We are reprinting this article, which appeared on pages 126-133 of Volume 18, No 4, October to December 1988 as the figure, one table and some text were omitted. We apologise to John Lippmann and to our readers for our mistakes.

DIVE COMPUTERS

John Lippmann

Since decompression sickness in humans first reared its ugly head back in the mid-1800s, scientists and others have sought ways to improve and simplify decompression calculations and procedures.

Haldane introduced his model and schedules at the beginning of this century, and since then many decompression tables have been published. Although some of the very latest tables include methods for compensating for parts of a dive spent shallower than the maximum depth, most tables require a diver to choose a no-decompression or decompression schedule according to the maximum depth and bottom time of a dive. The calculation assumes that the entire bottom time was spent at the maximum depth, and that the diver's body has absorbed the associated amount of nitrogen. However many dives do not follow that pattern. A scuba diver's depth normally varies throughout a dive, and often very little of the bottom time is actually spent at the maximum depth. In this case a diver's body should theoretically contain far less dissolved nitrogen than is assumed to be present when using the tables in the conventional manner. Some divers feel penalised for the time of the dive not spent at the maximum depth.

The ideal situation is to have a device that tracks the exact dive profile and then calculates the decompression requirement according to the actual dive done. Such devices have emerged since the mid-1950's, some gaining some notoriety.

Probably the best known of the early decompression meters is the *SOS decompression meter* which was designed in 1959 and emerged in the early 1960s. The meter, which is still currently available, appears to represent a diver's body as one tissue. It contains a ceramic resistor through which gas is absorbed before passing into a constant volume chamber. Within the chamber is a bourdon tube which bends as the pressure changes, and the pressure level, which represents the amount of absorbed gas, is displayed on an attached gauge. On ascent gas escapes back through the resistor and eventually, when enough gas has escaped, the gauge will indicate that a safe (supposedly) ascent is possible. A number of problems arise with the use of the SOS meter. Individual meters often vary greatly, and the no-decompression times for dives deeper than 60 ft (18 m) exceed the US Navy no-decompression limits (NDLs). The meters give inadequate decompression for repetitive dives when compared to the USN and most other tables. In 1971, the first six divers requiring treatment at the Royal Australian Navy School of Underwater Medicine chamber were divers who had ascended according to SOS decompression meters.[1]

The Defence and Civil Institute of Environmental Medicine (DCIEM) of Canada developed a decompression meter in 1962. It utilised four resistor-compartments to simulate nitrogen uptake and elimination in a diver. Initially the compartments were set up in parallel so that each compartment was exposed to ambient pressure and thus absorbed gas simultaneously. When tested, this configuration produced an unacceptable bends incidence. The four units were then re-arranged in a series arrangement, so that only the first was exposed to ambient pressure and gas passed from one compartment into the next. This configuration was tested on almost 4,000 test dives and produced a very low incidence of bends.[1]

The meter gave effective half-times from five to more than 300 minutes, and it indicated current depth and safe ascent depth. The DCIEM unit never became available to sport divers as it would have proved to be very expensive and would have required extensive and costly maintenance.

In 1975 Farallon released its *Multi-Tissue Decomputer* which was designed to be a no-decompression meter. It consisted of four permeable membranes, two of which absorbed gas and two which released it. The Royal Australian Navy tested two meters in 1976 and found them to give very divergent results. One became more conservative while the other became more radical. In addition, various mechanical problems eventuated. Tests done in the USA confirmed that the NDLs given by the meter often greatly exceeded those of the USN tables.

Over the past ten years or so, various methods of extrapolating the USN (and some other) tables to credit a diver for the shallower portions of a multi-level dive have emerged. These methods require manipulations that are too complex for many divers and require the dive plan to be known in advance and rigidly followed. They are generally unvalidated, and their safety is a subject of dispute. In addition, if time is spent at more than two or three levels the calculations become prohibitively complex.

By the mid-1970s with the advance in microprocessors (a chip which can contain a series of pre-programmed instructions) it became possible to construct a small computer capable of doing very complex multi-level calculations. Recent technological innovations have overcome some of the early technical restraints and the scuba diver now has access to the convenience of automatic and more accurate depth and time recording, together with accurately computed multi-level decompression schedules, at far more affordable prices.

A microprocessor is capable of reading a pressure transducer (which converts pressure into electrical impulses) very rapidly and can apply nitrogen uptake and elimination algorithms (the mathematical equations which represent gas uptake and release) to this information every few seconds. These computers can therefore track a diver's exact profile and calculate decompression requirements according to it, rather than by the "rounded-off" profile which is used with decompression tables.

Despite, and in some cases because of, these features, some reputable diving scientists, doctors and educators remain very critical of these devices. Some argue that a diver will become too machine-dependent and would be at a loss and in a potentially dangerous situation if his computer failed while in use. However some diving instructors feel that modern decompression computers are less likely to fail than divers are while reading the tables and that there are some reasonable bail-out procedures in case of meter failure. *Probably the major fear of the computer critics is that some computers bring a diver far too close to, or beyond, the limits of safe diving, especially during repetitive dives.*

The decompression models programmed into the model-based computers are designed to simulate nitrogen uptake and release in a diver's body. However they are just models and cannot completely predict the gas flow in and out of our actual tissues. Our physiology is not always so predictable as many factors influence the rate of gas uptake and elimination and the possibility of consequent decompression sickness. So even though the computers follow their models exactly and the theoretical tissues programmed into the computer load and unload as expected, our bodies might not be behaving quite so predictably. There is no safety margin built into most computers which substantially compensates for this difference. Tables, on the other hand, usually contain an inherent safety margin and, in addition, since we must "round-up" any intermediate depth and/or time to the nearest higher or longer tabled depth and/or time, we partly, but not always fully, compensate for our own body's deviation from the model.

A table-based non-multi-level computer retains any inherent and/or "round-up" safety margin of the table, a table-based multi-level computer retains a small amount of the margin and a model-based computer retains no margin at all unless it is built into the model itself.

Comparing computers to tables for no-decompression dives

When no-decompression times allowed by various computers are compared to those allowed by various tables (even those based on the same model) for the same dive, vast differences often appear. These differences become greater for repetitive dives. Tables 2 and 3 compare the times allowed by various computers and tables for two series of repetitive dives that I carried out in a water-filled pressure chamber. I have conducted a variety of other simulated and real dives with similar results. Some of the reasons for these differences will be discussed in this section.

SINGLE DIVES

Table 1, below, compares the single dive NDLs of various computers to those of the USN and Buehlmann (1986) tables.

TABLE 1

COMPARISION OOF NO-DECOMPRESSION LIMITS OF VARIOUS COMPUTERS AND TABLES

Depth m	Depth feet	USN	Buehlmann	Aladin (Guide)	Datamaster 2	Edge	Microbrain	SME-ML	Skinnydipper
9	30	-	400	-	220	234	199	215	234
12	40	200	125	125	120	136	113	132	136
15	50	100	75	75	70	77	65	74	77
18	60	60	51	51	50	53	46	53	53
21	70	50	35	35	40	40	30	38	40
24	80	40	25	25	30	31	22	29	31
27	90	30	20	20	25	24	17	23	24
30	100	25	17	17	20	19	13	18	19
33	110	20	14	14	15	13	10	13	13
36	120	15	12	12	10	11	8	11	11
39	130	10	10	10	5	9	7	9	9

SINGLE RECTANGULAR DIVES

It can be seen from Table 1 that the single dive No-Decompression Limits of the computers are more conservative than the USN limits and are generally similar to the limits of the Buehlmann Table. Therefore *for a single rectangular dive these computers will usually give a more conservative no-decompression time than the USN Tables.*

It has been shown experimentally that divers who dive right to some of the USN NDLs will be quite likely to bubble during or after the ascent. By shortening the initial NDLs and in some cases slowing down the ascent, these computers (and modern tables) attempt to minimise bubble formation during or after a dive.

SINGLE MULTI-LEVEL DIVES

On a multi-level dive the computers will normally extend the allowable no-decompression dive time far beyond that allowed by the tables.

This occurs because the computer constantly calculates the (theoretical) gas uptake or release at all levels of the dive, rather than just at the maximum depth as tables do. This function is demonstrated in Figure 1 which shows a dive profile allowed by a Suunto SME-ML. At each level of the dive there was one minute of no-decompression time left when the ascent was commenced to the next level.

This single dive required no decompression according to the computer, but required decompression of 15 minutes at six metres and 31 minutes at three metres according to the USN Tables.

On a single multi-level dive of 30 m for five minutes, followed by 20m for 10 minutes, followed by ascent to 15m, the Suunto SME-ML allows a further 46 minutes of dive time at 15m before a decompression stop is required. The Huggins table allows 25 minutes at the 15m level before requiring decompression.

REPETITIVE DIVES

The dives shown in Tables 2 and 3 were rectangular dives so that the multi-level capability of the computers was minimised and the times allowed by the computers could be compared to the times allowed by the tables.

It is obvious that the computers allowed substantially more time for these repetitive dives than the tables would give. We know that it is unwise, and at times hazardous, to dive the USN Tables to their limits, especially on repetitive rectangular dives. How then can the generous times given by these computers be justified?

As previously mentioned, divers who dive right to some of the USN limits will be quite likely to bubble during or after the ascent. Some of these divers will develop manifestations of bends, but most will be asymptomatic. In either case these bubbles will slow down the out-gassing process and give rise to more residual nitrogen for repetitive dives than there would be if no bubbling had occurred.

By shortening the initial NDLs and slowing down the ascent rate, these computers attempt to minimise the bubble formation after the initial dive. This should enhance out-gassing, reduce residual nitrogen and thus enable longer no-decompression bottom times for repetitive dives. The Buehlmann Table works on this premise. It utilises shorter initial NDLs than the USN Table, followed by a slow ascent, and this is why it sometimes allows longer no-decompression bottom times than given by the USN Table for repetitive dives. However, as you can see from the examples, using the Buehlmann Table for repetitive dives is still more conservative than using most computers.

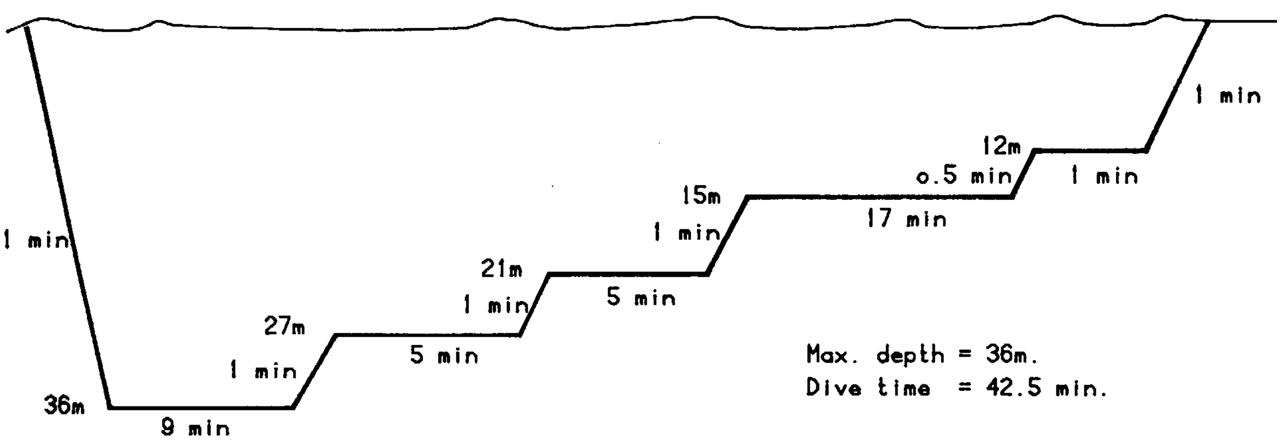

Figure 1. Dive profile allowed by a Suunto SME-ML. At each depth there was one minute of no-decompression time left when the ascent was commenced to the next level

TABLE 2

The times given are in minutes unless otherwise specified.

Dive 1	
Depth	36 m
Allowable no-decompression bottom time	
Aladin	8
Microbrain	8
Edge	11
Skinnydipper	10
SME-ML	10
USN Table	15
Buehlmann Table	12
Bottom time (actual)	10
Decompression time required	none
Ascent time	1.3 minutes

Dive 2.	
Surface interval	60
Depth	30 m
Allowable no-decompression bottom time	
Aladin	14
Microbrain	13
Edge	19
Skinnydipper	19
SME-ML	19
USN Table	11
Buehlmann Table	8
Bottom time (actual)	18
Decompression time required	
Aladin	40 seconds at 3 m
Microbrain	2 min at 3 m
Edge	none
Skinnydipper	none
SME-ML	none
USN Table	15 min at 3 m
Buehlmann Table	2 min at 6 m and 7 min at 3 m
Ascent time	2.3 minutes

Because most tables are based on the off-gassing of a single slow tissue during the surface interval they often have a safety margin built into them, whereas the computers carry no such margin. Repetitive Groups and Residual Nitrogen Times given in tables are designed to account for the highest gas loading that is theoretically possible and are usually based on a single tissue compartment only. Since this tissue is a "slow" tissue it out-gasses slowly on the surface. The tables assume that all of the tissue compartments are unloading at this rate and so may over-estimate the theoretical gas loads of the faster tissue compartments. This results in shorter repetitive dive times than would be allowed if the actual (theoretical) gas load in the faster compartments was considered. So this crudeness of the table's calculations may lead to longer surface intervals than are required by the model, but introduces a margin of safety by assuming the

TABLE 3

The times given are in minutes unless otherwise specified.

Dive 1	
Depth	27 m
Allowable no-decompression bottom times	
Aladin	19
Microbrain	18
SME-ML	22
USN Table	30
Buehlmann Table	20
Bottom time (actual)	18
Decompression time required	none
Ascent time	3.5 minutes

Dive 2	
Surface interval	32 minutes
Depth	30 m
Allowable no-decompression bottom times	
Aladin	14
Microbrain	14
SME-ML	16
USN Table	3
Buehlmann Table	6
Bottom time (actual)	16
Decompression time required	
Aladin	4 min at 3 m
Microbrain	4 min at 3 m
SME-ML	none
USN Table	15 min at 3 m
Buehlmann Table	2 min at 6 m and 7 min at 3 m
Ascent time	2.5 min to 3 m
Decompression done	4 min at 3 m

Dive 3	
Surface interval	32 minutes
Depth	36 m
Allowable no-decompression bottom time	
Aladin	7
Microbrain	8
SME-ML	10
USN Table	none
Buehlmann Table	none
Bottom time (actual)	10
Decompression time required	
Aladin, decompression was indicated	but cleared during (rapid) ascent
Microbrain	5 min at 3 m
SME-ML	none
USN Table	15 min at 6 m and 31 min at 3 m
Buehlmann Table	4 min at 6 m and 9 min at 3 m
Ascent time	1 minute

diver has more residual nitrogen than the model dictates. However many depth and time combinations may lead to the same Repetitive Group although, in reality, the nitrogen contents in the various body tissues are quite different.

Computers calculate repetitive dive times according to the exact (rather than the maximum possible) gas loading given by the model, taking into account all the tissues used in the model. This usually allows more dive time for repetitive dives than is allowed by tables. However in some situations the times can be similar. The deeper NDLs are determined by fast tissues which absorb gas rapidly and which off-gas rapidly at the surface. Repetitive Groups are based on slower tissues. If repetitive dives are compared for NDLs in the depth range where the Repetitive Group tissue controls the NDL (i.e. shallow to moderate depths), then the limits given by the tables and the computer should be close.

On some long dive sequences or in situations where repetitive dives are done over many consecutive days, the computers are sometimes slower to unload as they are programmed with slower tissues than are used to determine the repetitive groups in tables. This may lead to the situation where the tables will allow you to begin a new days diving without considering residual nitrogen from the previous day's diving, whereas a computer may still carry over a penalty. *This will normally only apply to the first dive of the day and the computer will then allow longer bottom times for the following dives that day.*

Are the computers safe ?

The safety of these devices is still the subject of many a heated debate.

The main criticisms focus on the following arguments:

1. The models on which the computers are based are not completely accurate. Decompression computers will retain inaccuracies until the devices can directly measure an individual's actual tissue nitrogen levels.

2. The inherent safety margin of the tables as well as the extra security gained by "rounding-off" the tables is lost in the computers. This will give a diver more time, but will at times put him more at risk.

3. Although some of the models on which the tables are based have been well-tested for fixed-depth dives, there have only been a few well-controlled, documented tests of the validity of the multi-level applications. The number of these tests has been insufficient to determine the validity of the multi-level applications with any statistical significance.

Before releasing the *Edge* in 1983, Orca Industries conducted a study to evaluate the safety of the algorithm programmed into the *Edge*. Twelve divers did a series of ten "chamber dives". Nine of the profiles were multi-level no-decompression profiles, and the tenth required decompression. The divers were monitored with Doppler bubble detectors. In the 119 profiles completed, bubbles were detected in one diver and were the lowest grade of bubbles.[2] None of the divers showed definite signs of bends. Two divers were slightly fatigued, one had some skin itchiness (which often occurs in chamber dives) and another had slight tingling in one leg. Tingling was a condition this subject often had after diving but it was reported as it was stronger than usual. No conclusions could be drawn as to whether the manifestations of fatigue and tingling were due to decompression stress or other factors. However significantly more dives are needed to establish the risk of decompression sickness for the various schedules. For example, for each schedule a minimum of 35 dives without bends is needed before a bends rate of less than two per cent can be claimed with 95% confidence.[3]

Orca Industries report that more than 500,000 dives have been done by divers using the *Edge* (to my knowledge at the time of writing, the vast majority of these dives have not been documented or validated) and that 14 cases of bends in divers "properly" using the *Edge* had been reported to Orca and the Divers Alert Network (DAN) by the end of 1987.[4]

Uwatec, the manufacturers of the *Aladin (Guide)*, report that between 50,000 and 100,000 incident-free dives have been done using the *Aladin* (to my knowledge at the time of writing, the vast majority of these dives have not been documented or validated) by the end of October, 1987. These dives included 290 documented dives done, by a British scientific expedition, in Lake Titicaca, 3,812 m (12,580 feet) above sea-level.[5]

With well over half a million apparently safe dives carried out by computer-users, it might appear that the computers are indeed safe devices. However, as with tables, it is difficult to determine whether it is the computers themselves that are safe, or if the apparent safety lies in how divers are using them and the type of dives that they are normally using them on. Since most of the 500,000 plus dives were undocumented, it is not known whether or not the divers dived to the limits given by their computers. If the units are not dived to their limits then we still do not know how safe the actual limits are. This is especially relevant to multi-level and repetitive dives.

More than 200 divers were treated for bends in Australasia in 1987. The vast majority of cases displayed neurological effects. These cases often arose after dives, often repetitive dives, that were conducted in accordance, and at times well within, conventional tables. Some had done a multi-level dive but had surfaced within the no-decompression limits specified by the table for the maximum depth.[6]

With such a high incidence of bends when diving within conventional limits, some fear that more cases might be expected to occur when the limits are extended, especially for repetitive dives. As computers become more and more common a better understanding should emerge.

By mid 1988, 79 cases of bends in divers using computers had been reported to DAN. In England in 1987, 16% (11/69) of the divers treated for bends had been using a diver computer.[7] Recent (as yet unpublished) figures from Aberdeen show a substantial bends incidence in divers who used computers for multi-day repetitive diving.

I believe that to a large extent the bends rate in dive computer users will depend on how divers dive when they use their computers, on the type of dive profile and on their rate of ascent.

It appears that a diver who ascends slowly will have less chance of getting bends, especially neurological bends, than one who ascends more rapidly. I believe that a diver should ascend no faster than about 10 m/minute when shallower than 30 m. Many computers include a warning to tell a diver when he is exceeding the recommended ascent rate. The rate varies between computers, but I believe it should roughly equate with the above recommendation. This function is a highly desirable, if not essential, function of any dive computer.

If you exceed the recommended ascent rate at any stage during a dive, especially at or near the end of a dive, reduce your dive time substantially from that given by the computer for the rest of that dive and for repetitive dives. If bubbles form as a result of the faster ascent, they will slow down out-gassing and make the times given by the computer far less realistic.

I also highly recommend that a diver goes to the maximum depth early in the dive and then gradually works shallower. If a diver begins a dive in the shallows and then progressively gets deeper and deeper before ascending to the surface, the nitrogen load in the "slower" tissues is likely to contribute more than usual to bubbles which are subsequently formed in the "fast" or "medium" tissues during or following ascent.

If you are using a dive computer I believe that you should:

Ascend slowly. Never exceed the recommended ascent rate and generally ascend at about 10 m/minute or slower.

Go to the maximum depth early in the dive and progressively and slowly work shallower. End the dive with at least five minutes at 3-6 m. *Avoid rectangular dive profiles.*

Do not dive right to the limits given by the computers. They do not cater for individual susceptibility to bends.

Avoid using the computer for deep repetitive dives, especially those with rectangular profiles (in fact avoid doing deep repetitive dives!).

In the event of a computer failure, ascend slowly to 3-6 m (nearer to 6 m if possible) and spend as much time as possible there before surfacing.

The future

It appears that dive computers are here to stay and they will develop enormously as knowledge and technology advance. The current models are based only on depth and time, but future computers might be programmed to include other variables such as degrees of individual susceptibility to bends, exertion, water temperature and delayed out-gassing due to a rapid ascent. I am told that a computer which will do the latter is currently nearing completion and I believe this to be a large step towards improving computer safety.

The ultimate computer would measure the nitrogen level within an individual diver's tissues. I have put my order in already!

Summary

Dive computers are designed to calculate the decompression requirement for the actual dive profile, rather than for the "rounded-off" profile which is used with tables.

Most current computers are programmed with an actual decompression model rather than with tables.

Computers eliminate errors in table calculations, and usually provide much more bottom time than is given by the tables.

Tables include inherent or added margins which provide a degree of safety if our body absorbs more nitrogen than predicted by the model. Computers do not include such margins as they follow the model exactly.

For single rectangular dives the computers usually give more conservative NDLs than the tables.

On a multi-level dive the computers will normally extend the allowable no-decompression bottom time far beyond that allowed by the tables.

The computers usually allow far more time for repetitive dives than is allowed by tables. This is an area of risk for the computers as is multi-day diving.

The safety of dive computers has not been determined as too few validated tests have been done to determine the bends risk associated with their use. However, this is also true for most decompression tables!

The computers generally rely on a slow ascent rate and the times given are less valid if a diver has ascended faster than recommended.

Computers can and do fail and the diver must have an appropriate back-up procedure.

If using a computer it is important to:

Go to depth early and then work shallower throughout the dive. Ascend at the appropriate rate. Do not dive right to the limits. Allow for predisposing factors of bends. End all dives with a few minutes at 3-6 m.

For multi-day diving rest every third day.

The above article is taken from a book relating to various aspects of diving which John Lippmann is currently finalising for publication in 1989. No part of this article may be reproduced without the prior consent of the author.

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BUOYANCY AND UNNECESSARY DIVING RELATED DEATHS

Wong Ted Min

Introduction

Man emerged from the prehistoric seas 350 million years ago. Throughout the ages, he still found it necessary to return to the sea and dive for subsistence, for recreation or out of curiosity. The early dives have been limited by his inability to remain underwater for long, a skill which he had lost an aeon ago when he traded his gills for air breathing lungs.

In the attempt to prolong his endurance underwater, various techniques of prolonging the air supply have been tried. Diving bells, helmets, surface supply equipment and various contraptions have been used but all of them required manpower and large unwidely equipment. It was not until 1943 when Jacques-Yves Cousteau and Emile Gagnan developed the modern demand intake valve that the sport of scuba diving became assessible to the general public.

Today, there are dozens of diving organisations and even more diving schools all over the world teaching the more adventurous the skills of scuba diving. With the exception of some of the more dubious characters conducting the 1-day "Introduction-type" diving courses, most reputable dive organisations have a reasonably comprehensive diving course. There are many books available which give the potential divers information on the dangers of decompression sickness, air embolism, barotrauma, nitrogen narcosis, hypothermia and dangerous marine animals. Often, diving techniques, buddy breathing, emergency ascent drills and basic resuscitation are included.

It is therefore of great concern that many divers still die every year of problems related to scuba equipment. Many of these divers have little or no previous experience with scuba equipment and are totally ignorant of safety procedures.

Diving Related Deaths

A study of the statistics on diving fatalities have revealed that in New Zealand in 1983, five out of six scuba-related deaths involved inexperienced or untrained divers. All these six dead divers were found with their weight belts on, although they might have survived if the weight belts had been removed. Three deaths can be directly attributed to poor buoyancy control and being overweighted at depth[1].

In 1985, ten diving related deaths occurred in Australia[2]. Five out of these ten were untrained or newly trained divers. Of the newly trained divers, two deaths occurred due to problems with buoyancy compensators (BCs) and another two had medical conditions which should have rendered them unfit for diving.

The statistics for diving fatalities from the United States National Underwater Accident Data Centre (NUADC) between 1970 and 1982 revealed that 42.5% of diving fatalities occurred during the first few dives[3]. Investigations revealed that in 80-90% of these cases the weight belts were not removed by the victims and this may be a major contributory factor to the fatalities[4]. A large proportion of these deaths were reported to be due to drowning or asphyxiation (about 65%), which should not have occurred if there had been a good understanding of the principles of buoyancy. The San Diego City Lifeguard Service published statistics for the period between January 1975 and June 1975 which revealed that only twelve weightbelts had been abandoned, in seven hundred and seventeen diver rescues, prior to the lifeguard arriving at the scene[5].

These deaths are largely preventable. Although most aspects of diving are taught in diving courses and information is easily obtainable in many diving manuals, an area which does not have sufficient practical information is the topic of buoyancy. The US Navy and the RN Diving manuals as well as several other dive manuals explain aspects of positive, neutral and negative buoyancy and Archimedes' Principle. However, the practical implications of the actual amount of buoyancy lost at depth by a wetsuited diver have not been discussed, nor has the ineffectiveness of BCs at low tank pressures at depth been explained.

This information is important for all divers, especially novices. When diving deep for the first time, the novice may find it impossible to overcome the negative buoyancy due to wetsuit compression. This can lead to a situation where the diver is unable to swim back to the surface, unless the weight belt is dropped. This problem was recently illustrated in a tragic accident, where a prominent barrister was drowned.

CASE REPORT

This sport diver was a forty year old man. He was 20% overweight for his age and height. Prior to his death he had only done eight previous dives, all conducted by his diving school. Most of the dives were between 4 to 12 m (15 and 40 feet), with only one dive to 24 m (80 feet) for 5