Original articles

Comparative incidences of decompression illness in repetitive, staged, mixed-gas decompression diving: is 'dive fitness' an influencing factor?

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Key words
Decompression diving, mixed gas, wreck diving, DCI rate, dive fitness, acclimatization

Abstract

(Sayer MDJ, Akroyd J, Williams GD. Comparative incidences of decompression illness in repetitive, staged, mixed-gas decompression diving: is 'dive fitness' an influencing factor? *Diving and Hyperbaric Medicine*. 2008; 38: 62-7.)
Wreck diving at Bikini Atoll consists of a relatively standard series of decompression dives with maximum depths in the region of 45–55 metres' sea water (msw). In a typical week of diving at Bikini, divers can perform up to 12 decompression dives to these depths over seven days; on five of those days, divers can perform two decompression dives per day. All the dives employ multi-level, staged decompression schedules using air and surface-supplied nitrox containing 80% oxygen. Bikini is serviced by a single diving operator and so a relatively precise record exists both of the actual number of dives undertaken and of the decompression illness incidents both for customer divers and the dive guides. The dive guides follow exactly the dive profiles and decompression schedules of the customers. Each dive guide will perform nearly 400 decompression dives a year, with maximum depths mostly around 50 msw, compared with an average of 10 (maximum of 12) undertaken typically by each customer diver in a week. The incidence of decompression illness for the customer population (presumed in the absence of medical records) is over ten times higher than that for the dive guides. The physiological reasons for such a marked difference are discussed in terms of customer demographics and dive-guide acclimatization to repetitive decompression stress. The rates of decompression illness for a range of diving populations are reviewed.

Introduction

In 1946, the United States initiated a series of nuclear weapon tests at the Bikini Atoll in the Marshall Islands. Over 12 years a total of 24 tests were carried out at Bikini with a cumulative explosive force of over 78.5 megatons (over 3,400 times the force of Hiroshima); the final test conducted there was in 1958. For the two initial tests, named "Able" and "Baker", a diverse range of vessels was used with the intention of measuring any differences in the effects of nuclear weapons on different types of naval and merchant craft. The Able test was an airborne delivery that exploded approximately 250 metres in the air above the fleet; Baker was submerged at 25 metres' sea water (msw) and was exploded subsurface. Both blasts were 23 kiloton detonations (identical to those detonated at Hiroshima and Nagasaki) but although some of the wrecks that still remain in the Bikini lagoon were either sunk during Able or scuttled because of the resulting level of damage, Able was largely ineffective and the majority of the present-day wrecks occurred as a result of the Baker blast. The book *For the Good of Mankind*, by Jack Niedenthal, gives a detailed description of the tests, the ships that were used, and the present-day wrecks as well as the fate of the Bikini islanders.[1]

The residual radiation levels on Bikini were considered to be safe for limited visits to begin in 1996. Almost immediately diving started on the wrecks there. The Bikini wrecks present some major challenges for recreational diving. All the wrecks lie at the bottom of the Bikini lagoon at relatively similar maximum depths of 50–55 msw. In addition, because of the remoteness of Bikini, the associated travel times, the single flight there per week and the consequential desire of the divers going there to dive as many of the wrecks as possible in a finite time, the weekly dive schedule that has developed is dominated by relatively deep, repetitive decompression diving. The necessary dive programme, which is described in more detail below, would certainly be outside that considered normal for recreational diving.

There are a number of issues that contribute toward making the diving situation at Bikini unique. Firstly, the diving operation there, which is run by the Bikini people themselves as the wrecks are now their property, is isolated totally from any other diving operators. There are occasional yachts that do make it to Bikini, but local bylaws insist that a Bikinian or a Bikini-trained dive guide must accompany all diving carried out in the lagoon. As such, the staff at Bikini Atoll Divers are able to record all the dives that are undertaken in the lagoon. Secondly, because of the significant decompression obligations that accumulate during a week's diving at Bikini, the dives tend to be undertaken in an extremely standard fashion, that is, the same dives are done at the same stage of the week and adhere to the same profiles. Therefore, the diving is replicated fully within and between the respective diving groups. The third aspect that makes this dataset of interest is that there are two very distinct diving populations, the paying customers and the dive guides, both of whom are undertaking the exact same dive profiles and diving programmes and who are incurring the exact same decompression obligations and dealing with them in exactly the same way. The only difference is that, whereas the customer divers are typically diving for a week, the dive guides may be repeating the same dive schedules for as many as 36 weeks in every year.

This account describes the procedures supporting the staged, mixed-gas decompression diving undertaken at Bikini in detail. It then describes the decompression illness (DCI) incident rate as a combined total before comparing the DCI rates between the two groups. Because the authors did not have access to the medical records describing the incidents that occurred at Bikini, the term 'DCI' has been employed throughout the account as there was no way of differentiating between the forms of dysbarism that presented.

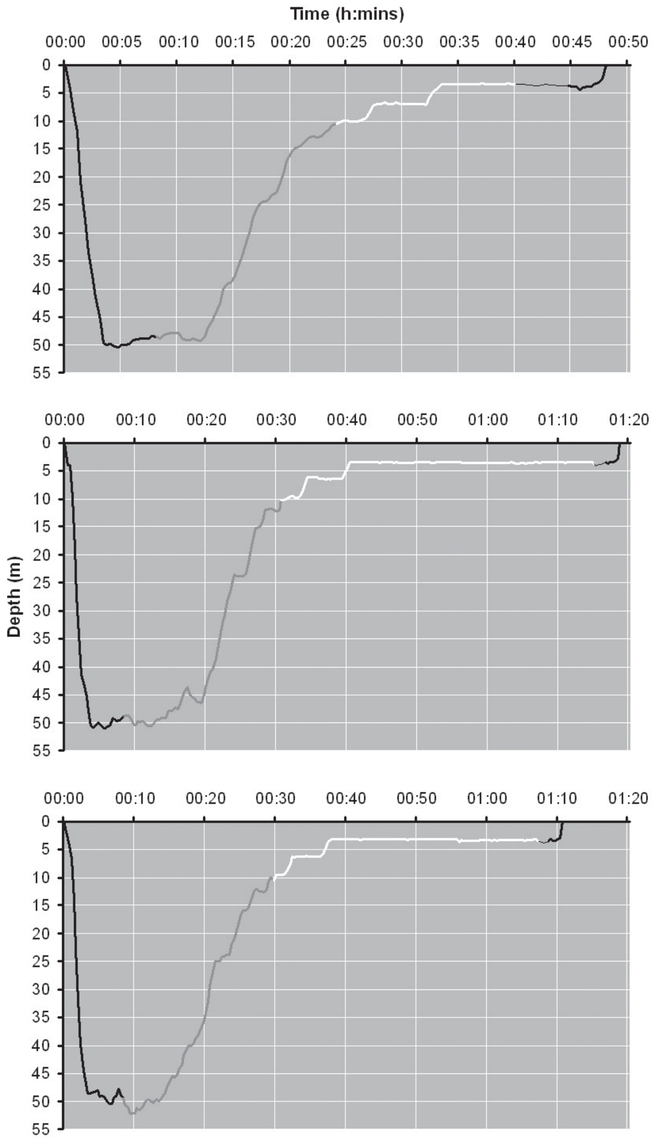
Staged, mixed-gas decompression diving at Bikini

Detailed records of diving trends at Bikini are available from 2004 to 2007. Diving at Bikini is available from the first week of March to the last week of November with a three-week break half way through the year. Therefore, in total, there are 36 diving weeks a year. In a typical week of diving at Bikini, divers perform up to 12 decompression dives: two single dives on days one and seven and five days of two decompression dives per day on days two to six. In order to maximise safety within the context of repetitive decompression diving, and to minimise the decompression obligations, a multi-level, staged air and nitrox decompression schedule is employed.

Selected dive profiles from a series of typical Bikini dives are shown in Figure 1. The area of the Bikini lagoon where most of the dive sites are has a relatively consistent maximum water depth of 50–55 msw. Many of the points of interest are at or near to the seabed and so a significant proportion of the majority of dives undertaken in a week is at depths of 50 msw or greater. When diving at those depths breathing air, one's dive computer will start to register a decompression obligation after approximately 10 minutes of dive time; ascents are initiated typically after 13–20 minutes' bottom time (Figure 1).

The bottom times employed are dictated by the maximum depth of the points of interest, the number of such points, and the size and attitude of the ship. The final ascent tends to occur at or just over 30 minutes into the run time of the dive (Figure 1). The decompression schedule starts at depth on air and is then completed shallower than nine metres by using surface-supplied nitrox with oxygen content of 80%. The minimum decompression schedule, irrespective of what divers' own dive computers may indicate, for every

Figure 1
Three dive profiles undertaken at Bikini (redrawn from data downloaded from a Mares NEMO™ dive computer). Top profile – dive six of a series, second dive of the day; middle profile – dive seven, first dive of the day; bottom profile – dive nine, first dive of the day. Thick black lines – breathing air and no decompression required; grey lines – breathing air, computer registering decompression required; white lines – breathing 80% nitrox, computer registering decompression required; thin black lines – breathing 80% nitrox and no decompression required.



decompression dive at Bikini is shown in Table 1. This involves stops at 24 and 12 msw on air, before performing the nitrox phase of the decompression from 9 msw to the surface. The nitrox phase is conducted with the aid of a multi-level decompression trapeze (with horizontal bars set at 9, 6 and 3 msw) supplied with surface-supplied 80% nitrox with sufficient take offs for all customer divers and dive guides. If a diver's computer indicates additional decompression the diver would undertake this, but if the decompression indicated is below the minimum then the diver defaults to the 'Bikini schedule'. This schedule does not differ markedly from standard air decompression tables in terms of total time when considering a single square-profile dive irrespective of the gas mixtures being employed. However, the Bikini schedule produces a slower 'deep stop' type of ascent profile compared with navy-style tables that maximise time spent at 9, 6 and 3 msw (Table 1).

In recent years at Bikini, most divers have chosen to manage their decompression obligation by using models of dive computers that are capable of being initially set to air but which can then be switched to nitrox during the staged decompression phase of the dive; this can reduce the decompression obligation markedly. Alternatively divers can choose to keep their dive computers set in air mode but employ nitrox during the decompression phase to reduce the risk of DCI. If divers switch their computers to nitrox for the decompression phase then they have to re-set them to air before surfacing.

The main concentration of wrecks within the Bikini lagoon is in close proximity to the dive centre on the main island. As a consequence, the short transfer times between dive sites and the shore mean that surface intervals greater than four hours can be easily accommodated within a normal diving day. In addition, safety is further promoted through a series of comprehensive dive briefings that ensure that divers know the exact time for departing the bottom of the dive as well as the minimum decompression schedule. The dive equipment configurations employed promote redundancy as well as surfacing with air reserves that are adequate to complete decompression obligations even if the surface-deployed trapeze is missed. Typically divers dive with twin 13-litre steel cylinder rigs compressed to 220 bar; divers are instructed to leave the bottom with no less than 140 bar remaining. Finally, divers are advised to pay special attention to their hydration levels during diving activities.

Results

Although there is the potential to undertake 12 dives per week, in reality issues with missed dives caused by transfer delays and missed diving because of illness or for increased safety mean that the average number of customer dives is closer to 10 per week. Dive parties average 10 in number and are always split into two groups, and two dive guides will always dive with each group meaning that all four dive guides will dive an average of 11 decompression dives a week, for 36 weeks.

Over the four years that data have been collated, there have been 27 incidents of presumed DCI in total. With the lack of any medical examination or confirmation by recompression, there remains a level of doubt as to whether all catalogued cases were actually DCI. Conversely the poor communications at Bikini make any follow up near impossible and so there may have been further incidents during airborne flights home. For this study, it is assumed that incorrect diagnoses balance unreported incidents and so the DCI total comprises 26 incidents in the customer-diver group and one incident in the dive-guide group.

Of the total of 27 incidents, only five required evacuations by air to recompression facilities at the earliest opportunity; the five cases that were evacuated all had a neurological component with vestibular manifestations. Air evacuation was either by specially arranged flights from the Marshall Islands airline or by the US military. Specialist treatment and recompression was received either at the Kwajalein military base or, following onward transfer, at Guam or even

Table 1
Minimum decompression schedule for decompression dives at Bikini (see text for explanation). Also shown are the air decompression schedules for three 54 msw dives on the RNPL11 tables[2] modified to fit the same format (BT – bottom time).

Bikini decompression schedule			RNPL11 decompression table[2]		
			54 msw	54 msw	54 msw
Depth (msw)	**Time** (min)	**Gas breathed**	BT 10 min	BT 15 min	BT 20 min
24	2	air			
24–12	2	air			
12	2	air			
12–9	1	air			
9	2	EANx80		5	5
9–6	1	EANx80		1	1
6	5	EANx80	5	4	9
6–3	1	EANx80	1	1	1
3	10	EANx80	9	14	14
3–0	1	air	1	1	1
Total deco	27		16	26	31
Deco at ≤ 9 msw	20		16	26	31

Table 2
Rates of DCI recorded at Bikini, 2004–2007, in total and for two diver groups: customers and dive guides. Sample numbers: Customers – 1440 divers; Guides – 8 divers

	Average divers per week	Dives per diver per week	Total person dives per year	Total person dives in four years	Cases of DCI in four years	DCI rate per 1,000 person dives
Customers	10	10.0	3,600	14,400	26	1.81
Guides	4	11.0	1,584	6,336	1	0.16
Total	14	10.3	5,184	20,736	27	1.30

Honolulu. No emergency evacuations took place sooner than 16 hours after the onset of symptoms and most took place over 24 hours after; the divers were tended during that time under the supervision of the dive guides with medical guidance obtained by radio-link. The other 22 divers treated had relatively minor symptoms that were predominantly cutaneous DCI. They were treated on-island with vigorous hydration and normobaric 100% oxygen and departed the island as scheduled. Medical records or follow-up accounts were not available to this present study; no diving fatalities were recorded. None of the cases of DCI resulted from physical diving accidents, equipment malfunction or missed decompression. Therefore, all could probably be described as cases of decompression sickness (DCS).

Excepting the caveats on the denominators and the accuracy of diagnosis, expressed in terms of DCI events per 1,000 person dives, the presumed total rate for diving at Bikini is 1.30 (Table 2). Split into the two groups, customer divers had a DCI rate of 1.81 per 1,000 person dives; the dive guides had a rate of 0.16 (Table 2).

Discussion

The present study gives an overall estimated DCI incident rate of 1.30 per 1,000 person-dives (customers 1.81, dive guides 0.16). However, the dive-guide rate was calculated based on a single DCI event; approximately 1,440 divers contributed to the customer DCI value whereas only eight dive guides were employed during the four years of the study. It is likely, therefore, that the total and customer incident rates will be more representative of the performance of the respective populations.

Although the exact number of dives is not available for this study, and the lack of precise medical diagnosis and/or recompression in some cases means that some of the incidence of DCI must be presumed, the study remains notable because the decompression incidence rate for customer divers is markedly higher than that for the dive guides. This is so despite the two populations performing the exact same dives, and incurring and contending with the exact same decompression obligations using the exact same decompression theory and practices. Of note, however, is that all the cases of DCI could be described as pathophysiological in that none occurred through physical diving accidents. The obvious conclusion is that the two populations of divers are physiologically different when it comes to contending with significant decompression commitments.

There are many ways to explain the differences in performance between the two groups, but these can be distilled into two main influencing factors. Firstly, it cannot be assumed that the two groups are physically similar. Physical factors that are known to influence the incidence of decompression sickness (which is most likely the primary form of DCI occurring at Bikini) include gender, age, physical ability and body mass.[3,4] Although not measured, it is possible that the financial cost of getting to and spending a week diving at Bikini, plus the age of the associated history, may attract a more aged population of divers that may be less likely to be of optimal physical fitness. Conversely, the vocation of dive guide tends to attract a younger population that are more likely to be closer to their optimum fitness. However, it is unlikely that these differences alone explain a ten-fold difference in decompression incident rates.

The second major influencing factor, and possibly the more important one, is that of physiological acclimatization. Many studies have long noted that repetitive and recent exposure to pressure reduces the likelihood of developing DCS.[3–9] Even more pertinent to the present study is the suggestion that although the risk of decompression sickness may decline over prolonged series of pressure exposures (as would occur with the dive guides in this study), there is possibly elevated risk early in multi-day diving series (corresponding to the diving customers).[9]

Although a physiological basis of acclimatization is unknown, several theories have been put forward.[9] For example, the decomplementation or depletion theory suggests that small amounts and sizes of bubble generation produced during regular repetitive diving may disrupt the complement system of the blood plasma protecting tissues from larger bubble formations that may occur in subsequent dives.[10] Alternatively, the induction theory postulates that the bubbles generated during earlier dives may cause stresses in tissues and precondition them to subsequent or repeated bubble formation.[11,12] In any event, numbers of detectable bubbles in divers have been recorded to decline over the first 6–8 days of multi-day diving supporting suggestions that DCS is more likely to occur during the first few days of diving operations and following lay-off periods of a week or more.[3,4,9] Both are trends that would include the vast majority of the customer divers who may either not be regular divers or not have dived for several days because of the duration of travel required to get to Bikini.

A review of published DCI/DCS rates (the studies vary in how they report DCS, DCI or both) shows a considerable range from 0.00 to 9.55 incidents per 1,000 dives (Table 3). The rates reported in the present study (0.16, 1.30 and 1.81) fall within the previously published range. The present study is lacking in that the exact number of dives undertaken is estimated and that the decompression incidents can only be presumed in the absence of medical records and/or trial by recompression. However, the same will also be true for many of the studies included in Table 3 and the figures quoted are considered to be largely representative of decompression incidence trends for different diving sectors. Although incident rates at or above 1.00 per 1,000 dives are toward the higher end of the overall range, there can be no doubting that the multi-day decompression wreck diving undertaken at Bikini lies at the more challenging end of the recreational scope. As such, these rates deserve to be ranked against comparable diving groups, diving techniques or diving depths.

Probably the closest study to the present one was conducted on recreational groups diving the wrecks of some of the interned World War One German High Seas Fleet scuttled in 1919 at Scapa Flow in the Orkney Islands in Scotland; estimates of DCI rates in that study ranged from 0.25 to 0.49 per 1,000 dives.[17] Although the maximum depths at Scapa Flow are shallower than Bikini (35–45 msw compared with 45–55 msw), the effects of this depth difference could be offset in part by the influence of the differences in temperature (approximately 6–14°C in Scapa compared with 26–29°C in Bikini) or even effects caused by the differences in the availability of alcohol (alcohol is restricted in Bikini whereas Scapa is in Scotland![29]). Previous studies have all noted the contributing effects of greater water depths, lower water temperatures and alcohol consumption to increased DCS risk.[3]

However, in other comparisons, the headline rates at Bikini compare better: DCI/DCS incident rates for US Navy deep air diving trials to 150 feet sea water (fsw) were much higher at 9.55 per 1,000 dives (although in that study DCI/DCS was not being categorized by medical staff);[13] rates for scuba divers working at 100–165 fsw on oil platforms in the Arabian Gulf were 1.03 per 1,000 dives.[16] In addition, those two studies involved divers who were more likely to be acclimatized to the diving.

With only a single reported occurrence of DCS in the dive guide group (a case of apparent cutaneous decompression sickness) it is not possible to make any firm comparisons of incident rates with other diving populations. Nevertheless, the consequential rate of 0.16 incidents per 1,000 dives for the Bikini dive guides is within the range for general recreational diving (Table 3) and is well below the rates discussed above for deeper and/or wreck diving. In addition, some of the studies summarised in Table 3 report fatality rates (not shown); no fatalities were recorded in the present

Table 3
Published DCI /DCS rates per 1,000 dives, including the present study. Rates in parentheses have been calculated based on a single incident of DCI/DCS. The retrospective definitions of DCI and DCS vary between authorities and may not necessarily include a recompression.

Type of diving	DCI/DCS incidence per 1,000 'dives'*	Reference
US Navy: deep air diving (150 fsw)	9.55	13
UK commercial offshore air diving (1982–86)	3.06	14
UK commercial offshore air diving (1987–88)	1.49	14
US Navy: 4th quartile of no-stop time (USN57)	1.28	15
Commercial (oil platform) scuba 100–165 fsw	1.03	16
Commercial (oil platform) all diving 165 fsw+	(0.76)	16
UK multi-dive multi-day wreck diving	0.25–0.49	17
Tropical multi-dive multi-day	0.29–0.33	18
US Navy shallow no-stop air diving	0.29	15
US Navy: 1st quartile of no-stop time (USN57)	0.22	15
Overseas US military community	0.14	19
Commercial (oil platform) all diving 30–99 fsw	0.14	16
West Canada amateur scuba	0.10	20
Caribbean amateur scuba	0.09	21
UK recreational/amateur divers	0.07	22
UK scientific diving	(0.06)	23
Japan recreational scuba	0.05	24
US scientific diving	0.05	25
International scientific diving	0.04	26
US scientific diving (1998–2005)	0.02	27
Australian scientific diving	0.00	28
Multi-day decompression diving 45–55 msw (all)	1.30	This study
Multi-day decompression diving (customers)	1.81	This study
Multi-day decompression diving (guides)	(0.16)	This study

* Dive is assumed to be a 'person dive', but not all studies make this clear

study. The DCI rate reported here plus the lack of fatalities illustrates, therefore, that the type of deep, multi-day, staged, mixed-gas decompression diving that has evolved at Bikini since it was opened for diving can be undertaken with safety rates that are comparable to other diving sectors operating less challenging diving programmes. It is most probable that factors such as physical fitness and diving acclimatization are contributing to the higher incidences of DCI being recorded for the diving group as a whole.

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