Breath holding after breathing of oxygen[1]

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KLOCKE, F. J. AND H. RAHN. *Breath holding after breathing O_2.* J. Appl. Physiol. 14(5): 689–693. 1959.—Following normal breathing of O_2 seven untrained subjects held their breath beginning with a maximal inspiration. Breath-holding times ranged from 3.1 to 8.5 minutes and 'breaking-point' alveolar CO_2 tensions from 51 to 91 mm Hg. Under these conditions, the maximum breath-holding time in minutes (x) can be related to the rise in alveolar CO_2 tension in mm Hg (y), according to the equation $x = 0.13\,y + 1.4$. After hyperventilation on O_2, the breath-holding times were noticeably extended ranging from 6 to 14 minutes, but the breaking-point alveolar CO_2 tensions did not exceed those noted above. In all cases, the measured changes in lung volume can be explained by the uptake of oxygen alone since the amount of CO_2 is essentially unaltered during apnea. The decreases in lung volume observed are related to the total breath-holding time, about 13 minutes being required for a change in lung volume equal to the vital capacity. Three subjects were able to absorb their entire vital capacity volume during breath holding since no volume could be expired at the breaking point.

IN THE PAST, several parameters have been shown to influence the maximum time of a voluntary apnea. These may be summarized under three headings: oxygen lack, carbon dioxide excess and neurogenic factors arising from mechanical stresses somewhere within the chest. The last-named factors are influenced by the size of the lung volume at which the breath is held (1, 2), and by any momentary expansion of the lung during which its gas composition is not appreciably altered (3).

It has long been recognized that the breath-holding time can be prolonged by hyperventilation or by breathing oxygen. The former lowers the CO_2 content of the tissues so that a longer period is obtained before the P_{CO_2} breaking point is reached. The latter prevents the development of an hypoxic stimulus which otherwise rapidly occurs when the breath is held after breathing room air. By combining hyperventilation with oxygen breathing one might expect to attain the longest possible voluntary apnea, provided that the neurogenic factors do not become limiting. This study describes the relationship between breath-holding time, alveolar CO_2 tension and lung volume changes after breathing oxygen and hyperventilation on oxygen.

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METHODS

Breath-holding times were studied in six male and one female subject after breathing oxygen (99.5%) and after hyperventilation on oxygen. These individuals were all members of the laboratory staff between the ages of 22 and 46 and, with one exception, had no previous experience with breath holding. The experiments were all conducted in the supine position and each breath-holding period was begun following a maximal inspiration. The experimental procedure consisted of obtaining an alveolar gas sample before and after breath holding and measuring, with appropriate spirometers, the total change in lung volume which occurred during the apnea.

After a preliminary period of 30–45 minutes of rest breathing room air, a Haldane-Priestly gas sample was obtained for analysis of the resting alveolar CO_2 tension. By way of a three-way stopcock the subject was then connected to a Douglas bag filled with oxygen and continued to breathe at his resting rate for an additional 6–8 minutes. If, on the other hand, hyperventilation were to precede the breath-holding period, a gas meter was included in the inspiratory circuit and placed in such a position that the dial of the meter was easily viewed by the subject. At 5-second intervals (as indicated by an audio signal), the subject would inspire either 1 or 2 liters of O_2, depending on whether moderate or extreme hyperventilation was desired. The hyperventilation was continued for 10 minutes.

After these periods of either normal breathing with O_2 or hyperventilation with O_2 the subject was asked to expire completely through the three-way valve and then to inspire maximally and commence breath holding. During the expiration process the inspiratory circuit was diverted from the Douglas bag O_2 reservoir to a 6-liter spirometer filled with oxygen. Thus the subject's final maximum inspiration was drawn from this spirometer, giving a measurement of his initial lung volume (inspiratory vital capacity) at the beginning of breath holding. At the completion of the breath-holding period, when the breaking point had been reached, the subject again expired maximally into another spirometer con-

TABLE 1. *Breath Holding After Normal Breathing and Hyperventilation on O_2*

After Normal Breathing of O_2						After Hyperventilation on O_2						
Subject	Resting		Breath holding			Subject	Resting		$P_{A_{CO_2}}$ after hyperventil. mm. Hg	Breath holding		
	$P_{A_{CO_2}}$ mm Hg	Vit. cap. l.-STPD	Time min.	Final $P_{A_{CO_2}}$ mm Hg	Δ Lung vol. l.-STPD		$P_{A_{CO_2}}$ mm Hg	Vit. cap. l.-STPD		Time min.	Final $P_{A_{CO_2}}$ mm Hg	Δ Lung vol. l.-STPD
	1	2	3	4	5		6	7	8	9	10	11
HR	40.7	4.20	6.2	68.9	1.97	*HR*	40.1	4.20	19.2	14.0	66.4	3.47
HR	42.8	4.20	5.9	66.9	1.73	*HR*	42.2	4.20	26.3	8.6	69.6	2.22
ET	41.8	3.53	7.4	82.6	1.91	*ET*	39.8	3.53	26.8	9.4	77.5	2.73
ET	40.3	3.53	8.5	88.3	2.11	*ET*	37.1	3.53	14.2	11.8	69.0	2.74
MF	36.6	3.22	3.1	50.9	0.98	*ET*	39.8	3.53	19.4	11.4	79.0	2.91
MF	38.4	3.22	3.2	55.4	0.78	*MF*	36.4	3.22	17.8	10.0	47.1	
PE	41.0	4.12	7.0		2.94	*PE*	42.1	4.12	38.2	8.0	81.4	2.54
PE	40.2	4.12	7.1	90.5	2.78	*PE*		4.12	20.1	10.2	63.2	2.37
JC	43.5	4.04	3.4	57.5	0.97	*PE*	42.1	4.12	19.3	10.9	64.5	2.60
JC	40.0	4.04	4.2	67.5	2.01	*PE*	42.6	4.12	32.1	7.4	76.2	2.55
JC	40.5	4.04	4.1	72.3	2.23	*JC*	40.5	4.04	32.4	6.1	75.5	2.76
MT	45.0	3.94	4.2	67.0	1.00	*MT*	44.4	3.94	16.5	12.5	72.0	3.76
MT	45.9	3.94	8.5		2.72	*MT*	45.7	3.94	29.8	9.4	83.0	2.71
MT	46.6	3.94	6.4	84.6	2.29	*MT*	45.0	3.94	21.6	13.8		3.94
SH	39.2	3.55	4.9	66.5	1.60	*SH*	39.8	3.55	22.7	13.0		3.55
SH	39.4	3.55	6.6	75.7	2.04	*PE*	42.8	4.12	22.4	12.2		4.12

nected to a Haldane tube for collecting the alveolar gas sample. Thus the change in lung volume during breath holding was obtained by subtracting the final gas volume delivered from the initial gas volume inspired.

The alveolar CO_2 tension was obtained by analyzing the last few cubic centimeters of gas expired into the Haldane tube. In the hyperventilation experiments, the alveolar CO_2 tensions at the end of the 10-minute period of hyperventilation were obtained in a similar manner just before the maximal inspiration prior to breath holding. All gas analyses were carried out by the same person in duplicate with a Scholander gas analyzer. Ambient pressures varied between 728 and 745 mm Hg.

RESULTS

Table 1 presents the data obtained in breath-holding experiments carried out after normal breathing of oxygen and when repeated on the same subjects after hyperventilation on oxygen. *Column 1* provides the resting alveolar CO_2 tension before breath holding and *column 4* the values obtained at the breaking point. *Column 2*, the vital capacity, provides the initial lung volume prior to breath holding and *column 5* the changes in lung volume which occurred during breath holding. These lung volumes are purposely expressed as STPD volumes and are therefore smaller than the conventional BTPS volumes by about 18%.

Breath-holding times after normal breathing of oxygen varied from 3.1 to 8.5 minutes. The alveolar CO_2 tensions at the breaking point ranged from 51 to 91 mm Hg. and the decrease in lung volume from 0.8 to 2.7 liters. Breath-holding data after various degrees of hyperventilation are shown in *columns 6–11*. These data include the resting alveolar CO_2 tension before hyperventilation was started (*column 6*) as well as the alveolar CO_2 tension at the end of 10 minutes of hyperventilation (*column 8*). The periods of apnea were noticeably extended and ranged from 6 to 14 minutes. (*Subject HR* who held his breath 14 minutes repeated this performance on two other occasions. The breath-holding periods were 13.6 and 14.4 minutes, but no other data were obtained.) It is interesting to note that in all subjects the alveolar CO_2 breaking point never exceeded similar values obtained after normal breathing of oxygen.

DISCUSSION

Changes in CO_2 tension with breath-holding time. When the changes in alveolar CO_2 tension (*columns 1, 4*) are plotted against breath-holding time (*column 3*) we obtain the relationship shown in the upper right quadrant of figure 1. The least squares regression for these points has the equation $x = 0.13\,y + 1.4$ and a correlation coefficient of 0.89 where x = breath-holding time in minutes and $y = \Delta\ P_{A_{CO_2}}$ in mm Hg. This line does not pass through the origin of the graph because, during the maximal inspiration prior to breath holding the alveolar CO_2 tension drops below its previously measured resting value by an extrapolated value of 10.7 mm Hg. This decrease in alveolar CO_2 tension appears to extend the subjects breath-holding time by an average of 1.4 minutes. That is, an 'extra' 1.4 minutes of breath-holding time was gained by beginning breath holding at maximum lung volume rather than at FRC. Our predicted drop of 10 mm CO_2 after maximum inspiration agrees with the decreases in arterial CO_2 tension observed by Ferris *et al.* (4), and is only 3–4 mm Hg greater than the alveolar CO_2 decreases observed by Cain (5).

It is of interest now to turn our attention to a similar

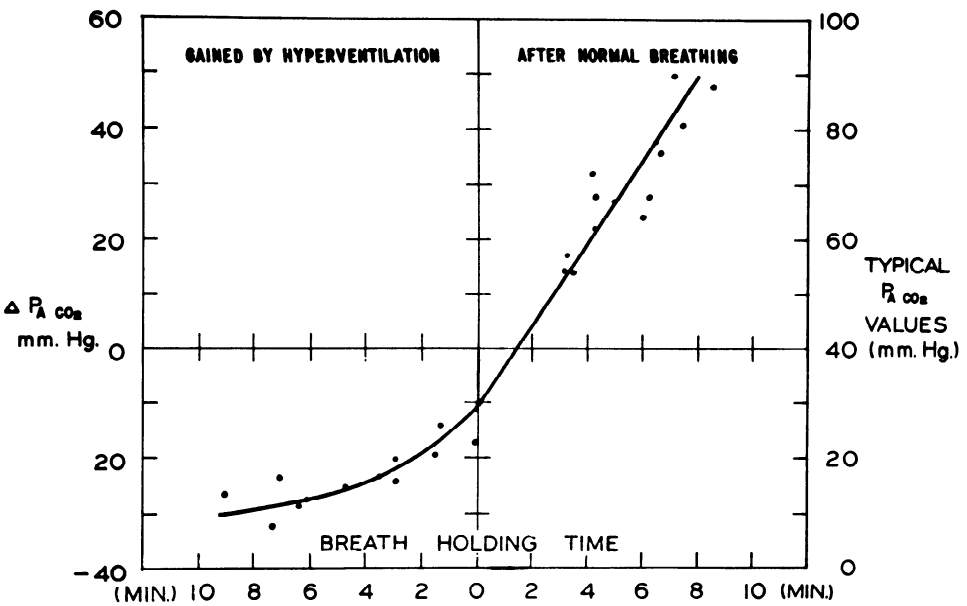

FIG. 1. *Upper right quadrant*: changes in alveolar CO_2 tension (*left ordinate*) plotted against breath-holding times after normal breathing of O_2. *Right ordinate* provides typical absolute values. *Lower left quadrant*: changes in alveolar CO_2 tension between resting value and that at beginning of breath holding after hyperventilation plotted against breath-holding time 'gained by hyperventilation.' For calculation of both of these values see text.

relationship between the change in alveolar CO_2 and breath-holding time following a hyperventilation of 10 minutes. In this case, the initial CO_2 at the beginning of breath holding is considerably less than 30 mm (or the initial P_{CO_2} when breath holding was done at rest). If one now assumes that, once the CO_2 tension has risen above 30 mm, the rate of change of CO_2 with time is identical to the equation given above, it is possible to estimate the breath-holding time 'gained' by the previous hyperventilation. This procedure may be best illustrated by an example. In *subject HR*, the breaking point CO_2 after hyperventilation was 66 mm and the total breath-holding time 14 minutes (table 1). The regression line in the upper right quadrant of figure 1 indicates that with breath holding at rest this value of 66 mm would have been reached in approximately 5 minutes. Therefore 14 − 5, or 9 minutes, is the additional 'time gained by hyperventilation.' The time gained was plotted against the decrease in alveolar CO_2 tension effected by the hyperventilation and maximum inspiration preceding the actual breath-holding period. Thus the points shown in the lower left quadrant of figure 1 were obtained. The entire line shown in figure 1 now summarizes the relationship between alveolar CO_2 tension and breath-holding time in all our experiments.

The CO_2 tensions as plotted in the lower left hand quadrant of figure 1 require further explanation. These represent not the CO_2 values found at the end of the 10-minute period of hyperventilation (as shown in *column 8*, table 1) but the calculated values which would obtain following the maximal inspiration just prior to breath holding. To estimate the latter we multiplied the observed values after 10 minutes of hyperventilation by 0.74 to give us the best estimate of the existing P_{CO_2} tension just prior to breath holding. The factor 0.74 was based on the change in resting alveolar CO_2 tension following a maximal inspiration as calculated previously. For example, if the resting CO_2 tension was 40 and after 10 minutes of hyperventilation was 20 then we estimated that this value dropped to 20 × 0.74 after a maximal inspiration. Thus, 15 mm Hg was assumed to be the initial CO_2 tension at the beginning of breath holding and this value was plotted as 40 − 15, or a change of 25 mm, in the lower left quadrant of figure 1.

The fact that the breaking point CO_2 values were, in most cases, lower after hyperventilation than after normal breathing is worthy of comment. One possible explanation can be found in the observations (1, 2) that even after normal breathing a small lung volume will precipitate the breaking point earlier and at a lower CO_2 than a large lung volume. Since the absolute lung volumes at the end of breath holding after hyperventilation were considerably smaller than after normal breathing (cf. *column 11* and *5*), it may be this mechanical factor (neurogenic) which forced the breaking point at lower CO_2 values.

Finally, it is of some interest to consider the general shape of the breath-holding curve in figure 1. If we assume that during breath holding the CO_2 production of the tissues remains relatively constant, one can substitute 'ml CO_2 stored' for the time scale and obtain a CO_2 dissociation curve which resembles the dissociation curve of the blood and/or tissues. Particularly striking is the change in slope of our curve in figure 1 near the CO_2 tension of 30, indicating a much higher CO_2 storage capacity below this value.

Changes in lung volume. The large changes in lung volume during breath holding suggest that the oxygen taken up by the blood is not entirely replaced by the CO_2 produced. In fact, it is rather startling to calculate that over the whole period of breath holding, whether or not preceded by hyperventilation, the total amount of CO_2 found in the lung at the beginning of breath

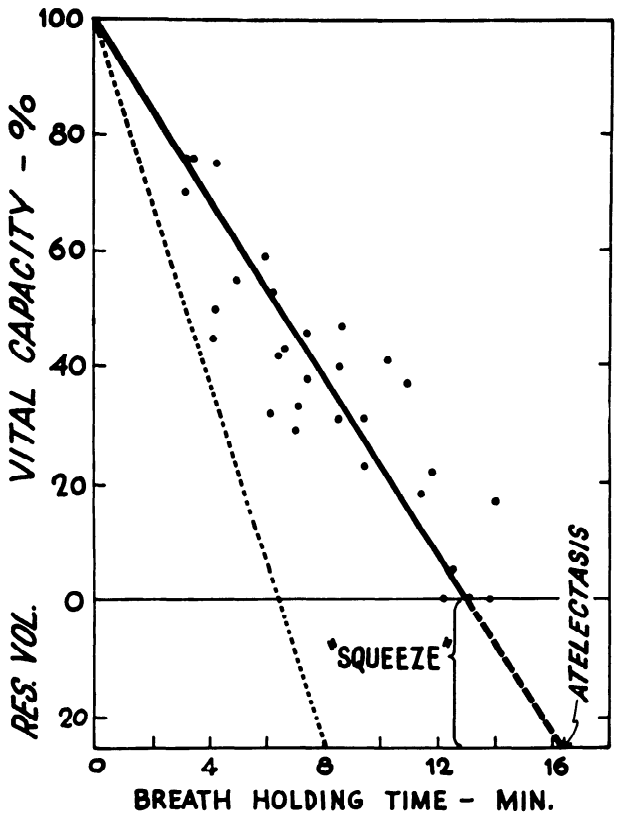

FIG. 2. Lung volume at end of breath holding (expressed as % of vital capacity) plotted against time. All data of table 1 are included. In each case breath holding was started at maximal inspiration, or 100% vital capacity. Average vital capacity volume was 3820 ml (STPD). After 13 minutes average lung volume will be reduced to residual volume.

holding is, within a few milliliters, the same as found at the end of the period. This was calculated in each subject from the initial CO_2 values and lung volumes (assuming that the residual volume was equal to 25% of the vital capacity) and contrasted with the values calculated at the breaking point. This means that the decrease in lung volume due to the oxygen uptake concentrates the alveolar CO_2 as rapidly as it rises in the blood and that the net transfer of CO_2 either into the lung or out of the lung into the blood is very small indeed. Therefore, we may attribute all the changes in observed lung volume to an equivalent uptake of O_2 by the blood. This concept agrees with a similar conclusion reached by Stevens *et al.* (6). As long as O_2 consumption remains constant we would, therefore, expect a linear decrease of lung volume with time. We have plotted in figure 2 the breaking point lung volume (% vital capacity) against the observed breath-holding time and elected to draw a straight line through these points which intersects the zero vital capacity volume at 13 minutes.

The three points shown at a lung volume of 0% vital capacity deserve particular mention. They stem from the last three experiments listed in the right half of table 1. Each subject exhibited unusual discomfort at the end of breath holding and was unable to deliver a measurable amount of gas from the lungs. It is believed that in each case the lung volume was reduced at least to residual volume. If the lung volume becomes reduced even further one might expect to experience the uncomfortable phenomenon of 'squeeze' or 'barotrauma' which is reported from skin divers who descend to depths where their initial lung volume becomes compressed to a volume smaller than residual volume. Thus, as suggested by Otis *et al.* (7), it does seem that under these conditions a decrease in lung volume to the residual volume or smaller volume may indeed become the decisive factor in causing the termination of breath holding. In our three cases we suggest that such perhaps was the case.

If, on the other hand, the glottis remains closed beyond the average 13 minutes, one would predict complete atelectasis at 16 minutes. That atelectasis does develop with time in the linear manner suggested by the extrapolated dotted line of figure 2 has been demonstrated in dogs (8) where one lung was blocked and its rate of collapse could be computed from bronchospirometry measurements on the contralateral side.

The slope of the line in figure 2 deserves some additional comments. If the change in lung volume is equal to the O_2 uptake then it is apparent that the slope will be a function of the oxygen consumption during breath holding. In our resting subjects the average vital capacity was 3820 cc STPD (or 4700 cc BTPS) and the calculated total capacity 4770 cc STPD. The latter figure divided by 16 minutes yields an average O_2 uptake of nearly 300 cc STPD/min. Doubling the O_2 uptake would double the slope, as shown by the dotted line in figure 2 which intercepts the time axis at 8 instead of 16 minutes. Furthermore, the slope would also increase with a decrease in barometric pressure. At ½ atmosphere (18,000 ft. alt.) the predicted volume-time curve would also coincide with the dotted line, provided the O_2 uptake now remains unaltered. Thus, if the vital capacity lung volume becomes the limiting factor the maximum breath-holding time under the conditions of our experiments will be inversely proportional to the O_2 consumption and directly proportional to the vital capacity and barometric pressure. This relationship can be expressed as follows:

$$\text{max. breath-holding time (min.)} = \frac{\text{Vit. Cap. BTPS}}{\dot{V}o_2\ \text{STPD}} \times \frac{P_B - 47}{863} = \frac{\text{Vit. Cap. STPD}}{\dot{V}o_2\ \text{STPD}}$$

where P_B = barometric pressure, 47 represents the vapor pressure of water in the lung and 863 is a constant for converting the BTPS lung volume to STPD.

Thus one would predict that if our experiments were repeated in a low pressure chamber at the total barometric pressure of 147 mm Hg (39,000 ft. equivalent alt.) and the O_2 uptake is 300 cc/min. that the BTPS vital capacity volume of 4700 cc would disappear in 1.8 minutes and atelectasis would occur 0.5 minutes later.

Some further mention should be made of neurogenic

factors possibly influencing the termination of breath holding. As shown by Fowler (3), Cain (5) and others such factors do exist and apparently are operative at least in shorter breath-holding periods (under 2 minutes) after breathing room air. Unfortunately, this study is unable to offer additional information on these factors, except to point out that they apparently do not prohibit extended breath-holding periods under the conditions of our experiments. In a summary of the role played by the lungs in the reflex control of breathing, Wyss (9) describes two sets of afferent fibers, responsible respectively for the 'proprioceptive' (Hering-Breuer) and 'nocioceptive' adjustment of respiratory movements. The latter are 'deflation' afferents responding only to conditions beyond the normal limits of respiratory movements, particularly lung collapse. It is of interest to speculate whether or not these deflation afferents become important neurogenic factors when the breaking point is achieved at lung volumes equal to or possibly less than the residual volume.

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