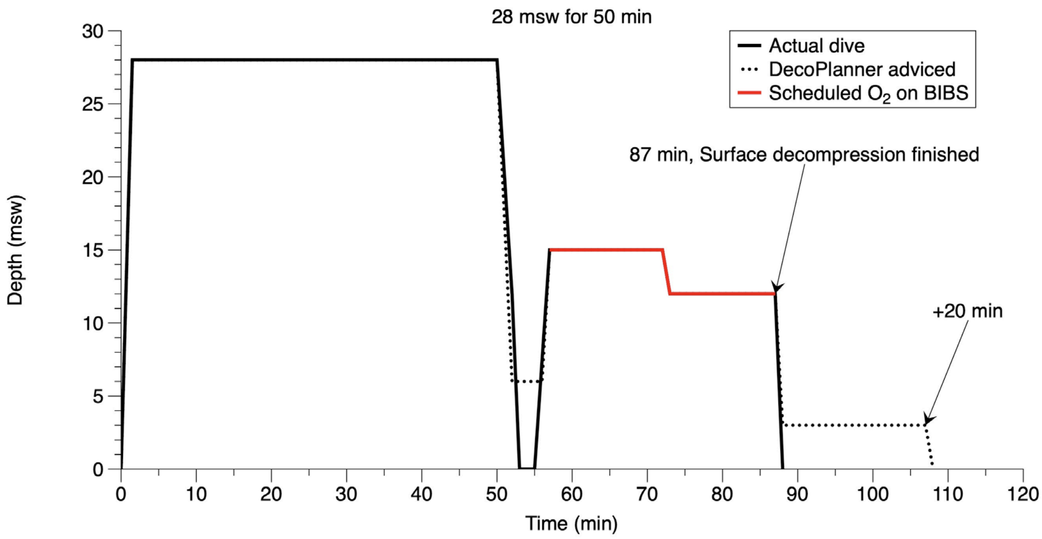


Figure 2

Comparison of a typical dive profile in the present diving project (continuous line) and a recommended decompression as calculated by DecoPlanner (dotted line) for the dive. As can be seen, DecoPlanner (Bühlmann algorithm) would advise a 20 min stop at 3 msw before surfacing. The red line indicates the time the diver should breathe oxygen on BIBS according to the Norwegian Diving and Treatment Tables[5]



In this work we have reported two cases of DCS occurring in 91 dives assumed to be conducted using $SurDO_2$, a 2.2% incidence rate. This incidence rate is much higher than commonly reported in Norwegian in-shore[5] and off-shore[10] surface-oriented diving and this can be attributed to the inappropriate breathing gas. As explained earlier, the $SurDO_2$ decompression tables in the Norwegian Diving and Treatment Tables[5] are slightly modified (metric converted) versions of $SurDO_2$ tables published in USN Diving Manual Rev 7.[3] The schedules used in this diving project would be expected[4] to have a DCS incidence rates ranging 2.5–3.1% with a 95% confidence interval of approximately ± 0.5% if the divers had been provided oxygen during surface decompression. It is tempting to speculate why the observed DCS incidence rate for schedules with inappropriate breathing gas didn't exceed that predicted by the probabilistic model. It is possible that divers under-report symptoms and that the true incidence of DCS in this project was higher. We will return to that later.

Table 1

Symptoms reported by the divers to the company diving medical advisor 14–26 days following the last incidence of DCS. None of the symptoms were reported to the dive supervisor or the company diving physician during the project period. NRS – numeric rating scale /10

Diver	Symptoms experienced during the project period
1	Case #1. No complaints until the day he experienced decompression sickness.
2	Case #2. Slight itching after one of the dives. Can't remember which.
3	Telephone interview day 14: Dived twice. Felt discomfort over left elbow after both dives. Relationship to dive unknown. Lasted for a couple of days.
4	Telephone interview day 14: Slight itching and numbness on dorsal aspect of left hand after dive #1/10. Slight bilateral shoulder discomfort after dive #4/10 persisting for 12 days, no remaining symptoms 23 days after the dive. Day 4 examination by diving physician: Slight shoulder discomfort as described above. No abnormal findings.
5	Telephone interview day 25: No symptoms experienced during project period. Day 4 clinical examination by diving physician: No symptoms. No abnormal findings.
6	Telephone interview day 14: He experienced slight headache after dive #3/11 and #4/11. Experienced foul smelling diesel fume in the helmet during these dives. Headache NRS 5 presenting approx. 1 h after finished dive. No headache in the morning on the succeeding days. Day 4 examination by diving physician: No remaining symptoms. No abnormal findings.
7	Telephone interview day 14: He might have experienced some additional fatigue in the evenings, but no focal symptoms.
8	Telephone interview day 14: He experienced pain in right knee and both elbows. Itching lower back, both wrists and both underarms. Headache after the first dives (NRS 2–3). Can't remember relationship between symptoms and diving in any further detail. No residual complaints. Day 4 clinical examination by diving physician: Complaints during previous dives as described above. No remaining symptoms. No abnormal findings.
9	Telephone interview day 14: He noticed bilateral elbow pain for a few days during the project, pain exaggerated by physical exertion. This coincided with a period of intense physical exercise. The pain appeared unrelated to diving and developed gradually. No remaining symptoms.
10	Telephone interview day 19: He did not experience any problems during the diving period
11	Email day 19 and telephone interview day 26: He experienced temporary itching after one of the dives (can't remember which). This occurred on the same day he started to use a new diving suit undergarment. No remaining symptoms.

It should be recognised that DCS incidence rates predicted by the probabilistic model are based on dives completed with diving depth and bottom time equal to the scheduled depth and bottom times in the USN Diving Manual Rev 7.[3] While working depth was almost constant for each dive in this diving project, it did not necessarily reach table depth, neither did actual bottom time equal the maximum allowed bottom time. This fact is shared with similar studies on DCS occurrence in operational diving and calls for a caveat when reporting decompression table safety based on epidemiological studies. While two DCS incidents occurred in 92 dives (2.2%) before the error was corrected, it should be appreciated that the binominal 95% confidence interval ranged from 0.3–7.6%, illustrating that the true underlying incidence might have been higher. A better analysis of the dives would require access to a probabilistic model which regrettably was unavailable for us. To partly compensate for this fact, we have estimated the amount of omitted decompression time if the dives had been planned according to Bühlmann ZHL-16C algorithm. Ninety-one dives had omitted 4–26 min of decompression time, while only two of these resulted in DCS. This finding seems to support the notion that the effect of adding or subtracting 5–10 min of decompression, such as commonly applied when modifying the 'conservatism factor' of a dive computer, will have relatively small effect on the DCS risk. Others have stated that "Also large increases in TST are required to effect relatively small decreases in DCS risk due to the low slope of the P(DCS)min/TST line" (TST: Total stop time).[11]

Seven divers retrospectively reported having suffered minor symptoms during the project period. These were not reported to the dive supervisor or medically investigated (Table 1). It is the authors' opinion that five of these divers have experienced symptoms that might have been caused by DCS or alternatively a variety of trivial and not necessarily diving-related causes. It is not possible to retrospectively establish a diagnosis with any confidence, but the findings demonstrate symptom under-reporting in commercial diving. Such reporting bias can likely affect DCS estimates reported in epidemiological studies. Experimental studies designed to validate decompression tables typically report DCS incidence of 2–5% depending on study objective,[6] whereas much lower numbers are reported in epidemiological studies.[1,7,8] One group recently reported findings of a prospective study in which questionnaires were completed by 55 Finnish technical recreational divers.[12] They completed 2,983 dives during the one-year observation period, 27 (1%) resulted in symptoms that could have been caused by DCS. All but one was self-treated, i.e., the incidence of therapeutically recompressed DCS was 0.03%. A similar finding was reported in a 1994 questionnaire study involving 1,200 Norwegian recreational and 800 occupational divers.[13] The survey reached a 63% response rate. Forty-eight of 365 in-shore occupational divers had been treated for DCS. Fifty percent of the divers reported previous decompression-related but untreated symptoms. Central nervous system symptoms such as forgetfulness, irritation, depression, and attention deficits were reported by 21% of divers treated for DCS. However, 67% of the divers reporting decompression-related but untreated symptoms complained of such symptoms. The findings of these studies[12,13] suggest that unreported decompression-related symptoms may be common and possibly be associated with long term neurological sequelae.

Case 1 developed hypotension and needed fluid replacement following the inappropriate recompression treatment when he was breathing compressed air rather than oxygen on BIBS. A similar development was reported in another case report.[14] However, severe cardiopulmonary DCS (chokes) is usually associated with severe omitted decompression such as the one reported by Arjomand et al.[15]

Conclusions

We have reported two divers exhibiting DCS following surface decompression. This was most likely caused by erroneous breathing gas in the BIBS. One of them suffered relapse with severe pain, hypotension and intravascular hypovolaemia following a recompression treatment involving the same error (breathing air in the BIBS). While these two incidents were expected due to the inappropriate breathing gas, it should be noted that 89 dives (98%) were completed uneventfully despite incorrect breathing gas and omission of a median decompression time of 17 min.

References

1 Mitchell SJ, Bennett MH, Moon RE. Decompression sickness and arterial gas embolism. N Engl J Med. 2022;386(13):1254–64. doi: 10.1056/NEJMra2116554. PMID: 35353963.

2 Shields TG, Duff PM, Wilcock SE, Giles R. Decompression sickness from commercial offshore air-diving operations on the UK continental shelf during 1982 to 1988. Society for Underwater Technology (SUT) Subtech '89 «Fitness for Purpose». Aberdeen, Scotland: Kluwer Academic Publishers; 1989. p. 259–77.

3 Supervisor of Diving. U.S. Navy Diving Manual Revision 7 Change A. Washington, DC; 2018. Report No.: SS521-AG-PRO-010. [cited 2021 Dec 31]. Available from: https://www.navsea.navy.mil/Home/SUPSALV/00C3-Diving/Diving-Publications/.

4 Gerth WA, Doolette DJ. VVal-79 Maximum permissible tissue tension table for Thalmann algorithm support of air diving. Report No.: NEDU TR 12-01. Panama City (FL): Navy Experimental Diving Unit; 2012. [cited 2021 Dec 25]. Available from: https://apps.dtic.mil/sti/pdfs/ADA561928.pdf.

5 Risberg J, Møllerløkken A, Eftedal OS. Norwegian Diving- and Treatment Tables, 5th ed. Bergen: Personal publisher; 2019. [cited 2021 Dec 25]. Available from: http://dykketabeller.no/onewebmedia/NDTT%20Ed%205.pdf.

6 Thalmann ED, Parker EC, Survanshi SS, Weathersby PK. Improved probabilistic decompression model risk predictions using linear-exponential kinetics. Undersea Hyperb Med. 1997;24:255–74. PMID: 9444058.

7 Imbert JP. Decompression tables versus decompression procedures: an analysis of decompression sickness using diving data bases. EUBS annual meeting proceedings: Heraklion, Greece; 1991. p. 223–31.

8 Arness MK. Scuba decompression illness and diving fatalities in an overseas military community. Aviat Space Environ Med. 1997;68:325–33. PMID: 9096830.

9 Gerth WA, Doolette DJ. VVal-18 and VVal-18M Thalmann algorithm air decompression tables and procedures. Report No.: NEDU TR-07-09. Panama City (FL): Navy Experimental Diving Unit; 2007. [cited 2021 Dec 25]. Available from: https://diving-rov-specialists.com/index_htm_files/scient-c_298-VVal18-and-VVal18M-thalmann-algorithm.pdf.

10 Petroleumstilsynet. Rapport fra Petroleumstilsynets dykkedatabase DSYS – 2022 [Report from Petroleum Safety Authority Norway's diving database DSYS – 2022]. 2023. [cited 2024 Apr 13]. Available from: https://www.havtil.no/contentassets/7284426234ae40cdaa62e2037ed2bf35/dsys_2022-rapport.pdf.

11 Tikusis P, Gerth WA. Decompression theory. In: Brubakk AO, Neuman TS, editors. Bennett and Elliott's physiology and medicine of diving, 5th ed. Edinburgh: Saunders; 2003. p. 419–54.

12 Tuominen LJ, Sokolowski S, Lundell RV, Raisanen-Sokolowski AK. Decompression illness in Finnish technical

divers: a follow-up study on incidence and self-treatment. Diving Hyperb Med. 2022;52:78–84. doi: 10.28920/dhm52.2.74-84. PMID: 35732278. PMCID: PMC9527095.
13 Brubakk AO, Bolstad G, Jacobsen G. Helseeffekter av luftdykking. Yrkes og sportsdykkere. Revisjon 1 [Health effects of air diving. Occupational and recreational divers. Rev 1]. Report No.: STF23 A93053. Trondheim: SINTEF UNIMED; 1994.
14 Klapa S, Meyne J, Kähler W, Tillmans F, Werr H, Binder A, et al. Decompression illness with hypovolemic shock and neurological failure symptoms after two risky dives: a case report. Physiol Rep. 2017;5(6):e13094. doi: 10.14814/phy2.13094. PMID: 28325788. PMCID: PMC5371546.
15 Arjomand A, Holm JR, Gerbino AJ. Severe decompression sickness associated with shock and acute respiratory failure. Case Rep Crit Care. 2020;2020:8855060. doi: 10.1155/2020/8855060. PMID: 33204543. PMCID: PMC7661127.

Acknowledgements

We appreciate the kind support of David Humphreys (NUI a.s.) reviewing the text.

We appreciate the generous support from SubseaPartner providing funding to let this manuscript to be released immediately for public access.

Conflicts of interest and funding: nil

Submitted: 13 April 2024
Accepted after revision: 9 August 2024
