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BREATHHOLDING BREAKPOINT AT VARIOUS INCREASED PRESSURES

by

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OPERATIONAL SIGNIFICANCE

This study of breathholding provides evidence that length of rest period, if the rest period is short (varying from five to ten minutes), has little demonstrable effect upon the length of breathholding. The study also provides confirming evidence that the breath may be held longer in proportion to the increase in pressure, at least up to four atmospheres absolute which is equivalent to ninety-nine feet in sea water.

As to the application of the former findings, in S.E.A.* training and escape work there would seem to be little need to carefully time the period between escapes, other factors being equal. As to the second finding, this, though known before, is now confirmed and should be incorporated in the pre-escape part of S.E.A. training, particularly if men are to try free escapes in addition to those done with the S.E.A.

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* Submarine Escape Apparatus

ABSTRACT

This study confirms earlier findings that the duration of breathholding varies with the partial pressure of oxygen. Further, it indicates that the influence of oxygen partial pressure was not eliminated at the breathholding breakpoint even at pressure equivalent to four atmospheres absolute. It is shown that in the alveolar air at the breathholding breakpoint there is a linear relationship between pCO_2 and $\log^{10} pO_2$ with two parameters which vary between individuals. It does not appear to be acceptable to apply the formula expressing the pCO_2 - pO_2 relationship for normal respirations to the situation of breathholding.

INTRODUCTION

Breathholding ability as a means of studying respiratory physiology has intrigued a number of investigators. In one study, Shilling, Hansen and Hawkins (2) reported that for twenty-five experienced divers the average breathholding time at atmospheric pressure was 91.0 seconds and at six atmospheres it was 216.5 seconds. In the field of aviation medicine, Otis, Rahn and Fenn (1) studied alveolar air samples at the breathholding breakpoint (BHBP). Their work was done with a variety of mixtures of oxygen and nitrogen at various reduced pressures. They found the duration of breathholding was decreased at decreased partial pressures of oxygen. Related to this general research area, Gray (3) developed a Ventilation Ratio (V.R.) formula based on the concept that normal respirations are controlled by the blood pH, CO_2 accumulation and O_2 depletion (Appendix 1). According to this formula oxygen plays no role in stimulating normal respirations when alveolar oxygen partial pressure is 100 mm. Hg. or greater. In their investigations, Otis, et al applied Gray's formula to data obtained at the breathholding breakpoint with the idea that some V.R. value might represent the maximum voluntary inhibition of respiration, i.e., the breathholding breakpoint. They pointed out that this was applying a formula designed for a steady state to an unsteady state. They found what appeared to be a rather good fit of their BHBP data to the V.R. curve having a numerical value of eight.

The physiology of respiration in general and the problems surrounding breathholding in particular are of concern to those working in the field of submarine medicine. They have a patent relationship to Submarine Escape Apparatus (S.E.A.) training and escape work. The writer considered it worthwhile to investigate what factor or factors force a person to inspire when he is voluntarily holding his breath. It was hypothesized that CO_2 accumulation might be the crucial factor rather than the blood pH or oxygen depletion when the partial pressure of oxygen was above some undetermined level. It was hypothesized further that the blood pH would not vary significantly under increased pressure or during a series of breathholds conducted within an elapsed time of 1 to 2 hours. Accordingly an investigation was undertaken involving a study of alveolar air at the BHBP under various increased pressures.

Incidentally, it should be noted that in experiments involving breathholding it is difficult to obtain a constant end point or "true breathhold." The writer paid special attention to this matter and is reasonably confident that full breathholding was accomplished. Subjects were told that the end point would not be reached until they experienced involuntary spasms of the diaphragm. It was observed in the course of this experiment that when the involuntary spasms once set in they came in increasingly rapid succession. However, the spasms could be interrupted by the act of swallowing, but they soon recurred at a more rapid rate. Usually it was possible for the subject to interrupt these spasms twice but certainly after the third interruption there was no denying or restraining them. As a result of this rigorous imposition of end point the subjects sometimes became mentally confused and the alveolar sample was lost. To avoid loss of data, the subjects were encouraged to hold their breath until the spasms had been interrupted at least once but above all to stop while they could still give a satisfactory sample. Any breathhold which did not reach this end point was excluded from the data. Without a doubt this contributes markedly to the consistency of the results reported later in this paper.

Some investigators have noted that the duration of the rest period between breathholds seems to have an influence on the breathholding time. This posed a problem since the investigator wished to utilize the shortest rest period between breathholds consistent with reliable results inasmuch as the subjects would be exposed to increased pressures and the attendant prolonged periods of decompression. It was necessary therefore to investigate the effect of length of rest period upon duration of breathholding.

In summary then, the principal problem under investigation involves effect of increased pressure upon breathholding, but a necessary collateral problem involves effect of length of rest period upon breathholding.

THE PRESENT STUDY

The subjects finally chosen for the study were three instructors at the Escape Training Tank, U.S.Naval Submarine Base, New London, Conn. They were, incident to their work, accustomed to being under pressure in the recompression chamber and to holding their breath. The method used was similar to that of Otis, et al. The breath was held at the end of a normal exhalation to the limit of physical endurance. Each subject wore a nose clip during each breathhold. When the breath could be held no longer the subject placed one arm of a three-way valve between his lips, exhaled forcibly and turned the valve to trap a sample of alveolar air in the tube connected to the valve. A sample of this gas was drawn immediately into a tonometer over mercury. The duration of the breathhold was timed. The alveolar air was analyzed in the Haldane apparatus for CO_2 and O_2 content.

The results of the study of the duration of the rest period are shown in Table 1. The series of ten breathholds was considered about the largest number that could be performed on a single day and yield reliable data because of the strenuous nature of the test. The table contains summarized data concerning breathholding time, pO_2 and pCO_2 at the BHBP. Alveolar gas tensions are given in mm. Hg. at body temperature and sea level pressure (barometric

Table 1.- Influence of length of rest periods between breathholds upon duration of breathhold

	First Series (N = 10)			Second Series (N = 10)			Third Series (N = 10)			Combined (N = 30)		
	Time (sec.)	pCO_2 mm.Hg	pO_2 mm.Hg	Time (sec.)	pCO_2 mm.Hg	pO_2 mm.Hg	Time (Sec.)	pCO_2 mm.Hg	pO_2 mm.Hg	Time (sec.)	pCO_2 mm.Hg	pO_2 mm.Hg
Five minute rest period between breathholds												
M	56.6			75.9			62.0			64.8		
S.D.	9.2			6.8			4.7			10.8		
M		49.6			48.6			50.0			49.4	
S.D.		1.2			.9			1.0			1.4	
M			43.3			38.4			44.7			42.1
S.D.			2.5			2.1			3.0			3.7
Ten minute rest period between breathholds												
M	59.6			62.7			56.6			59.6		
S.D.	6.8			7.2			7.6			7.6		
M		48.6			49.6			51.2			49.8	
S.D.		.6			.8			.6			1.3	
M			43.7			41.9			44.9			43.5
S.D.			2.4			1.3			1.1			2.2

S.D. = Standard Deviation

N.B. In this preliminary study only one subject was used and he was used throughout all trials.

pressure less 47 mm. Hg. vapor pressure in the alveoli). From Table 1 it can be seen that the mean values for alveolar pCO_2 were remarkably consistent for all six series (range 2.6 mm. Hg.). When the combined series using the five minute rest period was compared with the combined series using the ten minute rest period the average value of alveolar pCO_2 and the standard deviation showed no significant difference. The values for the alveolar pO_2 and the duration of the breathholds were very close for biological data when the two series were compared. This was all the more remarkable since each series of breathholds was done on a different day. It was apparent that the five minute rest period would be adequate for the purposes of the study. No significant difference either in pO_2 or pCO_2 data was evident that might be inferentially attributable to varying the length of rest period from five minutes to ten minutes.

In the second phase of the experiment three subjects carried out a series of breathholds, conforming strictly to the procedure previously described, at various pressure depths in the recompression chamber. Due to the fact that as chamber pressure is increased the temperature rises, it was not possible to maintain temperatures less than 86° F. under pressure even under conditions of maximum ventilation. Alveolar pO_2 and pCO_2 tensions at the BHBP at various pressures are given in Table 2.

Resting alveolar pCO_2 and pO_2 tensions for each of the subjects at sea level and in the resting state are as follows:

Subject	Alveolar pO_2	Alveolar pCO_2
I	98.2	37.3
II	98.7	40.9
III	85.0	45.9

An inspection of Table 2 reveals that at all depths for which data are available none of the subjects showed pO_2 values within the range of 70 or less which marks likely onset of anoxia. These data substantiate the point that oxygen depletion is of no great consequence at the BHBP in depths of thirty-three feet and more. An interesting translation of the pO_2 data gives the following equivalents in terms of percentage of oxygen content of alveolar air at BHBP converted to sea level pressure (figures for the data at thirty-three feet are shown):

Subject I	13.5% O_2
Subject II	12.3% O_2
Subject III	11.2% O_2

These values are above the levels where the respiration is markedly influenced.

Table 2.- Effects of various pressures on breathholding breakpoint (Following normal exhalation) *

Depth		Sea Level	33 Feet	66 Feet	99 Feet
		Barometric Pressure - 47			
Effective Pressure BT Dry mm. Hg		716	1473	2233	2987
Subject I					
pO_{2A}	N	10	9	9	6
	M	39.84	96.02	227.39	362.18
mm. Hg	S.D.	1.76	13.96	13.90	27.32
pCO_{2A}	N	10	9	9	6
	M	50.37	59.15	63.59	64.97
mm. Hg	S.D.	.26	.53	2.36	.5
Time (sec.)	N	10	9	8	6
	M	62.71	113.47	117.24	142.28
	S.D.	6.11	9.25	7.49	12.05
Effective Pressure BT Dry mm. Hg		714	1482	2242	3006
Subject II					
pO_{2A}	N	9	9	6	6
	M	30.73	88.09	206.49	294.39
mm. Hg	S.D.	2.18	18.00	28.24	32.70
pCO_{2A}	N	9	9	6	6
	M	55.00	68.80	71.07	80.11
mm. Hg	S.D.	1.09	1.73	1.62	.75
Time (sec.)	N	9	10	6	6
	M	90.31	152.26	199.57	229.37
	S.D.	4.21	11.83	19.84	21.97
Effective Pressure BT Dry mm. Hg		719	1473	2233	
Subject III					
pO_{2A}	N	11	9	6	
	M	42.3	79.94	205.66	
mm. Hg	S.D.	5.25	7.23	11.61	
pCO_{2A}	N	11	9	6	
	M	50.97	58.56	63.19	
mm. Hg	S.D.	2.37	4.13	4.47	
Time (sec.)	N	11	9	6	
	M	53.34	94.39	118.3	
	S.D.	7.40	9.14		

S.D. = Standard Deviation

* Body Temperature, Pressure, Dry

It is of considerable interest to note that for each subject the alveolar pCO_2 rose as the alveolar pO_2 increased. One might expect that when oxygen depletion was no longer a factor, which circumstance ensues somewhere between thirty-three and sixty-six feet depth, the maximum effect of alveolar pCO_2 would have been manifest. Although the difference between the pCO_2 at sixty-six and at ninety-nine feet is not great for Subject I, there is an appreciable difference in this pressure range for Subject II. Unfortunately the data are too limited to draw conclusions.

It seemed pertinent to compare these results with those of Otis, et al by placing them in the V.R. formula. The V.R. values obtained are given in Table 3 and these are plotted with the data of Otis, et al in Figure I. Although the individual points obtained are sufficiently circumscribed in range to justify confidence (Table 2) the V.R. values obtained by using the formula are not consistent for the various depths. Additionally, the values obtained for a single individual vary so that caution is indicated in accepting values based on average results obtained from a number of individuals. Figure I is a plot of the data of Otis, et al, the data obtained in this study and the curve of V.R. equals 8. In this plot the data of Subjects I and III appear to fit the V.R. equals 8 curve even better than the data of Otis.

A study of this presentation (Figure I) led to a replotting of the same data with oxygen represented on a logarithmic scale (Figure II). The linear relationship of the data for each of the subjects in this study is evident and in contrast to the disparity with the form of the curves of Gray's formula (V.R. equals 8 is shown). The data from the experiments of Otis in which the subject was breathing air are also shown for purposes of comparison.

All these data were referred to Dr. von Schelling* with the request that he examine the impression that pCO_2 was linear with $\log^{10} pO_2$ in closer relationship than with the formula of Gray. He applied the formula:

$$pCO_2 = (a \log^{10} pO_2 + b) \pm \sigma pCO_2$$

to the data in Table 2 and the data of Otis and found the following:

Subject	σpCO_2	a	b
I	1.41	15.18	27.27
II	2.81	22.86	21.80
III	1.53	17.26	23.99
Otis, et al	1.33	32.56	-6.65

* Hermann von Schelling, PhD, Biomathematics Consultant, U. S. Naval Medical Research Laboratory

Table 3.- Ventilation ratio formula applied to breathholding breakpoint data

$$V.R.\ H\text{-}CO_2 = 0.4\ pCO_2 - 15$$

$$V.R.\ O_2 = \frac{105}{1.09\ pO_2}$$

	V.R.	Surface	33'	66'	99'	Avg. V.R. T
Subj. No.1	H-CO_2 O_2 Total	5.15 3.22 8.37	8.66 .02 8.68	10.44 .000 10.44	10.98 .000 10.98	9.6
Subj. No.2	H-CO_2 O_2 Total	7.00 7.15 14.15	12.52 .04 12.56	13.44 .000 13.44	17.04 .000 17.04	14.3
Subj. No.3	H-CO_2 O_2 Total	5.36 2.62 7.98	8.42 .096 8.51	10.28 .000 10.28		8.9

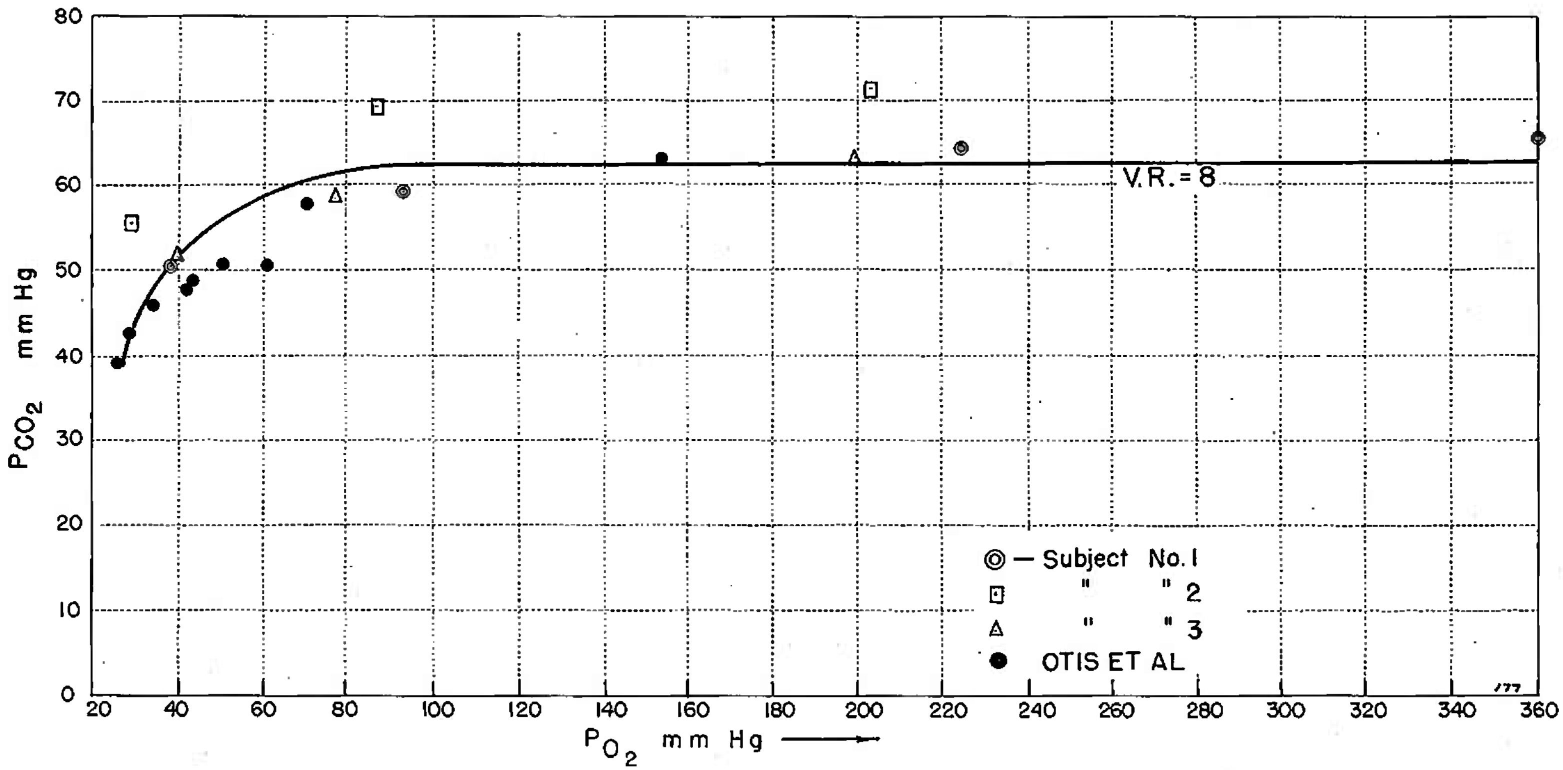

Fig. I

Alveolar Air At Breathholding Breakpoint

The lines representing these formulae are drawn on Figure II. These standard deviations are small for biological data, being within 5% of the mean pCO_2. The data including that of Otis, et al seem to follow the linear function better than Gray's formula. The parameters a and b vary between individuals.

DISCUSSION

It was found that by selection of subjects who were accustomed to breathholding and exposure to pressure, and by careful observance of the conditions of the endpoint, reliable data, narrowly circumscribed, may be obtained. The reproducibility of the endpoint is excellent when the subjects have a rest period of five minutes duration between breathholds. Extending the rest period to ten minutes did not produce significant changes in the values.

The most important point revealed by these data is that within the range of these two studies, Otis, et al and the one being reported (breathing air under conditions so that the pO_2 varied from 69 to 621 mm. Hg.), no asymptote indicating the maximum CO_2 effect was found. Oxygen depletion could be ruled out as a stimulus to respiration, at depths below thirty-three feet. Just as there must be an asymptote of reduced oxygen at which a person cannot stop breathing to hold his breath for even the shortest period, there must be another asymptote for CO_2 accumulation that will not permit further breathholding. The CO_2 asymptote was not reached within the range of these experiments but there is the suggestion that Subject I was close to such a point. On the other hand, this was not the case for Subject II.

The objection may be raised that these data are too few for drawing firm conclusions and one must agree that equally reliable points further extended on the curve would be most desirable. The concern expressed by Otis and his colleagues concerning the applicability of Gray's formula to the BHBP situation is amply justified. The relationship between pCO_2 is linear with $\log^{10} pO_2$.

Gray pointed out that persons acclimatized to altitude have an increased sensitivity of ventilatory response and hence would follow a V.R. curve of low value. It is of interest to note that the line representing the data of Subject II rests above the V.R. = 8 curve (Figure II). Table 2 shows that his alveolar pCO_2 levels at the BHBP were consistently higher than the other subjects. This finding raises the possibility that by further study the individual variations of parameters a and b in the formula of von Schelling might give a measure of CO_2 tolerance.

Up to the pressures included in the study the pCO_2 at the BHBP was increasing. Since even moderate amounts of CO_2 reputedly enhance the onset of oxygen toxicity one wonders if there might be some pressure depth at which breathholding would be terminated by symptoms of oxygen toxicity. For the time, this question and other equally stimulating ones concerning CO_2 tolerance continue unanswered.

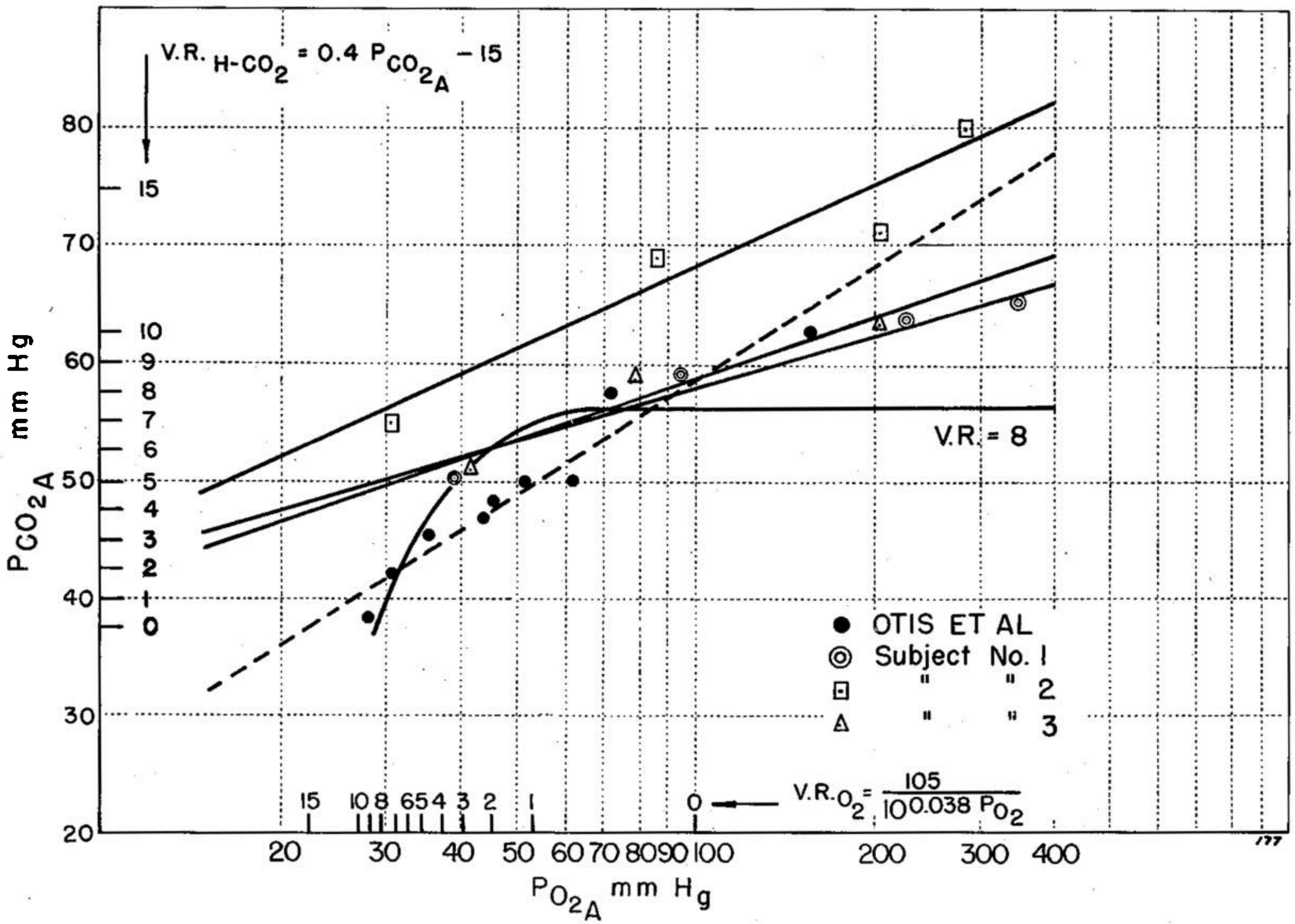

Fig. II

Alveolar Air At Breathholding Breakpoint

SUMMARY

1. Alveolar pCO_2 is a more consistent value at the breathholding breakpoint than alveolar pO_2 or duration of breathholding. This is true for various increased ambient pressures.

2. The difference between a five and a ten minute rest period between breathholds is of no importance as regards pCO_2 values. The range of values for pO_2 and for breathholding times is somewhat less for the ten minute rest period series.

3. Subjects are able to hold their breath after breathing air for longer periods and to higher alveolar pCO_2 levels as ambient pressure is increased. (Tested to the equivalent of ninety-nine feet depth in sea water.)

4. Although oxygen is presumed to play no important role in limiting breathholding beyond thirty-three feet, no asymptote indicating a maximum effect of CO_2 was encountered even at four atmospheres absolute (equivalent to ninety-nine feet of sea water).

5. At the breathholding breakpoint the alveolar pCO_2 appears to have a linear relationship to $\log^{10}pO_2$ alveolar. A formula is presented for this relationship.

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3. Gray, J. S., Science 103:739, 1946.

Appendix 1

Formulas used

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1. Gray's multiple stimulus to breathing formula (Ventilation Ratio).

$$V.R. = 0.22\ H + 0.262\ pCO_{2_A} - 16 + \frac{105}{10^{0.038\ pO_{2_A}}}$$

2. Modified Ventilation Ratio Formula (Otis, Rahn and Fenn).

If bicarbonate capacity is normal, H and pCO_{2_A} are so related that

$$0.22\ H + 0.262\ pCO_{2_A} - 16 = 0.4\ pCO_{2_A} - 15$$

Then

3. $V.R. = 0.4\ pCO_{2_A} - 15 + \dfrac{105}{10^{0.038\ pO_{2_A}}}$

4. Breathholding breakpoint formula (von Schelling).

$pCO_2 = (a \log^{10} pO_2 + b) \pm \sigma pCO_2$ for alveolar air parameters a and b vary with individuals.

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