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Research on Nitrogen-Oxygen Saturation Diving with Repetitive Excursions

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Abstract For some tasks of underwater operation the need for longer dive duration and more working divers necessitates the use of saturation diving techniques with excursions. Saturation diving with excursion has high working efficiency. A collaborative experiment with Chinese Underwater Technology Institute, American National Office of Research Undersea Program and Hamilton Research Ltd. was conducted at our Institute in Shanghai. The main experiment objectives were to assess the longer, deeper repetitive excursions during nitrogen-oxygen saturation situation, oxygen exposure management, nitrox saturation decompression after excursions and performance aspects. Four Chinese professional experienced divers were saturated at 25 msw for 5 days at the hyperbaric facility, where they did 15 air excursions to depths between 50 and 75 msw, for duration up to 240 min. Decompression from excursions to the storage were mostly no-stops, but 5 required stops for 3 to 116 min. Saturation decopression began with the "precursory" ascent following a brief return to 25 msw. Doppler bubble detection showed some bubbles of Spencer Grade II and occasionally III, following excursions and during saturation decompression, especially after muscle flexing. No symptoms of decompression sickness were reported: one diver was more of fatigued on one occasion than other times. Oxygen exposure reached its peak of 3103 Oxygen Toxicity Units on Day 6. The only subjective symptom of oxygen toxicity was mild and transient numb fingertips. No significant change was seen in vital capacity.

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Introduction

In past few years there has been many of the researches on nitrogen-oxygen saturation diving with excursions at different depths in a hyperbaric chamber complex or open sea (Shi et al., 1988). But there has been no experiment of saturation diving with repetitive excursions in our country. The research on repetitive excursion procedure during nitrox saturation was funded by American NOAA's Underwater Research Program to improve and extend the decompression procedures for underwater operation (Hamilton et al., 1988). This project resulted in new decompression tables for saturation-excursion diving, including repetitive excursion and longer ones requiring decompression stop and a table for the final saturation decompression which included a method for dealing with the last excursion. Further, a simple but effective algorithm for managing exposure to elevated levels of oxygen over multiday exposures was produced. Our objective of this research was to perform 5 days of nitrogen-oxygen-air excursion diving with every excursion calculated to the limit of the algorithm. To get as many test results of excursions as possible in an efficient way, we selected a storage depth of 25 msw. This was shallow enough to allow extensive deeper excursions to 50, 60, 70 and 75 msw, and would mean that some of them would require stops. A deeper storage depth would make the excursion so long that only a few could be performed. To confirm safety of the decompression procedures we planned to monitor the divers with dopple bubble detection after each excursion and during the saturation decompression. Another objective of our experiment was to study the managing multiday oxygen exposure, in this case for a 6-day exposure to daily levels slightly above the previous limits (Hamilton et al., 1988).

Materials and Methods

The experiment consisted of 5 days of saturation with four experienced divers at 25 msw pressure in a diving simulator at 0.32 bar of oxygen, with several daily excursions to higher pressure: this was followed by saturation decompression. The physical characteristics of subjects are given in Table 1.

The experiment was carried out in a hyperbaric chamber shown in Fig. 1. Chamber No. 1 was used for the living space and Chamber No. 2 was kept in readiness for treatment of decompression sickness (DCS), if it occurred.

Table 1 The characteristics of subjects

Diver number	No. 1	No. 2	No. 3	No. 4
Age (years old)	36	28	28	27
Weight (Kg)	76	67.5	57.5	77
Height (Cm)	176	173	167	170
Fitness level	Very good	Good	Fair	Good
Daily exercise	2 hrs	2 hrs	1 hr	1 hr
Smoke?	Yes	No	Yes	Yes
Diving school?	Yes	Yes	Yes	Yes
Professional diving, yr	18	10	11	10
Approx number of dives	420	200	220	150
Previous DCS	No	No	No	No
Previous skin bends	No	No	No	No

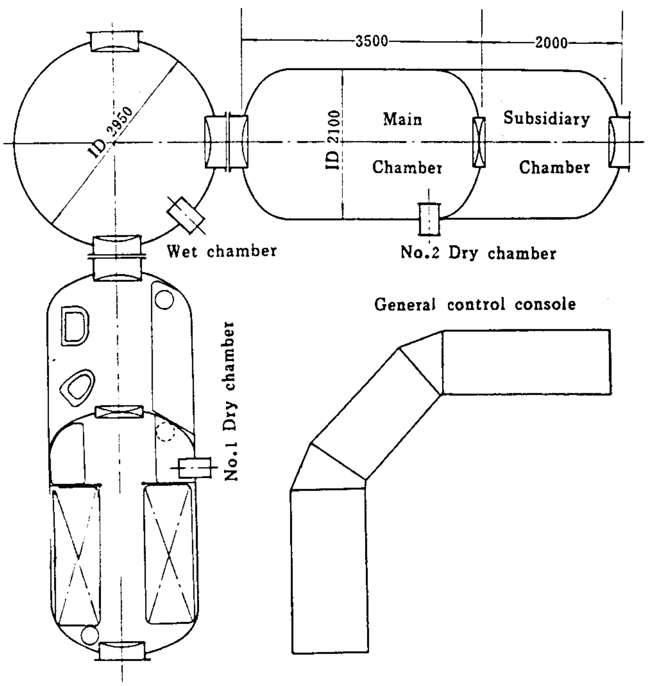

Fig. 1 Chamber complex for experiment. The divers stayed in No. 1 chamber, lower left, and performed excursion dives in the dry area of the wet chamber. The No. 2 chamber was ready for DCS treatment in case during the project.

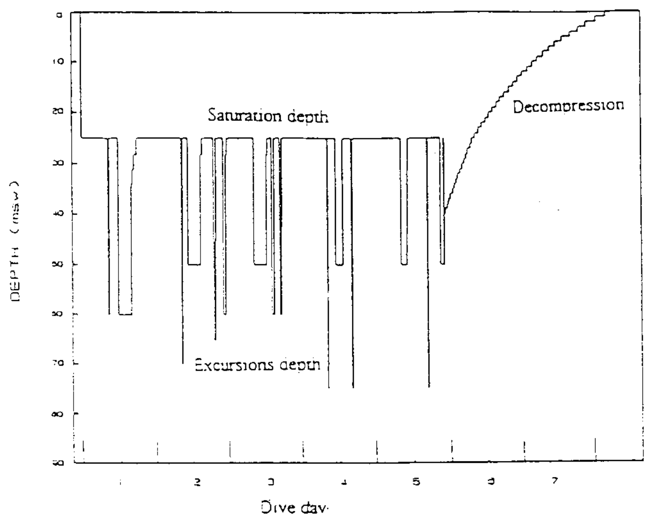

Fig. 2 Profile of saturation, excursion and decompression.

The dry area at the top of the wet chamber was for the repetitive excursions, when an excursion was made, the divers locked into the excursion chamber and pressurized according to the procedures. The profile of the repetitive excursions during the nitrogen-oxygen saturation storage is shown in Fig. 2. After each excursion and during the saturation decompression we recorded the bubble information, using the bubble detection with a Techno-Scientific Inc. doppler ultrasonic monitor Model DBM-8703. The measurement was recorded with the diver standing still again and after a single deep knee bend. Scoring was based on a hybrid of Spencer (Spencer, 1976).

Results and Discussion

The experiment was carried out according to our subscribed plan for researching the repetitive excursion procedures during the nitrogen-oxygen saturation exposure. The schedule was followed quite well to the whole process of the experiment. The compression was done with the Auto Control System. All excursions and the decompression from every excursion and final saturation were carried as planned with occasional deviations of only one or two minutes. The Auto Control System was used to control the pressure and oxygen level in the diver's living chamber thoughout the saturation time and decompression process. The excursions were calculated to stress the limits of the saturation-excursion' relation algorithm by computing the entire as a single profile. The calculations were made with Hamilton Research' Decompression Computation and Analysis Program, Version 5.560, using the Haldane-Workman-

Table 2 The excursion summary

No	Excu. No	Dive day	Excu. depth (m)	Excu. time (min)	First stop (m)	Interval after (min)	Excu. OUT	OUT Day	Total OUT
1	1-1	1	60	40	-	164	77		
2	1-2	1	60	240	37	870	501	578	578
3	2-1	2	70	30	28	108	74		
4	2-2	2	50	240	28	233	361		
5	2-3	2	65	30	-	142	66		
6	2-4	2	60	60	28	526	115	616	1194
7	3-1	3	50	240	28	95	353		
8	3-2	3	60	40	-	104	77		
9	3-3	3	60	40	-	883	77	507	1701
10	4-1	4	75	16	-	154	49		
11	4-2	4	50	128	-	167	184		
12	4-3	4	75	20	-	929	58	291	1992
13	5-1	5	50	130	-	374	187		
14	5-2	5	75	15	-	246	46		
15	5-3	5	50	60	(40)	-	90	(450)	2442

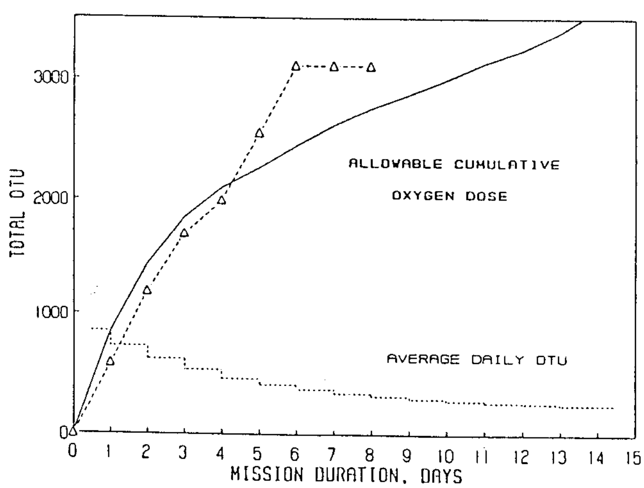

Fig. 3 The oxygen exposure limit. The solid curve indicates allowable cumulative oxygen dose (OUT) that oxygen tolerance unit be limited to for a given day. The dotted line with triangles shows the cumulative oxygen dose in the present study.

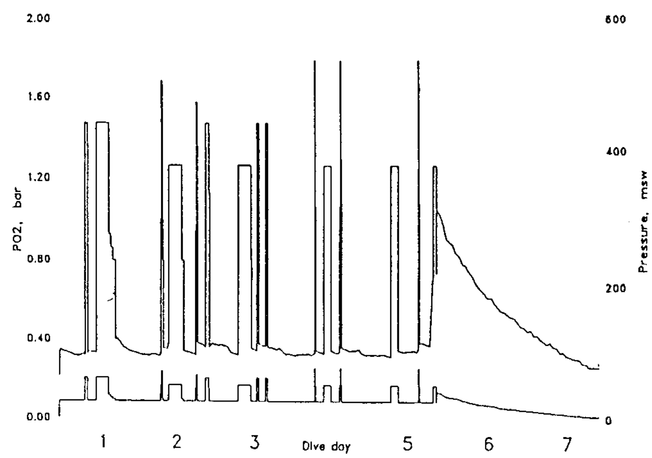

Fig. 4 Oxygen exposure during experimental process. Upper line shows oxygen partial pressure. Lower line shows pressure profile.

Schreiner computational model. The decompression from each excursion was based on the gas loading presented at the time. In the computation of the repetitive excursions we took the gas loading, that is the controlling factor into account determining of repetitive decompression. The profile of time and depth for every excursion is shown in Fig. 2. And a summary of the repetitive excursions is shown in Table 2. All decompressions were carried out as planned by our computational procedure and there were no reported symptoms of DCS. The total time for decompression from the last excursion to the surface was 53 hr 50 min, which 9 hr 59 min was in the precursory decompression and 43 hr 51 min in the pull from 25 msw. The results of the doppler monitoring are shown in the upper half of Fig. 5 for Divers 1 and 2 and the lower half for divers 3 and 4. These figures show five different bars of 0, 1, 2, 3 and 4 for bubble grades corresponding to O. I. II. III and IV, respectively. Bars at the upper part of the figure for each diver shown are scores at rest, and the lower part are the scores after single "flex", of a knee bend. Diver 1 showed only five grade I readings at rest, and no bubbles at all in the resting readings during and after saturation dive decompression. After flexing more than half the readings showed at least grade I, a few grade II's were scattered over the dive, and one grade III was heard after the end of decompression. Diver 2 showed some

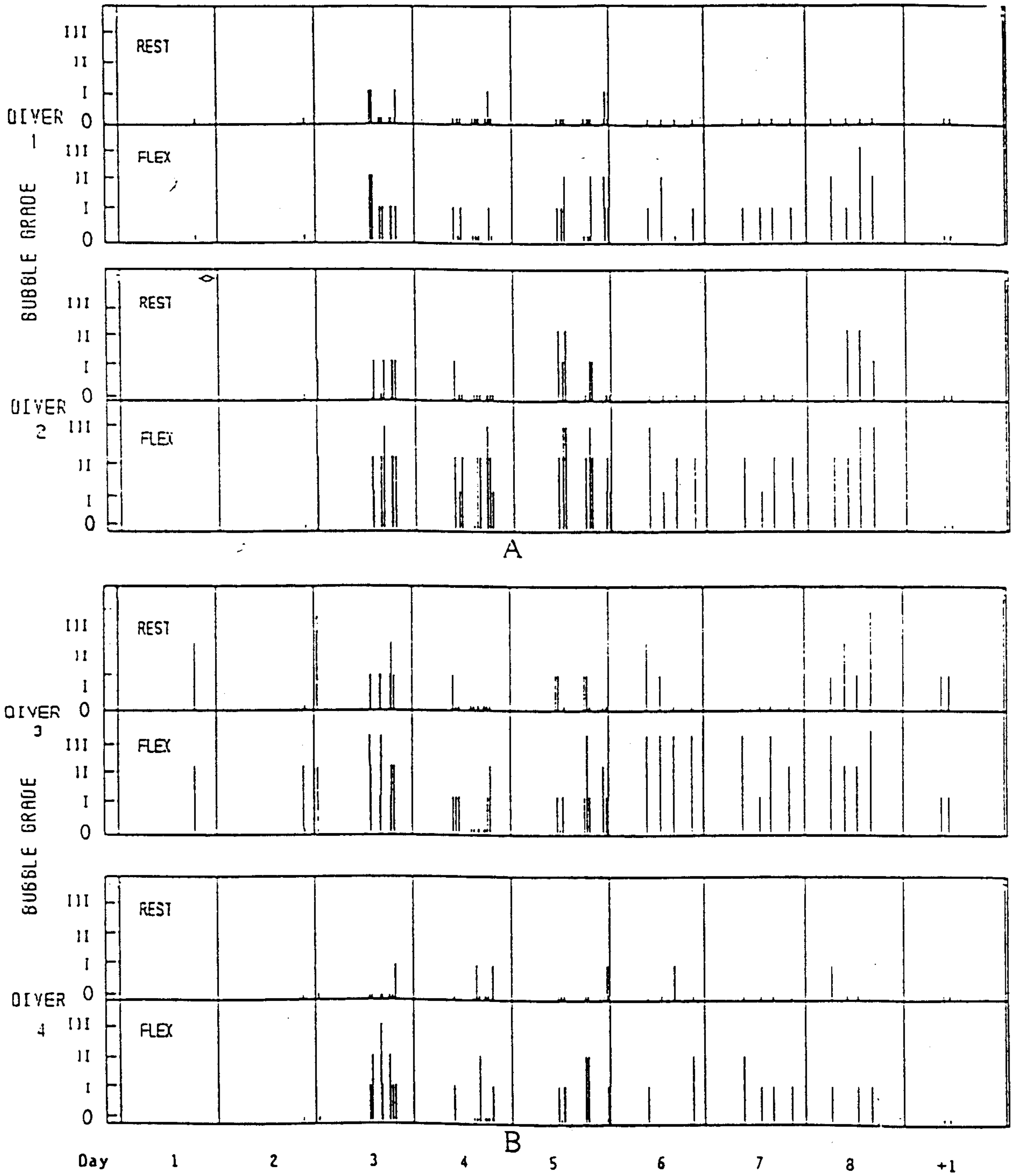

Fig. 5 Doppler results for Divers 1 and 2 (A) and 3 and 4 (B). Bar height shows doppler grades 0-IV; upper panel for each diver taken with diver at rest, lower panel after a knee bend flex.

grade I and III bubbles at rest (four of grade II), the II's were on the last day of excursion after the end of decompression. Some (8) III's bubbles were detected after flexing, at least one on Day 3, 4, 5, 6 and 8. This diver had no bubbles at rest during saturation decompression. Diver 3 had mostly 0's a nd I's at rest but had four of grade II and two of grade III. After flexing some grade III were heard after excursions and several each day during decompression. After the end of decompression one reading was judged as grade IV after flexing but there was disagreement about this score. Since other scores were not vetted, the dispute about this one should be disregarded. This diver had grade I bubbles more than 24 hr after surfacing. Diver 4 had a few grade I bubbles scattered over the dive with the rest of the resting reading being 0. After flexing he had one III and seven of grade II again spread evenly over the whole exposure. Our results suggest that the evaluation of some 60 man-excursions and saturation decompression of four divers could conclude with a reasonable validation, quite fit for the excursion algorithm, good but with minor reservations for the saturation decompression. The process of decompression from a full schedule of descending excursion over 5 days according to the computational algorithm was without symptoms of DCS. Some grade I and a few grade II doppler ultrasonic bubbles were found, indicating that the excursion decompression was stressful, but the conclusion was that the process was satisfactory. The saturation decompression was also carried out without symptoms of DCS, but like the excursions it also induced some doppler bubbles. The results would support the continuous use of the profile for saturation diving with repetitive excursion during the same depth. Oxygen tolerance: The divers had no significant problems with the oxygen exposure during the experimental process. No definitive lung symptoms, but there were some numb fingertips, at the beginning of saturation decompression. The overall daily exposure based on Oxygen Tolerance Units is given graphically in Fig. 3. This shows that for overall exposure the divers got 3103 units by the end of Day 6, which is a few hundred units more than allowable cumulative dose according to the previous experiment (Hamilton, 1989). This was intended to go just far enough beyond the Hamiltoms' limit to provide a "worst case" verification. The maximum oxygen exposure by the Auto Control is plotted on Fig. 4. This shows the oxygen partial pressure that was in the living chamber when the divers were there, plus the oxygen encountered during excursion. Because the return of the oxygen to the control level of 0.32 bar was delayed a little after each excursion, and because the divers moved into air 5 min before each excursion, the actual oxygen exposure was slightly greater than that indicated in the figure. There was a definite increase in "background" oxygen exposure at the beginning of decompression from the storage depth when the composition of the living chamber atmosphere was switched to air. This increase in oxygen is seen clearly in the top of Fig. 4. After the last excursion the oxygen exposure was well tolerated by the divers. Three out 4 divers mentioned mild numbness in the fingertips on Day 5 shortly after the switching to air in the living chamber for the decompression. Diver 1's finger numbness was first noticed after the gas switching to air: this diminished during decompression and was barely noticeable after surfacing. Diver 2 noted "a little chest tightness," and had the same finger symptoms. Diver 3 did not have the finger numbness. Diver 4 reported much the same finger symptoms as Divers 1 and 2, but did not any other symptoms. Another traditional measure of tolerance of continuous exposure to high pressure of oxygen is pulmonary function. As part of the pulmonary function studies, forced vital capacity was taken daily both in the living chamber and during one of the excursion, and showed some day-to-day variation but no clear trends. No other lung or whole-body symptoms reported. The divers denied coughing when perfoming the pulmonary function test: this was a fair indication that was no significant lung or bronchial irritation.

The development of numb fingertips in 3 out 4 divers after the switch to air at the beginning of the final decompression is a classical and mild symptoms of what we call "whole body" oxygen toxicity. The point of all this is that the experimental divers had a very mild and transient, easily tolerable and acceptable as a side effect of necessary of even operation necessity. This much oxygen exposure would not be used under normal circumstances, however, and the symptoms would therefore be unlikely. On the basis of our experimental results mentioned above, we conclude that the repetitive excursions form nitrogen-oxygen saturation of 25 msw can be effectively performed to 50–75 msw using these procedures.

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