Residual Oxygen Time Model after Dives to PO_2 = 1.3 atm

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Many mixed gas rebreathers operate at PO_2 = 1.3 atm.

Of concern: accumulation of pulmonary oxygen toxicity with multiple dives.
How long do pulmonary oxygen effects last after diving?
How does one account for a recent dive when planning?

Despite many dives with PO_2 = 1.3 atm at Navy Experimental Diving Unit (NEDU) (Tables 1a and 1b) we can answer those questions directly in very few instances.

Modeling potentially can fill the gaps.

Table 1a. Resting Dives – PO_2 = 1.3 atm

3-hr	# divers	4-hr	# divers	6-hr	# divers	8-hr	# divers
At least 1 dive	48	At least 1 dive	75	At least 1 dive	42	1 dive	71
2-hr SI, then 18-hr SI		*20-hr SI*		*28-hr SI*			
4 dives	12	At least 2 dives	49	At least 2 dives	28		
4-hr, then 16-hr SI		At least 3 dives	31	5 dives	15		
4 dives	24	At least 4 dives	28	*42-hr SI*			
6-hr, then 14-hr SI		At least 5 dives	27	At least 4 dives	14		
4 dives	12	At least 8 dives	10	6 dives	13		
		10 dives	9				
		44-hr SI					
		2 dives	18				

SI = surface interval

Table 1b. Dives with Exercise – PO_2 = 1.3 atm

3-hr	# divers	4-hr	# divers
At least 1 dive	54	At least 1 dive	107
21-hr SI		*20-hr SI*	
At least 2 dives	16	At least 2 dives	44
5 dives	15	5 dives	14
4-hr, then 16-hr SI		*15-hr SI*	
At least 2 dives	38	2 dives	28
At least 4 dives	18		

Methods

Recovery of vital capacity after exposures to hyperbaric oxygen[1–4] can be expressed as an exponential function of time with time constant a function of either exposure PO_2[5] or exposure duration.[6]

As a function of exposure duration,

$$\Delta VC(t) = \Delta VC_0 \cdot e^{-[c + g / T_{dur}] \cdot t},$$

where ΔVC is change in vital capacity from baseline, ΔVC_0 is that at the start of recovery, T_{dur} is the exposure duration, t is elapsed recovery time, and c and g are constants to be fitted.

Vital capacity changes measured during exposures to PO_2 between 1 atm and 1.5 atm [1,3,4,7] are linear in time for exposure durations < 500 min,[8]

$$\Delta VC_0 = a \cdot T_{dur}.$$

For any partial recovery, residual injury can be described as equivalent to that which would have occurred immediately following a shorter exposure time. We define residual oxygen time t_r as that equivalent exposure duration.

$$\Delta VC(t) = a \cdot t_r = a \cdot T_{dur} \cdot e^{-[c + g / T_{dur}] \cdot t},$$

where t_r is a function of both recovery time t and T_{dur}.

We assumed similar functional forms for all pulmonary injury at PO_2 = 1.3 atm and recovery at PO_2 = 0.21 atm and considered t_r at the end of a surface interval SI.

$$t_r = T_{dur} \cdot e^{-[c + g / T_{dur}] \cdot SI}$$

Values of t_r based on incidences of signs and symptoms were assigned to the dives of Tables 1a and b. For example, after four three-hour dives with SIs four hours then 16 hours, incidences were like those after two four-hour dives.

No recovery was considered until SI = T_{dur}. Iterative adjustment led to values c = 0.029 hr^{-1} (standard error [SE] 0.020) and g = 0.41 (SE 0.09), which were used to generate a table of residual oxygen times.

Results

Table 2. Residual Oxygen Time (min)

Effective T_{dur} (Actual T_{dur} + t_r at the start of the dive) (min)										
30	4									
60	*60*	9	2							
90	*90*	39	15	6	2	1				
120	*120*	*120*	43	22	11	5	1			
150	*150*	*150*	87	51	30	17	6	2		
180	*180*	*180*	*180*	93	60	39	16	7	1	
210	*210*	*210*	*210*	145	102	71	35	17	4	1
240	*240*	*240*	*240*	*240*	153	113	62	34	10	3
270	*270*	*270*	*270*	*270*	*215*	166	98	59	21	7
300	*300*	*300*	*300*	*300*	*300*	227	144	92	37	15
SI (hrs)	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**10**	**14**	**18**

Discussion

Residual time should be added to planned time to determine the effective duration of later dive.

Residual time is short if T_{dur} is short and long if T_{dur} is long. It is preferable to do short dives before long dives.

One must accept a risk of pulmonary toxicity and choose a maximum effective dive duration accordingly.

NEDU currently has chosen four hours. After a single four-hour dive with moderate exercise, 18% of divers (95% confidence interval 9–30%) experience symptoms, and 7% (2–17%) have short-term changes in pulmonary function.

Conclusions

Modeling can be used to interpolate recovery times after dives of multiple durations.

The residual oxygen time concept can facilitate planning of dives with PO_2 = 1.3 atm.

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