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CARDIO-RESPIRATORY RESPONSES TO EXERCISE IN AIR AND WATER AT 1 AND 2 ATA

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ABSTRACT

Six men performed graded leg exercise in air, in 30 C water, and in 15 C water at one and two ATA, breathing air from SCUBA in all cases. The external work ranged up to approximately 750 kg·m per minute. With respect to surface-equivalent monitoring, it was found that the oxygen uptake ($\dot{V}_{O_2}$) at a given heart rate was higher in water than in air, and higher in the colder water. These differences are significant over wide ranges of heart rate. $\dot{V}_{O_2}$ at a given heart rate was higher at 2 ATA than at 1 ATA, partially due to a drop (approx 8%) in resting heart rate at 2 ATA. The relationship between $\dot{V}_{O_2}$ and $\dot{V}_E$ followed identical trends, but the differences had limited significance. Maximum voluntary ventilation (MVV) measured on a spirometer at 2 ATA was 20% less than on a spirometer at 1 ATA, and MVV on SCUBA at 2 ATA was 42% less than on a spirometer at 1 ATA. A marked increase in $P_{A_{CO_2}}$ with increasing $\dot{V}_{O_2}$ was indicated by post-end-tidal alveolar samples, but was attributable to increased $\dot{V}_{CO_2}$. $P_{A_{CO_2}}$ values calculated (using the Bohr equation) from the mixed expired P_{CO_2} indicated no change in $P_{A_{CO_2}}$ with pressure or work level.

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INTRODUCTION

The expansion of human activity in the sea has led to a need for estimating the energy cost of underwater tasks. In particular, the safe and efficient management of extended diving operations requires a means of predicting the work and thermal loads of diving in order to establish the nutritional, rest, and thermal recovery needs of divers.

In turn, this requires the development of adequate means of estimating energy expenditure during typical underwater tasks via a practical physiological measurement. This has been the subject of several previous investigations (4, 5, 11, 16) which focused on oxygen uptake ($\dot{V}_{O_2}$) as a measure of energy cost, and on heart rate (f_h) and ventilation ($\dot{V}_E$) as estimators of $\dot{V}_{O_2}$.

Accordingly, the present work was undertaken to verify the existence and magnitude of the effects of water temperature and pressure on the relations between oxygen uptake, heart rate, and ventilation in exercising SCUBA divers.

METHODS

Six healthy adult males, all experienced SCUBA divers, served as subjects at one-week intervals. Their average physical characteristics are given in Table 1.

The experiments comprised graded leg exercise in air, 30 C water, and 15 C water, at both 1 and 2 ATA. The subjects breathed air from SCUBA in all cases, using a standard 71 ft^3 tank and a two-stage, double-hose regulator (U.S. Divers Co., Santa Ana, Calif.).

The experimental regimen is shown in Figure 1. Each experiment began with a rest period, with the subject immersed in the milieu to be tested, followed by five minutes of moderate exercise and another rest period. The subject then performed, without interruption, four minutes of "heavy" exercise followed by two minutes of "forced" exercise. The loads and repetition rates imposed at each level are indicated in the figure. The stroke length was an individual variable, ranging from 11 to 16 inches. During the last minute of each exercise and rest interval, expired air was collected to determine ventilation and oxygen uptake. A cardiac steady state was obtained at each exercise level. Thus, this was essentially a steady-state experiment. $\dot{V}_{O_2}$ was calculated using the following equation, which corrects for R:

$$\dot{V}_{O_2} = \dot{V}_E \cdot \left(F_{I_{O_2}} - F_{E_{O_2}} - F_{I_{O_2}} \cdot F_{E_{CO_2}} \right) \Big/ \left(1.0 - F_{I_{O_2}} \right)$$

in which $\dot{V}_E$ is in STPD.

Heart rate was determined from a continuous ECG record obtained from precordial surface leads. Respiration rate was recorded continuously by means of a thermistor sealed in the mouthpiece. The exercise stroke frequency was set by a metronome, and was verified by recording the output of a photocell whose triggering beam was interrupted by one of the ergometer pedals.

TABLE 1. MEAN PHYSICAL CHARACTERISTICS OF SUBJECTS

Characteristic	Mean ± SE
Age (yrs)	25.8 ± 2.0
Height (cm)	173.0 ± 3.2
Weight (kg)	74.3 ± 2.2
Vital cap. (liters, BTPS)	5387.0 ± 346.0
Max. breathing cap. (liters/min, BTPS)	236.0 ± 14.4
$\dot{V}_{O_2}$ max. (liters/min, STPD)*	3.33 ± 0.27

*Estimated by the method of Åstrand (Åstrand, P.-O. Work Tests with the Bicycle Ergometer. Varburg, Sweden: AB Cykelfabriken Monark, p. 1-35, 1965.)

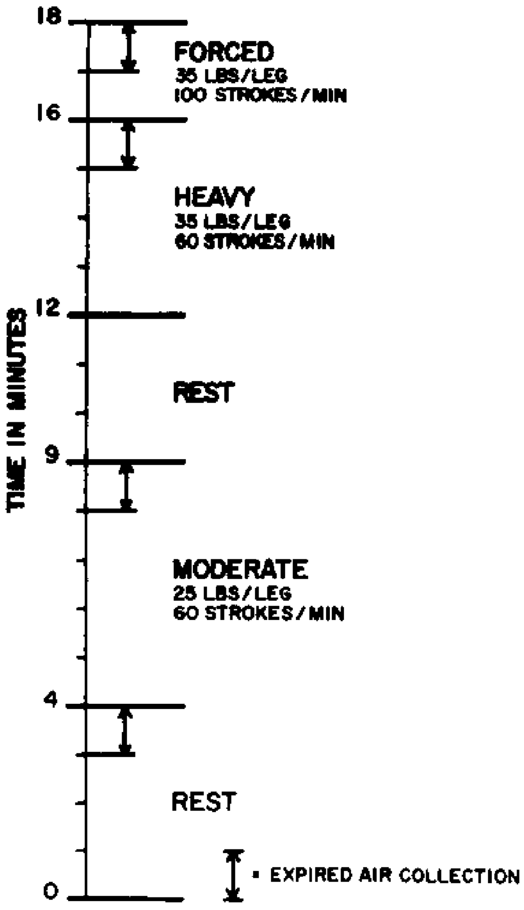

Figure 1. Experimental Protocol, Indicating Duration, Load, and Repetition Rates of Exercise Periods

The exercise apparatus is shown in Figure 2. The exercise machine uses a pulley system to convert the horizontal pedal excursions into vertical displacement of the weights. The machine and subject may be fully immersed in a constant-temperature water bath, with the exception of the weights, which are external to the bath to facilitate their variation.

All experiments were conducted within a pressure vessel (30 feet in diameter by 40 feet deep) located at the Look Laboratory of Oceanographic Engineering.

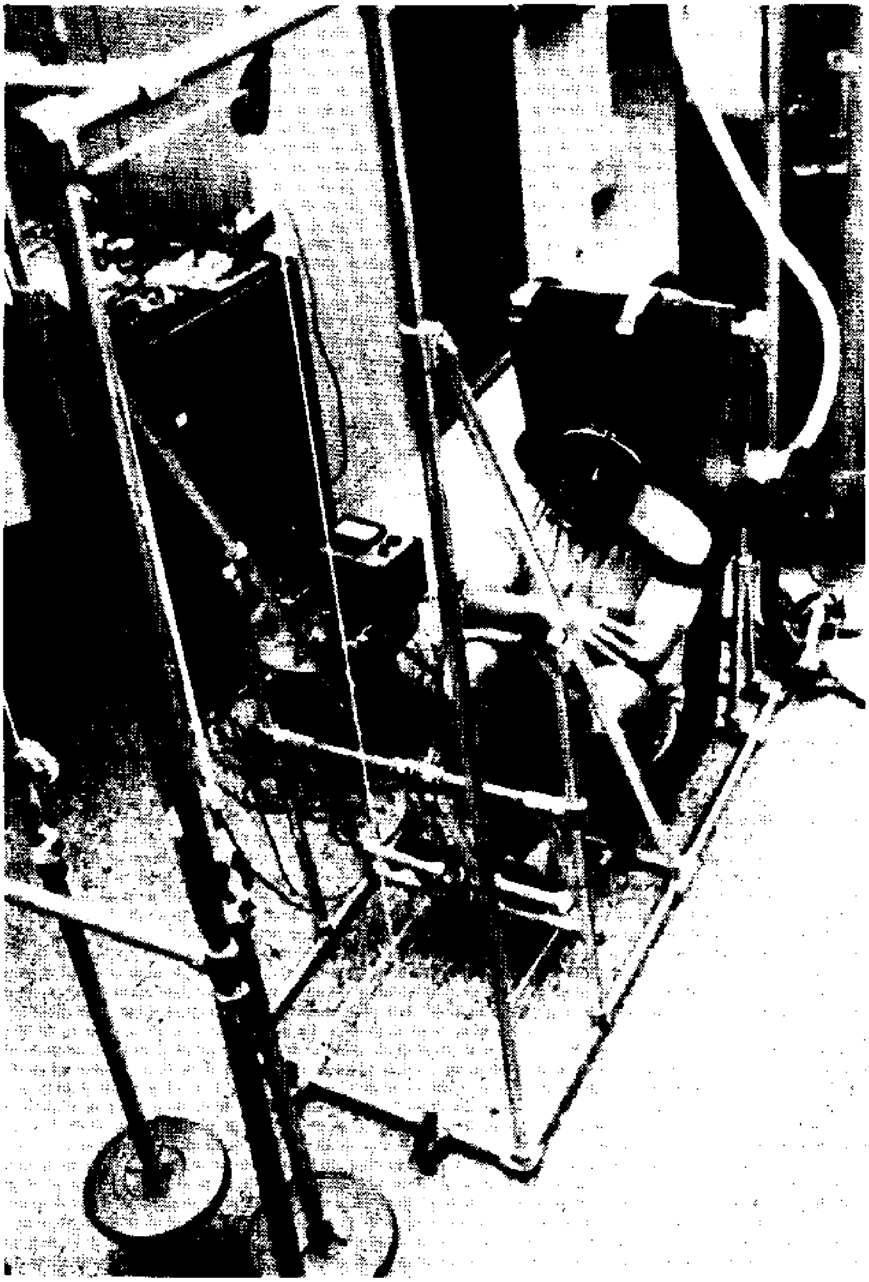

Figure 2. Photograph of Exercise Machine, Showing Vertically Suspended Weights Operated by Horizontally Moving Pedals

RESULTS

In the following, $\dot{V}_E$ is reported in ATPS units, as conversion to BTPS offered no normalizing advantage. Heart rates (f_h) were obtained by counting over one-minute intervals, and are in bpm. $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are in STPD.

Table 2 summarizes the pertinent mean data, grouped by work level category, obtained under the various conditions tested.

The primary analytic tool employed was simple linear regression rather than comparison of grouped data. Under each condition, the data on all six subjects were used to calculate mean squares regression lines for $\dot{V}_{O_2}$ *vs* f_h and $\dot{V}_{O_2}$ *vs* $\dot{V}_E$. These two sets of lines are graphed in Figures 3 and 4, which also give the corresponding correlation coefficients (R). It can be seen that, in general, at any given f_h or $\dot{V}_E$, the $\dot{V}_{O_2}$ is higher under water than in air, and higher in the colder water. Under a given condition of immersion, the $\dot{V}_{O_2}$ tends to be higher at 2 ATA than at 1 ATA.

The $\dot{V}_{O_2}$ is given in absolute terms, since the SD of the body weight is 5.3 kg (SE = 2.2) which is only 7% of the mean body weight. Moreover, the load weight is not proportioned to body weight and the exercise stroke is essentially horizontal. For these reasons, the normalizing advantage of using $\dot{V}_{O_2}$ per kg is small in this case.

A more detailed evaluation of the regressions yields the statistics given in Table 3, which tabulates a basic analysis of variance for each case.

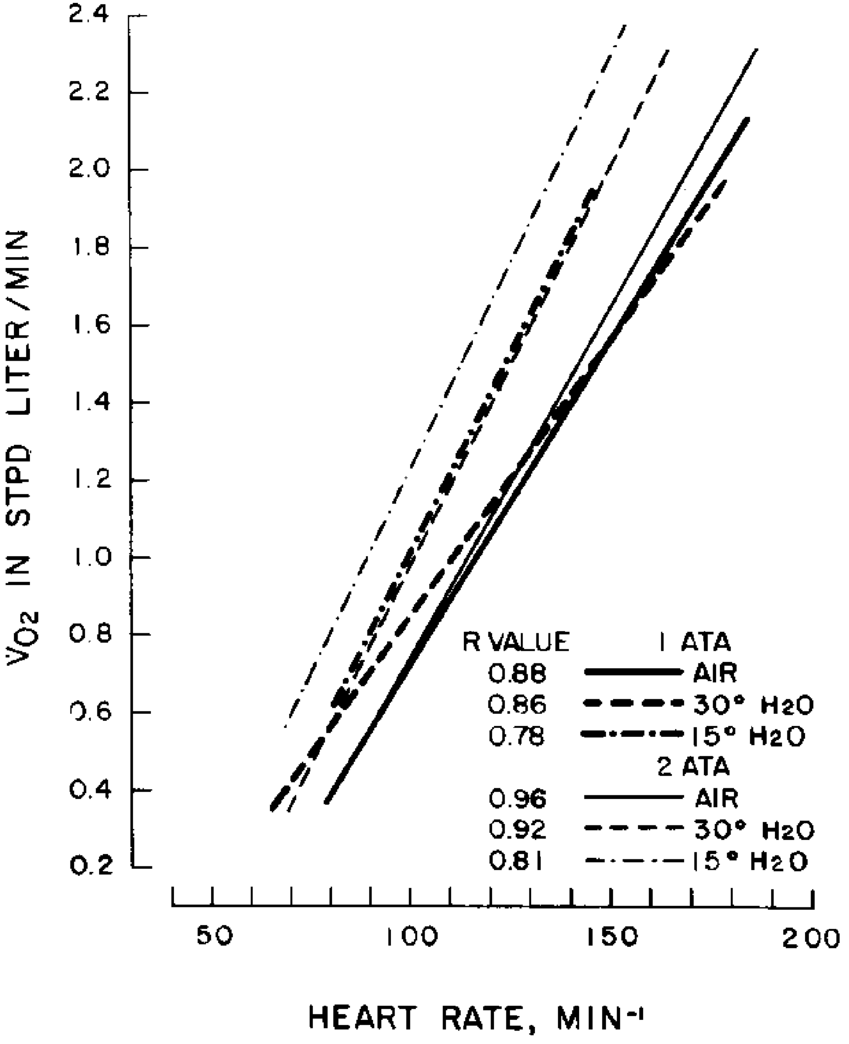

Figure 3. Plots of Regression Lines (least mean squares) of $\dot{V}_{O_2}$ *vs* f_h (Range of lines indicates approximate range of experimental data.)

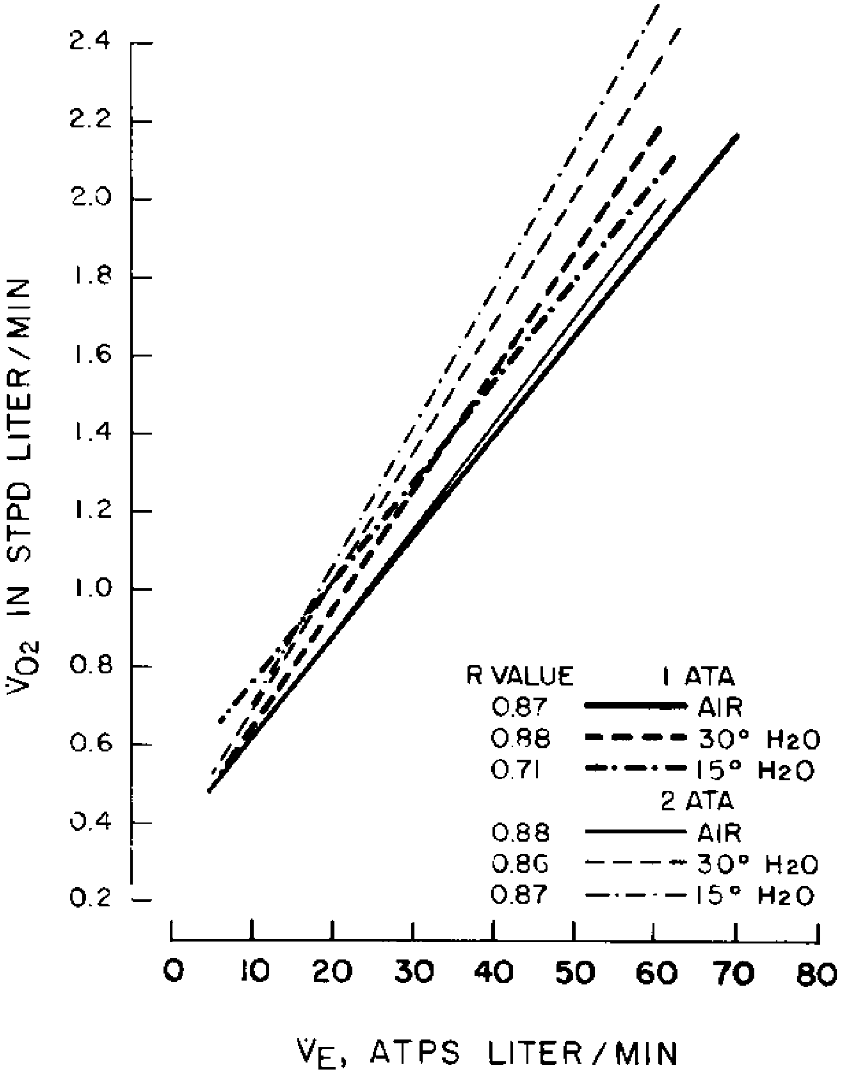

Figure 4. Plots of Regression Lines (least mean squares) of $\dot{V}_{O_2}$ *vs* $\dot{V}_E$ (Range of lines indicates approximate range of experimental data.)

TABLE 2, PART I. EXPERIMENTAL RESULTS FOR EXERCISE AT I ATA IN EACH MILIEU

Exercise Level	Milieu								
	Air			30 C Water			15 C Water		
	N	Mean	SE	N	Mean	SE	N	Mean	SE
				$\dot{V}_{O_2}$ (STPD liters/min)					
Rest	6	.35	± .05	6	.52	± .07	5	.57	± .11
Moderate	6	1.10	± .09	6	.93	± .08	6	1.19	± .10
Heavy	6	1.35	± .08	6	1.21	± .11	6	1.55	± .12
Forced	6	1.67	± .15	5	1.49	± .21	5	1.66	± .08
				$\dot{V}_{CO_2}$ (STPD liters/min)					
Rest	6	.35	± .04	6	.49	± .07	6	.54	± .08
Moderate	6	.90	± .08	6	.78	± .08	6	.95	± .11
Heavy	6	1.36	± .13	6	1.14	± .15	6	1.39	± .08
Forced	6	1.88	± .23	5	1.78	± .30	5	1.66	± .14
				Heart Rate (bpm)					
Rest	6	87	± 3.2	6	78	± 4.1	5	88	± 1.5
Moderate	6	116	± 2.3	6	112	± 2.6	6	106	± 2.2
Heavy	6	137	± 5.2	6	125	± 5.8	6	120	± 2.6
Forced	6	157	± 8.0	5	148	± 9.1	5	136	± 5.3
				$\dot{V}_E$ (ATPS liters/min)					
Rest	6	11.6	± 1.9	6	13.5	± 2.0	6	17.7	± 3.1
Moderate	6	21.7	± 2.8	6	18.1	± 2.1	6	22.1	± 3.4
Heavy	6	34.1	± 4.6	6	24.3	± 3.0	6	31.9	± 4.0
Forced	6	50.3	± 8.0	5	39.3	± 7.7	6	40.6	± 7.1
				Respiration Rate (breaths/min)					
Rest	6	12.5	± 2.2	6	7.1	± 1.4	6	9.3	± 1.5
Moderate	6	16.3	± 3.5	6	9.3	± 1.5	6	9.3	± 1.8
Heavy	6	21.3	± 3.5	6	11.3	± 1.6	6	12.7	± 2.1
Forced	6	27.7	± 4.2	6	15.6	± 2.5	6	16.3	± 2.8

TABLE 2, PART II. EXPERIMENTAL RESULTS FOR EXERCISE AT 2 ATA IN EACH MILIEU

Exercise Level	Milieu					
	Air		30 C Water		15 C Water	
	N	Mean + SE	N	Mean + SE	N	Mean + SE
			$\dot{V}_{O_2}$ (STPD liters/min)			
Rest	6	.34 ± .01	6	.34 ± .04	6	.54 ± .09
Moderate	6	.93 ± .11	6	1.09 ± .07	5	1.36 ± .20
Heavy	6	1.29 ± .18	6	1.43 ± .11	6	1.68 ± .16
Forced	6	1.67 ± .15	6	1.71 ± .14	6	2.01 ± .18
			$\dot{V}_{CO_2}$ (STPD liters/min)			
Rest	6	.29 ± .03	6	.31 ± .05	6	.44 ± .09
Moderate	6	.78 ± .11	6	.80 ± .07	5	.95 ± .17
Heavy	6	1.22 ± .23	6	1.19 ± .13	6	1.34 ± .16
Forced	6	1.75 ± .28	6	1.65 ± .23	6	1.88 ± .23
			Heart Rate (bpm)			
Rest	6	80 ± 2.3	6	74 ± 2.9	6	79 ± 3.5
Moderate	6	109 ± 5.0	6	103 ± 3.2	5	104 ± 3.2
Heavy	6	131 ± 9.3	6	120 ± 4.4	6	115 ± 4.2
Forced	6	150 ± 10.3	6	137 ± 4.9	6	133 ± 5.7
			$\dot{V}_E$ (ATPS liters/min)			
Rest	6	9.5 ± 1.4	6	9.7 ± 2.0	6	16.2 ± 3.4
Moderate	6	20.2 ± 3.0	6	18.3 ± 2.0	5	22.9 ± 3.8
Heavy	6	28.8 ± 5.2	6	26.6 ± 2.9	6	30.7 ± 4.1
Forced	6	45.8 ± 9.2	6	39.4 ± 7.7	6	46.9 ± 8.0
			Respiration Rate (breaths/min)			
Rest	5	10.8 2.4	6	8.9 1.5	6	8.9 1.5
Moderate	5	16.4 4.3	6	8.7 1.0	6	9.8 1.3
Heavy	5	16.8 4.0	6	10.6 1.3	6	11.8 1.6
Forced	5	23.3 6.4	6	15.2 2.7	6	16.6 2.4

TABLE 3, PART 1. RESULTS OF $\dot{V}_{O_2}$ *vs* f_h REGRESSIONS

Statistic	Experimental Conditions					
	1 ATA			2 ATA		
	Air	30 C Water	15 C Water	Air	30 C Water	15 C Water
Variance about mean	.296	.209	.231	.332	.325	.452
Variance due to regression	.230	.156	.139	.308	.271	.299
Residual variance	.0664	.0531	.0921	.0242	.0510	.153
Correllation coefficient	.881	.864	.776	.963	.913	.813
Intercept	-.942	-.566	-1.024	-.993	-1.088	-1.268
Variance of intercept	.0553	.0430	.163	.0153	.0424	.168
Slope	.0166	.0141	.0203	.0175	.0205	.0247
Variance of slope	3.42×10^{-6}	3.18×10^{-6}	1.26×10^{-5}	1.04×10^{-6}	3.42×10^{-6}	1.39×10^{-5}

TABLE 3, PART II. RESULTS OF $\dot{V}_{O_2}$ *vs* $\dot{V}_E$ REGRESSIONS

Statistic	Experimental Conditions					
	1 ATA			2 ATA		
	Air	30 C Water	15 C Water	Air	30 C Water	15 C Water
Variance about mean	.297	.209	.257	.332	.321	.452
Variance due to regression	.227	.161	.130	.257	.238	.339
Residual variance	.0699	.0482	.128	.754	.0838	.113
Correlation coefficient	.874	.877	.709	.879	.860	.866
Intercept	.355	.334	.497	.341	.369	.369
Variance of intercept	.0106	.00899	.0276	.00961	.0125	.0208
Slope	.0259	.0306	.0259	.0274	.0329	.0350
Variance of slope	8.86×10^{-6}	1.32×10^{-5}	2.87×10^{-5}	9.51×10^{-6}	1.64×10^{-5}	1.83×10^{-5}

The question arises, Are the regression lines really different? In terms of the significance of the differences between slopes and intercepts, only marginal differences ($p \approx .1$ to $.2$) exist for these regressions. However, this does not answer the question of whether, at a given abscissa, the values of $\dot{V}_{O_2}$ predicted by two lines are or are not different. In order to evaluate the difference between two predicted values ($\hat{y}$) of $\dot{V}_{O_2}$ at a given abscissa (x), the following test was made: The variance of each $\hat{y}$ was calculated as

$$S^2_{\hat{y}} = \frac{1}{n} S^2_{xy} + \frac{(x - \bar{x})^2}{(n - 1) \cdot S^2_x}$$ as derived in Draper and Smith (7).

Noting that in this case the standard error is the square root of the variance, a t value was computed as:

$$t = \frac{\Delta\hat{y}}{\left(S^2_{\hat{y}_1} + S^2_{\hat{y}_2} \right)^{\frac{1}{2}}}$$

Since the variances and n's were, in general, not the same, the p level for each difference tested was determined by an appropriate method recommended in a standard statistics text (13). The ranges of the independent variable over which significant differences were found are tabulated in Tables 4 and 5.

$\dot{V}_{O_2}$ vs f_h

As shown in Table 4, the t-test procedure above revealed that the differences between the regression lines are statistically significant over wide ranges of heart rate for most pairs of lines, indicating that cold stress and pressure do indeed alter the relationship between $\dot{V}_{O_2}$ and f_h.

TABLE 4. RANGE OF HEART RATE* OVER WHICH ANY TWO REGRESSION LINES PREDICT SIGNIFICANTLY DIFFERENT OXYGEN UPTAKES

*Heart rate shown in bpm.

Pressure and Milieu	1 ATA 30 C Water	1 ATA 15 C Water	2 ATA Air	2 ATA 30 C Water	2 ATA 15 C Water
1 ATA Air	No difference	93 - 182 ≥ 88	No difference	≥ 90 ≥ 85	≥ 81 ≥ 77
1 ATA 30 C Water		≥ 104 ≥ 101	No difference	≥ 104 ≥ 101	≥ 90 ≥ 88
1 ATA 15 C Water			91 - 164 87 - 188	No difference	105 - 138 100 - 157
2 ATA Air				≥ 85 ≥ 80	≥ 79 ≥ 75
2 ATA 30 C Water					96 - 159 92 - 192

Legend: x - xx range for $P \leq .05$

x - xx range for $P \leq .1$

TABLE 5. RANGE OF VENTILATION* OVER WHICH ANY TWO REGRESSION LINES PREDICT SIGNIFICANTLY DIFFERENT OXYGEN UPTAKES

*Ventilation shown in ATPS liters/min.

Pressure and Milieu	1 ATA 30 C Water	1 ATA 15 C Water	2 ATA Air	2 ATA 30 C Water	2 ATA 15 C Water
1 ATA Air	No difference	No difference	No difference	≥ 22.5 ≥ 19.5	≥ 21.5 ≥ 18.5
1 ATA 30 C Water		No difference	No difference	No difference	- 26.0 - 45.0
1 ATA 15 C Water			No difference	No difference	- 35.5 - 63.0
2 ATA Air				26.0 - 44.5 21.0 - 66.0	≥ 22.5 ≥ 19.5
2 ATA 30 C Water					No difference

Legend: x - xx range for $P \leq .05$

x - xx range for $P \leq .1$

$\dot{V}_{O_2}$ vs $\dot{V}_E$

In this case, the data (Table 5) indicate that the relationship between $\dot{V}_{O_2}$ and $\dot{V}_E$ is relatively unaffected by pressure and affected by cold stress to a lesser extent than the f_h relation.

Alveolar P_{CO_2}

Since there has been some suggestion that divers retain CO_2, the alveolar P_{CO_2} was estimated from the mixed expired P_{CO_2} using the Bohr equation, with Radford's rule of thumb that the dead space in ml equals the body weight in pounds. The results are tabulated by exercise category in Table 6, in which the three immersion conditions are pooled. By this method of estimation, no evidence of CO_2 retention is seen.

Effects of Gas Density and SCUBA Resistance

The effect of increased gas density and SCUBA airflow resistance were tested by measuring MVV on a 13.5-liter bell spirometer and on SCUBA at 1 and 2 ATA. These data are presented in Table 7 in terms of the reduction in MVV under each condition as a percentage of the MVV achieved on the spirometer at 1 ATA.

TABLE 6. ALVEOLAR P_{CO_2} CALCULATED FROM PE_{CO_2} ASSUMING CONSTANT DEAD SPACE*

*Dead space in ml assumed equal to weight in pounds after Radford.

Exercise Level	Mean Alveolar P_{CO_2}			
	Exercise at 1 ATA		Exercise at 2 ATA	
	SE	Mean	Mean	SE
Rest	1.1	30.8	28.2	1.1
Moderate	1.2	39.5	39.2	1.3
Heavy	1.7	40.1	41.2	1.4
Forced	2.5	38.9	39.7	2.6

TABLE 7. PERCENT REDUCTION IN MVV RELATIVE TO MVV ON SPIROMETER AT ONE ATA

Method of Measurement	Percent Reduction*	
	At 1 ATA	At 2 ATA
Spirometer		20.3 ± 3.2
SCUBA	18.8 ± 2.9	42.3 ± 4.5

*Shown as mean ± SE.

DISCUSSION

$\dot{V}_{O_2}$ vs f_h

The major point of interest is the apparent divergence of the regression lines with cold stress and pressure. With respect to the calibration of $\dot{V}_{O_2}$ *vs* f_h, the numerous and wide ranges of significant difference given in Table 4, together with the fairly consistent arrangement of the lines, prompt the conclusion that these differences are real. The import of this may be illustrated as follows: Suppose that a subject exercised at 2 ATA in 15° water at an f_h of 125 bpm. The $\dot{V}_{O_2}$ predicted from the 1 ATA air data would be .69 liter/min lower than that predicted by the 2 ATA 15 C data. This error is 38% (of the 2 ATA value) and is significant practically as well as statistically. Thus, estimating $\dot{V}_{O_2}$ from f_h under extreme conditions is a very approximate procedure.

The reasons for the relative reduction in heart rate at a given $\dot{V}_{O_2}$ (*i.e.*, increasing O_2/pulse) are controversial. However, it is known that a cold bradycardia may be elicited in man, at least at rest (1), and that the heart rate and respiratory responses accompanying a change in $\dot{V}_{O_2}$ vary with the nature of the activity producing that change. The observed increases in O_2/pulse, then, may be due to a baro-receptor-mediated bradycardia due to peripheral vasoconstriction, or a direct bradycardia reflex from cold receptors. It is also possible that the change in f_h due to increased thermogenesis with increasing cold stress may be disproportionately small compared with the change in $\dot{V}_{O_2}$ for reasons unrelated to the reflexes suggested above. In any case, the present data show a resting bradycardia in 30 C water compared with air at both 1 and 2 ATA. The resting heart rates in 15 C water are nearly identical with those in air at both pressures, although the $\dot{V}_{O_2}$'s are twice as high in 15 C water as in air.

One might expect that such a resting bradycardia would diminish with time as the receptors accommodate, or that it would be overridden during exercise. However, recent work on face-immersion breath-hold bradycardia in our laboratory (12) has suggested that this type of f_h response to cold may be related to heat flux rather than just skin temperature. If this is so, then an f_h decrement due to cold exposure may be expected to remain during exercise, since the heat flux then increases due to the reduction in body insulation that accompanies increased muscle perfusion, as shown dramatically by Keatinge (9).

Thus, there may be at least two factors contributing to the observed increases in O_2/pulse with increasing cold stress:

1. A cold bradycardia that persists during exercise.
2. A disproportionately small f_h response to the thermogenic $\dot{V}_{O_2}$ increase.

The present data do not allow us to identify the mechanism.

The increased O_2/pulse at 2 ATA compared with the comparable immersion condition at 1 ATA is also interesting. Taunton *et al* (15) have reported a similar finding in subjects breathing air at 2 ATA, and have reported that the O_2/pulse increases even more while breathing pure O_2 at 2 ATA. Cook (3), who studied exercise in hyperbaric environments without hyperoxia, found no change in O_2/pulse in going to 2 ATA, and a significant decrease in going to 3 ATA. Thus, it appears that the pressure-related relative decrement in heart rate reported here is actually P_{O_2} induced, presumably by peripheral chemoreceptors.

$\dot{V}_{O_2}$ vs $\dot{V}_E$

In contrast to the $\dot{V}_{O_2}$ *vs* f_h data, there are only four pairs of lines for which significant differences exist at the .05 level. These are the extreme cases, comparing exercise in air at 1 and 2 ATA with exercise in 30 C and 15 C water at 2 ATA (Table 5).

Interestingly, at any given level of $\dot{V}_{O_2}$, the range of $\dot{V}_{O_2}$ estimated from $\dot{V}_E$ over the range of conditions tested is less by a factor of 2 or 3 than the range of $\dot{V}_{O_2}$ estimated from f_h. The relative lack of variation with cold stress may be attributable to the fact that the $\dot{V}_E$ response to a thermogenic $\dot{V}_{O_2}$ increase is quite similar to the $\dot{V}_E$ response to a comparable exercise $\dot{V}_{O_2}$ increase, as indicated by preliminary studies in our laboratory. The lack of any significant decrease in ventilatory equivalent for O_2 (VE_{O_2}) at 2 ATA, compared with the same condition of immersion at 1 ATA, is not in agreement with previous reports. Both Taunton *et al* (15) and Cook (3), for example, have reported substantial reductions in VE_{O_2} at 2 ATA. The consistent arrangement of the regression lines suggests that the relative decrement in $\dot{V}_E$ at 2 ATA may be more real than the statistics indicate. In any case, it seems reasonable to assume that increases in O_2/pulse (due to cold or P_{O_2}) would be accompanied by increases in A-V O_2 difference and increased O_2 extraction.

Alveolar P_{CO_2}

Post-end-tidal alveolar samples were obtained at the ends of the rest and exercise periods in an effort to estimate $P_{A_{CO_2}}$. However, the high $\dot{V}_{CO_2}$ during exercise vitiated those estimates. Accordingly, the $P_{A_{CO_2}}$ was calculated as described in "Results", yielding the data shown in Table 6. These results indicate no change in $P_{A_{CO_2}}$ with increasing exercise load or increasing pressure, and imply no CO_2 retention. However, these estimates assumed that each subject's dead space was constant. There are reports that dead space increases during exercise (which would make our estimates too low), but this is quite controversial, for reasons summarized by Bouhuys (2). We state only that, by our analysis, there is no reason to suspect any significant CO_2 retention in our subjects under the conditions tested.

Effects of Gas Density and SCUBA Resistance

The data of Table 7 show a 20% reduction in MVV at 2 ATA. Mid-maximal expiratory flow also decreased about 20%. These results agree with those of Maio and Farhi (10) on the effects of gas density. Table 7 also suggests that, within the experimental error, the effects of gas density and SCUBA resistance are simply additive. This conclusion has recently been questioned by Sterk (14), and should be tested over wider ranges of gas density and external resistance, since a knowledge of this combined effect has practical importance.

CONCLUSIONS

It has been shown that the calibration of $\dot{V}_{O_2}$ *vs* f_h varies appreciably with cold stress and pressure, while the variation of the calibration of $\dot{V}_{O_2}$ *vs* $\dot{V}_E$ due to these factors is 2 to 3 times less. Therefore, if surface equivalent estimation of $\dot{V}_{O_2}$ is to be used, ventilation is the predictor of choice.

It should also be noted that for non-steady-state exercise, the $\dot{V}_{O_2}$ *vs* f_h calibration disintegrates altogether (8), while the fast neurogenic component (6) of exercise hyperpnea makes it more feasible to follow intermittent work by measuring $\dot{V}_E$.

It is also worth noting that a diver's ventilation can be estimated by recording tank pressure as a function of time, and that this pressure can be measured free of artifacts due to motion or seawater conductivity. Indeed, for closed-circuit SCUBA, the tank pressure decrement is a direct measure of O_2 consumption, since the oxygen supply is a tank of pure O_2.

For these reasons, it is recommended that attention be given to the accurate measurement and telemetering of tank pressures, rather than heart rate, as a solution to the problem of measuring the energy cost of underwater work.

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