Original articles

Analysing dive-computer profile integrations from incidents of suspected and actual decompression illness using cumulative nitrogen loading

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Key words
Decompression illness, computers diving, nitrogen, models, treatment

Abstract

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The depth/time data derived from the dive computers of 48 divers presenting with actual or suspected decompression illness at the Dunstaffnage Hyperbaric Unit near Oban, on the west coast of Scotland, were integrated using pressure-dependent algorithms that generated totals of nitrogen loading. The profiles of dives that preceded the incident dives were also integrated and nitrogen penalties were added to the incident totals as dictated by surface-interval durations using half-life values of either two or four hours. The final matrix of totals was compared with the no-stop square-wave profiles for the BSAC/RNPL 11 tables using the published ascent and descent rates. The nitrogen loading index was derived when expressed as a proportion of the no-stop values at the same maximum or average profile depth indices. The calculation of the nitrogen loading index permitted direct comparison of multi-level, computer-controlled dive profiles with simple depth/time tables. The profiles were analysed by three sub-categories whereby the incident dive was (a) part of a multi-dive series, (b) had an ascent rate that generated a rapid ascent warning, and/or (c) was deeper than 35 metres' sea water. In general, the presenting group tended to exceed the no-stop table values when the analyses employed maximum depth of the incident dive, used a 4-hour half-life for calculating penalties from the preceding dive(s), and the incident dive was part of a multi-dive series and/or was deep. There were no significant relationships between any of the variables examined and the extent of hyperbaric oxygen treatment received.

Introduction

The majority of recreational divers presenting to hyperbaric treatment centres for recompression therapy rely on dive decompression computers as their primary method of decompression calculation.[1] Many dive decompression computers have a facility to store dive-profile information at varying levels of resolution and duration.[1–3]

The ability to download dive-computer information from patients presenting to recompression chambers gives the treating physician an indication of the nature of the incident dive and the preceding dive history. This can be of assistance where the diver is confused or has no physical record of the dive history. Often, within the limitations of the respective computer logging regimes, the dive profile can show an exaggerated record of the patient's perception of the incident dive.[2] However, although the treating party gains a visual representation of the incident dive or dive series and is presented with an electronic record of the preceding dive history, unless there is a very obvious indicator of what has caused the incident (e.g., a rapid and uncontrolled ascent from depth) it can be difficult to relate the given profiles to the severity of presentation. The treatment of divers who present with dive computers that can be interrogated must be one of the few areas of medicine whereby the physician can access such a detailed and accurate record of the incident(s) that has caused the illness. However, few studies have investigated these profiles in detail within the context of the eventual treatment regimes.

Diving activities that base their decompression calculation on dive computers tend to generate a different dive profile than diving operations at work or controlled by decompression tables. Because computers continuously re-calculate the decompression schedule based on the ongoing depth changes, they allow for extended-duration diving to be undertaken if the majority of the dive is carried out in water shallower than the maximum depth reached. This contrasts with most decompression tables where a single, maximum depth value is used in the calculation.[3–6] It could be assumed that regimes of single- or multi-day diving that undertake one or more multi-level, decompression algorithm-controlled dives at, over or close to the limit of not incurring decompression stops, are provocative in terms of contracting symptoms of decompression illness. At present, it is difficult to compare algorithm-generated decompression schedules with tables derived from extended development histories.

The objectives of this study are to derive a method that produces evaluations from dive-computer downloads of the likely severity of decompression illness that the presenting diver could experience. The development of a standardised index of exposure will allow for direct comparisons between computer-derived and table-derived dive profiles and decompression schedules. Finally, the exposure indices are compared with the type of treatment and the eventual outcome of treatment for a selection of patients.

This study is based on downloads obtained from the UWATEC Aladin™ series of dive computers from patients presenting to the Dunstaffnage Hyperbaric Unit near Oban from 1996 to 2002. The choice of these computers reflects only the popularity of that series of dive computers during the study period. They also have a relatively high level of data storage, retained the same software format over the total duration of the study and it was possible to interrogate the raw data sets. It is in no way a reflection of any relative effectiveness of this family of dive computers for controlling decompression schedules.

Methods

The UWATEC Aladin™ dive computers, when downloaded using the proprietary PC interface and software, give a varying amount of data depending on the model used and the information entered into the computer prior to the dive. However, the minimum download information given by these computers is a depth/time profile graphic based on the maximum achieved depth during 20-second time increments, visual representations of tissue saturation levels and some basic information on water temperature. In addition, a logbook is generated in electronic format that collates records of all the dives undertaken with that computer. If not downloaded regularly, it will store the last dives in detailed format only if the cumulative dive times are within a maximum of 180 minutes. Using independent additional interrogation software, the original logbook download can be presented differently in order to display rates of depth change, air consumption (where an integrated air-pressure monitor is employed), and tissue model saturation, and all the raw data can be transferred into standard spreadsheets for analysis.[7]

Data for this study were obtained from 48 dive-computer records obtained from some patients treated at the Dunstaffnage Hyperbaric Unit from July 1996 to May 2002. From those 48 computer downloads there were, in total, 127 dives recorded in detail or related directly to the incident dive. Downloaded dives were ignored if there was a break of more than 24 hours between them and the incident dive, or them and the first dive in the series resulting in the incident dive. Raw data from all the data logbooks were transformed into spreadsheet format. Where nitrox was used by the diver as a breathing gas the equivalent air depth (EAD) was calculated using the formula:

$$\mathbf{EAD} = \frac{\mathbf{Depth_{abs} \times fN_2}}{\mathbf{0.79}} - \mathbf{10}$$

where Depth_{abs} is the gauge depth in metres' sea water (msw) + 10, and fN_2 is the fraction of nitrogen in the mixture.[2] The raw data (both for air and equivalent air dives) for each dive were integrated using the partial pressures of nitrogen (ppN_2) calculated for every depth at the recorded 20-second intervals. The integration assumed a direct linear progression between each depth recording and standardised to values per minute using the trapezoid equation:

$$0.5 \times (pN_{n-1} + pN_n) / 3$$

where pN_n was the recorded ppN_2 value at time n and pN_{n-1} was the preceding ppN_2 value. Cumulative values of ppN_2 (ΣppN_2) were obtained for each downloaded dive through summation of all values standardised to a minute's duration.

In a series of dives that produced an incident of decompression illness, penalties were calculated by reducing by half the ΣppN_2 values for the previous dive in either 2-hour or 4-hour increments of the surface-interval time to produce 2-hour or 4-hour half-life penalties. Each temporal increment needed to be complete to generate the next half-life reduction and the resultant penalty was added to the next dive.

In order to compare the computer dives with a recognised decompression table, simulated dives were interrogated as above in accordance with the no-stop limits on the BSAC/RNPL 11 tables and employing the prescribed ascent and descent rates for those tables. This produced curvi-linear relationships of no-stop values for ppN_2 for either the maximum or average depth reached in a dive. Average depths were employed to compensate for dive profiles where the time at maximum depth was minimal compared with the total duration of the dive. Average depth for both the table-generated profiles and the dive-computer download profiles was a calculated mean of all the 20-second interval profile depths.

Using the methodologies detailed above, single values of ΣppN_2 were calculated for each of the dive series examined for each of the two half-lives employed. Initial analyses of the data compared resultant ΣppN_2 (with both 2-hour and 4-hour half-lives) for each casualty with the BSAC/RNPL11 no-stop relationship using either maximum or average incident-dive depths. ΣppN_2 values for each casualty were classified as being:

- multi-dive series (where there was at least one dive preceding the incident dive by no more than 24 hours)
- rapid ascents (where the ascent rate of the incident dive exceeded the dive-computer guidance and generated an ascent warning on the download)
- deep dives (where the maximum depth of the incident dive was deeper than 35 msw).

Expressing the dive-computer ΣppN_2 values as a proportion of the BSAC/RNPL 11 no-stop limits for the same depth (either maximum or average) generated indices termed here as the nitrogen loading index (NLI). This gave values of 1.0 to all no-stop profiles so that index values greater than 1.0 exceed no-stops for that decompression table. The NLI values were calculated for all the dive-computer downloads and were again analysed in the groups of multi-dive series, rapid ascents and deep (> 35 msw) dives.

The following primary recompression tables were used in the treatment of the 48 divers in this study:

- Unmodified Royal Navy Table 62[8]
- Modified Royal Navy Table 62 (with extensions at 18 msw and/or 9 msw)[8]
- Royal Navy Table 62 converted to US Navy Table 7.[9]

Where residual symptoms were still present following primary treatment, some patients were retreated with varying numbers of one of the following two secondary tables:

- Comex 12[10]
- Royal Navy Table 66.[8]

For each patient, the total therapy received in all primary and secondary treatments was calculated as 'oxygen units of treatment', which were the sums of the partial pressures of oxygen per minute breathed by the patient, assuming 100% delivery. The hyperbaric treatments, expressed in oxygen units, were then assessed against the maximum or average depths of the incident dive, the ΣppN_2 values and the NLI for the three incident groups.

Results

Without added penalties, the ΣppN_2 values ranged from 38 to 161. Use of the stated maxima for descent and ascent rates for the BSAC/RNPL 11 decompression tables results in a greater proportion of the total dive time being taken up with travelling to and from maximum depth as the maximum depth increases. In addition, there is a decreasing fraction of total dive time permitted at the maximum depth with increasing depth following the no-stop parameters. As a result, if the no-stop times are followed, the average dive depth values equate approximately to the maximum dive depths from 10 to 24 msw before tending toward an asymptotic value of between 32.1 and 34.2 msw. The relationship between maximum and average depths of a dive profile will differ markedly with profile and in the incident dives examined there were marked differences between rapid-ascent and staged decompression profiles. However, in the total dataset examined here, there was a positive linear relationship between the maximum and average depths of the incident dives whereby:

$$d_{avg} = (0.29 \times d_{max}) + 9.85$$

where d_{avg} is the average depth (msw) and d_{max} the maximum (msw), although the relationship was not strong ($r^2 = 0.376$).

Both maximum and average depths for the no-stop BSAC/RNPL 11 profiles were used to generate ΣppN_2 values for the table-generated profiles and produced negative curvilinear relationships of higher ΣppN_2 values at shallow compared with deeper depths (Figure 1).

The ΣppN_2 values for each incident were calculated: without penalty; with penalties added throughout the series of dives, where applicable, assuming a 50% reduction in the relative values from preceding dives after each 2-hour period of surface interval (2-hour half-life); and with penalties calculated with a 4-hour half-life. Twelve out of the 48 incident dives carried no penalty prior to the dive taking place. Of the other 36 incident dives the penalties preceding the incident dive ranged from 0.07 to 79.31% of the final cumulated total when calculated using a 2-hour half-life ($\mu = 24.6\%$ following arcsin transformation), and 4.00 to 86.05% when using a 4-hour half-life ($\mu = 35.4\%$ following arcsin transformation).

All three penalty categories of ΣppN_2 were plotted against the curvi-linear BSAC/RNPL 11 no-stop relationships for both maximum and average depths (Figures 2 and 3). If it is assumed that cumulative totals that occur above the no-stop relationships represent the potential for being outside the decompression limits of the table, then using the maximum depth attained during the incident dive explains 54.2% of the incidents (Figure 2). Adding 2-hour and 4-hour half-life derived penalties for previous diving activity increases the level of explanation to 70.8% and 72.9% respectively (Figure 2). Use of average depth of the incident dive reduced the strength of the trend and only 20.8%, 35.4% and 47.9% of incident dives had totals above no-stops (incident dive, incident dive with 2-hour half-life penalty, incident dive with 4-hour half-life penalty, respectively; Figure 3).

Figures 4 and 5 illustrate the 4-hour half-life data set subdivided by category of incident dive and analysed for either maximum or average depth of incident dive. The influences of analysis format and depth vary between groups

Figure 1
Cumulative partial pressures of nitrogen against maximum (open squares) and average (filled circles) depths (metres) for the no-stop depth profiles as prescribed by the BSAC/RNPL 11 decompression tables.

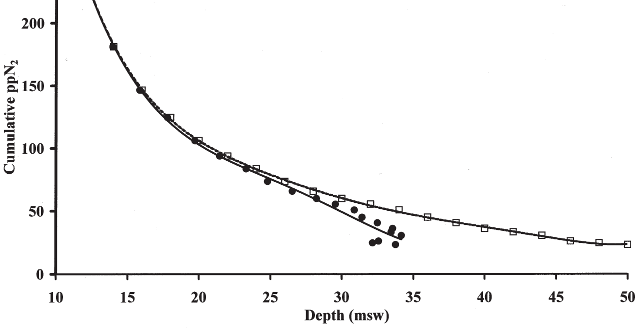


Figure 2
Cumulative partial pressure of nitrogen values plotted against the maximum depth (metres) of the incident dive, without penalty (o), with a 2-hour half-life for off-loading (•) and a 4-hour half-life for off-loading (hatched circles). The solid line represents the BSAC/RNPL 11 no-stop relationship for cumulative partial pressure of nitrogen against maximum depth.

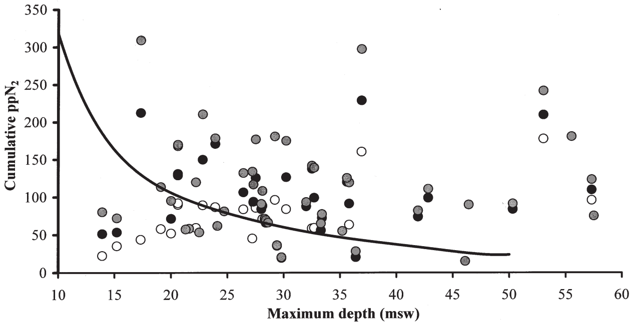
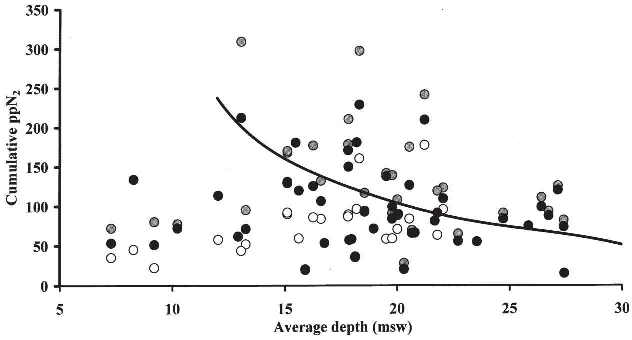


Figure 3
Cumulative partial pressure of nitrogen values plotted against the average depth (metres) of the incident dive, without penalty (o), with a 2-hour half-life for off-loading (•) and a 4-hour half-life for off-loading (hatched circles). The solid line represents the BSAC/RNPL 11 no-stop relationship for cumulative pressure root time against maximum depth.



and the only clear trend is that rapid ascents produce the lowest percentage of incident dives exceeding the no-stop values for the BSAC/RNPL 11 decompression tables (Table 1). The percentages for exceeding no-stop values in the multi-dive series and deep dive categories were much higher (61.9–90.9%) with most of the higher values obtained when analysed by maximum depth of incident dive (Table 1, Figures 4 and 5).

The NLI derived using the maximum depth of the incident dive (NLI_{max}) ranged from 0.34 to 10.37 with a mean (±sd) value of 2.07 (±1.77; n = 48). Using the average depth of the incident dive, the NLI values (NLI_{avg}) ranged from 0.16 to 2.67 with a mean (±sd) value of 1.10 (±0.58; n = 44). The difference in sample number between the group using the maximum depth of the incident dive and that using the average depth was caused by four samples having average depths shallower than depths that could be computed on the BSAC/RNPL 11 decompression tables. The NLI_{max} and NLI_{avg} groups were tested for deviation away from the

Figure 4
Cumulative partial pressure of nitrogen values with a 4-hour half-life penalty from preceding dives plotted against the maximum depth (metres) of the incident dive for:
(a) all dives; (b) multi-dive series; (c) rapid ascents; and (d) deep dives (>35 msw).

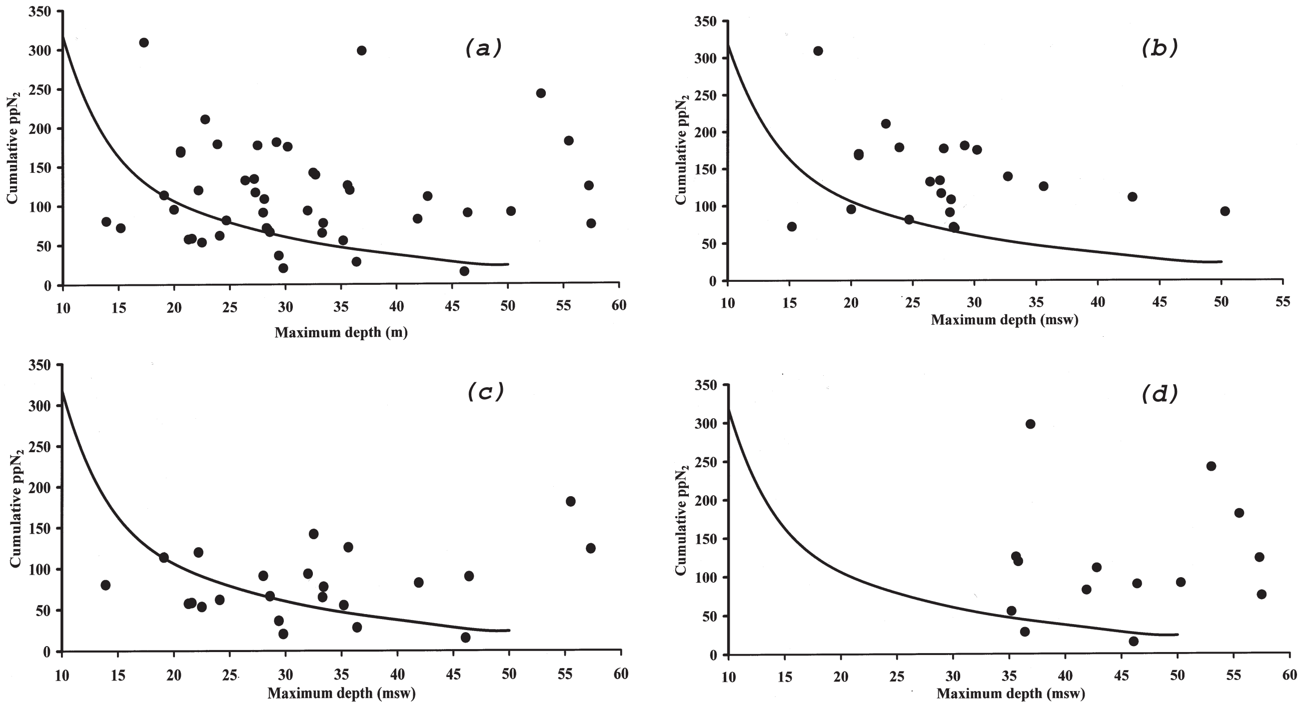


Table 1
Percentage (%) of incident dives exceeding the no-stop values for the BSAC/RNPL 11 decompression tables as derived from the integration of the computer profiles using cumulative partial pressure of nitrogen and either the maximum or average depths of the incident dive. All values carry a penalty from any previous dives as calculated assuming a 50% reduction in values after every four hours of surface interval. The data are presented for four categories of incident dive (a single incident dive could be in multiple categories).

	% incident dives using	
	Maximum depth	**Average depth**
All dives	72.9	47.9
Multiple dive series	90.9	61.9
Rapid ascents	52.2	26.1
Deep (>35 msw) dive	85.7	71.4

normalised no-stop value (1.00) using chi-squared analysis following tests for homogeneity of variance where the assumption was that the no-stop value was the expected variable. Taken as a single group, NLI_{max} levels were significantly greater than the no-stop values (χ^2; $P < 0.001$); NLI_{avg} levels were not significantly different from 1.00 (χ^2; $P > 0.05$).

The NLI values for both the maximum and average depths of the incident dives were divided into the three analysis categories: multi-dive series, rapid ascents and deep dives. Incident dives that had classified deep maximum depths produced the highest values (Figure 6). NLI_{max} levels for all analysis categories were significantly greater than the no-stop values (χ^2; $P < 0.05$) apart from the value for multi-dive series (χ^2; $P > 0.05$; Figure 6). NLI_{avg} values for multi-dives and deep dives were significantly greater than those for rapid ascents (Student's t-test; $P < 0.01$ in both cases; Figure 6). Deep dives produced significantly greater NLI_{avg} values compared with multi-dive series (Student's t-test; $P < 0.05$).

The total hyperbaric treatments employed on the cases detailed in the present study, as calculated in terms of oxygen units, ranged from 0 to 2240 (mean ± sd, 882 ± 357; n = 48). These totals could result from no treatment (in one of the 48 cases), a single treatment or a series of treatments. When total oxygen units of treatment were compared separately against all incidents, incidents from multi-dive series, incidents from rapid ascents, and incidents from deep (>35 msw) dives using ΣppN_2, there were no significant relationships ($P > 0.05$ in all cases). In addition, there were no significant relationships between resultant hyperbaric treatment and the maximum or average depth of the incident dive, the pre-incident dive penalties, or the NLI values for maximum or average depths of the incident dive ($P > 0.05$ in all cases).

Figure 5
Cumulative partial pressure of nitrogen values with a 4-hour half-life penalty from preceding dives plotted against the average depth (metres) of the incident dive for:
(a) all dives; (b) multiple dive series; (c) rapid ascents; and (d) deep dives (>35 msw).

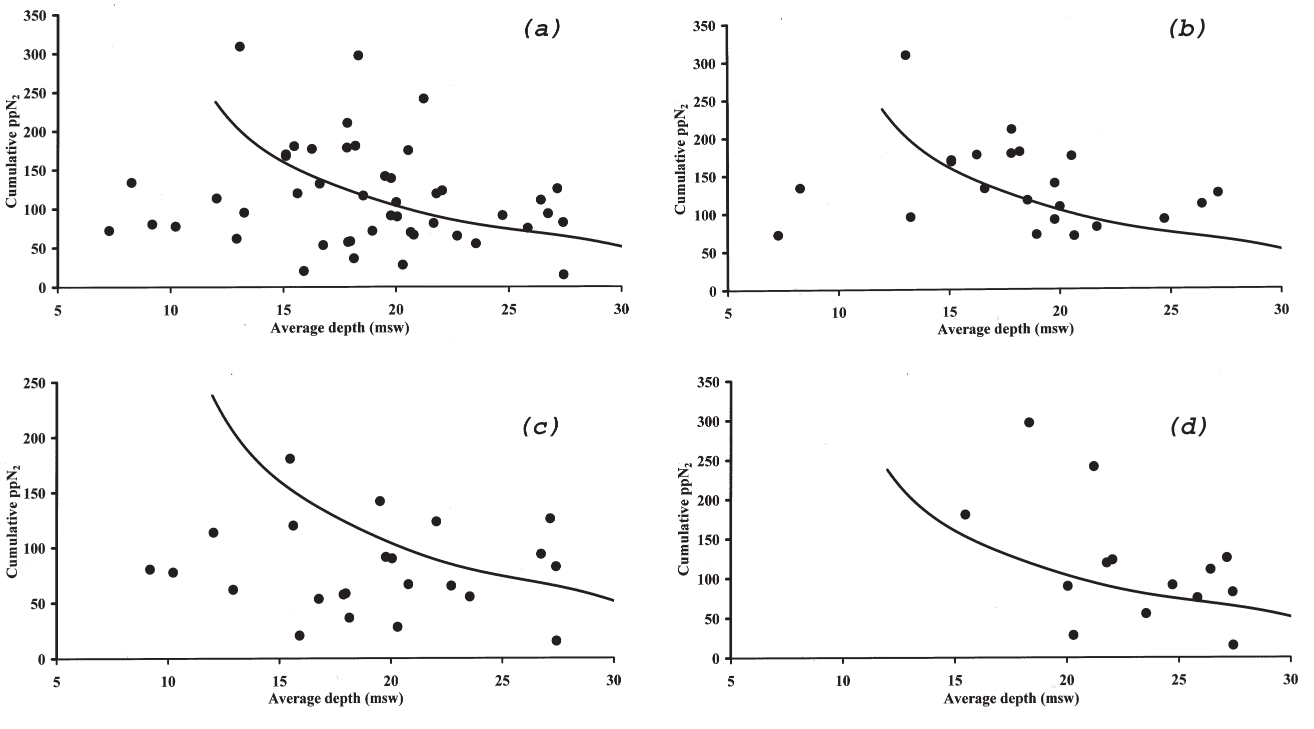
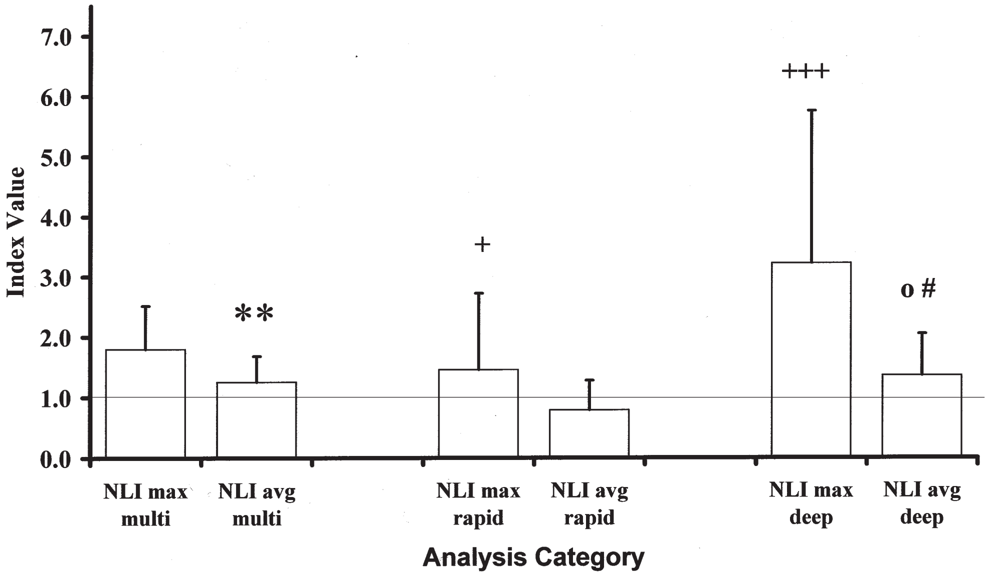


Figure 6
Nitrogen loading indices (NLI) derived for the maximum and average depths of the incident dives analysed against and between the categories of multi-dive series (multi), rapid ascents (rapid) and deep dives (deep). Significant values are indicated for deviation from no-stop levels (+), differences between rapid and deep categories (o), differences between multi and rapid categories (*), and differences between multi and deep categories (#). Number of symbols indicates the levels of significance (one = P < 0.05, two = P < 0.01, three = P < 0.001); horizontal line is the no-stop value where NLI = 1.0.



Discussion

This study presents a method of assessing multi-level, decompression computer-managed dives from divers presenting with actual or suspected decompression illness (DCI) and of comparing the outcomes of those dives with no-decompression dives derived from a set of long-established square-profile decompression tables. High rates of predicting DCI from cumulative nitrogen loading alone occur only when the incident dive was:

- the last of a multiple dive series
- relatively deep (a maximum depth greater than or equal to 35 msw)
- the calculations used the maximum depth of last dive
- if a surface-interval half-life of four hours was employed.

Even if the ‘worst-case’ factors were used to obtain estimates of the potential severity of the resultant decompression illness, these estimates did not relate to the duration or type of eventual hyperbaric oxygen treatment.

The present study has examined the profiles from the dive computers of divers who have presented with decompression illness. The overall objective of the study was to determine whether the type and/or duration of hyperbaric treatment could be informed following the integration of the profiles of the incident dives or series of dives. The methodology employed in the present study was designed to produce single indices of nitrogen loading. However, there are a number of limitations to the approach used. Although the modern versions of dive computers give indicative profiles of the dives undertaken, memory restrictions yield relatively basic levels of data recording. For the series of computers used in the present study, records were limited to only the deepest depth reached during every 20-second period and only the last 180 minutes of profile information. The last 180 minutes of storage was again limited to complete dives only. So, if the last dives were long (and, in particular, where prolonged periods of staged decompression were employed) or the incident occurred as part of a long series of dives, some dives that may have affected the resultant indices could have been missed. However, the level of detail in the recording analysed in this study does satisfy the minimum levels of accuracy suitable to describe dive profiles for analysis of decompression data.[11,12]

All of the analyses undertaken in the present study were made against the profile information of the final dive in the series. The assumption was that the last dive was the one that most influenced the actual incident. However, there were occasions when the onset of decompression illness could well have begun earlier in the series. Diving for three days or more without a break increases the risk of contracting DCI on subsequent dives irrespective of the predictions of the decompression model employed.[13] Despite this, the only significant outcomes from the analyses were obtained when maximum depth of the final dive was used.

As an influencing factor, maximum depth will be a true descriptor of the dive profile only when the average depth is closer to the maximum. Related to this effect is the fact that nearly all the dive series where the final dive was classified as being deep were correlated against the derived indices. Some of those correlations will be anomalies of the methodology employed in that the total values will continue to accumulate as the diver ascends irrespective of whether the diver is following a staged decompression profile or not. In addition, the methodology employed here is too simplistic to calculate the benefits of decompression that is intentionally staged at set depths and times, or where it is concomitant through a normally controlled, non-staged ascent. Similarly, the cumulative methods used in the present study will ignore the effects of rapid ascents and, in effect, the quick cessations in the pressure-affected values caused by rapid ascents will generate low cumulative index values. The model-independent methods of the present study also ignore the more generally accepted Haldanian theory of multi-compartmental approaches to decompression modelling and could have further examined the differences and rates of relative change between compartmental and ambient pressures.[14,15]

The use of a single half-life value for calculating the effects of off-loading between dives in a series is simplistic but is based on the square-profile tables used to derive no-stop values in this study.[16] In effect, this methodology is employing a single-compartment approach to determining decompression risk with the exponential off-loading rates for that single compartment of either two or four hours. Decompression algorithms based on Haldanian theory and the computations of Buhlmann can use between 6 and 16 tissue compartments with half-life times ranging from 2.5 to 640 minutes.[1,17] In the present study, the only significant indications of decompression problems were obtained when a 4-hour (240-minute) half-life was employed. Although that value compares with the upper range of tissue half-lives used in many decompression computers, this ignores the subtlety of the multi-compartmental approach. However, it cannot be discounted that in multi-day, multi-level diving, the controlling compartments are more likely those attributed to the slower tissues.

The fact that there were quite a few profiles that, once analysed, did not exceed the no-stop values was partly related to the use of one of the least conservative decompression tables.[16] The no-stop values for the BSAC/RNPL 11 table will yield much higher cumulative values for nitrogen that form the maximum no-stop line in the analyses reported here compared with other decompression tables. That line would be lower if other tables, such as those derived by the Defence and Civil Institute of Environmental Medicine (DCIEM), were used, and lower again if pre-dive penalties were employed for the assessment of multi-dive series. In addition, the indices derived as a proportion of the maximum no-stop line would increase if more conservative or multi-dive values were used.

The sample size for the study was relatively small (n = 48) and no additional breakdowns attributed to age, sex, experience, etc., were attempted. Dividing the main population into sub-sets depending on the type of incident dives (rapid ascent, multi-day diving and/or deep diving) reduced the population sizes further (n = 15–23). The study was restricted in that entry to it was limited to a single type of dive computer and a single recompression treatment centre. In addition, the population analysed in this study was pre-selected in that the profiles were from divers with actual or suspected decompression illness. There are no comparisons with the profiles generated by divers who do not show signs or symptoms of decompression illness even though they may be diving at depth and/or multi-day diving. Therefore, neither the distributions shown here nor the scale of the generated indices can, at this time, be given as potential indicators of decompression illness.

In the present study recompression treatment time, recorded as cumulative oxygen units, was used as a proxy indicator of the severity of decompression illness that was treated, based on the assumption that more severe cases of decompression illness require more prolonged treatment. However, no trends at all were discernible with the duration of treatment(s). Again, the effects of rapid ascent are not represented well by the analysis technique. In addition, treatment time cannot contend with differences in patient self-assessments that may influence the treatment duration. Finally, there is evidence to suggest that changes in the treatment service over the duration of the present study may have influenced the efficacy of treatment where these changes were directly related to treatment time through employment of either extended primary treatments or multiple secondary treatments.[18]

This present study has demonstrated methods that can be used to compare multi-level, computer-controlled dive profiles against square-wave, empirically-tested, table-derived decompression schedules. By using the maximum depth of the last dive in any series combined with a 4-hour half-life for nitrogen off-loading between dives, a significant number of incidences of DCI, whereby the dives are part of a series or the last dive is deeper than 35 msw, can be explained using this approach. However, this is a relatively simplistic approach that fails to compute any beneficial effects of staged or unstaged decompression, or the negative effects of rapid ascent. There are a number of studies that have used probabilistic decompression modelling to attribute risk values to specific diving regimes and/or profiles.[2,19–22] The use of similar approaches on profiles that have resulted in decompression illness, when compared with other diving groups, would inform future acceptable limits of probabilistic risk.

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