

Technical diving accidents in France: a 15-year retrospective study reporting a high prevalence of musculoskeletal decompression sickness

Emmanuel Gouin^{1,2,3}, Anaïs Caillard^{2,3}, Colin Veses⁴, Marc Luciani⁵, Charlotte Lecomte⁶, Emmanuel Dugrenot^{1,2,7,8}, François Guerrero², Jean-Éric Blatteau⁹

¹ Divers Alert Network, Durham, NC, United States

² University Brest, Laboratory ORPHY EA 4324, IBSAM, Brest, France

³ CHRU La Cavale Blanche. Anesthesiology, perioperative and intensive care Units, Brest, France

⁴ Pasteur University Hospital, Hyperbaric Oxygen Therapy Department, Nice, France

⁵ Notre-Dame de la Miséricorde Hospital, Department of Hyperbaric Medicine, Ajaccio, France

⁶ Sainte Marguerite Hospital, APHM, Department of Hyperbaric Medicine, Marseille, France

⁷ Joint Department of Biomedical Engineering, The University of North Carolina and North Carolina State University, Chapel Hill, NC, USA

⁸ Subaquatic Operational Research Team (ERRSO), Military Institute of Biomedical Research (IRBA), Toulon, France

⁹ Military Teaching Hospital Sainte-Anne, Department of Hyperbaric Medicine and Diving Expertise, Toulon, France

Corresponding author: Dr Emmanuel Gouin, Laboratoire ORPHY, EA 4324, Université de Bretagne Occidentale, 6 Av. Le Gorgeu, 29200 BREST, France

ORCID: [0000-0003-3691-5870](https://orcid.org/0000-0003-3691-5870)

emmanuel.gouin@univ-brest.fr

Keywords

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Abstract

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Introduction: Technical diving, involving rebreathers and/or helium-based gas mixtures for deeper and longer dives, may influence risk and clinical presentation of injuries due to helium's properties, equipment constraints, or exposure conditions. This study aims to describe the specific characteristics of this accidentology.

Methods: A retrospective study was conducted across five French coastline hyperbaric units. Medical records of technical divers presenting with decompression sickness (DCS), immersion pulmonary oedema (IPO), or gas-toxicity between 2010 and 2024 were reviewed.

Results: 127 technical divers were included, three declined participation, leaving 124 cases for analysis. DCS was the most frequent condition ($n = 105$) followed by IPO ($n = 16$) and gas toxicity ($n = 3$). Median age was 45 [IQR 37–53] years, and 113 (91%) were male. Rebreathers were used in 94 (75.8%) cases and helium-based mixtures in 77 (62%). Previous diving-related accidents were reported in 36 (29%) cases. IPO occurred mainly after shallower dives in wetsuits and was frequently associated with procedural errors. Among DCS cases isolated musculoskeletal DCS predominated ($n = 36$), whereas spinal involvement was less frequent. When indicated, median recompression delay was 238 [IQR 135–555] minutes. Unfavourable outcomes occurred in 26 (25%) DCS cases, primarily with bone or inner-ear involvement.

Conclusions: Technical diving accidents exhibit distinct patterns from recreational diving, notably greater musculoskeletal involvement and a possible increased risk of dysbaric osteonecrosis (DON). Current evidence does not support different management, but the risk of potential initially silent bone lesions should not be overlooked. Further research on helium-related risks and hyperbaric treatment's role in DON prevention is needed.

Introduction

Although scuba diving is generally considered to be a relatively safe activity, it still carries inherent risks. The most frequently reported injuries are barotrauma of the ears and sinuses which predominantly affect entry-level divers. However, diving-related accidentology encompasses a much broader spectrum of injuries, some of which may result long-term complications or even fatalities.^{1,2}

Advances in specialised equipment, such as closed-circuit rebreathers (CCRs) and helium-based mixed-gases, have significantly expanded the possibilities for deeper and longer dives, referred to as technical diving.^{3,4} Following prolonged time at depth, the reduction in ambient pressure during ascent leads to the elimination of inert gases from saturated tissues, thereby linked with the risk of decompression sickness (DCS). The clinical manifestations of DCS range from mild to life-threatening and may involve multiple organ systems.⁵

Immersion pulmonary oedema (IPO) is another condition requiring particular attention, especially as the breathing resistance imposed by diving equipment is suspected to promote its onset.^{6,7} Furthermore, CCRs and gas mixtures increase the likelihood of technical and specific issues, such as gas toxicity.⁸

The physiological effect of different gas mixtures (e.g., helium-based mixtures referred to as ‘trimix’) and the expanded time and pressure of exposure could modify inherent diving-related accident risk. There are few data regarding specific accidentology in this area, though clinical presentation may differ from recreational air diving.^{3,9,10}

Advancing our understanding of diving accidentology is essential for enhancing both medical care and preventive strategies. The aim of this study was to describe the technical diving-related accidents referred to the French hyperbaric units and to investigate the influence of potential risk factors associated with the different pathological entities.

Methods

This multicentre, observational retrospective study was approved by the Regional Ethical Committee of Brest (B2024CE.31) and was prospectively registered on ClinicalTrials (NCT06627153). A letter of non-objection to the use of their data for the purposes of this research was sent to each eligible patient.

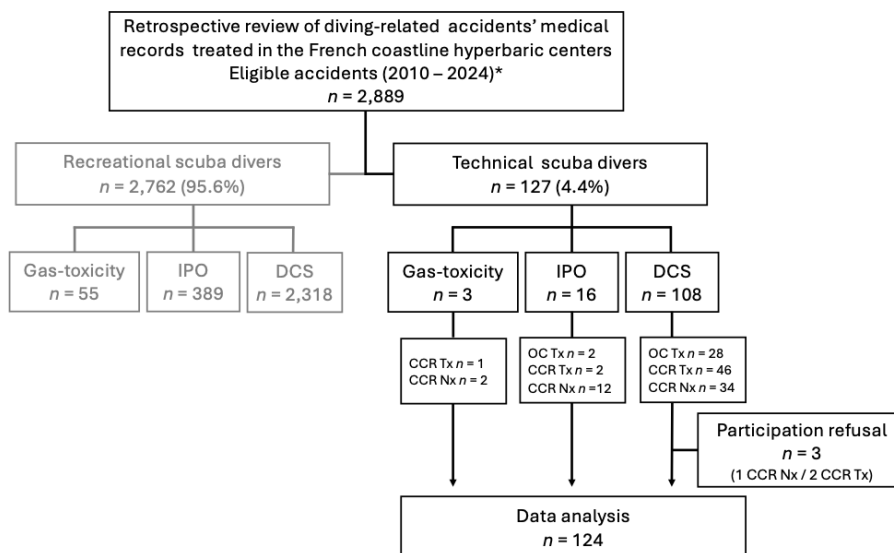
Technical diving was defined as the use of rebreathers regardless of the breathing gas (i.e., nitrox or trimix) and

open-circuit (OC) apparatus with trimix. Diving injuries resulting from military operations were excluded due to the significantly different context of practices. Sixteen hyperbaric chambers in mainland France treat diving-related injuries, though many are inland and remote from the most active diving areas. Given their proximity to dive sites, coastal hospitals are more likely to manage most diving incidents. Therefore, hyperbaric units located along the French mainland coastline were invited to participate in this study. One declined, resulting in the enrolment of five units (with number of contributed cases shown): Ajaccio Hospital (*n* = 5), Brest University Hospital (*n* = 7), Nice University Hospital (*n* = 17), Marseille University Hospital (*n* = 44), and Toulon Military Teaching Hospital (*n* = 54). The non-participating hospital reported no diving accidents involving technical divers in its unit over the past 10 years.

All medical records of patients diagnosed with DCS, IPO, or gas-toxicity following a technical dive between 1 January 2010 and 31 December 2024 were reviewed (Figure 1). All collected data were de-identified. Data collection was divided into three sections: 1) Demographics and diving experience, including age, sex, body mass index (BMI), medical history, diving experience and any prior diving-related injuries. 2) Incident-related data including breathing apparatus, gas mixture, dive plan and profile, symptoms, and onset delay. Given the complex profiles of some technical dives and frequent absence of dive computer records, only maximum depth and total dive time were reported. The initial DCS severity was classified as ‘mild’ or ‘severe’ presentations, following recent published clinical consensus.⁵ When available, the MEDSUBHYP neurological prognostic score

Figure 1

Flowchart of diving-related accidents among technical and recreational divers; recreational diver data (in grey) are shown for contextual comparison but detailed analysis of this group is beyond the scope of the present study. *All data covered the study period, except for data from the Hyperbaric Unit of Marseille (2013–2024), due to the unavailability of earlier medical records. CCR – closed-circuit rebreather; DCS – decompression sickness; IPO – immersion pulmonary oedema; Nx – nitrox; OC – open-circuit scuba; Tx – trimix (helium-based mixed gas)



was recorded.¹¹ 3) Pre-hospital and in-hospital management, delay for the first recompression treatment after symptom onset (or surfacing in case of underwater onset), total number of follow-up sessions, and the final diagnosis pronounced by physicians. Hospital stay duration and discharge outcomes were recorded. Incomplete recovery at discharge was defined by the presence of residual symptoms or magnetic resonance imaging (MRI) findings suggestive of dysbaric osteonecrosis (DON). In cases of combined diagnoses involving DCS, patients were categorised under DCS, as it primarily guided management.

STATISTICAL ANALYSIS

Statistical analysis was performed with GraphPad Prism v10.4.1 (GraphPad Software Inc., San Diego, CA, USA). Continuous variables are reported as median [interquartile range (IQR), Q1–Q3], and categorical variables as counts and percentages. Normality was assessed using the Shapiro-Wilk test. Group comparisons were conducted using unpaired *t*-test for normally distributed continuous variables and the Mann-Whitney U test otherwise. Categorical variables were compared using the Chi-square test or Fisher’s exact test in case of small sample sizes. Logistic regression analyses were performed to identify factors associated with

the risk of IPO versus DCS, including all variables with *P*-value < 0.2 in univariate analysis. Given the predominance of musculoskeletal (MSK) involvement, specific risk factors for this subgroup were further evaluated among the overall DCS population. A small proportion of divers suffered recurrent DCS episodes, introducing a partial dependency in the data. In the context of a descriptive study, which is event-based rather than individual-based, each episode was treated as an independent observation. Statistical significance was defined as a *P*-value < 0.05. Due to missing data in medical records, the reported **n* throughout the results reflects the number of cases with available information whenever it differs from the total study population.

Results

DESCRIPTION OF POPULATION

During the study period, 127 technical divers (4.4% of the entire injured-diver population) were admitted to the hyperbaric facilities for diving-related accidents. Three individuals (2.4%) declined participation, resulting in the analysis of 124 cases (Figure 1). The temporal distribution of accidents is shown in Figure 2, illustrating the gradual increase in CCR use relative to OC in technical diving. The median rate of admissions was nine [IQR 6–12] patients per year. Demographic data are summarised in Table 1. During the study period, six (4.8%) divers had two admissions (five for recurrent DCS and one for separate episodes of IPO

Figure 2

Repartition of injured technical divers referred to the French coastline hyperbaric units by primary diagnosis, breathing apparatus, and gas used, reported annually (2010–2024); CCR – closed-circuit rebreather; DCS – decompression sickness; IPO – immersion pulmonary oedema; Nx – nitrox; OC – open-circuit scuba; Tx – trimix (helium-based mixed gas)

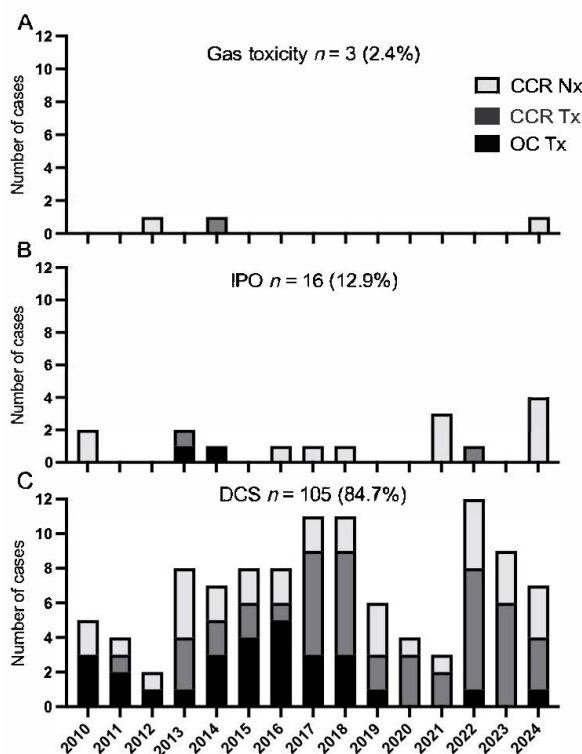


Table 1

Demographic data for injured technical divers; **n* refers to the number of divers for whom data were available; BMI – body mass index; DCS – decompression sickness; IQR – interquartile range; IPO – immersion pulmonary oedema

Parameter	* <i>n</i>	Overall population <i>n</i> (%) or median [IQR]
Male	124	113 (91.1)
Female	124	11 (8.9)
Age (years)	124	45 [37–53]
BMI (kg.m ⁻²)	106	25.4 [23.4–27.8]
Obesity (BMI > 30)	108	13 (12.0)
Active smoking	121	11 (9.1)
Hypertension	123	17 (13.8)
Diabetes	123	2 (1.6)
Heart disease	123	2 (1.6)
Medication	123	26 (21.1)
History of IPO	123	7 (5.7)
History of DCS	123	29 (23.6)
Years of diving	67	20 [13–30]
Total reported dive number	81	1,000 [600–3,000]

and DCS). Two divers (1.6%) were diagnosed with DCS associated with suspected IPO (one MSK DCS and one constitutional form).

INCIDENT DIVES

Open-seawater dives were involved in 120/123 (97.6%) events, and three (2.4%) cases occurred in caves. Five/121 (4.1%) dives took place abroad, and 13/121 (10.7%) in a different administrative jurisdiction than the treating hyperbaric unit. Eleven accidents (8.9%) occurred in a professional context; the remainder were recreational technical dives. Dive parameters are detailed in Table 2.

SYMPTOMS, TREATMENT AND DIAGNOSIS

A wide range of symptoms was reported with 87 (70.2%) divers exhibiting multiple complaints with a median of 2 [IQR 2–3] symptoms per individual. Musculoskeletal pain was the dominant symptom, particularly after trimix dives (Figure 3). The median onset time for DCS symptoms was 15 [IQR 1–60] minutes, with 15/102 (14.7%) experiencing symptoms during decompression stops. All IPO and gas-toxicity symptoms occurred either at depth or immediately upon surfacing. Initial DCS symptoms were classified as severe in 48/105 (45.7%) cases. The MEDSUBHYP score ($n = 14$) for spinal injury was 4 [IQR 2–7] among them, ten (71.4%) presented a score < 6.

First-aid oxygenation (FAO₂) was administered in 89/123 (72.4%) cases, and hydration in 51 (41.5%). On-site (para) medical assistance was provided in 78/119 (65.6%) cases, and 27/123 (22%) were evacuated by helicopter.

Delayed consultation (> 24 hours) occurred in 15 (12.1%) cases, all presenting with DCS symptoms. Acetylsalicylic acid was taken by 53/105 (50.5%) divers with DCS, including 32/53 (60.4%) during the prehospital phase. Other analgesics were used by 19/105 (18.1%) divers (paracetamol, $n = 9$; non-steroidal anti-inflammatory drugs (NSAIDs), $n = 9$; and morphine, $n = 1$). Corticosteroids (methylprednisolone) were administered to 61/105 (58.1%) divers, while 18/105 (17.1%) received no adjuvant drug therapy. Among patients with IPO, acetylsalicylic acid was administered on-site in 4/16 (25%) cases, furosemide in 2/16 (12.5%) and methylprednisolone in 3/16 (18.8%).

Recompression with hyperbaric oxygen treatment (HBOT) was provided to 103/105 (98.1%) individuals with DCS. Among patients with IPO, 4/16 (25%) received HBOT despite the absence of an associated DCS diagnosis: two due to missed decompression stops, and one with severe hypoxia secondary to associated drowning. Median time from symptom onset to recompression was 238 [IQR 135–555] minutes, with 68/103 (66%) patients commencing HBOT within six hours. HBOT protocols are summarised in Table 3. Twenty-two/105 (21%) received a 'long' initial treatment ≥ 180 minutes, including 17/22 (77.3%) with

Table 2

Incident-dive parameters and equipment used; in incidents other than those involving closed circuit rebreathers (CCRs), open circuit scuba was used. In incidents other than those involving trimix (helium-based mixed gas), nitrox (i.e., air diluent gas) was used. * n refers to the number of divers for whom data were available; procedural error encompassed predominantly fast ascent, buoyancy issues or missed deco stops; IQR – interquartile range

Parameter	* n	Overall population n (%) or median [IQR]
Dry suit	94	72 (76.6)
CCR	124	94 (75.8)
Trimix mixed gas	124	77 (62.1)
Breathing gas density at max depth (g.l ⁻¹)	102	6.4 [5.4–7]
Maximum depth (m)	122	53 [40–70]
Total dive time (min)	119	69 [50–90]
Procedural error	123	29 (23.6)
Exertion during dive	123	22 (17.9)
Tiredness before dive	123	89 (72.4)
Repetitive dive < 12 h	114	24 (21.1)
Dive in the previous 48 h	109	75 (68.8)

inner-ear or neurological DCS. The median number of additional HBOT sessions was 1 [IQR 0–5] and 39/107 (36.5%) underwent more than one additional session. The two suspected DCS cases who did not receive HBOT had an uncertain diagnosis of spinal or cerebral DCS, with consultations occurring on day three and day 10 post-dive, respectively. Final medical diagnoses are presented in Figure 4.

OUTCOMES

At hospital discharge, complete resolution was observed in 77/103 cases (74.8%) of DCS; outcome information was unavailable for two DCS cases. All cases of IPO recovered without sequelae. Two gas-toxicity cases involved hypoxia-induced loss of consciousness (LOC) at shallower depths; both divers were successfully rescued by their buddies and ascended without lasting complications. The third gas-toxicity case was declared deceased upon admission following hyperoxic seizure at 50 metres of seawater (msw), resulting in drowning and pulmonary barotrauma with massive arterial gas embolism secondary to a rapid ascent.

Among the 26/103 (25.2%) DCS-affected divers whose symptoms had not fully resolved at discharge, eight exhibited bone involvement confirmed by MRI and two reported incomplete pain resolution at discharge, with the underlying cause remaining uncertain. Eleven had persistent inner-ear injuries, eight with vestibular disturbances and three with persistent hearing loss. Only four divers had neurological

Figure 3

Distribution of symptoms among injured technical divers, according to the breathing gas used; multiple symptoms were common occurring in 87/124 (70.2%) of divers (nitrox: 81.8% vs. trimix: 59.7%). *P*-value for trimix vs nitrox – **P* < 0.05, ****P* < 0.001; LOC – loss of consciousness

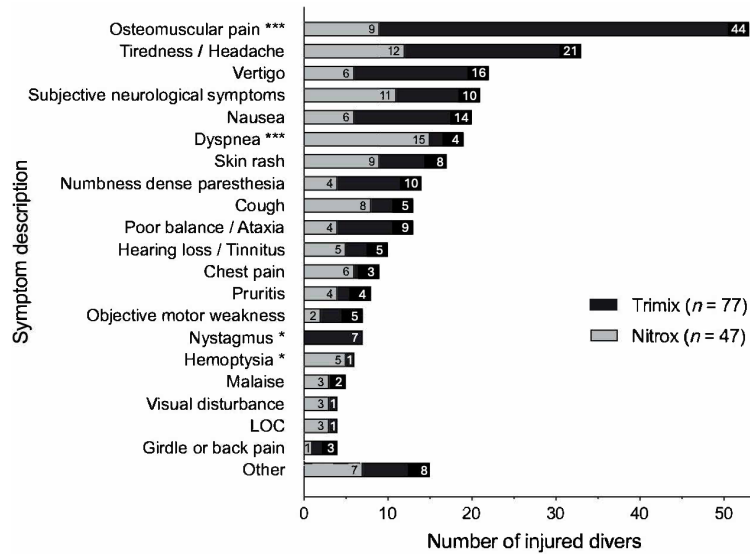


Table 3

Initial hyperbaric treatment tables administered to divers with decompression sickness (*n* = 103) and immersion pulmonary oedema (*n* = 4); O₂ – oxygen; Nx – Nitrox; Hx – Heliox (helium-based mixed gas); atm abs – atmospheres absolute

Treatment table	Pressure (atm abs)	Duration (minutes)	Breathing gas	Divers treated <i>n</i> (%)
A15	2.5	90	O ₂	12 (11.2)
A18	2.8	90	O ₂	4 (3.7)
B18	2.8	150	O ₂	55 (51.4)
C18	2.8	300	O ₂	6 (5.6)
Comex 12	2.2	130	O ₂	3 (2.8)
Comex18c	2.8	174	O ₂	8 (7.5)
Comex 30	4	420	Nx/Hx	10 (9.4)
Other	2.5–4	150–360	Nx/Hx	7 (6.5)
Unknown	–	–	–	2 (1.9)

sequelae, three with moderate symptoms (subjective motor weakness or paresthesia), and one with a severe outcome (spastic paraplegia and sphincter dystonia). The remaining patient experienced persistent fatigue and unspecified biological abnormalities. There was no significant outcome difference based on demographics, experience, equipment, diving profile or treatment (first-aid and initial HBOT table choice). Initial symptoms were reported as severe in 32/77 (41.6%) divers with favorable recovery and 15/26 (57.7%) with unfavorable recovery.

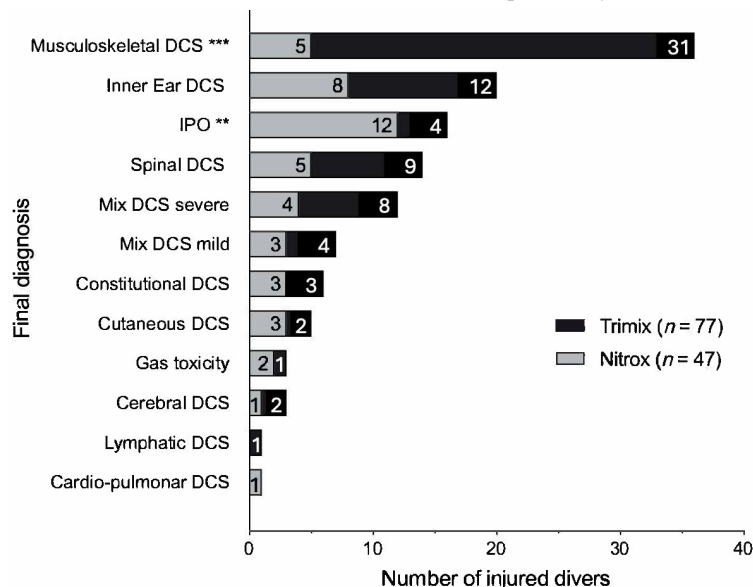
SUSPECTED CONTRIBUTING FACTORS TO IPO OR DCS

Considering the minimal occurrence of gas toxicity, only IPO and DCS were compared. A history of a similar injury (IPO

or DCS diagnosis regardless of manifestation, respectively) was not significantly associated with recurrence in univariate analysis (*P* = 0.7). However, 5/16 (31.3%) patients were admitted for recurrent IPO, and 28/105 (26.7%) for recurrent DCS. One IPO patient had a prior history of DCS, while two DCS patients had previous IPO episodes. Multivariate analysis showed that the use of a wetsuit and procedural errors were associated with a higher likelihood of IPO, which occurred more frequently after shallower dives compared to DCS. Procedural errors mainly included rapid ascent, buoyancy control problems, or missed decompression stops. In three IPO cases, additional issues such as poor loop volume management or significant flooding were also reported. IPO was observed more frequently during training dives, although the difference was not statistically significant (Table 4).

Figure 4

Final clinical diagnosis of injured technical divers according to the type of breathing gas; among cases of mix decompression sickness (DCS) classified as severe, there were two with cerebral involvement, three with cardiopulmonary involvement, five with inner ear involvement, and five with spinal involvement. All mild cases of mixed DCS presented with musculoskeletal symptoms, often accompanied by skin manifestations or mild and uncertain subjective neurological symptoms such as patchy paresthesia. *P*-value for trimix vs nitrox – ***P* < 0.01, ****P* < 0.001; IPO – immersion pulmonary oedema



SUSPECTED CONTRIBUTING FACTORS TO MSK DCS

Because MSK DCS was the most common manifestation, occurring in 47/105 (44.8%) of DCS cases, the analysis investigated potential contributing factors. Eleven/47 (23.4%) of MSK cases were mixed DCS (Table 5). Multivariate analysis revealed that the use of trimix, repetitive dives, younger age, and the absence of procedural errors were more frequently associated with bone involvement compared to other types of DCS (Table 6).

Divers with MSK involvement delayed consultation by more than 24 hours in 10/47 (21.3%) of cases (either pure MSK DCS or associated with cutaneous DCS), compared with 5/58 (8.6%) in other types of DCS. The median number of additional HBOT sessions was 0 [0–1] for MSK DCS and 0 [1–7] for other types (*P* = 0.04).

Discussion

The high number of diving-related accidents managed in these hyperbaric units highlights the intensity of diving activity in the Mediterranean coastline. This area is renowned for technical diving, supported by favorable bathymetry, and abundant marine life. Estimating the number of technical divers remains challenging. However, it is thought that there are 20,000 to 25,000 rebreather divers worldwide, representing less than 0.3% of the total global diving population.¹² The use of open-circuit for trimix diving has become marginal due to the high cost of helium and the logistical challenges associated with gas supply.^{10,13}

In contrast, the recent expansion of CCR use has redefined technical diving practices and now accounts for the majority of technical diving-related accidents.³

Few studies have specifically investigated the accidentology of technical diving. The demographics of injured divers were consistent with the technical diving community, which is predominantly composed of males aged 40–50 years.^{3,10} It is recognised that many divers self-treat their symptoms, while those experiencing more severe or concerning manifestations are more likely to seek medical attention.³ This suboptimal behaviour might be mostly prevalent in the technical diving community, although long-term recovery seems often favourable.^{1,3,10} Factors such as extended bottom times, inert gas composition, prolonged higher oxygen exposure associated with rebreathers and equipment constraints may all influence the clinical presentation of diving accidents. These observations are consistent with our findings and recent reports suggesting that technical divers face more frequent but often low severity DCS episodes.^{3,10}

CLINICAL PRESENTATION OF DCS

MSK DCS appeared to be overrepresented among technical divers, particularly in younger individuals following repetitive trimix dives performed without procedural errors and was unlikely associated with more severe presentation. Although not significant in multivariate analysis, the dive profiles leading to MSK DCS appeared more ‘aggressive’ (greater depth and longer total dive time) than those of other DCS presentations. Another area of concern involves inner-

Table 4

Comparison of potential contributing factors to immersion pulmonary oedema (IPO) or decompression sickness (DCS) occurrence; *n refers to the number of divers for whom data were available; CI – confidence interval; IQR – interquartile range; Trimix – helium-based mixed gas, in other cases nitrox (i.e., air diluent gas) was used in closed circuit rebreathers

Variables	IPO (n = 16)		DCS (n = 105)		Univariate P-value	Odds ratio (95% CI)	Multivariate P-value	Adjusted odds ratio (95% CI)
	*n	n (%) or Median [IQR]	*n	n (%) or Median [IQR]				
Gender female	16	3 (18.8)	105	8 (7.6)	0.2	2.8 (0.72–11.65)	NS	–
Body mass index	12	28 [23.8–0.9]	92	25.4 [23.3–27.7]	0.02	–	NS	–
Arterial hypertension	16	6 (37.5)	105	11 (10.5)	0.004	5.13 (1.42–15.02)	NS	–
Instruction dive	16	6 (37.5)	103	17 (16.5)	0.08	3.04 (0.91–9.5)	NS	–
Wet suit	11	10 (90.9)	83	12 (14.5)	<0.0001	59.17 (7.84–648.1)	0.001	11.16 (2.69–46.41)
Trimix mixed gas	16	4 (25)	105	72 (68.6)	0.002	0.15 (0.05–0.47)	NS	–
Procedural error	16	8 (50)	104	19 (18.3)	0.005	4.47 (1.38–12.57)	0.038	4.57 (1.09–19.23)
Max depth (m)	16	40 [27–52]	103	56 [42–72]	0.0001	–	0.015	0.94 (0.89–0.99)
Total dive time (min)	15	50 [38–68]	101	71 [56–93]	0.002	–	NS	–

Table 5

Diagnoses associated with musculoskeletal (MSK) decompression sickness (DCS); *mixed diagnosis considered as severe with vestibular, cochlear or consistent neurological symptoms

DCS variant	n (%)
Pure MSK DCS	36 (76.6)
MSK + skin DCS	3 (6.4)
MSK + subjective neurological	3 (6.4)
MSK + skin + inner-ear DCS*	2 (4.3)
MSK + cerebral DCS*	1 (2.1)
MSK + spinal DCS*	1 (2.1)
MSK + constitutional DCS	1 (2.1)
Total MSK DCS	47 (100)

ear DCS among technical divers,^{13–15} however, its prevalence in this study does not appear higher than in recreational diving.¹⁶ Prolonged helium supersaturation in the perilymph and endolymph, both acting as inert-gas-diffusion-limited reservoirs, may increase the risk of cochleovestibular DCS during deep dives.^{5,14} Interestingly, data from Malta revealed a rising incidence of inner-ear DCS following deep and repetitive dives, whereas MSK DCS became less frequent. The breathing gas was not reported, but it is speculated that many dives were conducted on air, despite the growing popularity of technical diving.¹⁷

Finally, our results contrast with reports from recreational diving, where spinal involvement is most frequently observed. Although subjective neurological symptoms, musculoskeletal pain, and constitutional symptoms also predominate in the recreational diving literature, these manifestations are frequently associated with more severe forms of DCS.^{16,18,19} Technical diving confirmed neurological cases were uncommon and typically presented with moderate severity at admission, such as a MEDSUBHYP score < 6, indicating a lower risk of sequelae.¹¹ The observed differences in DCS patterns may be partly attributable to helium use among technical divers, as suggested by contextual comparisons with the external database reported in Meusnier's study (Figure 5).¹⁶ Interestingly, more severe cases occasionally occurred after dives shallower than 40 msw, possibly reflecting the common use of air diluent at these depths and the associated higher nitrogen saturation contributing to their severity. Furthermore, shorter delays to symptom onset after a dive are often associated with more severe outcomes.^{5,11,20} In our study, the median time to symptom onset was relatively short even in mild cases, and particularly shorter in MSK DCS compared with other DCS forms.

The high prevalence of helium-based gas mixtures used in technical divers may partly explain this pattern, as helium has lower solubility and higher diffusivity in tissues than

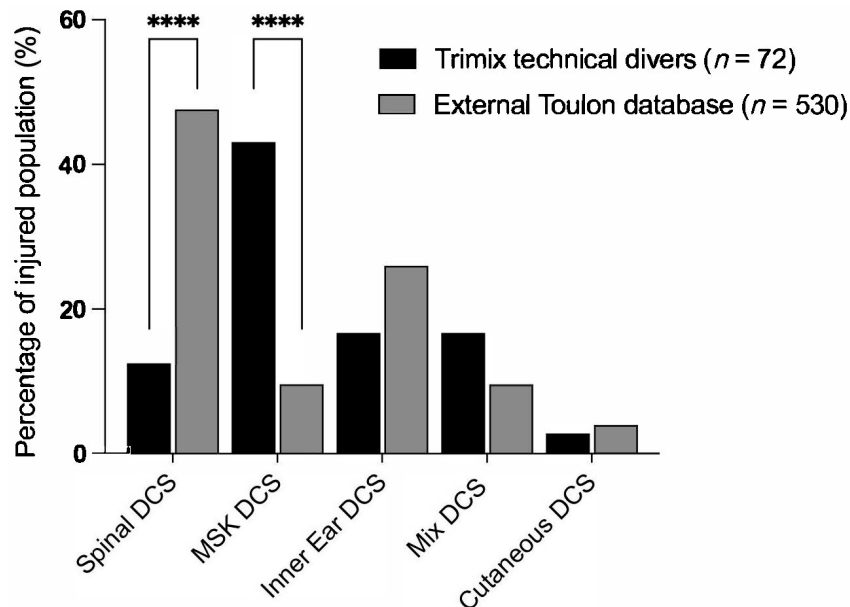
Table 6

Comparison of potential contributing factors to musculoskeletal (MSK) decompression sickness (DCS) or other type of DCS occurrence; **n* refers to the number of divers for whom data were available; CI – confidence interval; IQR – interquartile range; NI – not included in multivariate analysis due to missing data; Trimix – helium-based mixed gas; in other cases nitrox (i.e., air diluent gas) was used in closed circuit rebreathers

Variables	MSK (<i>n</i> = 47)		Other DCS (<i>n</i> = 58)		Univariate <i>P</i> -value	Odds ratio (95% CI)	Multivariate <i>P</i> -value	Adjusted odds ratio (95% CI)
	* <i>n</i>	<i>n</i> (%) or Median [IQR]	* <i>n</i>	<i>n</i> (%) or Median [IQR]				
Age (years)	47	38 [33–45]	58	49 [43–54]	< 0.0001	–	0.005	0.92 (0.87–0.97)
Body mass index	41	23.9 [22.5–26.1]	51	26.2 [24.8–28.4]	0.0003	–	NS	
Hypertension	47	0 (0)	58	11 (19)	0.001	0 (0–0.33)	NS	
Previous MSK DCS	12	9 (75)	16	2 (12.5)	0.0008	21 (2.93–116.3)	NS	
Instruction dive	46	5 (10.9)	57	12 (21.2)	0.2	0.46 (0.17–1.3)	NS	
Trimix mixed gas	47	38 (80.9)	58	34 (58.6)	0.02	2.98 (1.26–6.86)	0.031	4.6 (1.15–18.57)
Max depth (m)	46	66 (46–81)	57	50 (40–65)	0.008	–	NS	
Total dive time (min)	45	85 (60–118)	56	62 (48–80)	0.0006	–	NS	
Procedural error	47	3 (6.4)	58	16 (27.6)	0.005	0.18 (0.05–0.67)	0.04	0.17 (0.03–0.92)
Repetitive dive < 12 h	44	13 (29.6)	53	7 (13.2)	0.047	2.76 (0.98–7.05)	0.029	4.8 (1.17–19.88)
Max depth previous 24 h (m)	25	55 [40–70]	27	40 [38–55]	0.08	–	NI	

Figure 5

Descriptive contextual comparison for illustrative purposes only, presenting decompression sickness cases in trimix technical divers ($n = 72$) from the present study in parallel with data from an external Toulon Hospital database ($n = 530$), predominantly comprising recreational divers (air and nitrox), with 29 military divers and a negligible proportion of trimix divers (2011–2018).¹⁶ **** $P < 0.001$; DCS – decompression sickness; MSK – musculoskeletal DCS



nitrogen. Trimix diving, especially, when dives are repeated, may promote intermediate or slow ‘tissue compartment’ supersaturation (e.g., muscle, bone) rather than primarily affecting the nervous system, which is considered a fast ‘tissue compartment’ and is more susceptible to DCS in air diving.²¹ Helium may also facilitate rapid bubble growth within tissues, potentially contributing to bone involvement, as previously reported in heliox saturation diving, where bone lesions were frequent despite the absence of detectable circulating bubbles, supporting the concept of tissue-stationary bubbles.⁵ Another hypothesis is the organ-protective effect of helium, though this effect remains modest and inconsistent in human studies, with limited clinical validation in diving.^{22,23} In a rat model, helium preconditioning reduced neurological DCS risk, supporting potential protective benefits of helium in diving.²⁴

DCS TREATMENT AND OUTCOMES

Treatments followed standard clinical procedures applicable to all divers. It is well recognised that first-aid is often insufficient, both in recreational and technical diving.^{1,3,10} Most injured divers received FAO₂, as they were frequently managed by paramedics for whom this is part of standard practice in areas familiar with maritime injuries. Numerous drugs have been proposed as adjunctive therapies, but only NSAIDs have shown benefit, albeit with limited supporting data.⁵ In France, acetylsalicylic acid at antiplatelet dosing (< 500 mg) was recommended until recently despite weak evidence, though this practice is now being reconsidered. Corticosteroids have also been frequently used and often preferred to NSAIDs, yet their efficacy remains unproven

and HBOT remains the definitive treatment for DCS.⁵ Along the French coastline, the delay before recompression is often shorter than in other regions, due to the proximity of hyperbaric units to dive sites. While delays of up to six hours have been associated with a poorer prognosis, particularly in severely affected divers,¹¹ recompression after longer delays can still be effective, as reported in several studies.^{9,20,25} Spontaneous improvement without recompression is also often observed in mild cases, particularly among technical divers.^{3,10}

Severe symptoms are generally associated with poorer treatment outcomes.^{19,20,25} Some evidence suggests a more favourable prognosis among technical divers, mainly due to the higher prevalence of mild presentations.^{3,10} Long-term outcomes are difficult to evaluate in retrospective studies because of limited follow-up and frequent missing data. In our study, 75% of DCS patients achieved complete symptom resolution at discharge, consistent with previous reports showing 65 to 93% favourable outcomes after treatment in the diving community.^{9,18,20,25} Unfavourable outcomes were mainly associated with bone and vestibular involvement in our study. In France, follow-up bone imaging is routinely performed after any MSK DCS.²⁶ MRI findings suggestive of DON, likely asymptomatic for an extended period, were considered unfavourable but are often not reported in follow-up data from other studies. As MRI was available in only 30% of cases, the prevalence of DON may be underestimated given that abnormalities were detected in 57% of those imaged. Unfortunately, the timing of MRI and the frequent lack of follow-up in this study preclude a comprehensive assessment of risk, and a definitive link between imaging

abnormalities and a DCS event cannot be established without baseline imaging. Nevertheless, recent literature suggests that bone involvement, particularly in the shoulder or hip, may provide a substrate for subsequent juxta-articular DON development.²⁶ Although often considered mild, MSK DCS can be associated with a higher risk of DON and should not be overlooked by physicians or divers, especially in the technical diving community.^{26,27} If juxta-articular damage is suspected, MRI evaluation is recommended, and additional HBOT sessions may help reduce intraosseous oedema and prevent unfavourable progression.^{26,28}

LUNG INJURIES

IPO accounted for nearly 13% of admissions among technical divers, although this proportion is likely underestimated, as cases are not always referred to diving physicians. In our study, wetsuit use during shallower dives and more frequent procedural errors were independently associated with IPO rather than DCS. Procedural errors, such as omission of a decompression stop, may be a consequence of dyspnoea rather than its cause. All affected divers fully recovered, yet IPO remains a potentially life-threatening condition implicated in fatal cases not captured here. Female sex, older age, and arterial hypertension are recognised risk factors,⁷ though the very low number of women in our cohort precludes conclusions here. The high risk of recurrence was underscored by 31% of cases reporting a previous episode. Accordingly, a recent expert consensus advises against further scuba-diving after an IPO event.⁷ Rebreathers are suspected to increase risk through greater work of breathing and pressure imbalances, particularly with back-mounted counterlungs.⁶ Additionally, wetsuits may reduce pulmonary compliance.²⁹ Although comparison with recreational divers is not the primary aim of this study, overall diagnostic data from hyperbaric units during the study period (Figure 1) allow these distributions to be examined. In our cohort, rebreather use did not increase IPO incidence compared with recreational open-circuit scuba diving, with respectively 16/94 (17%) versus 389/2,762 (14.1%) cases ($P = 0.4$). Among non-professional or non-military profiles with lower exertion, the impact of CCR on work of breathing may be reduced.¹³ Interestingly, IPO was more common with air diluent than with trimix, usually at shallower depths during entry-level CCR training, indicating that diver inexperience (e.g., stress, buoyancy control, loop volume management) rather than gas density may have been the primary contributing factor.

GAS-RELATED TOXICITY

Serious gas-toxicity symptoms represented a rare cause of hospital admission. This aligns with reports from interviewed trimix divers.³ However, inappropriate breathing gas is frequently observed in CCR fatalities, which may introduce survivor bias and underestimate the true incidence of this risk.¹² This contrasts with military diving, where equipment and procedures differ. In that context, gas toxicity was found

to be the most common diving incident, with hyperoxic seizures and hypercapnia frequently reported, usually with favorable outcomes.⁸ The less frequent use of airway protection systems, such as mouthpiece retaining straps or full-face masks, by technical divers may also contribute to a higher proportion of fatalities when incidents occur, which may therefore go unreported in hyperbaric centers.³⁰ It is also likely that most non-fatal gas-related issues, which rapidly improve after surfacing, remain undocumented by the medical community.

LIMITATIONS

This retrospective study, based on medical records, was limited by substantial amounts of missing data. The potential impact of specific dive planning on accident risk could not be evaluated due to the lack of systematic information on breathing gas composition, detailed dive profiles, and computer conservatism settings. Furthermore, five divers experienced two DCS episodes during the study period, introducing a potential partial dependence of observations that may have modestly influenced the results by increasing the contribution of individual-specific risk factors. However, these cases accounted for less than 5% of the study population, and multivariate analysis of DCS patterns was primarily based on dive-related variables rather than intrinsic individual factors. Because the location of studied units, cave diving, a growing activity within the technical diving community, falls outside the scope of this study. Accident patterns in cave diving may vary due to differences in practices and environmental constraints compared to open-sea diving. These divers may be self-treated more frequently and/or admitted in inland hyperbaric units located near the cave systems.¹³

Conclusions

This study describes 15-years diving accident patterns among technical divers treated in hyperbaric units along the French coastline. DCS was the most prevalent condition, typically presenting with mild symptoms, with a high prevalence of MSK cases. Divers affected by MSK DCS tended to be younger and often used helium-based breathing mixtures, with no reported procedural errors, making these accidents difficult to predict. Current data remain insufficient to assess the impact of dive profile, decompression planning or gas mix composition. Although most cases receive prompt management, some do not experience favorable outcomes, with delayed bone lesions potentially leading to joint dysfunction and lifelong disability. Further research is needed on diving practices, preventive measures for this specific technical diver population, and the role of helium in accident risk.

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