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The Epidemiology of Injury in Scuba Diving

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Abstract

The epidemiology of injury associated with recreational scuba diving is reviewed. A search of electronic databases and reference lists identified pertinent research. Barotrauma, decompression sickness and drowning-related injuries were the most common morbidities associated with recreational scuba diving. The prevalence of incidents ranged from 7 to 35 injuries per 10,000 divers and from 5 to 152 injuries per 100,000 dives. Recreational scuba diving fatalities account for 0.013% of all-cause mortality aged ≥15 years. Drowning was the most common cause of death. Among treated injuries, recovery was complete in the majority of cases. Dive injuries were associated with diver-specific factors such as insufficient training and preexisting medical conditions. Environmental factors included air temperature and flying after diving. Dive-specific factors included loss of buoyancy control, rapid ascent and repetitive deep diving. The most common event to precede drowning was running out of gas (compressed air). Though diving injuries are relatively rare prospective, longitudinal studies are needed to quantify the effects of known risk factors and, indeed, asymptomatic injuries (e.g. brain lesions). Dive injury health economics data also remains wanting. Meanwhile, health promotion initiatives should continue to reinforce adherence to established safe diving practices such as observing depth/time limits, safety stops and conservative ascent rates. However, there is an obvious lack of evaluated diving safety interventions.

Ambient pressure increases by one atmosphere for each additional depth of 10 m of seawater. Laborers working underwater in caissons while building the Eads and Brooklyn Bridges breathed air at a pressure equivalent to the ambient pressure of the depth of the workplace and high enough to repel the surrounding water. Upon returning to the surface some would experience pain and adopt a posture reminiscent of a fashionable pose known as the '*Grecian bend*'. This affliction became known as 'the bends' [1]. A century ago, the Royal Navy commissioned J.S. Haldane and colleagues to produce a set of tables prescribing time limits for each depth a diver might safely work at while teams of sailors manned compressed-air pumps to force fresh air down against the pressure of the water. Then, during the Second World War, Jacques Cousteau and Émile Gagnan invented a dual-hose regulator which allowed divers to carry compressed gas in cylinders and to inhale it at a pressure equivalent to that in which they were diving. The *self-contained underwater breathing apparatus* (scuba) had arrived. Since first appearing in the late 1940s as a recreational pursuit, scuba diving has grown steadily in popularity and, concurrently, so too has the incidence of diving-related injuries. This review considers the epidemiology of injury resulting from the adventure sport of recreational scuba diving, conventionally defined as no-stop diving with compressed gas in open water to depths of ≤40 m. Military, commercial, technical, rebreather, cave, occupational harvester and breath-hold diving are not considered here.

An electronic search was made of articles indexed by Allied and Complementary Medicine (AMED), Ovid Journals, CAB Abstracts, EMBASE, ERIC, Medline and PsychInfo using the search terms 'div$ and (fatal$ or scuba or risk or injur$)' and Google Scholar using the search terms '(diver OR diving) AND (fatal OR scuba OR risk OR injury)'. Publications were assessed for relevance to this review and either rejected, downloaded from electronic archives or acquired in hardcopy from libraries. Each publication's reference list was examined for additional potentially relevant publications and those identified were also similarly obtained. One limitation within the literature that soon became apparent was the lack of uniformity in reporting incidence and prevalence of diving injuries. In Leicester, for example, mortality incidence was given per 100,000 divers and yet divers may make any number of dives from 1 to 500 within a single year [2]. The Professional Association of Diving Instructors (PADI) cite a number of deaths over a 10-year period without stating how many member-years that period included [3] while other studies estimate the incident rate of decompression sickness (DCS) at either 1 case per number of dives or else by the number of cases per 100,000 dives. Rarely are incidence rates given per dives (or divers), per year.

Who Is Affected by Injury?

Between 1995 and 2007 3,558 divers were treated for decompression illness (DCI) in Australia [4]. During the first 3 years of running dive tours to the deliberately scuttled (former HMAS) Swan shipwreck offshore from the south-west of Australia, a single dive tour operator documented 27,000 dives and 8 known cases of DCI, an incident rate of 29.6 cases per 10^5 dives, almost three times higher than the Australia-wide estimate of 10.7 cases per 10^5 dives [5]. One potential reason why these rates differ may be that the lower figure includes many dives made well within the prescribed time/depth limits while the higher figure may have resulted from divers maximizing their dive time on the shipwreck which, as Vann et al. [6] suggest in a recent review of DCS, would closer approximate the 'true' prevalence among dives made to the maximum limits. Diving morbidity studies identified during the literature search are summarized in table 1.

Table 1. Recreational diving morbidity studies

Diving morbidity	Study design	Method	Period	Sample size	Number of injured	Number of injuries per 10,000 divers per year	Number of injuries per 100,000 dives
Switzerland [7]	R	Q	–	230	28	–	25[a]
Australia [5]	R	RR	2002–2006	1,750,000[b]	188	6.7[c]	10.7
Canada [8]	P	RR, A	1999–2000	146,291[b]	14	–	9.6
UK [9]	R	RR	1986 1990	34,210 36,434	52 80	15.2 22.0	7.0 6.7
UK [10]	R	Q	1990–1994	2,250	87	–	19
USA [11]	R	Q	–	1,628	57	–	34
Sweden [12]	R	Q	1999	1,742	190	–	152 (males) 127 (females)
Okinawa [13]	R	RR, A	1989–1995	–	94	–	13.4
Saba [14]	P	RR, Q	1999–2000	47,307	122	15.5	64.7
Japan [15]	R	Q	1996–2001	2,975	52	35.0[c]	5.2
Orkneys [16]	P	RR, RD, Q	1999 2000	32,128[b] 36,700[b]	8 18	– –	24.9 49.0
Caribbean [17]	R	RR	1989–1990	77,680[b]	7	Diving Incidents Report	9.0
Western Australia [5]	R	RD	–	27,000[b]	8	Diving Incidents Report	29.6

R = Retrospective, P = prospective; RR = records review, RD = recorded dives; A = air fills, Q = questionnaire.
[a] Injured included recreational, military and commercial divers and 63% had a patent foramen ovale.
[b] Dives, not divers.
[c] Per 10,000 divers. It is not known how many diver-years were included.

Where Does Injury Occur?

The protean nature of diving injuries means there is barely a location on or within the human body that is not susceptible to insult. The most common injury involves trauma to the ears and/or sinuses [18], which may not require treatment and often go unreported [19]. Of 49 confirmed cases of DCS reported to the Diver's Alert Network (DAN) in 2007, 6 (12%) included loss of bladder control and 23 (46%) included skin manifestations [19]. Of 347 medical inquiries to DAN concerning barotrauma, 212 (62%) affected the ear, 57 (16%) were related to the sinuses, 51 (15%) to the lungs, 21 (6%) to the face, 3 (1%) to the stomach, and 3 (1%) were related to the teeth [19].

Table 2. DCS and CAGE symptom onset time following surfacing [26]

Time till onset	DCS (n = 70)	CAGE (n = 39)
On surfacing from dive	0 (0%)	27 (69%)
Surfacing to 10 min	12 (17%)	5 (13%)
11–30 min	14 (20%)	2 (5%)
31–60 min	5 (7%)	1 (3%)
61 min–6 h	13 (19%)	1 (3%)
6–24 h	15 (21%)	1 (3%)
Over 24 h	2 (3%)	0
Unknown or unclear	9 (13%)	2
Total	70 (100%)	39 (100%)

Pressure-related injuries usually occur during descent or ascent. The genesis of DCS occurs at depth, where tissues take on additional dissolved inert gas, though physical injuries manifest following ascent when the ambient pressure drops and relative supersaturation occurs. Though more commonly associated with diving to deeper depths, the minimum depth associated with inciting DCS is merely 6 m [20]. Pulmonary barotrauma (PBT) has no such minimum depth and has occurred in even shallow training pools [21].

When Does Injury Occur?

Injury Onset

A review of the records of 63 treated air divers referred to a French hyperbaric facility found the median delay between surfacing and onset of symptoms was 5 min (range 0–600) [22]. An analysis of several thousand military dives found the onset of symptoms after surfacing occurred as follows: 42% within 1 h, 60% within 3 h, 83% within 8 h and 98% occurred within 24 h [23]. Freiberger et al. [24] identified 382/2,222 (17%) cases of DCS where the first symptoms were reported either during or immediately after flying.

Chronometry

Examining 50 cases of sinus barotrauma, Fagan et al. [25] found symptoms developed during or immediately after descent in 34 cases (68%) and during or immediately following ascent in 16 (32%). Comparing 70 cases of neurological DCS with 39 cases of cerebral arterial gas embolism (CAGE) reported to the DAN in 1981/82, Dick and Massey [26] classified the onset of post-dive symptoms as shown in table 2. Clearly, DCS has a more latent onset than CAGE. In short, the onset of symptoms is linked to the mechanism of injury.

What Is the Outcome?

Injury type

The most common serious injuries are drowning-related, DCS and/or pressure-related, with the latter type generally classified as barotrauma, defined as '*tissue damage caused by expansion or contraction of enclosed gas spaces, due to pressure changes*' [27, p. 73]. A survey of 709 experienced recreational divers (with mean experience of 262 dives), found mild barotrauma to be the most common injury, with 369 (52%) suffering ear barotrauma, 245 (35%) sinus barotrauma, and 66 (9%) tooth squeeze [28]. 38 divers (5%) had suffered a ruptured tympanic membrane (burst eardrum), 8 (1%) a round window rupture, and 5 (1%) subcutaneous emphysema. DCS was reported by 31 divers (4.4%). DCI is used to more broadly include cases of both DCS and arterial gas embolism (AGE), between which a differential diagnosis may be difficult at presentation and irrelevant to the treatment regime of hyperbaric oxygen. Other acute injuries associated with compressed-gas diving include those caused by unsustainable gas mixtures for the depth at which breathed (inert gas narcosis, hypoxia, hyperoxia, hypercapnia, high-pressure neurological syndrome and contamination poisoning) [29–39], marine bites and envenomations [40–44], hyperthermia [45], hypothermia [46–48], and blunt force trauma (from boats, falling objects, etc.) [49, 50]. A survey of 208 diving mothers, 136 of whom reported diving during one or more pregnancies, found significantly more birth defects among children born to women who had dived while pregnant ($p < 0.05$) [51].

An Australian analysis of 859 reported diving incidents found 168 (19.5%) involved an out-of-air problem, 57 of which (35%) resulted in diver harm [52]. The distribution of types of morbidity for those 57 incidents is presented in table 3. In total, DCS, CAGE and PBT formed the majority (71%) of injuries that followed running out of air.

The annual Diving Incidents Report published by the BSAC summarizes British recreational diving fatalities, diving injuries, incidents occurring during BSAC dive trips and diver training, rescues and decompression treatments [53–63]. It should be noted that each incident is recorded in only one classification although some may equally have been classified in another category. Any diver suffering DCI was classified as DCI. Perhaps because of this among United Kingdom (UK) divers between 1998 and 2008 DCI was the most commonly reported diving injury (n = 1,245). There were a lesser number of other types of injuries (n = 632) and even fewer fatalities (n = 180). This contrasts with a survey of 304 recreational divers in Western Australia in 2005 which found DCS to be less common than other minor diving injuries [18]. Reported injuries are presented in table 4. Among 3,819 divers at Osezaki, Japan, 406 (10.6%) reported ear barotrauma, 208 (5.6%) sinus barotrauma and yet only 72 (1.8%) reported having suffered DCS [Nakayama, pers. commun., 2005].

Table 3. Morbidity associated with 57 out-of-air situations [52]

Morbidity	n (%)
Decompression sickness	24 (42)
Cerebral gas embolism	10 (18)
Pulmonary barotraumas	6 (11)
Saltwater aspiration	4 (7)
Near-drowning	3 (5)
Hypoxia underwater[a]	2 (4)
Pulmonary barotraumas/saltwater aspiration (suspected)	1 (2)
Decompression sickness(suspected)	1 (2)
Not stated	6 (11)
Total	57 (100)

[a] Rescue resulted in cerebral gas embolism.

Table 4. Prevalence of diving morbidity in a single year among 304 Western Australian recreational divers

Injury	n	%	Collective type	n	%
Vertigo/dizziness	13	4.3			
Hearing loss	9	3.0			
Tinnitus	4	1.3	ear injuries	24	7.9
Ruptured eardrums	2	0.7			
Ear/sinus surgery	1	0.3			
Physical injuries	11	3.6			
Other (free format)	8	2.7			
Blotchy/itchy skin	5	1.6	other injuries	27	8.9
Tooth squeeze	4	1.3			
DCS	3	1.0			

Injury Severity

The consequences of drowning, near-drowning and/or related complications range in severity from a full and speedy recovery through catastrophic neurologic damage to death [35, 64–67]. Barotrauma may range in severity from 'mask squeeze' with facial bruising, barodontalgia or 'tooth squeeze', ear injuries from bruising through to round window rupture, gastric injuries such as esophageal rupture, and PBT including emphysemas (subcutaneous or mediastinal), pneumothorax, up to the most serious of diving injuries; AGE, particularly the cerebral form (CAGE), a leading cause of death or drowning among recreational diving fatalities [21, 25, 67–79]. DCS, now widely accepted as attributable to the liberation of gas from solution to form bubbles in the tissues, manifests in seriousness ranging from the type I symptoms of skin rash, pain only and general malaise, through to the neurological type II symptoms of motor function impairment, loss of bladder control, sensory impairment, permanent paralysis and even, ultimately, death [72, 80–84].

Clinical Outcome

After a median follow-up of 54 months for 20 American males diagnosed with inner ear barotrauma, 3 (15%) had normal audiograms, 8 (40%) had some improvement but not full recovery, and 9 (45%) had no improvement since diagnosis [85]. All had returned to diving against medical advice. Among 15 consecutive cases of PBT treated in Germany, 8 (53%) recovered completely, 4 (26%) substantially, 2 (13%) had moderate recovery, and 1 (7%) recovered minimally, requiring permanent nursing care [86]. Furthermore, a retrospective review of 50 Hawaiian cases of mild DCS or serious DCI found 33 (66%) recovered completely, 12 (24%) substantially, 2 (4%) moderately, and 3 (6%) minimally [87]. These findings were similar to a study of 63 French air divers treated for suspected spinal cord DCS which found that 67% (n = 42) had fully recovered after 1 month, 8% (n = 5) still had minor symptoms, 13% (n = 8) had moderate symptoms with mild impact on daily living, and 13% (n = 8) still had severe disability with substantial impact upon daily living [22]. The odds of a substantial or complete recovery appear good among divers presenting for treatment.

Catastrophic Injury

Australian diving fatality reviews have been published annually since 1972 [88–95]. These reports indicate that Australia averages 10.0 recreational open-circuit compressed-gas diving deaths per year. Between 1972 and 1993 the two leading causes of death amongst the 178 scuba diving fatalities included in the reports were drowning (n = 100, 56%) and CAGE (n = 28, 15.7%) [88]. Table 5 lists diving mortality studies identified during the literature search.

Recently, the Australian Sports Commission estimates of resident participation and Queensland Government visitor activity surveys were compared to the number of scuba fatalities recorded in Australia by DAN Asia-Pacific [5]. The fatality rate in Australia between 2002 and 2006 was estimated at 0.57 per 10^5 dives (0.7 per 10^5 for Australian residents and 0.4 per 10^5 for overseas visitors) [97], which was lower than estimates for British Columbia in 1999–2000 ($2.05/10^5$) [98], the UK in 2006 ($0.8/10^5$) [60], and Okinawa in 1989–1995 ($1.3/10^5$) [13]. This may be due in part to differences in sampling and survey methodology. In British Columbia, Canada, the estimated number of air fills sold by dive centers formed the basis of the denominator, in the UK a retrospective survey was conducted and in Okinawa the number of air fills sold within a military community was used. At a popular former quarry in the UK there were 7 fatalities between 1992 and 1996, during which time 238,501 divers registered

Table 5. Recreational diving mortality studies

Diving mortality	Study design	Method	Period	Sample size	Number of diving deaths	Number of diving deaths per 10,000 divers	Number of deaths per 100,000 dives
Canada [8]	P	RR, A	1999–2000	146,291[a]	3	–	2.05
Western Australia [96]	R	RR	1992–2005	76,108	10	1.3[b]	–
Okinawa [13]	R	RR, A	1989–1995		9[c]	–	1.3
Australia[5]	R	RR	2002–2006	1,750,000[b]	50	0.4	0.57
UK [5, 60]	R	RR	2006	2,000,000[b]	16	–	0.8
UK [2]	R	RR, RD	1992–1996	238,501	7	0.3	–

R = Retrospective; P = prospective; RR = records review; RD = recorded dives; A = air fills.
[a] Dives, not divers.
[b] Diving deaths per 10,000 all-cause mortality aged ≥15 years.
[c] Not all divers were recreational.

to dive, generating a 5-year mortality rate of 2.9 deaths per 100,000 divers [2]. Figure 1 shows the declining deaths per 10,000 memberships among British Sub-Aqua Club (BSAC) members between 1965 and 2008 [63].

The mean number of diving deaths per year among BSAC members during the last 10 years has been 1.5 deaths per 10,000 members per year, though it is unknown how many members were engaged in non-recreational (e.g. decompression) diving during this period or how many dives each member made on average. McAniff [99] published estimates per 100,000 divers per year for the USA as shown in figure 2, based upon diver population estimates derived by training agency certifications minus estimated annual drop-out from diving. These estimates were then compared with estimates by other large-scale surveys including those conducted by Diagnostic Research Incorporated (1988) and the National Sporting Goods Association (1994). McAniff's estimates were challenged by Monaghan [100] to be inflated by an overly conservative drop-out rate and he estimated the real rate to be closer to 16.7 deaths per 100,000 diver-years. Regardless, Al Hornsby [101, p. 80] at PADI recently wrote '*. . . it appears that McAniff's estimate is currently the most suitable figure for use in scientific and medical analyses that require a diver population estimate*'.

An analysis of incident reports involving diving fatalities and membership figures for PADI generated estimates during a 10-year period of 1.66 fatalities per 100,000 divers, and 0.47 per 100,000 dives under supervision of a PADI member [3]. The fatality rate among PADI dive professionals over the same 10-year period was 1.1 per 100,000 members [3]. These rates of 1.1 and 1.66 per 100,000 divers/members over

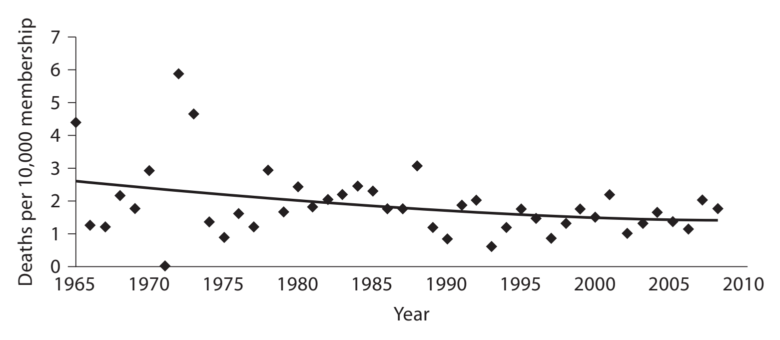

Fig. 1. Mortality rate among BSAC members, 1965–2008 [63].

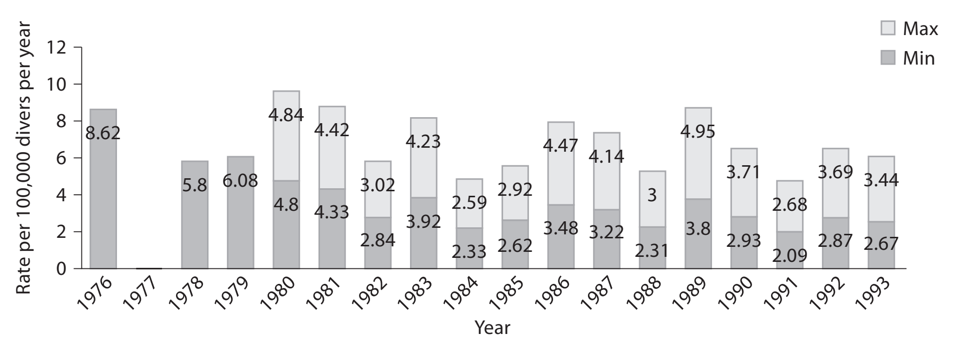

Fig. 2. Fatality rate per 100,000 divers per year in the USA, by year [99].

10 years could be a hundredth of that found by the BSAC if all of the divers and members were eligible for inclusion for the full 10 years (i.e. per 1,000,000 diver-years). These extremely low rates possibly reflect the increased safety associated with diving with appropriate equipment in a controlled training environment (in contrast with recreational dives made unsupervised in the open ocean).

In the United States, DAN recently compared their number of insured members against the number of dive-related deaths and, similar to BSAC, found a rate of 16.4 deaths per 100,000 member-years [102]. It should be remembered that these rates concern only fatalities that occurred during the performance of scuba diving. How the all-cause mortality rate among people who scuba dive compares with non-divers is yet to be assessed, therefore it remains unknown at this time how significantly (if at all), recreational scuba diving adds to the mortality rate of the cohort from which divers are drawn. What is apparent, however, is that fatalities involving recreational diving are extremely rare. In Western Australia there were 10 recreational diving fatalities recorded between 1999 and 2005, out of 76,108 deaths at age ≥15 years

Table 6. Causes of death among three recreational diving populations [106]

Cause of death	ANZ %[a]	NUADC %[a]	DAN %
Drowning	86	74	52
Pulmonary barotrauma	13	24	19
Cardiac	12	9	27
Aspiration of vomitus	6	1	1
Trauma	3	1	1
Asthma	2	–	–
Marine animal injury	1	–	–
Coincidental	1	–	–
DCS	–	–	1

[a] More than one cause of death could be nominated.

recorded in Western Australia during the same period, suggesting a rate of 13.1 recreational diving fatalities per 100,000 deaths [103]. A review of 100 consecutive Australian and New Zealand (ANZ) diving fatalities [104], 2,853 American diving fatalities reported to the National Underwater Accident Data Centre (NUADC) 1970–1997 and 83 reported in 1998 to DAN [105] found the most common cause of death was drowning (table 6).

In both the ANZ and NUADC studies, more than one cause was sometimes attributed to a single death, for example suffering PBT and drowning. Regardless, drowning is clearly the most common cause of death in all three samples. Similarly, a review of the Western Australia Coroner's Court records from 1992 to 2005 identified 24 recreational compressed-gas diving deaths, 14 of which (58%) were classed as drownings [96].

Economic Cost

It is not known what the average cost of such injuries is. A report into the costs of accidental near-drowning in Western Australia [107] put the average costs of a near-drowning according to the severity of the outcome, as follows: (i) moderate/severe at AUD 984,700; (ii) fully recovered (hospital admission) at AUD 6,700, and (iii) fully recovered (emergency ward only) at AUD 850.

Recent figures supplied by DAN Asia-Pacific indicate around 130 divers are recompressed for DCI each year in Australia, with an average of two treatments per diver, at AUD 900 per standard hyperbaric treatment, totaling AUD 234,000 per annum in base costs [J. Lippmann, pers. commun., December 2011]. This figure does not include afterhours call-out charges which can triple the cost of treatment because of staff call-back pay rates, nor costs associated with ambulance use or Royal Flying Doctor flights, nor extended recoveries in hospital. In rare cases, divers may even require months of physiotherapy and rehabilitation. From the above it should be clear

Table 7. Risk factors for running low on gas among 693 recreational dives

Risk factor	Adjusted OR	95% CI	p value
Surprised by low remaining gas	21.74	5.00, 90.91	<0.01
Male vs. female	13.51	6.41, 28.57	<0.01
Deeper average depth (per 5 m saltwater)	3.46	1.85, 6.48	<0.01
Younger age (per 10 years)	2.02	1.47, 2.77	<0.01
Time since last dive (per year)	1.51	1.11, 2.06	<0.01
Fewer dives in last 5 years (per 100 dives)	1.22	1.00, 1.49	<0.01
Higher SAC[a] (per $l \cdot min^{-1} \cdot kg^{-1}$)	1.14	1.09, 1.19	<0.01
Warmth (warm vs. cold)	4.25	1.28, 14.13	0.02
Smaller cylinder volume (per l)	1.01	1.03, 1.90	0.03

[a] Equivalent surface air consumption.

that diving injuries have the potential to comprise a substantial economic burden both to individuals with inadequate healthcare provisions and to health systems with finite resources.

What Are the Risk Factors?

The influence of individual dive and diver characteristics upon the risks of running out of compressed gas were prospectively measured in Western Australia by comparing 183 dives made by divers who surfaced with <50 bar of pressure remaining with 510 control dives made at the same time and place by divers who returned with >50 bar remaining. The *caeteris paribus* effect of associated factors upon the likelihood of running low on gas are presented in table 7 [108].

Intrinsic Factors

A review of 30 Swedish scuba diving fatalities occurring between 1960 and 1976 compared the author's impressions of the predominant causes to those of other diving fatality studies of the same period [109]. Insufficient knowledge or training was the most commonly attributed risk factor (36%) [109]. When added to the proportion attributed to inadequate physical condition (12%) it appears approximately one half of the 374 fatalities (48%) were thought caused by diver-related factors rather than dive equipment or the dive environment [109]. The comparison table is reproduced here as table 8.

Comparing 101 prospective cases of DCI referred for hyperbaric treatment with 101 healthy controls, Cantais et al. [110] detected a right-to-left shunt (RLS) in 59 (58%) of

Table 8. Perceived causes of 374 diving fatalities in the 1960s and 1970s [109]

	Miles (1964) UK n (%)	Webster (1966) USA n (%)	Bayliss[a] (1969) Australia n (%)	Lausche (1970) California n (%)	Unterdorfer (1974) Austria n (%)	Carlsson (1976) Sweden n (%)	Total n (%)
Insufficient knowledge or training	83 (50)	16 (19)	12 (17)	13 (43)	2 (40)	7 (41)	133 (36)
Equipment failure	30 (18)	23 (27)	12 (17)	2 (7)	–	5 (29)	72 (19)
Inadequate physical condition	33 (20)	2 (2)	6 (8)	0 (0)	2 (40)	3 (18)	46 (12)
Other factors	19 (12)	45 (52)	41 (58)	15 (50)	1 (20)	2 (12)	123 (33)
Total (100%)	165	86	71	30	5	17	374

[a] Bayliss did not classify the accident causes in the same way; the figures given here are only approximate.

cases and 25 (25%) of controls (OR 4.3, 95% CI 2.3–7.8; p = 0.09). RLS was especially associated with cochleovestibular DCI (OR 14.2, 95% CI 5.3–38; p < 0.01) and cerebral DCI (OR 12.9, 95% CI 4.0–42.0; p < 0.01). Similar prevalence of patent foramen ovale (PFO) was found by Germonpré et al. [111] when comparing 37 Belgian cases of neurological DCS with carefully matched control divers. Among the DCS divers a PFO was detected in 22/37 (59%) and in 13/36 (36%) among the controls. A meta-analysis of three combined datasets allowed Bove [112] to determine the risk of type II DCS increased 2.5 times in divers with a PFO, though the absolute risk remained relatively small (from 2.3 to 5.7 cases per 10,000 dives). A more recent meta-analysis of case-control studies found the combined odds ratio of neurological DCS in divers due to RLS was 4.23 (95% CI 3.05–5.87), which increased to 6.49 (95% CI 4.34–9.71) for divers with large RLS [113].

Extrinsic Factors

Whilst the association between PFO and DCS is now well established, one of the pioneering case-control studies, comparing divers with DCS (n = 85) to their uninjured dive buddies and other asymptomatic divers with >100 uneventful dives (n = 91), made a remarkable finding [114]. Wilmshurst [114, p. 35] wrote: *'Dive-related risk factors for decompression sickness (missed decompression stops, rapid ascents, post-dive ascent to altitude, dives deeper than 50 m, repetitive deep dives >40 m and frequent dives >3/day) were implicated in the majority of late neurological bends (78%) and limb bends (86%). When early neurological bends occurred, there were usually dive-related risk factors if the diver had neither shunt nor lung disease (67%) but rarely were there risk factors if a shunt was present (27%). No risk factors were present in those divers with early neurological symptoms and lung disease.'*

Table 9. Odds ratio for DCS by maximum depth on the last day of diving before flying [24]

Maximum depth last day of diving	Odds ratio (n)	95% CI
Depth <14.7 m saltwater	1 (125)	–
14.7 m ≤ depth ≤18.5 m	1.20 (128)	0.68, 2.10
18.5 m ≤ depth <26 m	2.97 (142)	1.65, 5.35
Depth ≤26 m	5.46 (140)	2.96, 10.01

This suggests divers with either a shunt or lung disease are at risk of early-onset DCS even when diving conservatively but also, importantly, that dive-related risk factors for late-onset DCS are a concern for otherwise healthy divers. In a later study, Wilmshurst and Bryson [115] observed that 52% (n = 52) of divers presenting with neurological symptoms had a large or medium RLS. These findings suggest that roughly one half of all cases of neurological DCS involve dive-related risk factors. An analysis of 114 cases of DCS treated at the Fremantle Hospital Hyperbaric Chamber concluded that multi-day repetitive diving, rapid ascents, multiple ascents and flying after diving were commonly associated risk factors for DCS in Western Australia [116]. Flying after diving is known to increase the risk of DCS due to the reduction in ambient pressure. Comparing 382 cases of DCS with 245 control divers, all with known dive profiles and flight information, Freiberger et al. [24] estimated the risk of suffering DCS to increase with maximum depth reached on the last day before flying as shown in table 9.

Comparing 177 British cases of DCS with recorded meteorological changes in barometric pressure, water, air and wind-chill temperatures, wind speeds and tidal phases, Broome [117] determined that post-dive, and to a lesser degree pre-dive, air temperature was associated with increased risk of DCS.

What Are the Inciting Events?

The most common forms of diving injuries follow running out of gas and/or ascending rapidly. Drowning was the most common cause of death among 2,404 American recreational diving fatalities between 1970 and 1992 [118]. The most common contributing factor among fatalities by the end of that review period, 1991–1992, was insufficient air (30%) [118]. This finding was reinforced by the analysis of 974 recreational open-circuit diving deaths from 1992 to 2003 which found the most common trigger commencing the series of events leading to death (41% of 346 deaths) was insufficient gas [119]. Emergency ascent then followed as the most common disabling agent, in 55% of 332 deaths where the disabling agent could be identified [119]. Factors involved in

Table 10. Distribution of primary contributory factors for DCI in the UK[a], 1998–2008 [53–63]

Factor	Average number per year 1998–2008	Total[b] n (%)
Depth >30 m	36	394 (29)
Rapid ascent	33	364 (27)
Repeat dives	25	270 (20)
Within limits	24	269 (20)
Missed stops	19	209 (16)
Total[c]	–	1,506 (100)

[a] Approximate figures, estimated from annual summary graphs.
[b] More than one factor was credited to some fatalities in 1998, 2000 and 2001.
[c] Total without duplicate listings was 1,347 factors.

cases of DCI reported to BSAC between 1998 and 2008 are listed in table 10 (note, more than one factor may have been attributed to each case) [120]. Although diving to >30 m appeared over the period to be decreasing in prevalence as a risk factor, 27% of cases of DCI in the UK primarily involved rapid ascents, only a fifth (20%) involved dives within the accepted recreational time-depth limits and a sixth (16%) involved exceeding those limits and missing the required decompression stops.

Running out of gas is, unsurprisingly, often followed by a rapid ascent to the surface. The distribution of morbidity among an Australian sample of recreational divers between air status and type of ascent is presented in table 11. As shown, even among divers who ran out of air (n = 168), approximately equally divided between rapid ascent (n = 89) and non-rapid ascent (n = 79), a combination of running out of air and ascending rapidly had a much higher prevalence of a resultant morbidity (91%) than merely running out of air alone (9%) [52].

A probabilistic risk assessment prepared for the British Health and Safety Executive (HSE) used the prevalence of contributory factors among 849 reported BSAC diving incidents, 57 of which (6.7%) were fatal, and 277 DAN reported fatalities as a proxy for the probability of occurrence [121]. For an estimate of the likely hazard of each factor, the study used inclusion in either the BSAC incidents or the DAN fatality subsets to indicate a factor contributed to the incident or fatality. In this way each potential contributory factor was given a likelihood of being reported and a likelihood of contributing to a fatality. The top ten contributory factors associated with diving fatalities and the corresponding estimates of prevalence in the BSAC subset are provided in table 12.

The two most influential diving-technique risk factors identified in the Edmonds and Walker ANZ study (table 6.6) were inadequate air supply in 56% of fatalities and

Table 11. Type of ascent and associated morbidity for 168 out-of-air incidents [52]

	Out-of-air type	Out of air n (%)	Morbidity n (%)
Rapid ascent (n = 89)	Octopus use[a]	21 (12.5)	9 (15.8))
	Buddy	14 (8.3)	7 (12.3)
	Other	54 (32.1)	36 (63.2)
	Subtotal 1	89 (53.0)	52 (91.2)
Non-rapid ascent (n = 79)	Octopus use[a]	39 (23.2)	1 (1.8)
	Buddy	10 (6.0)	3 (5.3)
	Other	30 (18.0)	1 (1.8)
	Subtotal 2	79 (47.0)	5 (8.8)
Total		168 (100)	57 (100)

[a] Octopus use refers to using the buddy's alternate air source.

Table 12. Ten highest ranked potential contributory factors in 286 diving fatalities [121]

Factor	Fatalities (n = 286)[1]		BSAC incidents (n = 849)	
	n	1 in diver-years[2]	n	1 event in dives[3]
Diver separation	126	11,349	53	165,094
Monitor buddy	99	14,444	25	350,000
Brief inadequate	83	17,229	43	203,488
Out of air	71	20,141	8	1,093,750
Fail surface on separation	65	22,000	26	336,538
Consider consequences	50	28,600	11	795,455
Buddy check	47	30,426	14	625,000
Solo dive	35	40,857	14	625,000
Fail to monitor air	32	44,688	49	178,571
Rapid ascent	30	47,667	101	86,634

[1] Cardiac deaths excluded.
[2] Based on an estimated annual fatality rate of 19.6 deaths per 100,000 divers and an annual average of 24 dives per diver, both of which appear higher than found elsewhere.
[3] Based on a mean 20 dives per diver per year.

buoyancy problems in 52% [104, 106]. The findings are similar to those of earlier study of 21 scuba deaths in New Zealand [122]. Differing inclusion criteria may account for the lower ranking of these factors in the HSE study (table 12), as mere inclusion within a fatality summary was assumed to imply that a factor contributed to the fatality. In the ANZ and New Zealand studies, diving medical examiners considered the

Table 13. Factors associated with 180 compressed-gas diving fatalities in the UK, 1998–2008 [53–63]

Factor	Total (n = 180) n_t (%)[a]
Separation	54 (30)
Buoyancy loss	50 (28)
Organized dive[b]	45 (25)
Rapid ascent[b]	31 (17)
Rebreathers	30 (17)
Medical	25 (14)
Out of gas	24 (13)
Panic[b]	24 (13)
Solo	21 (12)
Equipment fail	21 (12)
Seas/currents	18 (10)
DCI	11 (6)

[a] Note: More than one factor may relate to any single fatality.
[b] Factor not classed as causal in the summary statistics but identified in the vignette.

circumstances surrounding each fatality and counted only factors deemed to have played a role in the circumstances leading up to and including the fatality. Factors associated with 180 British recreational diving fatalities that were described as *'causal'* [53–63] are summarized in table 13. There may have been other underlying triggers that led to each death and causality in an epidemiological context remains unproven. Environmental factors 'rough seas and/or strong currents' were considered relevant in just 10% of cases and diver-specific factors were limited to medical conditions and were implicated in just 25 fatalities (14%). The majority of factors associated with these 180 diving fatalities were specific to the fatal dive (e.g. separation, buoyancy loss, panic).

Supporting this view, an examination of 29 Canadian diving fatalities compared the circumstances surrounding each fatality to the Safe Diving Practices Statement of Understanding, a set of 38 safe practices prescribed by PADI [123]. In the majority of cases (86%) at least one breach of safe practices was evident and, of those, 87% of the *rule violations* were thought to have contributed to the fatality. The same method was applied to a sample of 24 Western Australian diving fatalities and certified divers were found to have broken fewer safety rules than uncertified divers (4.8 vs. 8.5, $p < 0.01$) [96]. Of the 20 divers using scuba equipment, 4 (20%) ran out of air and 2 (10%) ran low on air. There can be little doubt this was relevant to the outcome.

Annual analyses of recreational diving fatalities conducted by DAN found the three most common problems experienced by certified divers during their final dive were running out of air, buoyancy problems and/or making rapid ascents [105, 119, 124–128]. In the previous HSE study of contributing factors (table 6.11), among both fatalities and reported incidents the most frequently reported incident (n = 101/849) was a rapid ascent, though no measured rate of ascent was specified [121]. Of the 34 fatal breath-hold embolisms examined in that study, 13 (38%) involved rapid ascents and 10 of those 13 (77%) were deemed due to running out of air. The report concluded [121, p. 26]: '*The statistics show that: (i) rapid ascent is the most frequently reported contributory cause of incident, and (ii) air embolism is the second most frequent principal cause of fatality.*'

The most frequent principal cause of fatality, however, was entrapment/entanglement, for example underneath ice or inside shipwrecks. Following on from this report, Cranfield University was commissioned by HSE to conduct a research report entitled Formal Risk Identification in Professional SCUBA (FRIPS) [129]. The authors used both Fault Tree Analysis (FTA), '. . .*to show the importance of human factors to the ultimate safety of divers*' [129, p. 2] and the predictive model, Failure Mode and Effects Criticality Analysis '. . .*to demonstrate how a formal risk assessment can be carried out on SCUBA hardware*' [129, p. 2]. Using Boolean OR and AND options, FTA is most useful when aiming to identify proximate causes [130]. Similar methods have been employed by DAN in the USA [119, 131] and in Australia [95]. As with the earlier HSE report, in the FRIPS analysis scuba deaths were deemed most often attributable to drowning due to running out of air or embolism after either a loss of buoyancy control or rapid ascent. Among living, adult recreational divers these three factors have been investigated using a case-control study design both retrospectively [132] and prospectively [108].

Injury Prevention

Though DCS, drowning and near-drowning appear to be relatively rare events, public health injury prevention initiatives have potential to reduce the economic burden to healthcare providers, potential that remains largely untapped. A study by DAN examined the probability of DCS among the recorded dive profiles of 100 cases of DCS and found that, in most cases, the dive profiles were within recommended limits [133]. These cases were then compared with 50 cases of experimentally induced DCS and to the profiles of 50,000 recreational dives with symptom-free outcomes. The authors concluded: '*The incidence of DCS in low-risk dives may not be possible to reduce further by controlling the depth-time exposure only*' [133, p. 187]. This suggests two avenues for improving diver safety; identifying additional risk factors associated with probability of DCS and increasing the proportion of recreational divers who are mindful of empirically established relatively-safe depth-time profile limits, including ascent rate. Among Western Australian scuba diving fatalities it was found that uncertified (or self-trained) scuba divers both breach significantly more established safe diving practices (4.8 vs. 8.5, $p < 0.01$) and account for 30% of all diving fatalities where the training status is known [96]. Uncertified divers have elsewhere been found to report significantly more diving injuries than certified divers (RR = 1.31, 95% CI 1.16–1.48; $p < 0.001$) [134] yet in many countries there is no requirement for self-trained divers (who are more likely to suffer an injury and yet who may still expect treatment at the expense of the local healthcare system), to undertake any form of diving skills assessment. This is surely one area in which minor regulatory changes might assist the most vulnerable divers underwater, by requiring every diver to master even just basic diving skills, such as those endorsed in a memorandum of understanding by the Recreational Scuba Training Council, a global affiliation of diver training agencies. Meanwhile, governments continue to sell fishing licenses to untrained and uncertified recreational divers [96].

Despite repeated calls for regular health assessments by doctors with training in dive medicine, there is little evidence that either periodic dive medicals or the exclusive use of physicians trained in diving physiology offer any tangible risk reduction. The current international standard requires dive-course candidates to complete a self-assessment questionnaire and to undertake a dive medical if answering in the affirmative to any known medical contraindications. Routine screening for PFO is considered unwarranted for recreational diving as the absolute risk of type II DCS is small [113], even with a PFO (5.7 cases per 10,000 dives) [112]. Once certified, divers are rarely required to undertake subsequent diving fitness assessments. The medical fraternity should not be relied upon to reduce diving morbidity. Public health promotion initiatives have far greater potential effect although there is a dearth of health economics research into the burden of diving injuries and hard data remains sorely needed to justify greater investment in diving safety initiatives.

Further Research

To date, the majority of diving injury studies are case-series designs, considered a '*primitive form of case-control study – one in which the controls are only implied*' [120, p. 54]. Notable exceptions are case-control studies investigating either environmental factors associated with DCS [117], physiological risk factors for DCS and PBT such as RLS and small airways disease [86, 113–115], and hyperbaric chamber experiments [135]. Larger, prospective cohort studies, though more expensive and time consuming, are needed to quantify the potential long-term effects of diving, both among those treated for diving injuries and the apparently asymptomatic [136]. Only then will divers have an accurate estimate of the risks they assume when returning to the underwater realm. Till these occur, we rely on physiological inferences and inconclusive, often controversial evidence, for example concerning the relative risk of PBT associated with asthma, the prevalence of brain damage in otherwise symptom-free recreational divers or the potential influence of gender on susceptibility of DCS. It is also recommended that future research uniformly report injury prevalence using the denominators 'per 10,000 divers' and/or 'per 100,000 dives', and incidence rates of 'per 10,000 divers per year' and/or 'per 100,000 dives per year'. From a population health perspective, the widest gap in our understanding of diving injuries awaits evaluated diving safety initiatives, which are sorely lacking. A wealth of knowledge concerning recreational scuba diving injuries has been compiled during the last half a century, more still has been studied and yet, to date, even more again remains to be discovered.

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