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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 minutes. This 24 m dive, according to the diving instructor, was to "check" if the victim was susceptible to nitrogen narcosis.

With only the experience of these 8 shallow dives, the victim and his buddy decided to explore a famous wreck, the "Anne Miller", which lies in 42 metres (140 feet) of water off Sydney. Both men used identical equipment, 7 mm wetsuits and weight belts of 14-16 kg (32-36 lbs). They dived to the wreck and spent 7 minutes looking around. At the end of 7 minutes, they had reached the red sector of their pressure gauge and they decided to ascend. By this time, the ascent line was nowhere to be found. Two minutes were spent on looking for the line and by this time, both had reached the limits of their air supply and were forced to begin their ascent. The buddy inflated his BC and began to ascend, venting his BC as the ascent became more rapid. The men became separated and the victim failed to surface. The buddy, on the other hand, ascended uncontrollably, and ran out of air before breaking the surface. On surfacing, the buddy was found to be in a confused state by his rescuers. He was rescued by the dive boat but the victim never surfaced. Later, the victim was found near the wreck in 42 metres of water. The search divers were unable to raise the body by inflating the BC. It was only wehn the weight belt was released that the body was noted to ascend rapidly to the surface.

A number of mistakes were made by these divers:-

a The victim was inexperienced at deep diving, having only done 8 previous dives, mostly at a shallow depth. The effects of nitrogen narcosis during his last dive, would certainly have clouded his ability to assess the situation, ditch his weight belt and activate his BC.

b There was a gross miscalculation of the amount of weight required to overcome the buoyancy of the wetsuit on the surface. With the descent to 140 feet, the amount of buoyancy in the wetsuit would have been reduced to less than one-fifth the surface buoyancy (by Boyle's Law). This reduction in buoyancy plus the excessive weight carried prevented the diver from surfacing even wit hthe BC inflated as described by those who recovered the body.

c The dive was not properly planned. The divers spent too much time looking for the ascent line, thus consuming the remaining air in their tanks.

d Separation of the divers occurred during the ascent.

e The victim did not drop his weight belt, despite being grossly overweight and facing the prospect of running out of air.

The death of this diver was most certainly preventable if he had gained more experience in deep diving. He should have gradually increased the depth of his dives, a procedure which will gradually enable him to experience the effects of nitrogen narcosis. This may have allowed him to achieve greater awareness of the reduced mental and motor coordination, and thus enabled him to voluntarily restrict his depth.

Neither diver should have dived until he ran out of air, especially at such depths, when the rate of air consumption is very rapid. If they had completed their dive earlier, then they would have had enough air to ascend comfortably and overcome other problems which might arise. The victim's BC should have been properly inflated if he had adequate air in his tank. There was certainly no reason for both divers to wear 32-36 lbs (14-16 kg) of weight under these circumstances and it showed clearly that both men did not consider the effects of proper buoyancy control.

Proper Buoyancy Control

Buoyancy was first defined by the Greek mathematician, Archimedes, who established that any object wholly or partly immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced by the object.

The buoyancy of any object is determined by its density and that of the liquid it is immersed in. The buoyancy of a diver is determined by his density and the equipment he wears. This buoyancy varies with time, as air is being consumed from the tanks, and with depth, when the volume of the wetsuit and of the air in the BC will vary according to Boyle's Law.

THE COMPONENTS OF BUOYANCY

Davey and Williams[6] found that sixteen of ninety-six college males were unable to float even with a full inspiration. Seventeen of one hundred and ten teenagers, of both sexes, were also similarly found to sink even at full inspiration. Tests done by Behnke et. al.[7] in 1942 showed that the specific gravity (SG) of normal males between 20 to 40 years fell between 1.021 and 1.097. Osserman et. al.[8] reported a somewhat similar range between 1.022 and 1.100 (with a mean of 1.068) and Howell, Moncrieff and Morford[9] had values of SG between 1.022 to 1.110 (a mean of 1.061) in 133 unselected male subjects. These values were corrected for residual lung volumes. In real terms, most people are positively buoyant at full inspiration and only 10.6% of subjects exceeded 1.000[9].

Behnke's subjects had a mean SG from 1.049-1.058 at full expiration and 0.990-0.998 at full inspiration. At full expiration, all would exceed an SG of 1.000, and so are negatively buoyant in fresh water. Only a few would remain positively buoyant in seawater (SG 1.025) at full expiration.

For a buoyant diver to descend, his buoyancy should be adjusted so that he is neutrally buoyant at the surface at full inspiration, with his eyes at the water level. Initially, the diver should put on his wetsuit and his tank, and the weight belt with what he assumes is adequate weight. He should then enter the water and see where he floats. If he is positively buoyant additional weights will have to be added to the weightbelt so that neutral buoyancy is achieved and vice versa. When weighted in this manner, remaining afloat will require only a minimal effort. If necessary, the weight belt and tanks can be ditched to give added buoyancy so that the diver can remain afloat indefinitely with the aid of his wet suit and BC.

To descend, the diver initially exhales, thus reducing his buoyancy. At this stage, he will start to descend, which may be aided by finning. With the compression of his wetsuit, the diver becomes progressively more negatively buoyant. An alternative method is to follow the anchor line of a boat down, pulling oneself downwards for the first few metres until wetsuit compression allows further descent without any further effort.

A diver wearing a wetsuit should normally put on an equivalent amount of weight to neutralise the buoyancy exerted by the wetsuit. This will pose possible problems when the diver proceeds to dive to a depth where there is compression of the bubbles trapped in the neoprene. He will experience a progressive increase in negative buoyancy. As the density of the soft rubber in neoprene is 1.1, almost all the upthrust provided by the wetsuit is provided by the air trapped in the neoprene. The air in the neoprene becomes progressively compressed at depth with the resultant fall of buoyancy. (Table 2.)

TABLE 1

BUOYANCY OF DIFFERENT TYPES OF WETSUITS

Type of Wetsuit	Dry Weight	Buoyancy
Civilian 3 mm	1.136	1.081 kg
Civilian 5 mm long johns	2.381	4.776 kg
Civilian 5 mm full suit	3.017	5.341 kg
RAN 7 mm full suit	2.910	7.410 kg

TABLE 2

BUOYANCY OF WETSUITS AT DEPTH

Type of Wetsuit	Buoyancy of Wetsuit at Depth (kg)				
	Surface	10 M	20 M	30 M	40 M
Civilian 3 mm	1.1	0.6	0.4	0.3	0.25
Civilian 5 mm long johns	4.8	2.4	1.6	1.2	0.96
Civilian 5 mm full suit	5.3	2.7	1.8	1.3	1.06
RAN 7 mm full suit	7.4	3.7	2.5	1.9	1.5

THE WETSUIT

A wetsuit is commonly worn by divers for thermal production. It is made of closed cell neoprene rubber to which two layers of synthetic fabric are usually bonded. The thickness, and therefore buoyancy, varies between 3 mm to 1.2 cm. The commonest wetsuits in use are 3, 5 and 7 mm in thickness. Thermal protection is afforded by the insulating layer of air trapped inside the neoprene. Different wetsuits have different buoyancies at the surface and these values also change with depth.

Four different types of wetsuits were tested in a saltwater pool to evaluate the amount of postiive buoyancy each exerted at the surface. The results are in Table 1.

A neutrally buoyant person diving with a 7 mm full suit will have to weigh himself down with 7.4 kg of weight on the surface. The actual weight required is slightly less than the calculated value as the scuba tanks are somewhat negatively buoyant. The diver's buoyancy at 40 metres will be one-fifth of 7.4 kg or 1.48 kg. He will be therefore overweighted by 5.92 kg. In the case of the barrister, he started off overweighted by about 8.5 kg. At the depth of 42 metres (140 feet), he would have been overweighted by (8.5 + 5.9) kg which is 14.4 kg (31.68 lbs)! This accounted for the fact that the rescuers were unable to raise the body until the weight belt was released.

Besides alteration of buoyancy at depth, wetsuits also limit the mobility of the diver. Mobility is important because if a diver is restricted in his range of movement, he may not be able to reach for the various buckles, straps and power inflators in order to save himself in an emergency. This ergonomic factor was previously studied by Egstrom et. al.10. In a comparison of three wetsuit configurations, he found significant differences in the loss of range of motion with wetsuit design, zipper placement and the type of material used. In some wetsuits, as much as 95 degrees of motion are lost.

A comprehensive analysis by Kise[11] in 1977 showed that a diver wearing a swimsuit, tank and a backpack with a deflated flotation vest had losses in range of motion of 17% for hip extension, 20% for trunk extension and 21% for trunk rotation. With a wetsuit, this diver would have lost another 43% of trunk rotation, 34% of trunk extension, 31% of hip extension and nearly 31% of neck movement. Thus the effects of reduced mobility must always be borne in mind. It is vitally important that all straps, release buckles, reserve levers, and emergency air bottles should not shift during the dive and that they are within easy reach.

WEIGHT BELTS

Weight belts have been introduced to counter the effects of positive buoyancy. More weights are required for thicker wetsuits and the risks increase proportionally. Weight belts frequently rotate during dives making them inaccessible to the diver or his buddy. Weight belts may be trapped by tank straps, leg knives, crotch straps so that if the buckle were released, the weights fail to fall away cleanly. Egstrom1[2] performed a number of tests with wetsuited mannikins to demonstrate how easily or not, weight belts fall from the diver. He found that no weight belts fell off when a wetsuited mannikin was placed between 30 to 90 degrees from the vertical. Between 10 and 30 degrees, most belts did not drop clear, owing to friction between the suit and belt material. This was largely caused by weight placement and/or failure of the buckle to completely release the belt. He also found that to drop the release belt by rolling, it was necessary to roll between 100 and 120 degrees from the horizontal. Release tensions for buckles varied from 0.7 to 7 kg of force depending on the tension of the belt.

BUOYANCY DEVICES

Buoyancy compensators have been introduced to enable the diver to adjust his buoyancy irrespective of depth. They come in various configurations and generate different amounts of lift, varying from 5 kg to 25 kg, proportional to the internal volume of the BC.

The basic BC consists of an oral inflation valve as a basic inflation system and a power inflation system of either a CO_2 cartridge or an inflation hose connected to the first stage of a regulator or to a small auxiliary air tank. The safest BCs are those with auxiliary air tanks as they provide a spare supply of air independent of the main breathing tanks. These small cylinders hold a larger volume of gas than the CO_2 devices, and are more reliable in service. The main drawback of the auxiliary air tank is the price. Power-inflators connected to the main tanks obviously have the advantage of reduced bulk but they cannot be relied upon to inflate the BC rapidly when the tank pressure is low. Having a power-inflator without an additional backup air supply is dangerous especially in an emergency. It is noteworthy that the British Sub-Aqua Club (BS-AC) strongly recommends the use of an independent air source for the BC. Few people nowadays depend solely on the CO_2 cartridge because of the poor reliability of the firing mechanism.

SCUBA TANKS

Scuba tanks have a negative buoyancy of 1 kg to 7 kg in water, depending on the configuration. There is a slight increase of the scuba tank buoyancy as air becomes consumed by the diver during the dive. The reduction of buoyancy in a 70 litre steel tank is about 3 kg. Hence, the scuba tanks do play a role in determining the buoyancy of a diver.

A more important practical factor, however, is the ability and speed in which a tank at its "reserve" pressure fills up a BC at various depths. In an experiment performed in a recompression chamber, the speed of inflation of a BC was tested. The tank used had a pressure of 35 bars gauge, which is the point where most divers begin to start their ascent to surface. The tests revealed that it required 46 seconds for the BC to inflate maximally at a depth of 30 metres. It was not possible to inflate the vest maximally whilst simultaneously respiring from the regulator at this reserve pressure, as the tank was emptied before completion of inflation. A carbon dioxide cartridge was also discharged into an empty vest at 30 metres to assess the degree of BC inflation. The amount of gas contained in the CO_2 cartridge was not enough to inflate the vest maximally at this depth.

The findings (Table 3) showed that it required about 57 seconds to inflate a BC at 30 msw with a power-inflator. It was not possible to completely inflate the BC at 30 msw if a diver continued to breathe from the regulator during the inflation. Secondly, a CO_2 cartridge recommended for this particular vest did not supply enough gas for an emergency ascent as the vest did not fill up adequately. Thirdly, if a diver had been negatively buoyant at depth, the BC will not likely overcome the negative buoyancy unless the weight belt was dropped.

Naturally, should the diver begin to ascend after ditching the weights and adequately inflating his BC, the rate of ascent will increase as the air in the BC expands. The ascent rate must therefore be controlled. The recommended rate of ascent is generally 18 msw a minute, but a rate as slow as this is usually difficult to achive in practice. Divers have been taught to follow the "smallest bubbles", but these bubbles gradually expand and accelerate with ascent. Therefore, divers must be taught to consciously look for new "smallest bubbles" during ascent, in order to minimise the risks of pulmonary barotrauma and air embolism. With an inflated BC at depth, the best way to control ascent speed is to continuously but gradually vent the BC during ascent. This avoids the pitfall of overventing the BC, which reduces

TABLE 3

TIME REQUIRED FOR INFLATION OF BC AT DEPTH WITH A POWER INFLATOR ATTACHED TO A TANK AT RESERVE PRESSURE

Depth (metres sea water (msw))	**0**	**10**	**20**	**30**	**40**
Duration of BC Inflation without simultaneous respiration (seconds)	12	25	39	57	78
Duration of BC Inflation with respiration at 15 breaths a minute (seconds)	18	40	(50)*	**	**

* Unable to fully inflate BC before tank emptied

** Tank emptied before adequate inflation of BC

its buoyancy resulting in the diver sinking, following the initial ascent.

Another technique which the diver may use to reduce his rate of ascent is to increase the drag on his movement by presenting a large surface area to the vertical plane of movement. This may be achieved by spreading his arms and extending his body backwards in a horizontal manner.

For these manoeuvres to be successful, divers should begin their ascent before they run out of air. It is extremely difficult to ascent properly with an empty tank as then the BC cannot be inflated. The hypoxic diver will find it nearly impossible to remove his weight belt and his chances of a successful ascent are exceedingly slim. The tragic consequence of this is death.

DIVER ENDURANCE

An experienced swimmer attempting to keep afloat on the surface, can usually keep his head above water for a fairly long time (exceeding 15 minutes). This ability allows rescuers sufficient time to reach him, for example, after falling overboard. This contrasts significantly with the time an overweighted diver can achieve. In a pool test, 3 male swimmers were made to keep their heads out of the water, while wearing a 5.47 kg weight belt (equivalent to 4.818 kg of submerged weight). The duration in which the swimmers were able to remain afloat was between 2 minutes 15 seconds and 6 minutes 21 seconds. Thus, when theire is a failure of his flotation device, an overweighted diver will not be able to remain afloat for very long.

Discussion

By looking at the causes of diving fatalities, common patterns are seen. Nearly all diving fatalities are preventable. The case report presented earlier illustrated that inexperience and miscalculations result in diving fatalities. Panic is a common denominator in almost all diving fatalities. It precedes the phase where consciousness is lost and the diver drowns. A proficient diver will not allow himself to reach the point of panic. The diver must concentrate on his equipment, air-supply, degree of buoyancy, onset of early narcosis, in order to take preventive measures.

A proper pre-dive assessment of the environmental conditions, limitations of equipment and personal endurance is necessary. Diving in foul weather, rough surf and extremes of cold should only be undertaken if adequate justifications prevail and precautions are taken.

Equipment limitations should be realised, especially at depth and when the air supply becomes low. Regulators generally require more effort to breathe from at low tank pressures. The BC requires proper training to maximise its effectiveness. Obviously, it will not perform its role if CO_2 cartridges are not installed, or if the power inflator hose is not connected. BCs are prone to degradation and leak when exposed to the sun and they require proper handling, maintenance and storage. They do not inflate enough to provide adequate lift at depth with the CO_2 cartridges. At low tank pressures in 30 msw, the power inflator attached to the low pressure port takes almost 1 minute to inflate a BC to its maximum capacity. In this situation, if air is continually utilised by the diver, the tank becomes empty before the BC achieves adequate inflation. Divers should be neutrally buoyant during all phases of their dive, unless they require to be negatively weighted in order to remove abalone or other embedded objects. In this situation, the diver should always be prepared, and able, to jettison the excess weights immediately should the need arise.

Wet suits become progressively compressed at depth and are, therefore, less buoyant. The thicker the wetsuit material, the more weight one requires to put on at the surface to counteract the buoyancy. This excess weight increases as one descends, and it may not be possible for the overweighted diver to ascend from depth.

Dropping the weight belt at depth results in an immediate positive buoyancy to the diver, which may enable him to ascend to the surface. Divers must be taught that at the hint of the slightest emergency, the weight belt should be unlatched and held at arm's length. In this way, should the crisis pass, the weight belt may be put on again. If the diver passes out, the weight belt will then fall out of his hands and the unconscious diver has a chance of being rescued. In addition, he is more likely to float to the surface unaided where his chances of rescue are far greater than if he should remain submerged.

Untrained divers should not be allowed to dive, unless doing a proper instructional course. Inexperienced divers must not attempt to exceed their own limits, until more dives have been logged. No one with a scuba certificate must agree to rent scuba equipment for his untrained friend. Diving should be treated as a dangerous sport. There are many instances where a diver finds himself in potential difficulties. A novice diver will be hopelessly lost with the amount of gear, hoses, gauges and buckles that make up the equipment used in scuba. All it takes is a simple mistake, a lack of understanding or inexperience to cause a loss of life. A person making a mistake or suffering an asthmatic attack or an epileptic fit on land does not drown. A similar misfortune occurring whilst diving inevitably leads to drowning and death.

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BLEOMYCIN
A RARE ABSOLUTE CONTRAINDICATION TO DIVING

John Knight

In the August 20-27th issue of the British Medical Journal there was a leading article on the rising incidence of decompression sickness in the UK[1]. A follow-up letter[2] drew attention to an absolute contraindication to diving that most people are not aware of.

Bleomycin is an anti-cancer agent which has among its effects the sensitisation of the lung to raised oxygen partial pressures. Bleomycin causes lung damage, which governs how much of the drug can be used in treatment. Mostly the damage resolves with the passage of time. But sensitisation to raised partial pressures of oxygen is long