The relative safety of forward and reverse diving profiles.

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McInnes S, Edmonds C, Bennett M. The relative safety of forward and reverse diving profiles. Undersea Hyperb Med 2005; 32(6):421-427. A recent workshop found that with no-decompression dives, "reversed dive profiles" (RDP) did not increase the risk of decompression sickness (DCS). Thus in *multi-level* dives, the deeper part of a dive may be performed later in the dive, and *repetitive* dives may progress from shallow to deep. This contradicts the conventionally recommended forward dive profile (FDP) when the deeper dive, or deeper part of the dive, is performed first. The RDP Workshop recommendations were made despite the absence of adequate data. We performed two groups of experiments to test this hypothesis. We exposed two matched groups of 11 guinea pigs each to forward and reverse *multi-level* diving profiles to determine any substantial difference between FDPs and RDPs. There was no evidence of DCS in any of the FDP animals, while six (55%) of the RDP animals exhibited symptoms of severe DCS and died. This difference was statistically significant (P = 0.01). We then compressed two groups each of 11 guinea pigs to *repetitive* dives to determine any substantial difference in the risk of DCS when two equivalent sets of three dives were conducted from the deepest to most shallow on the one hand (FDP), and from the shallowest to the deepest on the other (RDP). Over two such series of dives (the second extended in time and depth to increase DCS risk), there was a significantly higher incidence of severe DCS in those animals in the RDP group. Seven of 21 exposures (33%) in the RDP group resulted in severe DCS versus none in the FDP group (P=0.01). Our findings suggest that multi-level and repetitive dives performed in the established FDP manner are less hazardous than those performed in the reverse profile mode, at least for the exposures we chose. We believe the recommendations of the workshop should be re-examined.

INTRODUCTION

In 1999 a workshop organised by The Smithsonian Institute in conjunction with other diving organisations, considered the possibility of altering recommended safe diving procedures concerning multi-level and repetitive diving (1). The workshop challenged the traditional view that both multi-level and repetitive dives should be undertaken from deep to shallow. The participants promoted the concept of "reversed dive profile" (RDP) to supplement the established "forward dive profile" (FDP).

FDP involves performing the deepest part of the dive first (in multi-level diving) or the deepest dive first (in repetitive dives). Subsequently the dive or dives become shallower. The reasons for undertaking this type of diving are multiple and have been discussed elsewhere (1). RDP involves diving from shallow to deep, either in multi-level diving or repetitive dives. The reasons for wishing to undertake this type of diving are also discussed elsewhere (1).

Although a detailed analysis of the proceedings suggests there was little consensus, a final compromise was claimed between the participants. The workshop agreed to approve RDPs with very specific limitations. These had the virtue of restricting RDPs to relatively less stressful decompression exposures than if no restrictions were applied, but they were not supported by experimental data. The limitations were a depth limit of 40 metres sea water (msw), a differential between dive depths of no more than 12 msw, and the specific exclusion of decompression dives.

The belief that FDPs and RDPs are analogous and therefore require comparable decompression is based mainly on the assumption that, given the same depths and durations, both produce the same load of inert gas dissolved in the tissues – irrespective of the order of the exposures. This concept is inherent in many decompression meter algorithms, especially those that deal with dissolved inert gas loads, as opposed to induced-bubble models. Our search of the literature, however, did not reveal any experimental confirmation that RDPs and FDPs can safely have the same decompression requirements.

This study was designed specifically to test the hypothesis that there is no risk difference for decompression sickness (DCS) between the RDP and FDP, as they apply to multi-level and/or repetitive dives.

METHODS

Because we intended to deliberately expose subjects to potentially provocative dive profiles with the aim of producing DCS in a proportion of them, we selected an animal model with which we were familiar (the guinea pig). The experimental protocol was approved by the UNSW animal ethics committee and the animal care was overseen by a senior veterinarian.

Two groups of guinea pigs were selected for exposure to FDPs (FDP group) and RDPs (RDP group) respectively. To ensure the average body weights were comparable, the animals were graded according to weight. The first was allocated to one group, selected by a toss of a coin, and then each consecutive pair was allocated to each of the groups in turn. The guinea pigs were tagged and photographed for ease of identification.

If there were no significant differences in the rate of DCS between the FDP and RDP groups on the first dive profile, we planned to repeat an exposure every two weeks using sequentially more provocative profiles until 50% of the animals in at least one group did develop signs of severe and obvious DCS. Weights were to be re-assessed prior to each new dive sequence, as the weights of guinea pigs may fluctuate with time and food intake.

An initial dive profile was chosen that was believed to be clinically innocuous, both from our previous experience with these animals and as implied by others (2,3). We subjected the two equivalent groups of guinea pigs to dives within the recommended limits of the workshop previously referred to : maximum depth less than 40 msw, no differential depths of greater than 12 msw, and the initial exposures were well within the no-decompression limits for these animals.

We powered our study to reliably detect a large difference in risk between groups on the basis that small differences would be more appropriately sought through human trials. Power analysis suggested we needed 11 guinea pigs in each of four groups (two multi-level and two repetitive dive profiles) to achieve a power of 80% at a significance level of 0.05 to detect a 70% risk difference (10% versus 80%) in the incidence of DCS between the FDP and RDP groups. 44 guinea pigs were obtained through the UNSW and screened to be disease free. Statistically, the multi-level and repetitive dive profiles were to be assessed separately.

We defined serious DCS according to Albano (2): obvious respiratory distress, fitting, inability to walk or maintain balance, or death at any time during the 2-3 hours following final decompression to the surface. The animals were videotaped after the completion of the dive protocols and evidence of DCS recorded. Once DCS was diagnosed, animals were to be transferred to a 100% surface oxygen tent immediately and then treated on a modified oxygen table at 190.4kPa (9msw) for 45 minutes with any other animals that succumbed. We intended to exclude any animal with signs of DCS from all subsequent dives, along with a paired animal of similar weight in the other group, in order to maintain comparable average weights.

The dive exposures were conducted by qualified hyperbaric technicians and profiles confirmed by the use of an Aladin Pro dive computer in the chamber during the experiments, to verify the depths and durations.

Multi-level dives.

The initial FDP was 36msw for 30min, 24msw for 30min and 12msw for 30min. Ascents and descents were at 9 m/min. The RDP was to have the same exposure but in reverse i.e. 12msw, 24msw and 36msw. Subsequent dives would have an extension to 60min at each depth, then 90min at each depth, and so on until DCS occurred.

Repetitive dives.

The initial FDP, series 1, was 30msw for 30min, 20msw for 30min and 10msw for 30 min, with surface intervals of 15 minutes. All ascents and descents were at 9 m/min. The RDP, series 1, had the same exposure but in reverse order. The subsequent FDP, series 2, was 36msw for 40 min, 24msw for 40 min and 12msw for 40 min, with surface intervals of 15 minutes. The subsequent RDP, series 2, had the same exposure but in reverse order.

RESULTS

Multi-level Dives

The characteristics and dive profiles for each multi-level (ML) group are given in Table 1. Following decompression to the surface, all animals were observed for three hours before being returned to the animal facility.

Table 1. Group characteristics and dive profiles

MULTI-LEVEL DIVES

Group (N)	FDP.ML (n=11)	RDP.ML (n=11)
Weight in grams mean (SD)	792 (236)	795 (215)
Profile	36m for 30mins 24m for 30mins 12m for 30mins	12m for 30mins 24m for 30mins 36m for 30mins

During the observation period there were no signs of DCS in any animals in the FDP.ML group, versus six of the 11 animals in the RDP.ML group. This difference was statistically significant (Yate's corrected Chi-square 5.73, $P = 0.01$ by Fisher's exact test).

Details of each of the abnormal animals are given in Table 2. All six animals were placed on oxygen immediately after displaying DCS manifestations and were recompressed within 19 minutes on the oxygen treatment schedule described above. Two animals were dead before treatment could be instituted. At 42 minutes into the planned treatment table there was no movement from any of the guinea pigs and the treatment was aborted. All six animals were dead. As there was a statistically significant difference in the risk of DCS between the groups, no further ML dives were undertaken.

Five of the six animals that experienced DCS were noted to be above the mean weight of the group. A secondary analysis comparing the weight of animals in the RDP.ML group who suffered DCS with those who did not, suggested that weight was different in the two groups (mean weight and SD of survivors 670g +/-265, compared to DCS animals 899g +/-87), however this difference did not reach statistical significance, $P = 0.08$.

Table 2. Details of DCS in affected animals. (RR = Respiratory Rate, *indicates death before recompression could be instituted)
MULTI-LEVEL DCS DIVES

Onset of symptoms (mins after decompression to surface)	Weight (g)	Symptoms
8	964	Decreased movement, Increased RR, convulsion, and death*
10	900	Increased RR, dragging hind limbs, death*
11	902	Increased RR, dragging hind limbs, death
12	1009	Increased RR, dragging hind limbs, death
15	760	Increased RR, dragging hind limbs, death
17	857	Increased RR, dragging hind limbs, death.

Repetitive Dives

The characteristics and dive profiles for each repetitive dive (RD) group are given in Table 3. Following final decompression to the surface, all animals were observed for two hours before being returned to the animal facility. Two repetitive dive profiles were required, labeled series 1 and series 2, as described in the methodology.

Table 3. Group characteristics and dive profiles

REPETITIVE DIVES

	SERIES ONE		SERIES TWO	
Group (N)	**FDP1.RD (n=11)**	**RDP1.RD (n=11)**	**FDP2.RD (n=10)**	**RDP2.RD (n=10)**
Weight in grams mean (SD)	716 (205)	726 (212)	689 (196)	702 (209)
Dive 1	30m for 30mins	10m for 30mins	36m for 40mins	12m for 40mins
Surface interval	15 mins	15 mins	15 mins	15 mins
Dive 2	20m for 30mins	20m for 30mins	24m for 40mins	24m for 40mins
Surface interval	15 mins	15 mins	15 mins	15 mins
Dive 3	10m for 30mins	30m for 30mins	12m for 40mins	36m for 40mins

Series 1: One animal exhibited signs of DCS and died from the RDP1.RD group, leaving 10 animals in each group for the second series (guinea pig with closest weight removed from FDP.RD group).

Series 2: No animals suffered DCS in the FDP2.RD group, while six animals suffered severe DCS in the RDP2.RD group, of whom three survived. Two animals in FDP2.RD and one animal in RDP2.RD appeared as if they may be developing DCS during the surface interval between dives one and two (FDP) and two and three (RDP) respectively. In each case the animals soon appeared normal and completed the three dives and were unaffected during the following 2 hours observation period. These animals were not designated as DCS cases. Table 4 describes the DCS manifestations.

Over these two series, there was a statistically significant difference between these groups in the risk of suffering serious DCS (Chi-square 4.25, $P = 0.01$ by Fisher's exact test), but not of dying as a result (Chi-square 1.44, $P = 0.12$).

We were unable to perform any further series of dives because of the attrition following series 2 in the RDPs (only 4 of 11 animals available for further compression), so the experiment was terminated.

DISCUSSION

There are many arguments in favour of using animal models to define physiological principles of decompression (4). Indeed, Brubakk proposed such an investigation in order to clarify the hypotheses of the Workshop (1). Accepting that animal experiments cannot be directly extrapolated to humans, they can be used to test physiological concepts. We chose to use guinea pigs as a compromise model between the larger animals, such as the pig or goat, and the smaller animals, such as the rat. The guinea pig has previously been employed widely in this area (2-6) and is of a size practical in our facility.

Table 4. Details of DCS in affected animals. (RR = Respiratory Rate).

REPETETIVE DIVE DCS

Onset of symptoms (mins after decompression to surface)	Weight (g)	Symptoms
9	1031	Increased RR, dragging hind limbs, death at 16 minutes
10	682	Increased RR, dragging hind limbs, convulsion, death at 18minutes
11	788	Increased RR, dragging hind limbs, treated successfully.
14	958	Increased RR, dragging hind limbs, convulsion, death at 28 minutes.
15	733	Increased RR, dragging hind limbs, treated successfully.
17	625	Severe pulmonary symptoms, but successfully treated.
55	956	Increased RR, dragging hind limbs and death **

** This animal was from Group RDP1.RD, all other animals were from RDP2.RD.

The dive profile was chosen to comply with the depth recommendations of the workshop on forward and reverse profiles, for humans (see above) but the duration modified for this animal species, so that the exposure would approach the no-decompression limits. As there is a direct relationship between DCS susceptibility of a species and its body mass (2-7), guinea pigs have a considerably lower DCS susceptibility than humans. The application of "human" depth limitations, therefore, should carry much lower risks of DCS when applied to our experimental animals. Despite this, we have found a significant risk of serious DCS when applying the RDP schedule to these animals.

Albano (2) described the classical signs of DCS in his hundreds of experiments on guinea pigs and also highlighted the variation of presentations with different sized animals. Those weighing 500 gm could be exposed to 6 ATA for 180 minutes without decompression staging and displayed minimal signs clinically or pathologically at autopsy. As the weight increased, so did the incidence and severity of DCS manifestations. He stated that these guinea pigs never showed lesions of DCS when the exposure to inert gas was less than 4 ATA.

We took the diagnostic criteria for serious DCS from the work of Albano. He described minor signs as hard scratching, ruffling of hair, crouched position, limp, or lifting of affected limb, while serious manifestations included the dyspnoeic syndrome (10-20 mins after surfacing), decerebrate rigidity, convulsions and death (4-16 mins after surfacing).

Using data from our own experiments as well as those of Albano, and adding a conservative bias based on the estimated saturation time of approximately 200 min (5), along with the species/body weight relationship to DCS incidence (6,7), our first non-decompression profile (ML dives) was constructed for guinea pigs encompassing the weight range of our animals. The range of weights of the pigs was not a problem statistically, given that the two groups, FDP and RDP, were equivalent. The fact that none of the FDP.ML pigs were affected, even with mild symptoms, indicated that the multi-level profile we chose was acceptable as a no-decompression exposure and it certainly satisfied the depth and differential guidelines for such dives in humans, as recommended by the workshop.

To our knowledge, neither Albano nor others have reported on the decompression effects of repetitive dives with guinea pigs, and so the influence of surface interval was unknown. Our choice was made, however, in the knowledge that guinea pigs have much less body mass than humans, and therefore the application of human depth/duration limitations are presumed to be much less stressful when applied to the smaller animal. The body weight of small animals ensures much more rapid saturation and desaturation (uptake and release) of inert gas compared to man. Thus a surface interval of 15 minutes would be the equivalent of a much longer period in humans.

The catastrophic results when the multi-level profile was mirrored from forward to reverse, with six of the 11 pigs dying so rapidly with severe DCS, unresponsive to either surface oxygen or the oxygen recompression therapy, indicated to us that there is a substantial difference in the physiological processes involved in inert gas handling between FDPs and RDPs in multi-level dives.

The fact that none of the FDP pigs were affected during FDP1.RD dive, indicated that the repetitive dives we chose also approximated a no-decompression sequence. Nevertheless, the mirror image RDP produced one death and an attempt to extend the exposures resulted in another catastrophic increase in RDP casualties, seven in the two repetitive dive series, compared to none in the FDPs.

Because there are so many potential combinations of repetitive dives, any experimental model cannot cover all eventualities and thus is not capable of providing a prediction for the overall risk of DCS from RDPs. For at least some of the possible combinations of repetitive dives, there is a differential decompression obligation between FDPs and RDPs. In the repetitive dives we chose, the risk is much greater with RDPs.

The differences we have demonstrated in both the incidence and severity of DCS indicate that there is a substantial difference in the physiological processes involved in inert gas handling between FDPs and RDPs when applied independently to both multi-level and repetitive dives. We have not presumed any relationship between these two types of diving, and have not extrapolated from one to the other, as was done at the Workshop. Verification and/or refuting of the dangers of RDPs must be demonstrated independently for multi-level and repetitive dives.

Our planned oxygen treatment on the surface and at nine meters was highly unsuccessful in these animals. Surface oxygen was said to be effective in preventing the progression of DCS (8), and the nine meter table had previously been successful in our own experiments. Unfortunately, both these optimistic observations were on animals that had experienced relatively mild DCS from single dives or from FDPs. In this current experiment the RDP produced severe DCS and we should have employed the deep air treatments applicable to the excessive exposures or explosive decompressions described by others (9). We had not anticipated the enormous difference that was demonstrated by the no-decompression exposure of the FDP and the same exposure performed in reverse.

We demonstrated an increase in the risk of serious DCS from RDPs compared to apparently innocuous FDP equivalents in our animal model. This investigation, and a recent paper documenting trends implying greater risks to divers who employ RDPs (10), both suggest the recommendations of the Workshop should be re-examined. We have expanded on many of the more general issues raised in a critical assessment of the transcript of the 1999 Workshop, elsewhere (11). This current investigation shows that reverse profiles, as they apply to multi-level and repetitive diving, are not merely the mirror image of forward profiles and do not carry equal decompression obligations. We advise against advocating reverse profiles, until the limitations of this format are determined more factually and the decompression requirements are re-defined.

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