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DEEP DIVING AND SOME EQUIPMENT LIMITATIONS

Carl Edmonds, Michael Loxton, John Pennefather and Christopher Strack

Background

Reports of recreational diving fatalities in Australia[1] involved an analysis of the diving profile, observations of the witnesses, equipment assessment by a regulatory body, and a specialised autopsy. If the cause was not evident from the investigations, a re-enactment of the incident was often employed.

In re-enactment trials, the divers own equipment is reassembled and used, and the profile repeated by a diver of approximately the same stature, but hopefully without the same result. These techniques led to a number of breakthroughs in determining the causes of diving accidents in the Royal Australian Navy, as far back as 1967.[2]

One of the situations which has led to re-enacting dive profiles has been the observation that there is sometimes difficulty in obtaining sufficient air, either for breathing at moderate rates, or for inflating the buoyancy compensator (BC), at depths in excess of 30 m (100 feet). This is noted especially when the diver is getting "low on air".

Inadequate air supply situations have been highlighted as a significant cause of death in diving accident reviews.[1,3,4] Other workers have postulated the difficulty in obtaining adequate air through the regulator as a factor in diving accidents[5-7], and some explanations have been forthcoming.

Some of the factors which produce a limitation in the non-exhausted air supply, either to the diver, to the BC or to the alternative air supply line (octopus regulator), are obvious. These include a failure to fully open the cylinder valve, resistance or failure of the J valve (when used), and equipment malfunction problems causing regulator resistance. Laboratory investigations have demonstrated increased regulator resistance at, or near, reserve air levels, usually considered to be 35-50 bar.[6,8]

At the suggestion of one of us and while investigating a diving fatality, Wong[5] performed a series of experiments in 1988. These showed that in some circumstances, it is impossible to obtain adequate ventilation (especially under exercise conditions), while using the power inflator of the BC, once a reserve air level had been reached in the cylinder.

These problems led to a decision to observe what happens with a diver exercising (equivalent to moderately heavy breathing), at a significant depth, with the air supply on or near reserve, when using typical scuba diving equipment.

Methodology

The parameters chosen were as follows:

Depth 40 m (132 ft, 5 bar).

Cylinder pressure 35 bar (515 p.s.i.) in steel 72 cu ft (2038 litre) cylinders.

BC equivalent (a low resistance bellows volume meter) able to measure more than 10 litres i.e. sufficient to compensate for a 10 kg (22 lb) weight belt.

Six modern regulators, typically used by recreational divers, were included in the trials.

The following recordings were made at 40 m equivalent depth:

1 Time taken to inflate the 10 litre BC equivalent, while the "diver" breathed moderately heavily

2 Time taken to produce a subjective resistance to breathing, i.e. a low-on-air (LOA) situation.

3 Time taken to produce an out-of-air (OOA) situation.

4 Additional observations made by the divers and the researchers.

A separate experiment was conducted at 40 m depth to determine the speed at which the BC (volume meter) could be filled to 10 litres at different tank pressures within the reserve range (50 bar, 40 bar, and 30 bar).

As a follow-up observation, the contents pressure gauges supplied with the regulators were compared with each other as well as to a standardised pressure gauge used at the Royal Australian Navy (RAN). Volume and air consumption measurements were determined by use of the RAN standard pressure gauge, unless otherwise stated.

Six experienced armed forces divers were used, and the investigation was performed in a recompression chamber of the Royal Australian Navy, where the whole operation was under continuous, timed, video recording. Diving medics and physicians continuously monitored these chamber experiments.

The scuba diving equipment chosen was from the "up market" diving establishments who hire out this equipment. The equipment hired for the experiment included six typical regulators, pressure gauges, BCs and inflator hoses, available to any certified diver attending these establishments. The regulators would usually be hired out to experienced and certified divers, about every second weekend, and were considered by the dive operators and their clients to be in good condition. The suppliers were unaware that the equipment was to be used in experiments.

All the equipment supplied did appear to be of a remarkably high standard. The sets were modern and clean, and worked extremely well, at least on the surface.

Five of the six regulators were current models purchased less than a year before testing. All the regulators were reported to have had maintenance checks within the preceding three months.

Results

The results are given below for the time taken to inflate the BC to 10 litres when the regulator was not in use, the time taken to inflate the BC to 10 litres when a diver was breathing from the regulator, the duration of air supply at depth (starting with a cylinder pressure of 50 bar) before a LOA and OOA situation developed, the pressures at which these situations developed and the accuracy of the pressure gauges compared with the RAN gauge.

BC inflation time

Tests were performed on the equipment to determined how long it would take to supply 10 litres of air through the BC inflator line. It took 6-8 seconds for this on the surface, with a tank pressure of 30 bar.

At 5 ATA chamber pressure, when three different regulators were tested with tank pressures of 50 bar, 40 bar and 30 bar there was considerable variation in the time taken to inflate 10 litres. Although the times of inflation differed considerably between regulators, each regulator was fairly consistent. It took 20, 25 and 38 seconds to inflate from the three regulators tested when no other air outlet was in use (Table 1).

TABLE 1

TIME TO INFLATE BC TO 10 LITRES AT 40 m

Tank Pressure	50 bar	40 bar	30 bar
Regulator A	20 sec	20 sec	20 sec
Regulator B	23 sec	26 sec	26 sec
Regulator C	37 sec	39 sec	37 sec

It is evident from these results that, even with good quality, well maintained regulators, when respiration was not being performed at the same time, the time to supply 10 litres of air into the BC was between 20-40 seconds at 40 m depth. This was relatively independent of the tank pressure over the limited range tested.

Inflation time while breathing from regulator

The time to inflate the BC to 10 litres (at 5 bar) was measured while the diver breathed from the regulator (Table

TABLE 2

VOLUME ACHIEVED, TIME TAKEN AND PRESSURE REMAINING, WITH TIMES TO LOA AND OOA, WHEN BC INFLATION WAS ATTEMPTED AT 40 m DEPTH WITH A CYLINDER PRESSURE OF 50 BAR WITH THE DIVER BREATHING DEEPLY

	Litres inflated	Time taken	Remaining pressure at depth*	Time to LOA	Time to OOA	Cylinder pressure at OOA		Minute volume of diver
						at depth*	at surface**	
Reg A	10	37 sec	20 bar	46 sec	94 sec	7 bar	10 bar	40.1 l/min
Reg B	8.2	64 sec	0 bar	64 sec	68 sec	8 bar	0 bar	54.7 l/min
Reg C	3.2	50 sec	1 bar	41 sec	50 sec	6 bar	1 bar	86.9 l/min
Reg D	0.5	41 sec	10 bar	16 sec	41 sec	12.5 bar	10 bar	84.9 l/min
Reg E	10	28 sec	20 bar	28 sec	51 sec	9 bar	5 bar	67.8 l/min
Reg F	10	24 sec	20 bar	55 sec	101 sec	8 bar	5 bar	35.3 l/min
Mean		**40.6 sec**		**41.7 sec**	**67.5 sec**	**8.4 bar**		**61.6 l/min**
Range		**24 - 64+**		**16 - 64**	**41 - 101**	**6 - 12.5**		**35.3 - 86.9**

* Scuba gauge pressure read at 40 m depth. ** Cylinder pressure read on the surface on the standardised gauge.

2).

Only three of the six regulators allowed the full 10 litre inflation prior to the divers reaching an OOA situation. The other three regulators supplied 8.2, 3 and 0.5 litres, respectively. The two worst cases occurred with the two divers who had the highest respiratory minute volumes (over 80 litres/minute at 5 bar).

While breathing at an increased respiratory minute volume, there was often inadequate air to inflate the BC. Even those that did inflate, did so slowly and took a considerable period of time (24 - 37 seconds) to supply 10 litres at this depth.

Duration of the air supply

The reports of increased resistance (a LOA hand signal) were very variable and subjective. This happened after an average of 41.6 seconds, with a 16-64 second range. A total OOA situation developed in 41-101 seconds, with an average of 67.5 seconds. Those with a higher respiratory minute volume fared worse.

Although in general it appeared that the divers with the least minute ventilation volume were able to breathe without subjective resistance for longer periods of time, the concept of "resistance to breathing" was so subjective that it appeared not to be reliable.

Judging by the observed respiratory effort, it appeared as if many of the divers were coping with quite significant resistance, without complaining. This may reflect the diver's training and personality or the effects of narcosis.

Another factor to be considered is that the inflation of the BC might be related to the resistance to breathing. In the case of regulator E, the diver signalled that he was unable to continue breathing, until he stopped inflating the BC simulator. Once he did stop this inflation, he was able to breathe for another 33 seconds.

Pressure gauge readings

The divers' tank gauges showed considerable variation at 150, 50 and 20 bar between themselves (Table 3), and with the standardised gauge after the diver had subjectively reached an OOA situation. The range of pressures observed at depth when OOA was 0-10 bar and, making allowance for this depth, the variation between the divers gauge and the standard gauge at the OOA point was 0 to 7 bar (average =

TABLE 3
TANK PRESURE GAUGE READINGS

Pressure	150 bar	50 bar	20 bar
Regulator A	152	49	17
Regulator B	142	48	16
Regulator C	142	50	22
Regulator D	135	43	19
Regulator E	140	32	20
Regulator F	150	50	23

2.4 bar).

Discussion

These experiments were performed to observe what could happen, at a depth of 40 m, when an LOA situation was encountered.

It is likely that most divers are unaware of the time needed to inflate a BC adequately at depth. This is made more difficult, and may be impossible, with moderately increased respiratory volumes, caused by exertion or anxiety.

At these depths there are many more problems that a diver may have to face. They include the effects of narcosis, increased air consumption (and therefore reduced dive duration), very significant buoyancy changes (with the compression of the wet suit making it relatively non-buoyant), reduced sensory input, and cold exposure.

The experienced divers who were used in this experiment were asked to breath deeply from the regulators under test. The varying responses can be seen in the different minute volumes of the subjects. Despite the considerable effort employed by the subjects, the result (in the form of respiratory minute volumes) was not commensurate with the apparent respiratory effort being made. The minute volumes achieved were not excessive by conventional standards for moderate exercise. Minute volumes of 62.5 litres, were considered by others[9] to be a reasonable indicator of moderate exertion.

It is also probably not appreciated that so little time is available once a LOA situation has been reached. Although we accept that 35 bar (515 psi) is a LOA situation, many divers would still believe that this is an adequate air supply for other activities, such as swimming back to a shot line, freeing an anchor, adjusting equipment, assisting a buddy, etc. Our observations show that they might have much less than a minute to perform these task before reaching a total OOA situation.

An OOA predicament can appear without an intervening LOA observation. Thus it might be worthwhile to extend the experiments with various scuba tank pressures, to determine how much the diving activity is relevant to the outflow of air from the various orifices of the first stage regulator, under differing demands. Some laboratory work on the regulator induced resistance to air flow has already been done by Egstrom.[5] There have also been attempts, by ANSTI[9] and USN EDU[10], to compare the performance of different regulators.

What was evident from our results was that not only was there an insufficient supply of air through the regulator for breathing during sustained exertion, with a low tank pressure, but there was also an inadequate air supply available for other outlets (low pressure lines to the BC or "octopus" regulator).

From our observations, it is presumed that the higher the minute ventilation requirements, the greater the limitation of the air supply. Thus it is unlikely that subjects with low maximum breathing capacities will encounter difficulties with the same frequency as those with a higher breathing capacity or those who are exerting themselves more.

It is likely that the respiratory effort by divers is as much influenced by negative buoyancy[11,12] at depths, as by swimming speed. This might be aggravated by being deliberately overweighted (inexperienced divers, marine photographers), wearing thick wet suits at depth, problems with BC usage, or by following the advice, given by some diving operators, to exhaust the BC with ascent. The latter recommendation is made in order to overcome the hazardous effects of air expanding in the BC during ascent. It is inappropriate if there is negative buoyancy at depth and a LOA situation.

For a variety of reasons, problems that develop at great depths will be much harder for divers to solve than those occurring in shallower depths. At the greater depths, a minor problem may become magnified because of the limitations of the equipment inherent at these depths and/or the increased density of the breathing gas, as well as the physiological effects of narcosis.

One could speculate as to why these difficulties have not been widely appreciated in the past. Some experienced divers may be aware of such limitations and may well plan their dives accordingly to ensure that they do not make excessive demands on their air supply. Some divers who dive to 40 m may be unaware of the limitations imposed by scuba equipment at this depth, and may even claim that none exist if they have not personally experienced it. Some have experienced these difficulties and survived. Others have experienced the problems outlined above and died.

We believe that 40 m is an excessive dive depth, if problems such as negative buoyancy or an LOA situation develop. The consequences of diving to this depth include a very significant reduction in the ability to obtain positive buoyancy by inflation of the BC, and an inadequate air supply to the second stage regulator, be it for the diver's breathing or an octopus system. In the event of two of these three outlets being used concurrently, they would be compromised even more than they are individually.

Complete reliance should not placed on the calibration of pressure gauges, especially at low cylinder pressures. A LOA situation may develop even when the gauge implies sufficient cylinder pressure to permit adequate regulator function.

We had previously presumed that this air supply problem at depth was a rare one, contributing to only the occasional death. However it may be more widespread, and perhaps even the norm at these depths, with the scuba equipment currently in use. None of the findings should be used to denigrate any specific piece of equipment, which may be lifesaving in certain circumstances. The lesson is to understand and instruct others about the limitations of this equipment.

Conclusions

Once a LOA situation has been reached at depth, the reliable duration of the air supply for both BC inflation and breathing is very limited, and measured in seconds rather than minutes.

While engaged in tasks requiring moderate to heavy breathing (respiratory minute volumes of 35-90 litres/min) with a low tank pressure, it may take a considerable time (if it is possible at all) to inflate a BC with 10 litres of air at 40 m. This was only achieved by half of the inflator systems, when the diver was breathing from the second stage regulator. In the other half, the 10 litre volume was not achieved, at that depth, before the tank effectively ran out of air.

Problems of an inadequate air supply may exist no matter what low pressure outlet is used, a second stage regulator, buoyancy compensator inflator or octopus regulator second stage.

Recreational divers should avoid, as far as possible, exposure to depths in excess of 30 m, unless more effective equipment is available and training has been undertaken in buoyancy control and in the appreciation of equipment limitations.

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EVALUATION OF DECOMPRESSION SICKNESS INCIDENCE IN MULTI-DAY REPETITIVE DIVING FOR 77,680 SPORT DIVES

Bret Gilliam

Introduction

I conducted the logkeeping data contained here as a private project in association with my contract positions as Director of Diving Operations for Ocean Quest International (a dive/cruise company now defunct). The majority of the data is from personal review of dive boat logs, passenger records, diver interviews, recompression chamber histories and interviews with members of the professional dive staff of the ship.

I was responsible for the overall diving co-ordination of the ship including orientation of the sport dives each week, development of the computer diving program and certification course, supervision and operation of the recom-