

Relationship between the clinical features of neurological decompression illness and its causes

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A B S T R A C T

There is dispute as to whether paradoxical gas embolism is an important aetiological factor in neurological decompression illness, particularly when the spinal cord is affected. We performed a blind case-controlled study to determine the relationship between manifestations of neurological decompression illness and causes in 100 consecutive divers with neurological decompression illness and 123 unaffected historical control divers. The clinical effects of neurological decompression illness (including the sites of lesions and latency of onset) were correlated with the presence of right-to-left shunts, lung disease and a provocative dive profile. The prevalence and size of shunts determined by contrast echocardiography were compared in affected divers and controls. Right-to-left shunts, particularly those which were large and present without a Valsalva manoeuvre, were significantly more common in divers who had neurological decompression illness than in controls ($P < 0.001$). Shunts graded as large or medium in size were present in 52% of affected divers and 12.2% of controls ($P < 0.001$). Spinal decompression illness occurred in 26 out of 52 divers with large or medium shunts and in 12 out of 48 without ($P < 0.02$). The distribution of latencies of symptoms differed markedly in the 52 divers with a large or medium shunt and in the 30 divers who had lung disease or a provocative dive profile. In most cases of neurological decompression illness the cause can be determined by taking a history of the dive profile and latency of onset, and by performing investigations to detect a right-to-left shunt and lung disease. Using this information it is possible to advise divers on the risk of returning to diving and on ways of reducing the risk if diving is resumed. Most cases of spinal decompression illness are associated with a right-to-left shunt.

INTRODUCTION

Neurological symptoms may occur during or after ascent from a dive, on leaving a caisson or during sub-atmospheric decompression. There has been a call to

describe all cases using the encompassing term 'neurological decompression illness' [1]. This allows the treating doctor to ascribe a diagnostic label without determining aetiology [1]. Assessment of the risk of recurrence on returning to diving requires knowledge of the cause of an

Key words: airways obstruction, atrial septal defects, cerebral decompression illness, contrast echocardiography, decompression sickness, gas embolism, lung function tests, patent foramen ovale, pulmonary arteriovenous fistula, pulmonary barotrauma, smoking, spinal decompression illness.

Abbreviations: CT, computed tomography.

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earlier episode. In most, if not all, cases, decompression illness is caused by gas bubbles. If gas trapping as a result of lung disease or failure to exhale adequately during ascent causes pulmonary barotrauma, bubbles may invade the pulmonary veins to become arterial gas emboli. Decompression sickness occurs if ambient pressure is reduced sufficiently below the partial pressure of gas dissolved in tissues for bubbles to form *in vivo*. A contentious issue is whether such bubbles produce injury by an autochthonous mechanism (causing injury at the site where they are formed) or by embolism. Some cases might result from a combination of mechanisms.

Bubbles are common in the venous circulation after diving, but usually produce no symptoms because they are filtered by the pulmonary capillaries, where the gas diffuses along the concentration gradient into the alveoli. Exceptionally, when the dive profile is very provocative, massive venous gas embolism may overwhelm the filtering capacity of the pulmonary capillaries so that bubbles reach the systemic circulation. It is also possible that bubbles will pass through the pulmonary capillaries if there is transient recompression, as occurs during repetitive dives in a short time period. A case report and observational studies have suggested that paradoxical gas embolism across right-to-left shunts might have a role in the aetiology of some cases of neurological decompression sickness after conservative dives [2–4]. Such shunts usually occur across a foramen ovale, but occasionally shunting is through an atrial septal defect or a pulmonary arteriovenous fistula. A blinded case-controlled study showed that right-to-left shunts were particularly associated with neurological symptoms that occurred within 30 min of surfacing [5]. Neurological symptoms usually followed an unprovocative dive in divers who had a shunt, but were usually the result of a provocative dive if divers had no shunt [5]. Data extending these observations and a replication study performed under supervision of members of the Medical Research Council Decompression Sickness Panel have been reported [6,7]. There have been other human and animal studies which support the theory that neurological decompression sickness can be the result of paradoxical gas embolism [8–10]. However, the possibility that this mechanism may be associated with a significant number of cases of neurological decompression illness is contrary to established aetiology theories, and many experts in diving medicine remain unconvinced that paradoxical gas embolism is a numerically important cause of decompression illness [11–16]. A large controlled study proposed in 1990 by one of these groups [12] has not yet been published.

One objection is that between one-quarter and one-third of the population, and a similar proportion of divers, have a patent foramen ovale which might allow right-to-left shunting [5,17]. Considerably fewer than a quarter of divers develop decompression illness [18].

Many divers with a demonstrable shunt have no history of decompression illness [5,6,13,14]. Thus the relevance of a patent foramen ovale is disputed. This argument fails to take account of variations in risk based on shunt size, which is dependent on the anatomy and dimensions of the defect and the pressure gradient, and on venous bubble load, which is affected by individual susceptibility to bubble nucleation and the profiles of dives performed. Many dive profiles do not cause venous gas nucleation at a time when critical tissues have sufficient gas content to amplify gas emboli.

A second objection is that the greater blood flow to the brain generally ensures that embolic events in the spinal cord are much less frequent than in the brain, but involvement of the spinal cord is a common manifestation of decompression sickness. The pathological distribution of lesions and the time course of spinal cord decompression illness are considered by some to be incompatible with an embolic mechanism [11,19,20]. This led to the assertion that autochthonous bubbles must be the cause of spinal decompression illness [11]. There is one clinical study in humans which suggests that a patent foramen ovale is not associated with spinal decompression illness [10], but it was our impression from our previous studies that spinal decompression illness may be more frequent when the diver has a right-to-left shunt and that, in affected cases, the shunt size is considerably larger than in the general population [5–8,21]. We therefore believed that the role of shunts in the causation of spinal decompression illness may be greater than generally appreciated. There have been cases of spinal cord dysfunction after air embolism following pulmonary barotrauma during submarine escape training [22]. Therefore, in the present study, we investigated how shunt size is related to susceptibility to neurological decompression illness, and in particular to spinal lesions. The primary (pre-analysis) aims of the study were: (a) to compare the prevalence and size distribution of right-to-left shunts in divers with a history of neurological decompression illness and in unaffected control divers; (b) to determine the relationship between large and medium-sized right-to-left shunts and lesion site (spinal or cerebral) in divers with neurological decompression illness; and (c) to determine what proportions of episodes of neurological decompression illness were related to the presence of cardiac shunts, lung disease or a provocative dive profile.

METHODS

We performed a 'blind' retrospective analysis of 100 consecutive divers (34 female; 91 amateur and nine

professional) who were assessed following one or more episodes of neurological decompression illness. The first in this cohort was the next case seen after completion of our previous publication [8]. One episode occurred after a dry hyperbaric chamber dive in which air was breathed. The other episodes followed dives in water. One amateur diver had neurological decompression illness after a deep dive breathing trimix (helium, oxygen, nitrogen), with long nitrox (nitrogen and oxygen) decompression stops. All the other episodes of decompression illness followed dives in which air was breathed, but nitrox was used on one of the dives for decompression stops.

The referral and assessment of each amateur diver was in accordance with the Medical Standards of the United Kingdom Sport Diving Medical Committee. These require enquiry into the circumstances of the incident, including the dive profile, and investigations to exclude the presence of physical predisposition (i.e. to exclude a right-to-left shunt and lung disease). The professional divers were referred for the same reason, although there is no formal requirement. The cases studied have not been reported previously, except for six cases reported in description of closure procedures ([23], but see [23a]; [24]). Of the consecutive cases, 35 were treated for neurological decompression illness at a single centre (The Hyperbaric Medical Centre, Plymouth). The other referrals came from other recompression facilities, diving medical referees and general practitioners.

One of us (P.B.) retrospectively reviewed information about symptoms and signs at presentation with decompression illness to determine the lesion site. This was done blind to knowledge of the results of cardio-respiratory investigations. It was also blind to dive profile, except for the 35 cases from his own centre. Another (P.W.) had previously reported the contrast echocardiography and lung function tests and analysed the dive profile to assign an aetiology label. This was performed blind to categorization of the lesion site. Possible causes of decompression illness were: (a) a clinically relevant (large or medium size) right-to-left shunt (atrial or pulmonary) determined from contrast echocardiography; (b) lung disease predisposing to pulmonary barotrauma determined from lung function tests and chest X-ray; (c) provocative dive (rapid ascent or inadequate decompression, including missed stops and computer malfunction) determined from the history; (d) any combination of these; (e) unknown cause when there was no shunt or lung disease detected and the dive profile was considered unprovocative.

In all cases, transthoracic contrast echocardiography was performed to detect the presence of a right-to-left shunt and for semi-quantitative assessment of the size of any shunt detected [25]. We always perform contrast echocardiography before reading the referral letter and blind to history and physical findings, to avoid bias in

interpretation. We adhered to this practice for all cases and controls. The heart was imaged (apical four-chamber view) with a Hewlett Packard Sonos 500, 1000 or 2000 machine. Bubble contrast was produced by pushing approx. 5 ml of sterile saline (0.9% NaCl), 0.5 ml of the subject's blood and 0.5 ml of air back and forth between two syringes connected by a three-way tap until there were no visible bubbles. This mixture was injected through a 21-gauge butterfly needle into a left antecubital vein. The first contrast injection was performed with the subject resting and breathing normally. If no shunt was seen with the first contrast injection, up to five subsequent injections were performed with Valsalva manoeuvres, with the operator causing sudden release of the manoeuvre, as described previously [8]. The size of the shunt was graded according to the maximum number of bubbles seen in the left heart on frame-by-frame analysis: small shunts, fewer than six bubbles; medium shunts, six to 20 bubbles; large shunts, more than 20 bubbles [25]. On the basis of our previous observations, we believe that small shunts represent a low risk of predisposing to decompression illness, and in the present study they were considered to be clinically irrelevant. Late appearance of bubbles in the left heart was taken to indicate a pulmonary shunt. Such shunts usually appear as a constant stream of bubbles in the left heart, and atrial shunts usually appear as groups of bubbles. When a pulmonary shunt was suspected, additional tests, including pulse oximetry assessment of orthodeoxia and, in some cases, pulmonary angiography, were performed. The sizes of shunts in the divers with decompression illness were compared with results obtained by the same method in 123 historical control divers who had not had decompression illness. (Some of the results from this population of normal divers have been presented previously as an abstract [26].)

Lung function tests were performed after contrast echocardiography and after determining the latency of symptoms (the interval between surfacing and the first neurological symptom). In 17 cases the late onset of symptoms was considered to exclude pulmonary barotrauma, and lung function tests were not performed. (Our current practice is to carry out lung function tests in all cases of neurological decompression illness.) The presence of lung disease predisposing to pulmonary barotrauma was assessed by spirometry, flow volume loops and chest X-ray in 83 cases. Evidence of small-airways disease was sought by examination of the flow volume loops, as described previously [8]. The reading of these tests was also performed blind to the history of decompression illness (i.e. before reading the referral letter, taking a history or examining the patient).

The series of dives leading up to the episode of decompression illness was then analysed for provocative events. The series of dives was considered to have started

after the last 48 h dive-free interval prior to the episode of decompression illness. A dive series was considered provocative if the diver had made a rapid ascent or had performed inadequate decompression stops (as required by the decompression table or computer he/she used for the dive series, or if computer malfunction led to missed stops) or there had been both rapid ascent and inadequate decompression stops. Divers were also asked about unusual events during the dives. A history of tobacco smoking was taken.

One of us (P.B.), who regularly treats divers with decompression illness, was responsible for determining whether the neurological injury was spinal, cerebral, both spinal and cerebral, or indeterminate. This categorization was based on pre-treatment symptoms and signs, and was performed blind to knowledge of the presence of right-to-left shunts or lung disease. It was also blind to dive profiles, except in the cases he had treated. In the majority of cases referred from his own centre, P.B. had examined the patients during their acute illness and he based his diagnosis on his own clinical records. In the other cases, information about presenting features was obtained from the notes made by the treating centre or the referral letter. Neurological injury was considered to be spinal if there was a sensory level, Brown–Sequard syndrome, unimodal (sensory or motor) involvement of both legs in combination with girdle discomfort or bimodal involvement of both legs with or without girdle discomfort. There was considered to be cerebral involvement if there was disturbance of higher functions (including a fit or syncope), vision or speech, cerebellar signs, or unimodal involvement of an arm and the ipsilateral leg. In some cases there were criteria for both spinal and cerebral involvement on either a single or different episodes. Other cases with mild signs or subjective symptoms, particularly where there was unimodal involvement of one limb without a clear demarcation, were considered to be indeterminate.

Results are expressed as medians and range or mean \pm S.D. as appropriate. Statistical comparisons were with the Chi-squared test and Student's *t*-test. Results were considered significant when $P < 0.05$.

The investigations performed on cases (contrast echocardiography and lung function tests) were part of normal investigations performed to enable divers to receive advice about future diving. All patients were specifically referred to one of us (P. W.) for these investigations by doctors outside his hospital, and they were performed in accordance with national recommendations as part of a clinical service. The hospital ethics committee approved the review and analysis of data for research purposes. Patients gave written consent to the review and analysis. The historical control subjects used for comparison of shunt size were part of a study published in abstract form which had ethics committee approval, and all gave written consent.

RESULTS

The 100 divers studied had 115 episodes of neurological decompression illness: two divers each had three episodes, eleven divers each had two episodes and 87 divers had a single episode. With regard to lesions, 24 divers had spinal lesions in 26 episodes, 54 divers had cerebral lesions in 66 episodes, 14 divers had spinal and cerebral lesions in 15 episodes, and eight divers had lesions at indeterminate sites in eight episodes.

Comparison of the prevalence and size distribution of shunts in divers with a history of neurological decompression illness and in controls

Figure 1 shows the prevalence and size of right-to-left shunts detected by the series of six contrast injections in divers with a history of neurological decompression illness and in unaffected control divers. A single injection detected large shunts in 41% of cases and in 4.9% of controls. The detection rates for large shunts were increased to 51% and 7.3% respectively by use of up to six injections. Whether one considered large shunts, large and medium shunts or all shunts, there were significantly more shunts present in the divers who had decompression illness than in the controls, and this difference existed irrespective of the number of contrast injections given (for each comparison, $P < 0.001$).

The size criteria used in the present study is an established grading method [25]. Unfortunately it failed to reflect the massive degree of right-to-left shunting seen in many of the individuals with neurological decompression illness. In many cases the number of bubbles shunting was impossible to count, but there were clearly many hundreds, if not thousands, of bubbles in the left heart on image frames.

Relationship between large and medium-sized right-to-left shunts and lesion site (spinal or cerebral) in divers with neurological decompression illness

In the analyses described below it was only in the 51 divers with large shunts and the one diver with a medium shunt that it was considered that paradoxical gas embolism might be the mechanism for decompression illness. The six divers with small shunts (*a priori* defined as clinically irrelevant shunts) were considered to have suffered decompression illness by other mechanisms. In five of the six cases other mechanisms were found (one each of lung disease, rapid ascent, lung disease with rapid ascent, missed stops, and rapid ascent with missed stops).

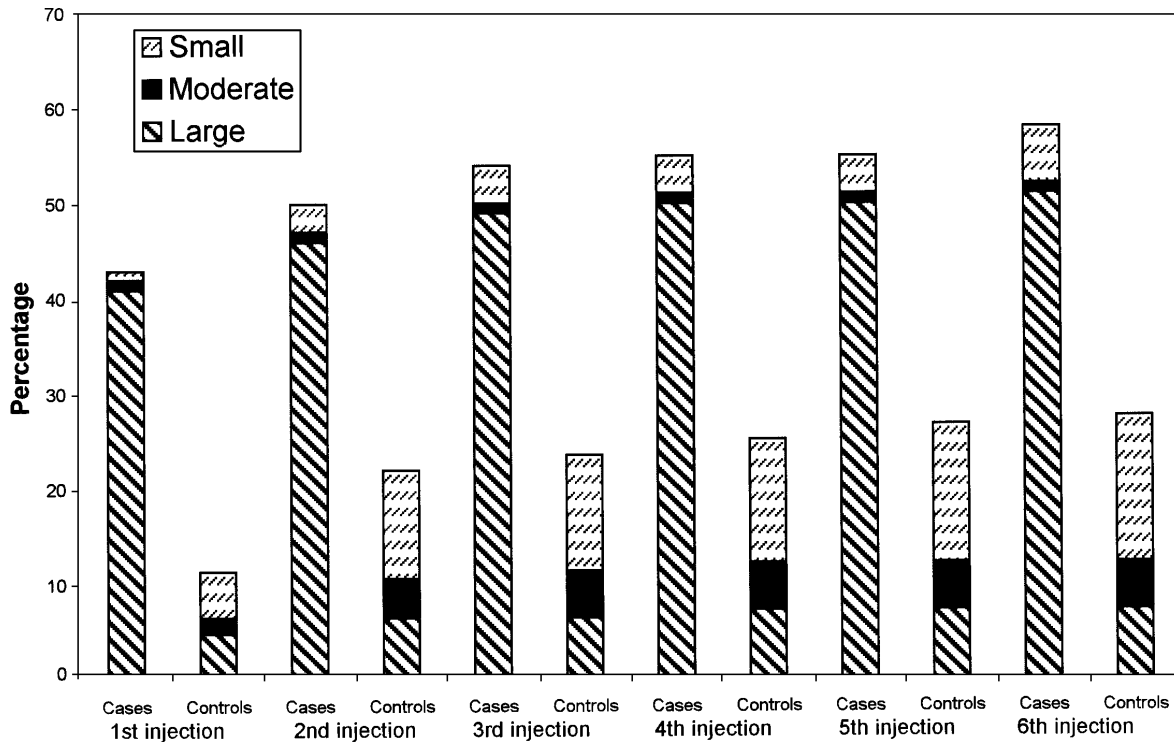


Figure 1 Comparison of prevalence and size of right-to-left shunts measured by contrast echocardiography in patients with neurological decompression illness and in controls

Up to six injections of contrast medium were performed.

Table 1 Relationship between causes of neurological decompression illness and lesion site

Cause	Spinal	Spinal and cerebral	Cerebral	Indeterminate	Total
No large or medium shunt					
Lung disease only	1 (9%)	2 (18%)	8 (73%)	0	11
Lung disease and rapid ascent	0	0	3 (100%)	0	3
Rapid ascent alone	0	1 (14%)	5 (71%)	1 (14%)	7
Rapid ascent and missed decompression stops	0	0	3 (75%)	1 (25%)	4
Inadequate decompression stops	2 (40%)	0	2 (40%)	1 (20%)	5
Unknown cause: short latencies	3 (25%)	3 (25%)	4 (33%)	2 (17%)	12
Unknown cause: long latencies	0	0	5 (83%)	1 (17%)	6
Total with no large or medium shunt	6 (13%)	6 (13%)	30 (63%)	6 (13%)	48
Large or medium shunt					
All divers	18 (35%)	8 (15%)	24 (46%)	2 (4%)	52
All divers	24 (24%)	14 (14%)	54 (54%)	8 (8%)	100

The sixth diver with a small shunt experienced symptoms 24 h after a dive to 12.2 m.

Table 1 shows the relationship between causes of neurological decompression illness and lesion site. Spinal decompression illness, with or without cerebral involvement, occurred in 26 out of 52 divers with large or

medium-sized shunts. In 22 cases with spinal lesions the shunt was large and present on the first contrast injection. Spinal involvement was significantly more frequent in divers with a clinically relevant shunt than in divers without. This was true whether comparisons were made of all six injections (26 out of 52 compared with 12 out of

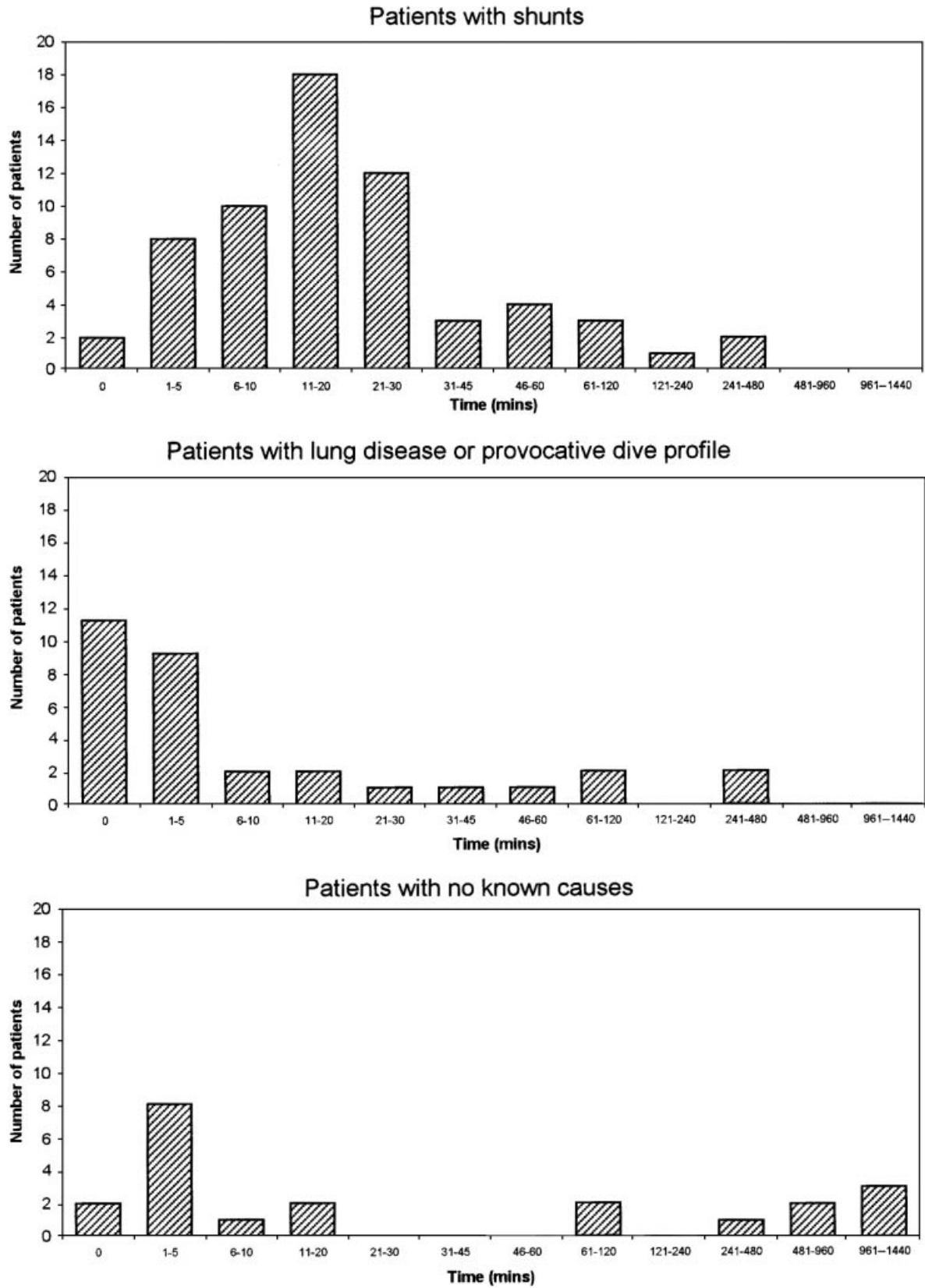


Figure 2 Time from end of dive to onset of symptoms of neurological decompression illness

Top, patients with shunts; middle, patients with lung disease or a provocative dive profile; bottom, patients with no known cause of decompression illness.

Table 2 Smoking habits of divers with decompression illness

Cause	Never smoked	Ex-smoker	Infrequent smoker	Daily smoker	Total
No large or medium shunt					
Lung disease only	4 (36%)	4 (36%)	0	3 (27%)	11
Lung disease and rapid ascent	2 (67%)	1 (33%)	0	0	3
Rapid ascent alone	6 (86%)	1 (14%)	0	0	7
Rapid ascent and missed decompression stops	4 (100%)	0	0	0	4
Inadequate decompression stops	4 (80%)	1 (20%)	0	0	5
Unknown cause: short latencies	5 (42%)	2 (17%)	0	5 (42%)	12
Unknown cause: long latencies	3 (50%)	1 (17%)	1 (17%)	1 (17%)	6
Total with no large or medium shunt	28 (58%)	10 (21%)	1 (2%)	9 (19%)	48
Large or medium shunt	35 (67%)	5 (10%)	4 (8%)	8 (15%)	52
All divers	63 (63%)	15 (15%)	5 (5%)	17 (17%)	100

48; $P < 0.02$), only for large and medium shunts seen on the first injection (22 out of 42 compared with 16 out of 58; $P < 0.02$) or for large shunts seen on the first injection (22 out of 41 compared with 16 out of 59; $P < 0.01$). (It was also true had small shunts been considered clinically relevant: 27 out of 58 compared with 11 out of 42; $P < 0.05$.) One diver with a large shunt suffered both spinal and cerebral decompression illness after a rapid ascent. No other diver with a large or medium shunt had any other risk factor for decompression illness.

In five cases with a clinically relevant shunt, bubbles appeared in the left heart late after opacification of the right heart, suggesting the presence of pulmonary arteriovenous fistulae. This diagnosis was supported by the presence of orthodeoxia on pulse oximetry in all cases and by cardiac catheterization in the two cases in whom this investigation was performed. Three of those with pulmonary shunts had spinal involvement.

The two divers who had neurological decompression illness (one spinal and one cerebral) after breathing nitrox at decompression stops (after deep trimix and deep air dives) and the diver with cerebral decompression illness after a dry hyperbaric chamber dive breathing air all had large shunts.

Associated non-neurological effects

A total of 13 divers with large shunts and two without shunts had associated non-neurological symptoms. Of the divers with shunts, 10 (including three with pulmonary shunts) had skin rashes, two had cardiorespiratory symptoms ('the chokes') and one had both a rash and cardiorespiratory symptoms. A diver without a shunt also had a skin rash, and another who made a rapid ascent had joint pain.

Latency of symptoms

In 30 cases, lung disease or an unsafe dive profile (rapid ascent or inadequate decompression stops, or both) were believed to explain the symptoms. In 18 cases there was no evidence of a significant shunt, lung disease or an unsafe dive profile. In Figure 2 the latency of symptoms is plotted for 63 episodes in 52 divers with clinically relevant shunts (top panel), 31 episodes in 30 divers with lung disease or an unsafe dive profile (middle panel) and 21 episodes in 18 divers where no predisposing factor was found (bottom panel). The time axis is not linear, but is plotted in a way that reflects the number preference displayed by many patients (particularly 5, 10, 15, 20, 30 or 45 min or number of hours after surfacing) and the skewed distribution of latencies. Zero latency was when divers reported symptoms during ascent or immediately on surfacing. It can be seen that, when divers had a shunt, the distribution of latencies was a skewed bell-shaped distribution, with a peak at 11–20 min (median 20 min), and only one case reporting symptoms immediately on surfacing. When divers had lung disease or an unsafe dive profile, the peak onset of symptoms was at time zero, with an exponential decline and a median 5 min after surfacing. When no predisposing factor was found the median latency was 5 min after surfacing, but it is clear that the data fell into two groups: 13 episodes in 12 divers with short latencies (0–20 min) and eight episodes in six divers with long latencies (2–24 h). These two subgroups were analysed separately.

The eight episodes in the cases without predisposing factors and with long latencies included the five episodes (out of 115) in which the latencies were greatest (mean 17.4 h; range 12–24 h). These five episodes were unusual in other respects: neurological abnormalities were entirely sensory, and only one was cured by recompression.

The maximum depths of the last dive preceding each of the eight long-latency episodes were remarkably shallow (13.3 ± 5.3 m). The maximum depths of the last dives preceding episodes were significantly greater in all other groups: 31.2 ± 10.2 m for divers with a clinically relevant shunt, 24.3 ± 6.9 m for divers with lung disease, 35.6 ± 6.6 m for lung disease plus rapid ascent, 27.1 ± 7.2 m for rapid ascent alone, 42.0 ± 16.8 m for rapid ascent and missed stops, 29.8 ± 16.2 m for inadequate decompression stops alone, and 26.4 ± 6.3 m for cases without predisposing factors and with short latencies.

Smoking history

Table 2 shows the percentages of daily smokers, infrequent smokers (defined as less than one cigarette each day on average), ex-smokers and those who had never smoked in each of the aetiology groups. There were significantly more smokers in the cases without predisposing factors and with short latencies than in the rest of the divers (five out of 12 compared with 12 out of 88; $P < 0.02$).

Events during dives

Three individuals with spinal lesions reported that they were stung by a jellyfish during the dive. In two cases there was positive identification of the lion's mane jellyfish (*Cyanea capillata*) and in the other the species was not identified. One of the three had a large right-to-left shunt present on the first injection of contrast. In the other two cases there was no shunt, lung abnormality or provocative dive profile. In two cases of neurological decompression illness, malfunctions of a decompression computer had occurred, and this may have been the cause of the illness.

Comparison of cases from the Hyperbaric Medical Centre with cases from other referral sources

Of the 35 cases referred from the Hyperbaric Medical Centre, 18 (51%) had significant shunts, seven had spinal lesions alone, 23 had cerebral lesions alone, three had both spinal and cerebral lesions and two had indeterminate lesions. These proportions were comparable with those in cases referred from other doctors.

DISCUSSION

Over half of the divers with neurological decompression illness in the present study had a large right-to-left shunt, and in most cases the shunt was detected with a single

contrast injection without the use of manoeuvres to accentuate shunting. This prevalence was considerably greater than in the control divers. Many of the divers with neurological decompression illness had very large shunts, with hundreds or thousands of bubbles shunting, but this was not seen in divers who had not had decompression illness. In the four divers from this series who had balloon sizing at the time of percutaneous transvenous closure, the mean atrial defect size was 12 mm (range 10–14 mm) [24]. A necropsy study of 965 human hearts where there had been no history of cardiovascular disease found that a patent foramen ovale was present in 263 (27.3%), but a defect 10 mm in diameter or larger was present in only 13 (1.3%) [17].

These data suggest that individuals with the largest right-to-left shunts across a foramen ovale, atrial septal defect or pulmonary arteriovenous fistula are at much greater risk of neurological decompression illness than individuals who have no shunt. The latter cannot suffer decompression illness by a mechanism involving paradoxical gas embolism. It is probable that individuals with a smaller shunt will have an intermediate risk, but other factors, including individual susceptibility to venous bubble nucleation and the dive profile on each occasion, will affect the risk for an individual. The majority of other episodes of neurological decompression illness could be explained by mechanisms that are not contentious, i.e. lung disease and unsafe dive profiles.

Symptoms of decompression illness occurred within 10 min of surfacing in 52 out of 115 episodes (45.2%) and within 1 h of surfacing in 97 episodes (84.3%). These percentages are comparable with the rates of 56.3% and 84.5% at 10 and 60 min after surfacing in a review of 1070 cases in the literature [27]. In the divers with lung disease or a provocative dive profile the peak time of onset of symptoms was immediately on surfacing, with an exponential decline. These latencies accord with our understanding of pathophysiology. A total of 22 episodes were attributed to lung disease or rapid ascent, or both. In such cases it is believed that pulmonary barotrauma and resulting gas invasion occurs during the ascent, and the onset of symptoms of arterial gas embolism occurs soon afterwards. In a few cases there may be delayed recognition of injury. Five episodes followed inadequate decompression stops. In these cases the pathophysiology is thought to be decompression sickness as a result of bubble formation *in vivo*. Bubble nucleation is delayed after decompression, with the most rapid onset of symptoms occurring when there has been the greatest deviation from a safe dive profile. Four episodes followed missed stops with rapid ascents; in those cases, either gas invasion or gas nucleation may have been responsible.

In divers with a shunt the distribution of latencies differed, with a delay after surfacing before symptoms started. This is consistent with data in pigs exposed to a provocative dive profile (rapidly decompressed after

30 min at 500 kPa) [9]. The maximum numbers of bubbles were detected in the pulmonary artery 5–30 min after surfacing, and animals with a patent foramen ovale had significantly more arterial bubbles, with the greatest numbers being detected between 15 and 30 min after surfacing [9]. In such circumstances, the manifestations of gas embolism should depend partly on the time after surfacing at which bubbles are present in the systemic arterial blood. Small amounts of arterial bubbles usually cause no symptoms in individuals who have tissue partial pressures of nitrogen lower than ambient pressure. In this circumstance small gas emboli to tissues dissolve rapidly without adverse effects. This is the situation during contrast echocardiography in patients with a shunt. Only when tissues contain dissolved gas (nitrogen in these cases) at a partial pressure greater than ambient pressure will bubble emboli be amplified to produce injury. The greater blood flow to the brain compared with the spinal cord means that when there are showers of bubbles in the arterial blood more will embolize the brain than the spinal cord. However, the greater blood flow means that the cortical grey matter has a much shorter nitrogen elimination half-life than the spinal cord: less than 1 min compared with 8 or 9 min [28]. If bubbles embolize during ascent, as occurs with pulmonary barotrauma, when brain and spinal cord are both supersaturated, symptoms will be determined by the greater emboli load to the brain. When there is a delay between surfacing and the arrival of bubbles in the arterial blood, as occurs when venous bubbles form and cross a shunt, the effects will often be determined not by the emboli load to a tissue but by the ability of tissues to amplify the bubbles by virtue of a greater amount of dissolved nitrogen. The dive profile will determine whether the spinal cord will be affected.

In our study group, 18 divers had 21 episodes of decompression illness for which there was no explanation using our criteria. There were two distinct groups, with short and long latencies: (1) 12 divers had 13 episodes with latencies of 20 min or less; and (2) six divers had eight episodes which started 2 h or more after surfacing, and five episodes in four divers started 12 h or more after surfacing; these were the most delayed onsets in any divers. These data suggest that there may have been different aetiologies in the two subgroups of divers in whom no cause was identified. In the first subgroup, the rapid onset (within 5 min in most cases) is compatible with pulmonary barotrauma. The depths of the dives performed were comparable with those for divers who had lung disease, but in this subgroup (by definition) lung function tests and chest X-ray were normal. This subgroup contained a higher proportion of daily smokers than the other diver groups. In this group the prevalence of smokers was also higher than the 17% prevalence found in the 1990 survey of British Sub-Aqua Club members (see [8]). These data extend observations of a

high prevalence of smoking in divers with onset of neurological symptoms soon after surfacing and no other explanation for their symptoms [8]. The lung function tests used may be insufficiently sensitive for detection of all forms of lung disease predisposing to pulmonary barotrauma. In particular, chest X-ray is less sensitive than computed tomography (CT) for detecting pulmonary bullae which predispose to pulmonary barotrauma in divers [29]. We have previously used a high-resolution CT lung scan to demonstrate a bulla in a diver who had neurological decompression illness soon after surfacing, had no right-to-left shunt and was unable to perform lung function tests because of residual paralysis [30]. Since the present study was completed, we have also seen a diver who smoked 30 cigarettes daily until 2 years before an episode of neurological decompression illness. Symptoms started immediately on surfacing. Contrast echocardiography, chest X-ray and lung function tests were normal. However, a CT scan of his lungs showed multiple bullae. These observations suggest that a CT scan of the lungs should be considered if a diver wishes to resume diving after an episode of neurological decompression illness starting on the ascent or soon after surfacing, when other tests for lung disease and right-to-left shunts are negative.

Six divers with no physical predisposition to decompression illness had eight episodes which started 2 h or more after surfacing from dives which were very conservative. Some of these episodes could have been the result of delayed recognition of mild symptoms. This is improbable. It is unlikely that venous bubble liberation would have occurred on any of the dives. It is possible that these episodes were a form of decompression illness with an unrecognized pathophysiological mechanism. It is also possible that these were coincidental neurological illnesses which were incorrectly labelled decompression illness because they occurred in the day after diving. The poor responses to treatment in this group supports such a view.

The findings in the present study have implications for divers who have suffered neurological decompression illness after dives during which a gas mixture with a high percentage of nitrogen was breathed. Such divers need careful evaluation to exclude right-to-left shunts and lung disease. If shunts are found, options include cessation of diving, and modifying future dive profiles and gases breathed to give a low risk of bubble formation or closure of the defect. The presence of lung disease requires cessation of diving, because even the most conservative dive profile can cause pulmonary barotrauma. If lung disease is suspected and basic lung function tests are normal, more sophisticated tests, such as CT scans, may be required. Episodes resulting from provocative dive profiles may require divers to be counselled about safer practices. Although the simplest approach would be to counsel all divers who have had neurological decom-

pression illness not to dive again, there are many divers who would not accept that advice.

These findings also have implications for diver selection. The increasing popularity of the sport makes screening all prospective divers for large shunts logistically difficult. If screening is performed, we have inadequate information to enable us to advise the 25% of prospective divers with medium or small shunts on their risk. It would be better to get all divers to follow decompression profiles with a low risk of bubble formation. This might also reduce the prevalence of brain lesions in divers with shunts who have not had decompression illness [31]. Unfortunately many divers would not agree to follow such conservative profiles. Divers should be advised not to smoke. If they are to be screened for lung disease, the most appropriate tests and frequency of testing are unclear.

These observations cannot necessarily be extrapolated to decompression illness where there has been a very different decompression profile or when gases with a low nitrogen content were breathed. They also raise questions about the assumptions used in production of decompression algorithms. We still need to explain why some divers with a shunt have experienced decompression illness after a theoretically innocuous dive profile when, on other occasions, more demanding decompression profiles did not affect them.

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