

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

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Abstract

Wreck diving at Bikini Atoll consists of a relatively standard series of decompression dives with maximum depths in the region of 45-55 metres. 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 perform two decompression dives per day. All the dives employ multi-level staged decompression schedules using air and surface supplied nitrox with 80% oxygen. Bikini is serviced by a single diving operator and so an accurate record exists both of the actual number of dives undertaken and of the incidence of decompression illness both for the customer divers and the dive guides. The dive guides follow the exact same dive profiles and decompression schedules as the customers. Each dive guide will perform over four hundred decompression dives a year with maximum depths mostly around 50m compared with the 12 dives undertaken typically by each customer diver. The decompression illness (DCI) incidence rate for the customer population is over ten times higher than that for the dive guides. The physiological reasons for such a marked difference are discussed; the DCI incidence rates for a range of diving populations are reviewed.

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

Introduction

In 1946 the United States initiated a series of nuclear weapon tests at 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 3400 Hiroshimas); the final test conducted there was in 1958. For the two initial tests, named “Able” and “Baker”, a number of ships and submarines were moored in the lagoon. These vessels tended to be craft that had seen active service in World War II and had sustained significant levels of damage rendering them redundant of further military use or were superfluous or were just of an age that made them outmoded. 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 two blasts that used the target fleet differed in that the Able test was an airborne delivery that exploded approximately 250 metres in the air above the fleet; Baker was submerged at 25 metres and was exploded subsurface. Both blasts were 23 kiloton detonations 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 subsequent Baker blast. The book “For the Good of Mankind”, by Jack Niedenthal, gives a detailed description of the tests, the ships that were used, the present day wrecks, as well as the fate of the Bikini islanders¹.

The residual radiation levels on Bikini were considered to be safe for limited visit periods to begin in 1996. Almost immediately diving started on the wrecks there. The Bikini wrecks present some significant challenges for recreational diving. All the wrecks lie at the bottom of the Bikini lagoon at relatively similar maximum depths of 50-55 metres. 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 in a finite time, the weekly dive schedule that developed would have to be dominated by relatively deep repetitive diving. The necessary dive programme would certainly be outwith that considered normal for recreational diving. Over time, a weekly diving programme developed that was based

around staged decompression employing surface supplied nitrox during the shallower stages (10 metres and less). That programme is described in more detail below.

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 the property of the Bikini people, 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 the 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, who 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) incidence 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, DCI has been employed throughout the account as there was no way of differentiating between the forms of dysbarism.

Staged mixed gas decompression diving at Bikini

In a typical week of diving at Bikini, divers perform up to 12 decompression dives each: two single dives on days 1 and 7 and then five days of two decompression dives

per day on days 2 to 6 (e.g. Table 1). 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.

A series of typical Bikini dives is shown in Figure 1. In general, the points of interest and how the ships or planes came to rest on the seabed follow the nuclear blasts dictate the depth/time profiles of the dives. The area of the Bikini lagoon where most of the dive sites are has a relatively consistent water depth of 50-55 metres. 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 metres or greater. At those depths breathing air, the non-decompression part of the dive will be over within the first 10 minutes of the dive; after that the dive will become a decompression dive (Figure 1).

The bottom times employed are dictated by the maximum depth of the points of interest and the number of points / the size of the ship, but tend to be in the region of 30 minutes into the run time of the dive (Table 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 that divers are advised to complete at the end of every dive at Bikini is shown in Table 2 and involves stops at 24 and 12 metres on air before performing the nitrox phase of the decompression from 9 metres and shallower. The nitrox phase is conducted with the aid of a multi-level decompression trapeze (with horizontal bars set at nine, six and three metres) supplied with surface-supplied 80% nitrox with sufficient take offs for all customer divers and dive guides.

In recent years at Bikini, the method that most divers choose to manage their decompression obligation is 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 220bar; divers are instructed to leave the bottom with no less than 140bar remaining. Finally, divers are advised to pay special attention of hydration levels for all dives.

Incident rates

Detailed records of diving trends at Bikini are available for the past four years (2004-2007). 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. On average, the number of customer divers per week at Bikini is 10; each customer diver will, in general, complete 12 dives per week. Dive parties are always split into two groups and two dive guides will always dive with each group meaning that all four dive guides will dive 12 decompression dives a week for 36 weeks.

Over the four years that data have been collated, there have been 27 incidents of DCI in total. This total comprises of 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. The other 22 had minor symptoms that were predominantly cutaneous DCI and were treated on island with vigorous hydration and normo-baric 100% oxygen before recovering completely and/or leaving on scheduled flights. Medical records or follow-up accounts were not available to this present study.

Expressed in terms of DCI events per 1000 person dives, the total rate for diving at Bikini is 1.12 (Table 3). Split into the two groups, customer divers had a DCI rate of 1.50 per 1000 person dives; the dive guides had a rate of 0.14 (Table 3).

During the reporting period there were no diving fatalities. In addition, none of the cases of DCI resulted from buoyancy-related diving accidents, equipment malfunctions or from missed decompression. Therefore, all could be described as cases of “physiological DCI”.

Discussion

The present study gives an overall estimated DCI incident rate for multi-day deep decompression diving of 1.12 per 1000 person dives. Split into the two diving groups, customer divers had a DCI rate of 1.50 per 1000 person dives but dive guides only 0.14. Although the total and customer incident rates were based on 27 and 26 cases of DCI respectively, the dive guide rate was calculated based on a single DCI event. It is likely, therefore, that the total and customer incident rates will be more representative of the performance of the respective populations.

Where this study is of note is that the DCI incidence rate for customer divers is over ten times higher than that for the dive guides, even though the two populations are performing the exact same dives, and incurring and contending with the exact same decompression obligations using the exact same decompression theory and practices. Of further note is that all the cases of DCI could be described as physiological in that none occurred through buoyancy-related accidents and/or equipment failures. The obvious conclusion, therefore, is that the two populations of divers are physiologically different when it comes to contending with significant decompression commitments.

There are many reasons that could be employed 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 mass². 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 are capable of explaining a ten times difference in DCI rates. The second major influencing factor in the present study, and possibly the more important one, is that of physiological acclimatization. Many studies have noted that repetitive and recent exposure to pressure reduces the likelihood of developing DCS^{2,3}. There are two main theories as to why acclimatization or adaptation may occur. The decompensation 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 protects tissues from larger bubble formations that may occur in subsequent dives⁴. 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^{5,6}. In any event, it is considered that DCS is more probable during the first week of diving operations and following lay-off periods of a week or more² which would include the vast majority of the customer divers who either may not be regular divers or who may not have dived for several days because of the travel required to get to Bikini.

There are other potential differences between the two groups that may enhance the disparity of the two rates of DCI but cannot account for it in total. For example, it cannot be discounted that the diving psychology of the two groups differs which may lead to over-reporting in the customer group (anxiety regarding the amount of deep diving being undertaken) and under-reporting in the dive guides (a reluctance to admit DCI or dismissal/denial of symptoms). Customer divers from other geographical regions and time zones may not be so tolerant of the climatic conditions at Bikini as the dive guides. Finally, it is likely that the customer group will include divers with diverse and unreported medical conditions (*e.g.* hypertension, diabetes etc.).

A review of published DCI/DCS rates (the studies range in how they report DCS, DCI or both) shows a considerable range from 0.00 to 9.55 incidents per 1000 dives (Table

4). The rates reported in the present study (0.14, 1.12 and 1.50) fall within the previously published range. Although incident rates at or above 1.00 per 1000 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 WWI German High Seas Fleet scuttled in 1919 at Scapa Flow in the Orkney Islands in Scotland¹⁰; estimates of DCI rates in that study ranged from 0.25 to 0.49 per 1000 dives. Although the maximum depths at Scapa Flow are shallower than Bikini (35-45m compared with 45-55m), the effects of this depth difference could be offset in part by the influences 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 Scotland²¹). Previous studies have all noted the contributing effects of greater water depths, lower water temperatures and alcohol consumption to increased DCS risk *e.g.*². However, in other comparisons, the headline rates at Bikini compare better: DCI/DCS incident rates for US Navy deep air diving trials to 150 fsw were much higher at 9.55 per 1000 dives⁷ (although in that study DCI/DCS was not being categorized by medical staff); rates for SCUBA divers working at 100-165 fsw on oil platforms in the Arabian Gulf were 1.03 per 1000 dives⁹. In addition, those two studies involved divers who were more likely to be acclimatized to the diving.

Comparisons between the incidence rates presented in this study and other published rates (Table 4) are compromised to some extent by the fact that no episodes of DCI at Bikini were caused by obvious diving accidents. Very few of the studies summarized in Table 4 detail the factor that had caused the problem. However, other studies that do analyse factors that have contributed to DCI tend to suggest that, in recreational divers, as many as 38-50% of all reported cases may be caused to some degree by loss of buoyancy control^{22, 23}. Both of those studies are dominated by dry-suit diving which may present more challenges to controlled buoyancy. That notwithstanding, subtractive extrapolation suggests that less than half of the incidents contributing to some of the rates summarized in Table 4 may have been physiology-only compared with the present study where all the cases were physiology-only. It is almost certain

that buoyancy problems have been controlled at Bikini through descents and ascents occurring on fixed moorings. However, the diving at Bikini is dominated both by depth, decompression and multi-day, repetitive diving; many studies identify strong links between these factors and increased risk of DCI ^{e.g.2, 9, 22, 23.}

With only a single reported occurrence of DCS in the dive guide group (a case of cutaneous decompression sickness) it is not possible to make any firm comparisons of incident rates between other diving populations. However, the consequential rate of 0.14 incidents per 1000 dives for the Bikini dive guides is within the range for general recreational diving (Table 4) and is well below the rates discussed above for deeper and/or wreck diving. In addition, some of the studies summarised in Table 4 also report fatality rates (not shown); no fatalities were recorded in the present study. Accepting that the rates for the present study may under-estimate in comparison with other studies because of domination by physiology-only causes, the DCI rate reported here plus the lack of fatalities illustrates 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 safely rates that are comparable to other diving sectors operating less challenging diving programmes (Table 4). It is 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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Table 1: A typical weekly dive programme undertaken at Bikini Atoll by both the customer divers and the dive guides. All the dives are decompression dives; the surface intervals on days with two dives is a minimum of 4 hours.

Day	Dive #	Max depth (m)	Bottom Time (mins)	Run Time (mins)
1	1	35	45	60
2	2	49	30	75
	3	40	35	75
3	4	53	30	80
	5	50	30	90
4	6	52	30	80
	7	53	45	110
5	8	49	30	80
	9	50	30	95
6	10	55	30	110
	11	50	30	95
7	12	37	45	80

Table 2: Typical minimum decompression schedule for every decompression dive undertaken at Bikini Atoll by both the customer divers and the dive guides.

Depth (metres)	Time (minutes)	Gas breathed
24	2	air
24-12	2	air
12	2	air
12-9	1	air
9	2	EANx80
9-6	1	EANx80
6	5	EANx80
6-3	1	EANx80
3	10	EANx80
3-0	1	air

Table 3: The rates of DCI recorded at Bikini over the years 2004-7 presented in total and for the two diver groups: customers and dive guides.

	Divers per week	Dives per diver per week	Diving weeks per year	Total man dives per year	Total man dives in four years	Cases of DCI in four years	DCI rate per 1000 dives
Customers	10	12	36	4320	17280	26	1.50
Guides	4	12	36	1728	6912	1	0.14
TOTAL	14	12	36	6048	24192	27	1.12

Table 4: A summary of a review of published DCI /DCS* rates per 1000 dives with additional rates from the present study. Rates in parentheses have been calculated based on a single incidence of DCI/DCS.

Type of diving	DCI/DCS incidence per 1000 “dives” **	Reference
US Navy: deep air diving (150 fsw)	9.55	7
US Navy: 4 th quartile of no-stop time (USN57)	1.28	8
Commercial (oil platform) SCUBA 100-165fsw	1.03	9
Commercial (oil platform) all diving 165fsw+	(0.76)	9
UK multi-dive multi-day wreck diving	0.25-0.49	10
Tropical multi-dive multi-day	0.29-0.33	11
US Navy shallow no-stop air diving	0.29	8
US Navy: 1st quartile of no-stop time (USN57)	0.22	8
Overseas US military community	0.14	12
Commercial (oil platform) all diving 30-99fsw	0.14	9
west Canada amateur SCUBA	0.10	13
Caribbean amateur SCUBA	0.09	14
UK recreational / amateur divers	0.07	15
UK Scientific diving	(0.06)	16
Japan recreational SCUBA	0.05	17
US Scientific diving	0.05	18
International scientific diving	0.04	19
Australian scientific diving	0.00	20
Multi-day decompression diving (all)	1.12	This study
Multi-day decompression diving (customers)	1.50	This study
Multi-day decompression diving (guides)	(0.14)	This study

* Some studies are specifically DCS; some are specifically DCI; some do not make the distinction

** Dive is assumed to be a “person dive” but not all studies make this clear.

Figure 1: A typical series of dives undertaken at Bikini to maximum depths of 47-53m. The profiles show air diving undertaken with no decompression obligation (blue); air diving with decompression (pink); and nitrox 80 decompression (green). These profiles were undertaken using air decompression schedules but employing nitrox 80 for additional risk reduction; some decompression at 3 metres employed air after nitrox (green followed by pink).

