Reverse dive profiles: the making of a myth

Carl Edmonds, Stephanie McInnes and Michael Bennett

Key words
Reverse dive profiles, decompression sickness, review article

Abstract

(Edmonds C, McInnes S, Bennett M. Reverse dive profiles: the making of a myth. *SPUMS J*. 2005; 35: 139-43.)
A consensus workshop in 1999 indicated that some previously established diving procedures used to reduce the incidence of decompression sickness (DCS) were not necessary under certain conditions. Specifically, the Workshop implied that it was not relevant whether one conducts the deepest dive or deeper part of the dive first (forward dive profile – FDP), or the deepest dive or deeper part of a dive last (reverse dive profile – RDP). The final recommendation of the Workshop was: "*We find no reason for the diving communities to prohibit RDPs within the no-decompression limits for dives less than 40 metres and with depth differentials less than 12 metres.*" The approval thus bestowed on RDPs has serious implications for diving safety, and deserves critical assessment before it is generally accepted. If applied, the recommendation may also result in adverse modifications to some decompression meter algorithms. We have reviewed the evidence concerning the relative safety of FDPs and RDPs, including some recent animal experiments. It is our opinion that recommendations were made by the Workshop in the absence of adequate data or critical evaluation. There is now sufficient evidence to demonstrate that FDPs and RDPs with analogous exposures within the recommendation of the Workshop have different decompression obligations, with the RDPs being more hazardous, at least in some situations. We conclude that the current practice of advocating forward dive profiles should be retained at this time.

Introduction

To challenge established diving procedures is both laudable and inevitable, but unless this is based on reliable data, experience and adequate testing, then changing recommendations is ill informed and constitutes a gamble with diver safety. A consensus conference is a fashionable way to achieve change, and is a legitimate procedure. This is especially so if the consensus is based on reliable data and does not disintegrate into a simple debate of beliefs during which a powerful chairman or the more eloquent delegates impose a predetermined position.

In 1999 a workshop considered the possibility of altering certain long-established and recommended safe diving procedures.[1] Specifically, this workshop proposed there would be no increase in the risk of decompression sickness (DCS) through the adoption of what is termed 'reverse dive profiles' (RDPs) to supplement the established 'forward dive profiles' (FDPs), without increasing decompression obligations.

An FDP involves performing the deeper part of the dive first (in multi-level diving), or performing the deepest dive first (in repetitive dives). Subsequently the dive or dives become shallower. An RDP involves diving from shallow to deep, either in multi-level diving or repetitive dives.

The RDP Workshop

The Reverse Dive Profile Workshop was arranged by the scientific divers of the Smithsonian Institute, in collaboration with the Divers Alert Network (DAN), the American Academy of Underwater Scientists (AAUS), the Diving Equipment and Manufacturing Association (DEMA) and *Dive Training* magazine. The issues it addressed were:

- the increasing use of RDPs
- RDPs being permitted by dive computers, and therefore becoming acceptable to divers
- the physiological basis for limiting RDPs
- the evidence for limiting RDPs
- a critical examination of the established limitations of RDPs as a logical extension of dive-computer technology.

The Workshop dealt almost entirely with beliefs, attitudes, theoretical concepts, decompression models and dive-computer analyses. Practical anecdotes and experiences were given little credence. Debate was spirited, but there was considerable agreement at least on one point – the absence of hard data on which to make valid recommendations. The Workshop seems to have ignored the maxim that an absence of evidence is not the same as evidence of absence.

The belief that FDPs and RDPs are equivalent and, therefore, require comparable decompression, is based mainly on the assumption that, given the diver is exposed to the same depths and durations underwater, both produce the same load of inert gas dissolved in the tissues. This concept is inherent in many decompression meter algorithms, especially those that deal only with dissolved inert gas loads, although not those employing 'bubble-based' models.

As the Convener properly stated: "*Does it really matter in which order dives are conducted as long as one keeps track* *of nitrogen loads and performs adequate decompression?*" The follow-up question that remained unanswered was: do RDPs and FDPs actually have the same decompression obligations, and can we therefore apply the same decompression requirements to them?

At the conclusion of the Workshop, a compromise was reached in which the Workshop approved RDPs with very specific limitations including a maximum dive depth of 40 metres of sea water (msw), a maximum differential depth between dives of 12 msw, and that all dives must be within no-decompression limits. While these limitations were based on as few relevant data as the justification for RDPs overall, they at least had the virtue of restricting such dives to less stressful decompression exposures than if there were none at all.

Based on the Workshop's recommendations, divers' advisors are withdrawing their preference towards FDPs and embracing the concept of RDPs as an equivalent and safe procedure.[2]

Views and reviews of the RDP Workshop

A reading of the full proceedings suggests that support for the recommendations was not as unqualified as the summary implied. In a later review of the Workshop, Hamilton and Baker did not refute the recommendations, but did point out that decompression modellers who took into account only gas loading (mainly the older algorithm models) drew different conclusions from those who considered the effect of bubble development (and thus slower out-gassing).[3] The former were more tolerant of the RDPs and tended to equate them with FDPs.

They also noted that the lack of diving data available to demonstrate any danger from RDPs might be due to the prohibition against such profiles being used, i.e., insufficient experience. This view has been mirrored in the popular diving press.[4] To quote Hamilton and Baker "*the discussion got a little bit heated…folk who work with bubble models had serious reservations about a complete retraction of warnings against reverse profiles…you might really get into trouble on an improperly planned or executed RDP.*"

Indeed, a reading of the general discussion section of the proceedings confirms that a broad range of opinions were expressed by the various identified delegates, often repeatedly, and these are now summarised.[5] Neuman pointed out that, while delegates were concerned about the paucity of evidence for the safety of RDPs, we do have a lot of data on FDPs, literally millions of dives with an acceptable incidence of DCS. Lewis noted that we have ample evidence that uptake and washout of inert gas are asymmetrical, a concept that is inconsistent with FDPs and RDPs being equivalent.

On a more experimental level, Gerth provided some evidence that the US Navy air diving tables may not be as safe with RDPs as with FDPs, and extended this to the dive-computer algorithms, while Huggins produced a retrospective analysis of the admittedly restricted numbers of DCS cases at Catalina Island. The difference did not reach statistical significance, but showed a tendency for RDPs to have more severe DCS and more delayed resolution. Yount, too, took issue with the claim that no evidence existed against RDPs, and illustrated this in his decompression model. The varying permeability model indicated that a shallow dive followed by a deeper one results in greater bubble formation. He stated "*We must not go away from here and gradually allow the myth to build up that RDPs are safe or even safer than FDPs...it depends on the precise profile.*"

Wienke, on the basis of his reduced gradient bubble model, also questioned the symmetry of RDPs and FDPs in the decompression obligations of two repetitive dives. He claimed that the differences between FDPs and RDPs were fewer with short, shallow dives, and increased as the dives became deeper and longer. For two consecutive dives, he suggested a limit of about 40 msw depth and a differential between depths of 12 msw. He specifically did not extend this concept to three or more dives or to multi-level dives, and Gerth supported these limitations.

Moon and Neuman summarised other RDP hazards with repetitive dives. They noted, for example, that a deep dive is one that is more likely to be associated with a variety of problems, and it may be preferable to encounter these with a low gas load. Moon reiterated the axiom that if adequate decompression procedures were initiated, RDPs would be safe. However, he then noted "*studies designed specifically to address the question have not been performed.*"

On the other hand, there were many proposals to remove the 40 msw limit and the no-decompression provision from the final recommendations. Both were retained on the bases of conservatism and current recreational limits, more than on practical evidence. The same could be said for the 12 msw differential.

Gernhardt cautioned "*I don't think it's wise to put a bunch of qualifications that we know nothing about...don't think we can draw qualifications that are stronger than the data we have*", while Beyerstein made a prescient comment, "*A consensus in a body like this gets written down and tends to become engraved in stone and has a life of its own*".

Finally, Brubakk argued that because the incidence of DCS symptoms is so low, any useful comparison between FDPs and RDPs would be best done using experimental animals.

Rationale for removing prohibition on RDPs

The case for RDPs as put by the conveners was based on four observations:

- RDPs are being performed in recreational, scientific, commercial and military diving

- prohibition of RDPs by recreational diver training organisations cannot be traced to any definite diving experience that indicates an increased risk of DCS
- no convincing evidence was presented that implied RDPs within the no-decompression limits lead to a measurable increase in the risk of DCS
- dive-computer algorithms do not differentiate between FDPs and RDPs.

It was also stated that FDPs had originally been employed to obtain more bottom time, that the US Navy did not prohibit RDPs, and that RDPs may be required for logistic reasons relating to the environment or military tactics.

One cannot contest the last of these reasons, as military operational parameters are infinite, and risk is relative. The same considerations partly explain the persistence of RDPs in a number of settings. Prohibitions limit the flexibility of an operational diving team to cover unexpected exigencies, not an option that any operational unit relinquishes readily. In the context of the Workshop, this operational consideration is used to infer that RDPs are routinely used by these organisations. While some experimental trials, by no means always successful, were quoted by Lewis, this does not mean that RDPs were routinely employed. On the contrary, Navy and commercial dive instructors would all be aware of the universal industry recommendation against such RDPs. To imply there is a vast amount of data somewhere out there demonstrating routine and safe RDPs is not tenable. As Wethersby and Gerth stated "*Over 1200 repetitive and multi-level exposures are present in the [Navy] database...only a few dozen are reverse.*"

The belief that FDPs were introduced only to obtain more bottom time is a myth that seems to have developed at the Workshop. Lewis did observe that, using old decompression concepts, FDPs allowed a longer bottom time than RDPs in repetitive diving. This does not mean it was the reason for the embargo on RDPs. Flynn, who was a dive instructor in the 1960s, stated in reference to repetitive dives that the 'deep dive first' recommendation specifically was a safety issue, and not promoted to prolong bottom times. Edmonds had made a similar statement in 1988 regarding multi-level diving.[6] "*If a multi-level dive is carried out [using a dive computer] then the deepest part of the dive should be performed first, and the diver should ascend throughout the dive, until he reaches a depth of 30 feet. We would be pleased to modify these restrictions, once we have information on which to base such a modification.*"

Both Flynn and Edmonds, who were active during the period when the RDP prohibition was promulgated, are supported by references in the popular texts of the time, including the *PADI open water diving manual*, the *British Sub-Aqua Club diving manual* and *Australian scuba diver*.[7–9] There is no reference to prolonging bottom times in any of these publications. The advice was based on experience and promoted for reasons of perceived safety. The rationale was the theoretical belief in bubble development and its slowing effects on out-gassing, and the repeated and frequent observation that divers who did deeper excursions at the end of a dive profile or dive sequence, such as to retrieve dropped equipment or release fouled anchor chains, seemed to be more frequently afflicted with DCS. Whilst neither reason is adequate to prove the FDP recommendation, neither can be summarily dismissed as irrelevant.

Finally, the assertion that dive-computer algorithms do not differentiate between FDPs and RDPs, is more contentious. It might be so for those that rely only on gas loading. Others do make some allowance for slower off-gassing with bubble production during decompression (usually the non-Haldanian, 'bubble-based' types). The degree to which decompression is made more conservative in the latter equipment varies and seems somewhat arbitrary. There is considerable variation in the decompression obligations imposed by different manufacturers, as shown by Lippmann and Wellard, for both multi-level and repetitive dives.[10] In any case, it seems a little perverse to hypothesise that because a machine-based algorithm permits a dive profile, then it should be safe and applicable to humans. It would be more reasonable to reverse the hypothesis and assert that only dives safe for humans should be incorporated in the machines we employ. The belief that dive computers indicate safe and innovative dive profiles has been shown to be misleading and dangerous in the past.[11–13]

RDP conditions imposed by the Workshop

"We find no reason for the diving communities to prohibit RDPs within the no-decompression limits for dives less than 40 metres and with depth differentials less than 12 metres."

RESTRICTIONS

The Workshop imposed restrictions on RDPs, as noted above. We are led to ask: if RDPs are safe and have the same decompression requirements as FDPs, why are extra restrictions necessary? As Tikiisis stated in the proceedings: "*You say there is nothing to suggest that there is a difference in safety [between RDPs and FDPs], then [with your restrictions] you imply there is a difference.*" Others had similar views. From a sceptic's point of view, these restrictions at least have the advantage of imposing some conservative factors on RDPs, thereby reducing the intrinsic extra risk. We might then question whether the restrictions are adequate to limit this extra risk to acceptable levels.

THE NUMBER OF REPETITIVE AND MULTI-LEVEL DIVES PERMITTED

The initial definition supplied by Lang limited the repetitive dives to two in a 12-hour period, or a single multi-level dive, presumably in a similar time frame. This limitation disappeared without explanation or discussion and is not evident in the final recommendations.

THE MAXIMUM DEPTH AND DEPTH DIFFERENTIAL PERMITTED

Wienke, whose work was the basis for the 40 msw/12 msw limitations, had stipulated that his calculations were based on only two consecutive dives employed using his reduced gradient bubble model. Under these conditions, the deeper the dives and the greater the difference between dives, the more hazardous the RDPs became. He did not describe any multi-level dives. Nevertheless, his work was extrapolated to more than two dives and to multi-level dives.

A depth differential (12 msw) without a stipulated minimum duration is illogical. Also, a diver who ascends or descends 24 metres at 6 $m.min^{-1}$ has the same gas load as a similar diver who ascends or descends at 12 $m.min^{-1}$ and stops half way for two minutes. Yet one has complied, the other not.

INADEQUACY OF THE RESTRICTIONS

If a diver does an RDP tri-level dive to 12 msw, 36 msw then 24 msw, he has not complied with the Workshop's recommendation of a 12-metre differential between levels. One descent involved a 24-metre differential. So did the final ascent to the surface. Although not stated, we have assumed that the differential depth changes should apply only to the ascents, not the descents, the omission by the Workshop presumably being a typographical error.

Application of the limitation to the final ascent is less clear. Indeed, it is obscure. If the final depth is greater than 12 msw, say 14 msw after a shallow multi-level dive, is the final ascent considered to conflict with the 12-metre rule? Possibly it does. But if not, why not?

MULTIPLE DIVES WITHIN NO-DECOMPRESSION LIMITS

If one considers multiple dives, say three or more, and reviews the information supplied at the Workshop, it is difficult to find any data on which to base any recommendation. Multiple dives, or multi-level dives, that do not approach the no-decompression limits, cannot and should not be used to compare FDPs and RDPs as neither are likely to produce DCS.

EXTRAPOLATION OF LIMITATIONS

Lumping an infinite combination of repetitive dives and multi-level diving all together, as if there is no substantial difference between them, and then applying a one-rule-fits-all solution for the final recommendations, was the most presumptuous of the Workshop's actions. It was neither questioned nor explained in the proceedings.

The above does not presume that the restrictions are incorrect. We simply make the point that they are unclear and unsubstantiated.

Clinical information

As suggested earlier, it is a frequent observation that divers who are compelled, by virtue of retrieving lost equipment or untangling anchors, to undertake a last deep but short dive seem at increased risk of DCS. Even if this were the only clinical information at our disposal, however, it should not be dismissed in the absence of contradictory evidence. In fact, we do have more information to consider, and there are several data sets that suggest the dangers of RDPs are all too real.

Huggins' analysis of DCS treatments at Catalina "*hints at the potential for more severe DCS with RDPs*". More recently, St Leger Dowse et al analysed female divers' log books, and indicated that symptom rates were higher in those using RDPs, although this difference did not reach statistical significance.[14] They indicated a greater risk with both RDPs and greater depth differentials between dives.

Unfortunately, in both of these surveys there were insufficient numbers of both dives and DCS cases to draw definite conclusions. More importantly, we have only limited information from these surveys on how close these divers were to their no-decompression limits. It is those divers who approach the FDP no-decompression limits who are likely to be at increased risk. Some no-decompression triple, repetitive dives, which did not follow the FDP concept, were described by Leitch and Barnard but were found to be too hazardous to recommend.[15] There certainly have been triple, repetitive RDP dives undertaken in the past, and many no-decompression dives that were close to the no-stop limit, but very few have been documented that combine both parameters.

Animal experimental evidence

It was clear at the Workshop that there was no experimental evidence to support or refute the relative safety of FDPs and RDPs. For this reason, we have recently performed and reported two controlled animal experiments.[16] Using matched-weight guinea pigs, we have examined multi-level single dives and a sequence of three repetitive dives in both forward and reverse profiles.

First, a multi-level, no-decompression dive (for guinea pigs) was made to 36 msw, then 24 msw, then 12 msw using an FDP, without incident in 11 pigs. The identical exposure, but with the sequence of depths reversed, caused death from DCS in 6 of 11 similar guinea pigs. The difference between the FDP and RDP was statistically significant ($P = 0.01$) and we concluded that it is likely to be of great practical significance. In essence, multi-level dives that did not require decompression when performed in the established forward-profile manner were hazardous if carried out in the reverse-profile mode.

Second, we performed a sequence of three no-decompression dives for another group of 11 guinea pigs using an FDP to

30 msw, then 20 msw and then 10 msw, with short surface intervals, again without incident. The identical exposures, but with the sequence of depths reversed, caused death from DCS in 1 of 11 weight-matched guinea pigs. Extending the exposures to 36 msw, 24 msw and 12 msw produced no DCS in the FDP group and 6 cases in the RDP group, including a further three deaths in the RDP group. The difference in the incidence of serious DCS between these FDPs and RDPs for repetitive dives was statistically significant (P = 0.01), and again of likely practical significance. Thus, at least with the profiles chosen, it was less dangerous to perform the deeper dives first than it was to perform them last.

An incidental observation of the Buhlmann bubble-based decompression meter used in these experiments supported the observation made by some Workshop participants that these meters apply some safety corrections for delays in out-gassing. They do differentiate FDPs from RDPs in practice and in their theoretical tissue levels. How close these modifications come to physiological reality is unknown, and will vary with each computer type.

We concluded, therefore, that reverse profiles, as they apply to both multi-level and repetitive diving, are not merely the mirror image of forward profiles, with similar decompression obligations. Extrapolating the decompression obligation from FDP to RDP in the profiles selected resulted in a statistically significant difference in the risk of DCS, despite complying with the current restrictions recommended by the Workshop. The application of FDP decompression calculations to RDP multi-level diving and repetitive diving is sometimes unsafe.

Conclusions

The wide divergence of opinion expressed at the 1999 Workshop on RDPs highlighted the paucity and limitations of the data available. Nevertheless, it is on these inadequate and conflicting data that established procedures advocating FDPs are now being revoked, and RDPs promoted as safe and equivalent alternatives. We believe there is adequate evidence from the dive experiences reported at the Workshop, clinical experience, and now animal experiments, that some RDPs are likely to require more decompression obligations than FDPs. The development of bubble-based decompression algorithms and the demonstrated temporal difference between uptake and elimination of nitrogen supports this conclusion.

References

1 Lang MA, Lehner CE, editors. *Proceedings of the Reverse Dive Profile Workshop*; 1999 Oct 29-30. Washington, DC: UHMS; 2000.

2 Mitchell S. Risk factors in decompression illness. *Alert Diver SEAP Asia-Pacific*. 2004 Apr/Jun: 6-10.

3 Hamilton RW, Baker E. Reverse Dive Profiles Workshop. *Pressure*. 2000; 29: 7-9.

4 Davison B. Always do your deep dive first? *Undercurrent*. 2000 May.

5 General discussion. In: Lang MA, Lehner CE, editors. *Proceedings of the Reverse Dive Profile Workshop*; 1999 Oct 29-30. Washington, DC: UHMS; 2000. p. 269-79.

6 Edmonds C. Dive computers. In: *Proceedings of the Dive Computer Workshop*; 1988 Sep 26-28. Catalina Is., California: American Academy of Underwater Sciences; 1988. p. 68.

7 *PADI open water diving manual*. Santa Ana: PADI; 1984-1990.

8 Sport Diving. *British Sub-aqua Club diving manual*. London: BSAC; 1988.

9 Morrison H, Sinclair S. *Australian scuba diver*. Perth: Lion Fish Publications; 1982. p. 111.

10 Lippmann J, Wellard M. Comparing dive computers. *SPUMS J*. 2004; 34: 124-9.

11 Edmonds C. Dive computers. In: *Proceedings of the Dive Computer Workshop*; 1988 Sep 26-28. Catalina Is., California: American Academy of Underwater Sciences; 1988. p. 59-68.

12 West DP, Edmonds C. *Evaluation of the Farralon decompression meter*. Royal Australian Navy School of Underwater Medicine; 1976. Report No.: 2/76.

13 Quick D. *Evaluation of the S.O.S automatic decompression meter*. Royal Australian Navy School of Underwater Medicine; 1974. Report No.: 2/74.

14 St Leger Dowse M, Gunby A, Moncad R, Fife C, Bryson P. A prospective field study of reverse dive profiles in UK female recreational divers. *SPUMS J*. 2004; 34: 183-8.

15 Leitch DR, Barnard EEP. Observations on no-stop and repetitive air and oxygen-nitrogen diving. *Undersea Biomedical Research*. 1982; 9: 113-29.

16 McInnes S, Edmonds C, Bennett M. The relative safety of forward and reverse diving profiles. *Undersea Hyperb Med*. In press 2005.

Carl Edmonds, MB, BS, DPM, MRCP(Lond), MRCPsych, FRACP, FRANZCP, DipDHM, FAFOM, is a Consultant Diving Physician in Sydney, Australia,
Stephanie McInnes is Senior Fellow and
Mike Bennett is Medical Director, Department of Diving and Hyperbaric Medicine, Prince of Wales Hospital, Sydney, and Senior Lecturer, Department of Medicine, University of NSW, Sydney, Australia

Address for correspondence:
Dr Carl Edmonds
11/69-74 North Steyne
Manly, 2095 NSW
Australia
Phone: *+61-(0)2-9976-5556*
E-mail: *<puddle@bigpond.net.au>*