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BUOYANCY COMPENSATION AND ASCENT RATE

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Introduction

Archimedes' observation, that a body immersed in water is buoyed up by a force equal to the weight of the volume of water that is displaced, has clearly benefited the diving community. It has also provided frustration, amusement and occasional hazards to health. Proper buoyancy control is being able to achieve neutral buoyancy at every depth and to maintain it throughout a dive. It is a skill that is fundamental for diving comfort and safety. Unfortunately many divers do not seem to understand the benefits of a high degree of skill in buoyancy control.

Neutral buoyancy

To teach neutral buoyancy in our training program, we get students to do a one finger handstand on the bottom of a 5 m deep swimming pool. A one finger handstand is not easy. One is not actually standing on the finger, but making negative buoyancy keep the finger in contact with the bottom. With adequate breath control one can keep a finger on the bottom. A big breath will start to float one away. We use this to get people to understand what they can do with breath control. A diver can have about 2-2.5 kgs of differential volume simply by exercising adequate breath control. When one is neutrally buoyant, weighted properly or with the correct sized buoyancy bubble, one can swing to positive or negative buoyancy with breath control alone.

The most important skill that has to be learned with any kind of buoyancy compensation system is to make the specific adaptation to that piece of gear so that, as one ascends, one can hover at any depth. I have to commend those on the boats that I have dived from, they are all able to hover.

Gas expansion

Where in the water is the greatest danger of gas expansion? Most people will say "In the first atmosphere of additional pressure below the surface of the water". Actually Boyle's Law produces an exponential curve and the greatest pressure/volume change takes place in the metre just below the air/water interface. Under certain conditions one can develop lung over-pressure accidents with as little as 90 mm Hg or 0.12 bar (less than 2 psi) differential pressure, which is a rise of about 1.2 m. Rising 1.8 m it is not difficult to achieve an accident, and with a 2.4 m rise it is easy. The statement "I've only used scuba in a swimming pool", tells me that they have only used compressed gas in the most dangerous part of the water column. If they do not know what they are doing, they can easily get into difficulties. Large volume buoyancy compensators (BCs) have shown that very close to the surface of the water is far more dangerous than we had believed. When we only had small bladder BCs, it was more difficult to make a rapid ascent.

Development of buoyancy compensators

Until the 1970s few divers used buoyancy compensation devices. Being correctly weighted to be neutral at the depth of the dive was considered adequate. If one needed any additional buoyancy one would blow some air into the wetsuit sleeve. This would form a bubble between the shoulders. To get rid of it, one raised an arm and the bubble ran out. Many people felt no need for a buoyancy compensator.

However as more people took cameras and other heavy objects underwater, it became obvious that it was handy to have some way to displace water so that one could achieve additional buoyancy at depth. At first the bag was in front of the chest. These did little to complicate the rate of ascent because the bladders were generally small, with only 6.8-8.2 kg of lift. Additionally, the divers of the time rarely put air in the bladder unless the need was critical. While this amount of lift was sufficient to increase the rate of ascent, the problem was not significant since the divers were skilled in the use of the devices, which were only intended to be used to maintain neutral states in the water column or float them on the surface. Later back mounted bladders and jacket configurations became popular.

Divers need to be able to displace water close to or just above their centre of mass. On the surface there is a portion of the buoyancy compensator that is only displacing air. To float the diver adequately there must be a significant amount of air underwater. Larger buoyancy compensators displace more air when they are on the surface but displace about the same amount of water as smaller ones, so the diver is not necessarily further out of the water. Underwater they can displace more water, but the bigger bubble causes increased lift, which is a matter of concern.

Buoyant ascent rates

A study at the University of California, Los Angeles, (UCLA) Underwater Kinesiology Laboratory in 1980 tested a number of buoyancy compensators, with positive buoyancies of 5 to 24.5 kg,[1,2] in our fresh water pool. The diver, in full ocean gear, 7 mm wet suit, booties and gloves, tank, regulator, backpack and an adequate amount of weight for neutral buoyancy was placed horizontally at a chest depth of 2.85 m (9 ft 4 inches), holding the sides of a weighted box. The BC was filled until the overpressure relief valve was activated. The diver was then signalled to exhale fully, relax and let go. The ascents were timed and video taped. All the divers changed from horizontal to vertical on the way to the surface. The smallest buoyancy compensator brought the diver up at an average speed of 20.6 m (68 ft) per minute.

Average ascent rates were calculated for the whole 2.85 m (9 feet 4 inches) ascent. We did hundreds of buoyant ascents. Some people came up awfully fast, although they were only coming up two to two and half times faster than they were supposed to when we looked at the average ascent rate.

When we studied the video tapes for the last 1.2 m it was a different story. The smallest vest came up the last 1.2 m at a slower rate than it did overall. The explanation is that the divers started horizontal, became vertical and then, because it was a small bubble high on the chest, they were arched backwards by the vest. This put them at a significant angle and consequent they were slowing through the last 1.2 m. On the other hand the medium and larger vests were accelerating through the last 1.2 m. These took the divers vertically, right up to and straight through, the air-water interface. Sometimes the diver came out of the water to his waist. Some of the larger over the shoulder models reached ascent rates of 76.5 m per minute. Table 1 summarizes the data derived from this study.

Ascent rates

Since 1951, the USN Diving Manual has told us to come up at 18 m per minute. About two and half years ago I was told how the USN chose 18 m per minute. Doctor Ed Lanphier had the job of recommending an ascent rate. He realized that there were two populations of Navy divers. One was swimmers who wanted to pop out of submarines and go as fast as they could to the surface. They were happy with 54-60 m per minute, and there were the Navy hard hat divers who were very satisfied with, and used to, 7.5 m per minute, which was the ascent rate for the then USN decompression tables. He reasoned that if the hard hat divers came up a little faster and the swimmers came up a little slower, things would be alright. He suggested that 60 ft (18 m) a minute, a foot a second, was a nice round number that sailors could remember. The committee discussed and accepted it. The 18 m per minute ascent rate has been used countless thousands of times, and it has turned out to be a really good guess. That it was nothing more than a compromise and had no significant research behind it was a bit of a shock to me.

Divers are often told to ascend at the rate of their smallest bubble. To find a bubble that goes up at 18 m per minute, one has to be pretty selective. The tiniest bubbles that one can see come up between 13.5 and 18 m a minute. That is the fuzz in the water. Anything bigger than fuzz is coming up faster than 18 m per minute. One of the worst things that a diver can do is to fix on a bubble and follow it up, because as it expands, it goes faster and faster.

TABLE 1

BUOYANCY COMPENSATOR SIZE, SHAPE, DESIGN AND ASCENT RATES

Size		Shape	Volume	Lift		Ascent rates Full distance (9' 4" = 2.85 m)		Ascent rates Last part (4' = 1.22 m)	
Inches	cm		litres	lb	kg	fpm	mpm	fpm	mpm
20x7"	51x18	Single bladder HC	5.1	11.2	5.1	68	20.6	43.3	13.1
23x18"	59x46	Single bladder HC	12.7	27.9	12.7	122	37	147.8	44.8
23x19"	59x49	Bladder in bag HC	15.5	34.1	15.5	132	40	185.8	56.3
24x19"	61x49	Bladder in bag HC	17.2	37.8	17.2	138	41.8	187.8	56.9
24x18"	61x46	Bladder in bag HC	17.5	38.5	17.5	143	43.3	205.7	62.3
25x20"	64x51	Bladder in bag HC	17.3	38.1	17.3	149	45.2	208.7	63.2
19x16"	49x41	Bladder in bag HC	21.6	47.5	21.6	156	47.3	213.3	64.6
		Large Jacket type	21	46.2	21	149	45.2	225.9	68.5
26x10"	67x25	BIB Backmounted	24.9	54.8	24.9	168	50.9	245.3	74.3
		BIB Overshoulder	21.2	46.6	21.2	150	45.5	254.7	77.2

HC donotes horse collar type of buoyancy compensator. BIB indicates bladder in bag. Wet suit expansion was assumed to be constant during the ascent..

In one study of ascent rates there was a wide variation with few ascents being slower than the recommended 18 m per minute. It was commonplace to witness divers ascending at two to three times this rate who, when questioned, would indicate they were travelling at the rate of their smallest bubbles as they did on all of their ascents. Telling people to follow the smallest bubbles as they come up may not be the best advice one can give.

Dangers of buoyancy bubbles

As buoyancy chambers got larger, there were more problems with rapid ascents. The development of larger bladder configurations, which could hold a bubble of gas in a variety of positions depending on whether the bladder was front mounted, back mounted, over the shoulder or around the body, requires careful attention to the size of the bubble since larger bubbles lead to larger changes in buoyancy with changes in pressure.

Large bladders, with buoyancy potentials up to 34.4 kg or more in some extreme cases, offer another potential risk for divers with poor water skills, as the large bladders can compensate for significantly greater amounts of weight. The diver could, by inflating or deflating the BC, move up or down in the water column with considerable speed. No longer was there the need to develop surface diving skills to overcome the slightly positive state which normally existed on the surface at the beginning of a dive where the diver was properly weighted. "Push button diving" permits the diver to constantly adjust buoyancy throughout the dive and the ascent.

Unfortunately the management of a large bubble in a buoyancy compensation system is infinitely more difficult than the management of a small bubble if one is not, unintentionally, to become positively buoyant during ascent. Ninety per cent of the fatalities in our area over the last 5 years were, in our opinion, overweighted. They also had large buoyancy compensators. People are wearing 7 mm wetsuits, with 11.8 to 12.7 kg of lead. Many of them insist that is how much they need to get down. That may be so with some of the newer, thicker foam materials. A thicker suit needs more lead to sink. But as soon as it goes down, the bubbles in the suit compress and the diver becomes considerably negatively buoyant. We no longer believe that one is correctly weighted for a dive when one floats with the water level with one's eyes and if one exhales one sinks. Now we want our divers neutral at 3 m rather than on the surface.

Additional buoyancy does not create a major problem when tackled properly. Anything that one does, putting one's arms out to the sides, spreading one's legs or arching one's back, will slow the ascent rate. All these will cause one to rise at an angle rather than vertically, in which position the ascent rate is faster. But they need to be initiated early in the ascent to be most effective in ensuring control through the entire ascent. Ascent control is a precautionary skill that must be put into effect early and reinforced often during the rise to the surface.

Jacket type compensators have loose arm holes for easy entry. When inflated underwater the bubble rises to the highest part of the jacket. When ascending the bubble is over the shoulders lifting the jacket up beside the diver's ear. During ascent, the diver may have to reach up well over his head to find the dump valve if it has floated free. There is plenty of room for air to expand in these large compensators. If a diver leaves 27 m with a partially filled compensator when he or she gets to about 6 m the gas will have expanded to practically fill the buoyancy compensator and he is not going to be able to stop.

Many people favour back mounted compensators because they want to have the front open. They need to understand that should they become unconscious, they will float face down. Once I watched a man wearing a newly purchased, back mounted compensator hanging off a line at the end of the dive. He gradually changed position. His feet came up and up. When he got horizontal, I recognised that something was going wrong. He ultimately went feet up and as he did, he let go of the line and made an attempt to pull the dump valve, which was located on the shoulder. Unfortunately, the dump valve was now below the air bubble and he shot to the surface. He embolized but not seriously. He did not have the insight to manage his bubble. As a consequence, he got himself into trouble.

Unfortunately the majority of the divers do not have good buoyancy skills. Most are buying equipment that will give them a large bubble and they do not take the time to learn the skills of how to manage a large bubble. Divers need to be able to vent gas from buoyancy compensators as they swim along. Around the world, we see people who put air in the buoyancy compensator, which is absolutely fine, and then when they start to ascend they forget that they have to start venting early and often. When they get up to somewhere around 4.5 m, even if they start thinking about venting air, in the time it will take to initiate the dump, they are going to continue to ascend and lose control. Accidents occur when a diver loses control. If one is able to regain control, then one avoids injury, but one still had the accident but avoided injury. If one does not regain control, then one can expect there is going to be injury.

The buoyancy compensator is a significant problem but it is not the only problem. Drysuits with large amounts of gas are also difficult to control, and divers have died after becoming inverted and being unable to get head up again at the surface. Drysuits must have a reliable rapid exhaust valve which can be used effectively whether the individual is in the horizontal or the vertical position. It is clear that the dry suit manufacturers, and instructors, who are advocating significant instruction prior to the use of the suit are providing fundamental knowledge and skill to the diver who wishes to use these devices. The American Academy of Underwater Sciences (AAUS) has made it in as a requirement, for scientific divers, to use a buoyancy compensator with a drysuit, largely because of the problems associated with trapping air in the legs and not being able to get back into a upright position.

How to stay out of trouble

One should make it a routine to weight oneself and deal with ones buoyancy so that one will be able to come up slower than 18 m per minute. Sixty feet per minute does not seem to create problems for most people. The recommendation however is to slow down and come up at a reduced rate, something of the order of 12 m per minute. This has some advantages.

The safety stop that has been the largest single step for safety that we have taken in the last few years. In my view its purpose is not to provide additional decompression time. It does and that is a benefit. The major benefit is that whatever a person's ascent rate was, a stop close to the surface means they are far more likely to be in control through the last few metres of ascent. They are far less likely to have the BC expanding so rapidly that they will be rushed to the surface and into trouble.

Safe ascent recommendations

A recent workshop, conducted by the American Academy of Underwater Scientists, published Safe Ascent Recommendations[3], with the comment that "It has long been the position of the American Academy of Underwater Scientists that the ultimate responsibility for safety rests with the individual diver. The time has come to encourage divers to slow their ascents". The recommendations were:-

1 Buoyancy compensation is a significant problem in the control of ascents.
2 Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice.
3 Before certification, the diver is to demonstrate proper buoyancy, weighting and a controlled ascent, including a "hover" stop.
4 Divers shall periodically review proper ascent techniques to maintain proficiency.
5 Ascent rates shall not exceed 60 feet of seawater (fsw) or 18 m per minute.
6 A stop in the 3-9 m zone for 3-5 minutes is recommended on every dive.
7 When using a dive computer or tables, non-emergency ascent are to be at the rate specified for the system being used.
8 Each diver shall have instrumentation to monitor ascent rates.
9 Divers using dry suits shall have training in their use.
10 Dry suits shall have a hands-free exhaust valve.
11 Buoyancy compensators (BCs) shall have a reliable rapid exhaust valve which can be operated in a horizontal swimming position.
12 A BC is required with dry suit use for ascent control and emergency floatation.
13 Breathing 100% oxygen above water is preferred to in-water procedures for omitted decompression.

It was the consensus of the group that produced the recommendations that, because there is no way to stop people from using whatever equipment they want, divers must learn how to to slow down their ascent rate and need to be taught buoyancy control as a skill. They need to be tested on buoyancy control and they need be to able to demonstrate that they can hover in any position before certification. This can be a difficult skill to learn.

Implications for training

The implications for diving instruction are clear. The training agencies are doing a far better job than they did in the past in getting their instructors to recognise that buoyancy control has to be taught as a skill. Diving instructors have to pay more attention to making sure that their students are skilled in the management of whatever the buoyancy system they are using. It takes time to develop these skills. Divers must understand that the controls for different buoyancy compensators work in different ways. They should take a good look their buddy's buoyancy control system before a dive to ensure that they know how to dump gas rapidly from it if the buddy loses control and starts floating rapidly to the surface. Buoyancy compensation is a tool and not a crutch.

References

1 Egstrom G. A few words on ascent rate, Proceedings: *International Conference on Underwater Education*. NAUI, San Diego 1982.
2 Egstrom G. Biomechanics of buoyancy compensation and ascent rate, *Proceedings of the Biomechanics of Safe Ascents Workshop*, Lang M. and Egstrom G. (eds) American Academy of Underwater Sciences, 1990.
3 Recommendations from the *Biomechanics of Safe Ascent Workshop* held at Woods Hole, Mass. Sept. 25-27, 1989.

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