Development of Trimix Decompression Tables for the Canadian Underwater Mine Countermeasures Apparatus (CUMA)

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Background

CUMA (***Figure 1***), commercially known as SIVA⁴, is a re-circulating semi-closed breathing apparatus that provides a breathing mixture with a nominal constant partial pressure of O_2 (PO_2) of 1.6 ± 0.1 atmospheres absolute (ATA) at all depths. This is achieved by combining a depth-dependant variable flow of diluent gas with a constant flow of O_2, producing a breathing mixture entering the CUMA breathing loop with a constant PO_2. Depending on the diver's working rate, the PO_2 in the breathing loop should be higher than 0.29 ATA when the diver is working strenuously and lower than 1.62 ATA if the diver is at rest.

Figure 1. CUMA diver.

CUMA decompression tables are calculated based on a time-weighted average (TWA) PO_2 of 1.0 ATA. In the 1990s, decompression tables were successfully tested at the Defence R&D Canada – Toronto (DRDC Toronto) to support CUMA diving to 81 metres of seawater (msw) on HeO_2, or ***heliox*** (Nishi & Warlow, 1997). These tables have been in-service with the Canadian Forces (CF), North Atlantic Treaty Organization (NATO) and non-NATO nations since 1997.

Trimix, a breathing mixture of N2, He and O_2, significantly reduces decompression. Due to its widespread use, the benefit of trimix have become apparent in terms of shorter decompression and hence longer working bottom times at reduced cost. Mathematical modeling using the DCIEM™ Decompression Model predicts considerable savings in overall decompression times (***Figure 2***).

Following a successful in-house pilot study, confirming the feasibility of trimix use in CUMA, new trimix tables, with 50%-50% He-N_2 diluent, have been calculated and are being validated by DRDC Toronto for use in the CF as a potential replacement for the heliox tables. This poster covers the validation of in-water oxygen (IWO_2) decompression profiles in dive Series 1 to 3 of Phase 1 of the program.

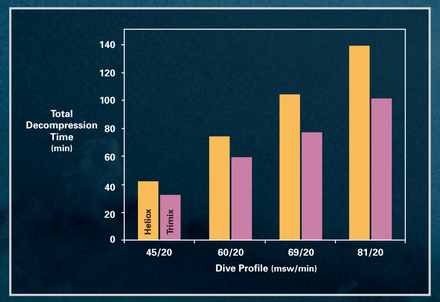

Figure 2. Total Decompression Times (TDT) for trimix dives versus heliox dives.

Methods

The dives were conducted in a similar manner to those used to validate the CUMA HeO_2 tables in 1991-2002 (***Figure 3***). The DRDC Human Research Ethics Committee approved the experimental protocol. All tests were carried out in the DRDC Toronto Diving Research Facility.

1. **Subjects:** 36 military qualified rebreather divers (ages of 24 and 47) participated in Series 1 to 3. All subject were certified medically fit to dive. Their informed consent was obtained before participation in the study. Remuneration complied with DRDC and the Department of National Defence guidelines.

Figure 3.
Four CUMA divers breathing trimix: 2 wet-working subjects on underwater bicycle ergometers (50 W; 5min cycling-5 min rest) wearing dry suits in 6-8°C water, one standby diver (resting, partially wet), and a team leader (dry, lightly working).

2. **Procedure and Measurement:** The format of the tables, procedures and rules for use were similar to those of other CF Decompression tables. Some of the profiles (depth and bottom time) are shown in ***Table 1***.

Descent rate: 12 msw/min (0-6 msw) and 18 msw/min (60 fpm) from 6 msw and deeper.

The PO_2 delivered by the set, inhaled PO_2 and PCO_2, and core temperature (for long duration profiles) were continuously monitored for all subjects. O_2 content was measured using a furnace type O_2 analyzer while CO_2 content was measured using an infrared analyzer.

Doppler ultrasound was used to monitor post-dive venous gas emboli (VGE) for at least 2 hours. Kisman-Masurel (KM) scale was used as a guide to decompression stress. KM BG > 2 (precordial at rest) means HIGH decompression stress.

Classic Symptoms of DCS are the ONLY criterion used for treatment.

The minimum times between the start of successive dives was 19-20 hours in Series 1, and 32-48 hours in Series 2-3.

Table 1: Example of Dive Profiles tested in Series 2 and 3.

Depth (msw)	Bottom Time (min)	Stop Times (min) at Different Depths (msw)* In-Water Stops ← Trimix breathing → 36	33	30	27	24	21	18	15	12	O_2 9	TDT (min)
45	20	-	-	-	-	-	-	-	-	6	25	32
60	20	-	-	-	-	-	4	4	4	4	42	59
69	20	-	-	-	4	2	4	4	4	4	54	77
81	20	-	4	2	3	3	4	4	4	6	70	101

References

Nishi RY & Warlow MRN. (1997) Development of CUMA HeO_2 Decompression Tables: Final Report, DCIEM Report No. 97-R-68.

Bouak F, Nishi RY & Beavis J. (2009) Development of CUMA trimix decompression tables: Series 1, in-water oxygen decompression profiles. DRDC Toronto TM 2009-032. Defence R&D Canada – Toronto.

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Results and Discussion

Table 2: Results of Dive Series – Summary.

Series No.	Dive Type	Number of Divers	Man-Dives	DCS	Ascent rate (msw/min)	Version
Pilot	IWO_2 and SurD O_2	9	44	0	10	1
1	IWO_2	10	44	5	18	1.1
2, 2-IH, 3	IWO_2	28	196	0	18	1.2
Totals		**47**	**284**	**5**		

Series 1: Eleven dives were completed. Three suspected and two unlikely cases of Neurological DCS occurred the same day after two dives to 81 msw for 20 min (2 after a morning dive and 3 after the afternoon dive). All five cases were completely resolved with hyperbaric treatment (***Table 3***).

Table 3: Cases of decompression sickness in Series 1.

	Role	Onset time post-dive	Symptoms and comments	Max BG post-Dive
Morning dive	TL	11 hours	DCS 2 (Neurological). Numbness left leg.	**3/4**- precordial **2/3** left shoulder **3-/3** right shoulder
	Wet	3 hours	DCS 2 (Neurological). Tingling right arm.	**3+/4** precordial **1/3+** left shoulder **3/3+** right shoulder
Afternoon dive	Wet	30 min	DCS 2 (Neurological). Initial symptoms. Tingling right & left hands + left arm. Initial treatment ~40 hours post-dive.	**1/3+** precordial **0/1** left shoulder **0/1** right shoulder
	Stdby	7 hours	DCS 2 (Neurological). Numbness left arm. Presented for treatment ~44 hours post-dive.	**2/3** precordial **1/2** left shoulder **1/3+** right shoulder
	Wet	12 hours	DCS 2 (Neurological). Shooting pains left arm.	**2/3** precordial **0/1** left shoulder **1/3** right shoulder

The first 2 cases were cleared before the start of the second dive and their DCS symptoms occurred after the afternoon dive. The experimental procedures and some predisposing factors were believed to have had significant effects (Bouak et al., 2009). The decompression schedules were modified to make them more conservative. Depending on the profile, the changes in Version 1.2 of the algorithm gave more decompression in the deeper stops, adding one or two stops deeper than the deepest stop of the same profile in Version 1.1. The number of subjects with high BG observed in Version 1.2 was, overall, fewer than in Version 1.1 (***Table 4***).

Table 4: Percentage of subjects with BG 3 or 4 (many bubbles): Series 1 (Version 1.1) versus Series 2-3 (Version 1.2).

Dive (msw/min)	Role	Prec. Rest (BG>2) Ver. 1.1	Prec. Rest (BG>2) Ver. 1.2	All Sites Max (BG>2) Ver. 1.1	All Sites Max (BG>2) Ver. 1.2
45/20	Wet	**0%**	**0%**	33%	75%
	Stdby	**0%**	**0%**	67%	0%
	TL	**0%**	**0%**	67%	0%
60/20	Wet	**33%**	**33%**	67%	67%
	Stdby	**33%**	**25%**	100%	75%
	TL	**67%**	**33%**	100%	33%
69/20	Wet	**67%**	**67%**	100%	78%
	Stdby	**33%**	**17%**	33%	50%
	TL	**100%**	**33%**	100%	67%
81/20	Wet	**25%**	**36%**	100%	86%
	Stdby	**50%**	**38%**	100%	75%
	TL	**100%**	**57%**	100%	86%
Totals		***39%***	***21%***	***75%***	***51%***

Series 2 and ***2-IH:*** 11 CF divers participated for a total of 91 man-dives.

Series 3: 9 dive profiles (***Table 5***) using 17 divers (Australia – 5, Canada – 10, and Netherlands – 2) were tested for a total of 52 successful dives.

Table 5: Post-dive Doppler scores for all dives sorted by Total Decompression Time (TDT) in Series 2 to 3. Results are presented as the number of subjects with BG > 2 (out of the total number of subjects in that profile.

TDT (min)	Dive (msw/min)	Trimix Series Nb.	Wet (BG>2) Prec. Rest	Wet (BG>2) All Sites Max	Stdby (BG>2) Prec. Rest	Stdby (BG>2) All Sites Max	TL (BG>2) Prec. Rest	TL (BG>2) All Sites Max	Total Subjects
21	60/10	2 & 2-IH	***0/6***	0/6	***0/4***	0/4	***0/4***	1/4	14
32	69/10	2	***0/6***	2/6	***0/3***	0/3	***0/3***	3/3	12
32	45/20	2 & 2-IH	***0/4***	3/4	***0/3***	0/3	***0/3***	0/3	10
43	60/15	3	***0/8***	4/8	***0/4***	0/4	***0/4***	3/4	16
44	45/25	3	***1/5***	1/5	***0/3***	0/3	***0/3***	1/3	11
45	81/10	3	***1/8***	2/8	***0/4***	0/4	***1/4***	2/4	16
54	45/30	3	***2/4***	2/4	***0/2***	1/2	***0/2***	1/2	8
55	69/15	2	***1/6***	1/6	***0/3***	1/3	***1/3***	2/3	12
59	60/20	2	***2/6***	4/6	***1/4***	3/4	***1/3***	1/3	13
64	75/15	3	***0/4***	2/4	***0/2***	2/2	***1/2***	1/2	8
73	81/15	3	***2/8***	6/8	***0/4***	3/4	***1/4***	3/4	16
77	69/20	2 & 3	***6/9***	7/9	***1/6***	3/6	***2/6***	4/6	21
101	81/20	2 to 3	***5/14***	12/14	***3/8***	6/8	***4/7***	6/7	29
130	81/25	3	***3/3***	3/3	***1/2***	1/2	***1/2***	2/2	7
Totals			***23/91*** ***25%***	49/91	***6/52*** ***12%***	20/52	***12/50*** ***24%***	30/50	193

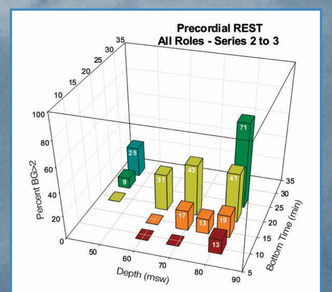

Figure 4.
Percentage of subjects with BG ≥ 3 or 4 in the precordial region at rest compiled by profile for all roles.

Criterion: If more than 50% of dive subjects were observed to have KM BG > 2 in the precordial region at rest (shaded columns in ***Table 5***) ⇒ Dive considered of ***high risk***.

Dives with similar decompression times appear to have similar decompression stress. For decompression times less than 45 min, BG of 3 or 4 are ***rarely*** observed in the precordial region at rest. As the decompression times get longer, higher bubble scores begin to be observed and the decompression stress becomes higher (***Table 6***). The results of the profile 69 msw/20 min are influenced to some extent by the response of individuals who are known to be **"high bubblers"**. Of the 6 occurrences of BG > 2, these individuals were responsible for 5. The profile 81 msw/25 min appears to be very stressful. No clear conclusion can be made at this stage on just 3 dives.

Table 6: Summary of all in-water dives (Series 2 to 3): all dives were grouped according to decompression stress – low, moderate and high decompression stress.

TDT (min)	Wet (BG>2) Prec. Rest	Wet (BG>2) All Sites Max	Stdby (BG>2) Prec. Rest	Stdby (BG>2) All Sites Max	TL (BG>2) Prec. Rest	TL (BG>2) All Sites Max	Stress Level
< 45 min	***1/29*** ***3.4%***	10/29 34.5%	***0/17*** ***0.0%***	0/17 0.0%	***0/17*** ***0.0%***	8/17 47.1%	Low
45 to 75 min	***8/36*** ***22.2%***	17/36 47.2%	***1/19*** ***5.3%***	10/19 52.6%	***5/18*** ***27.8%***	10/18 55.6%	Moderate
> 75 min	***14/26*** ***53.8%***	22/26 84.6%	***5/16*** ***31.3%***	10/16 62.5%	***7/15*** ***46.7%***	12/15 80.0%	High

A time-weighted average (TWA) of inhaled PO_2 was constantly calculated to ensure that it did not drop below the 1.0 ATA PO used to compute the decompression profiles. TWA PO_2 was higher than 1.0 ATA (***Figure 5***). If the actual PO_2 were followed, it would have resulted in a slightly shorter decompression. Trimix tables were developed for the "worst case" scenario.

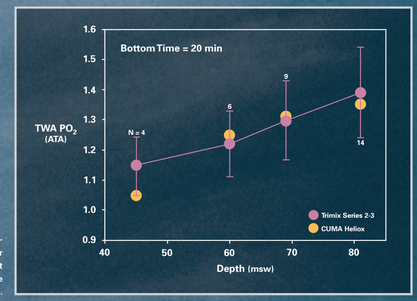

Figure 5.
TWA PO_2 on bottom for a 20-minute dive at different depths for the wet divers.

Summary and Conclusions

- These results show that trimix can be used to conduct CUMA dives safely.
- VGE data and TWA PO_2 are comparable to those of the CUMA heliox dive Series (which had an overall observed incidence of DCS of less than 1% during testing). DCS incidence for trimix profiles is expected to be low.
- Although some of the deep and long profiles violate the BG > 2 criterion, trimix IWO_2 decompression tables are overall satisfactory. More dives are required to conclusively validate all the profiles.
- Trimix decompression times are shorter than CUMA heliox tables. This will increase the operational effectiveness of military clearance divers.

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