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Estimation of oxygen uptake from heart rate response to undersea work

J. DWYER

Departments of Physical Therapy and Physiology, University of Southern California, Los Angeles, CA 90007

Dwyer J. Estimation of oxygen uptake from heart rate response to undersea work. Undersea Biomed Res 1983:10(2):77–87.—The efficacy of using a diver's heart rate (HR) response to work performed formed in the open sea to estimate the oxygen uptake ($\dot{V}O_2$) and work stress by general and depth-specific regression equations was examined in six scuba divers. A diver-carried data recording system and an underwater gas sampler were used to obtain measures of physiological responses to work in the ocean. The HR and $\dot{V}O_2$ were measured during dry cycling at 1 ATA, and during moderate to very heavy work fin-swimming against an ergometer at 2, 3, and 4 ATA. Underwater $\dot{V}O_2$ and HR at 2–4 ATA ranged from 1.41 to 3.89 liters/min (39%–89% $\dot{V}O_{2max}$ observed on land) and 105–180 beats/min, respectively. Individual data points at three work levels at 1–4 ATA were used to compute correlation coefficients *(r)* and regression equations. Only one significant difference in regression slopes was found (1 ATA vs. 4 ATA), but large differences in intercept were observed in each comparison. From 1 ATA to 4 ATA *r* decreased from 0.78 to 0.53 while the standard error of $\dot{V}O_2$ estimated from HR (s_{yx}) increased from 0.229 to 0.582 liters O_2. The regression equation for dry exercise (1 ATA) underestimated $\dot{V}O_2$ over most of the work range by 0.4 to 0.9 liters/min or 11% to 25% of $\dot{V}O_{2max}$. The accuracy of estimating $\dot{V}O_2$ from cardiac response by general (1 ATA) or depth-specific regression equations is insufficient to justify their use in research or diver monitoring systems. Attempts to estimate $\dot{V}O_2$ from pulmonary ventilation ($\dot{V}E$) gave similar results with more differences between slopes among the conditions. These observations and those of other investigators support the idea that underwater work loads and stress cannot be estimated or evaluated by simple HR measurements that are made during diving operations and interpreted in terms of sea-level standards.

oxygen uptake	underwater exercise
heart rate	work estimates
pulmonary ventilation	diver monitoring systems

The idea of monitoring the work stress of divers by heart rate telemetry is gaining greater acceptance among divers, diving scientists, and some hyperbaric physiologists. Kanwisher et al. (1) suggest that heart rate monitoring via acoustic telemetry enables surface personnel to closely regulate a diver's activities or recall him to the surface when physiological limits are exceeded. The use of telemetry in this way, however, requires that 1) the diver's physiological limits for underwater work be clearly defined, 2) reliable surface-to-diver communication is possible, and 3) the diver's activities be known from one moment to the next. Monitoring of heart rate for the purpose of avoiding excessive physiological stress cannot truly be accomplished unless diver activity is simultaneously observed. A heart rate of 150 beats/min may be interpreted as an unusual cardiac response if it is assumed the diver is swimming at a rate of 30 m/min (2). If he is performing heavy arm work, however, such a heart rate may be within the normal range (3).

Proponents of heart rate telemetry believe this single variable not only will provide information about a diver's physiological response to work and the degree of stress he experiences but also will describe his energy expenditure and psychological state, and that it will function as a useful estimate of underwater work loads in surface-equivalent terms (1, 4, 5). There are very few data, however, to support the validity and reliability of underwater heart rate measurements as indices of stress or any other well-defined physiological variable. Furthermore, attempts to equate underwater tasks and measured land work on the basis of heart rate have not led to definitive results (5). These investigations did not use oxygen consumption ($\dot{V}O_2$) as a basis for interpreting cardiac responses to diving activities or work on underwater ergometers. Without measurements of $\dot{V}O_2$ it is difficult to attach specific meaning to a variable such as heart rate that is influenced to variable degrees by immersion, cold, increased ambient pressure, PO_2, and many other factors. Furthermore, it is tenuous to use heart rate to compare work under two different environmental conditions (i.e., dry and immersed) when the energy cost of work in both cases is unknown and largely uncontrolled.

In view of considerable evidence for an altered heart rate-$\dot{V}O_2$ relationship due to immersion and hyperbaric and combined conditions (6–12), it is unlikely that cardiac responses would be accurate and reliable indices of $\dot{V}O_2$ during ocean work, particularly when it is interpreted in terms of the heart rate-$\dot{V}O_2$ relationship for exercise on dry land. The present study was, therefore, performed to examine the efficacy of using heart rate to estimate $\dot{V}O_2$ during open sea dives involving moderate to very heavy leg work at 2, 3, and 4 ATA. Furthermore, since Moore et al. (10) and Lally et al. (7) have suggested that pulmonary ventilation ($\dot{V}E$) may be a better variable for estimating $\dot{V}O_2$, the relationship between $\dot{V}E$ and $\dot{V}O_2$ was also studied.

METHODS

Land and underwater experiments were conducted at the University of Southern California Marine Science Center located on Santa Catalina Island, CA. Cardiorespiratory data were recorded during dives with conventional compressed-air scuba to 2, 3, and 4 ATA in the ocean; graded exercise was performed by fin-swimming against an ergometer during the dives. Water temperatures at the experimental depths were 14.5°C, 13.0°C, and 11.0°C, respectively. Depth and temperatures were monitored continuously throughout the experiments with carefully calibrated gauges. Six male scuba divers, each with more than 5 years of diving experience, gave their informed consent and volunteered to serve as subjects. Their selected characteristics are (mean ± SD): age, 26 ± 0.14 yr; weight, 75.4 ± 7.6 kg; height, 181 ± 8.3 cm; body surface area, 1.94 ± 0.13 m^2; estimated maximum oxygen consumption ($\dot{V}O_{2max}$), 48.3 ± 7.0 ml · kg^{-1} · min^{-1}.

Diving equipment

The divers wore complete wet suits with weight belts. A buoyancy compensator with compressed air inflation system was used to maintain neutral buoyancy as depth increased. Jet fins (Scubapro, Compton, CA) were worn to eliminate differences in kick thrust due to fin size and configuration. Air was supplied at ambient pressure by a single 71.2-ft^3 tank and a double-hose regulator (U.S. Divers, Anaheim, CA).

Underwater data acquisition

A multichannel underwater recording system developed by Pilmanis et al. (13) was used to obtain primary physiological data. This system consisted of a miniaturized electronics package and a small FM tape recorder. Each channel contained a signal conditioner, which filtered the signal, and a low-frequency oscillator. The conditioned signal caused the oscillator to be modulated in frequency and the output from each oscillator was then summed and the composite signal then recorded on magnetic tape by a Sony BM-10 recorder. The components were housed in a pressure-proof aluminum case. After a dive the tape cartridge was removed and placed in a modified Sony tape recorder for playback. The recorded composite signal was then passed through a bank of frequency discriminators and tape speed compensating amplifiers. The analog outputs for each channel were then recorded on a strip chart. Measures of heart rate (HR), pulmonary ventilation ($\dot{V}E$), ventilation frequency ($\dot{V}f$), water temperature, and water pressure (depth) were obtained in this way with appropriate transducers.

Measures of depth were obtained with a general pressure transducer (Type 4-366, Bell and Howell, Pasadena, CA), with a range of 0–100 psi, which was located on the exterior of the system housing. Water temperature was obtained via a glass probe thermistor exposed to the sea, while $\dot{V}f$ was measured with a glass probe thermistor placed in the mouthpiece (model GB 32P22, Fenwal Electronics, Los Angeles, CA). The ECG was recorded over a simple potential detector with appropriate amplification. The $\dot{V}E$ was obtained by monitoring tank pressure through a general pressure transducer (type 4-366, range 0-2500 psi, Bell and Howell). Tank pressure differentials over 1-min periods were used to compute $\dot{V}E$ (14).

Samples of expired gas were collected in phase with $\dot{V}E$ by an underwater gas sampler described by Dwyer (14). Resistance, measured at the mouthpiece, with the underwater gas sampler inserted in the regulator system, was 203 Pa · liter^{-1} · s^{-1} with a gas density equivalent to air at sea level. Resistance was 14 Pa · liter^{-1} · s^{-1} with the sampler removed. Divers reported subjectively that the system did not significantly affect the effort of exhalation. Postdive analysis of gas samples obtained with this system gave FE_{O_2} and FE_{CO_2}. Tidal volume (VT), $\dot{V}O_2$, and other variables were calculated from the primary data and mixed-gas analysis. Physical methods were used for gas analysis with calibration gases certified by Scholander analysis.

Underwater ergometry

Underwater work was performed in a fin-swimming mode on an underwater ergometer described by Pilmanis et al. (15), which was basically a drag board that the diver pushed through the water as he swam. A drag indicator on the device continuously informed the diver of the added resistance he was working against. Constant work rates were maintained by requiring the diver to maintain the drag indicator at specified levels. In swimming with the ergometer, the diver worked as he would if he were transporting equipment or any resistive object to an underwater work site. Each diver swam for 4 min at resistances of 1.5, 2.0, and 2.4 kg at each depth. Swims were made over a 50-m course with total distances ranging from 100 to 125 m in the 4-min tests. The HR, $\dot{V}O_2$, and $\dot{V}E$ were measured during the last minute of work. At 2 and 3 ATA, tests with 2.0 and 2.4 kg were performed during the same dive with a 2-min interval between tests. At 4 ATA each test was performed during separate dives.

Pauses between work tests were required to allow restoration of visibility by resettling of sand disturbed by the diver's swimming movements and recovery from CO_2 retention (16). The short work periods were imposed by limitations in scuba air supply, particularly at 4 ATA.

Land data acquisition

Each diver performed three submaximal work tests on a bicycle ergometer on land. The divers worked at 540, 900, and 1260 kpm/min for 6 min at each rate, with a 5-min rest period. These intervals allowed completion of gas analysis prior to the start of higher work rates. Data were collected during the final minute of each work period. The HR was computed from the ECG. A Collins (Warren E. Collins, Inc., Braintree, MA) high-velocity low-resistance valve was used, and the expired gas was collected over 1-min intervals in latex bags. Two 50-ml samples of mixed expired gas were taken from each bag and analyzed for $F_{E_{O_2}}$ and $F_{E_{CO_2}}$ by physical methods. Values for $\dot{V}_E$ and $\dot{V}_{O_2}$ were corrected to appropriate standard conditions, BTPS and STPD, respectively.

Because of the remote location of the laboratory, $\dot{V}_{O_{2max}}$ was estimated rather than measured directly. Individual estimates were made from HR-$\dot{V}_{O_2}$ regression curves extrapolated to age-predicted maximal heart rate.

Data analysis

To examine the efficacy of using HR to estimate $\dot{V}_{O_2}$ during ocean dives, individual data points were used to compute the Pearson product-moment correlation coefficient *r*, and least-squares regression equations for these variables at 1 ATA and each depth. A statistical test for differences between regression slopes, described by McNemar (17), was used to compare HR and $\dot{V}_{O_2}$ relationships between depths. Regression curves for HR and $\dot{V}_{O_2}$ were also composed with the raw data points of each diver under the four environmental conditions. From these curves individual HR values were interpolated for four levels of $\dot{V}_{O_2}$ ranging from 1.5 to 3.0 liters/min according to the method of McArdle et al. (9). The same procedure was used to compute the $\dot{V}_E$-$\dot{V}_{O_2}$ regression slopes and examine the $\dot{V}_E$ response at specific $\dot{V}_{O_2}$.

RESULTS

During dry cycling at 1 ATA, $\dot{V}_{O_2}$ averaged ($\pm$ SD) 1.43 $\pm$ 0.05, 2.06 $\pm$ 0.13, and 2.84 $\pm$ 0.15 liters/min, respectively. These values of $\dot{V}_{O_2}$ correspond to 39%, 57%, and 78% $\dot{V}_{O_{2max}}$, respectively, although some subjects exceeded 85% $\dot{V}_{O_{2max}}$ at the highest work rate. Mean ($\pm$ SD) HR values were 113 $\pm$ 16.4, 135 $\pm$ 14.9, and 165 $\pm$ 14.0 beats/min, respectively. Corresponding $\dot{V}_E$ values were 31.9 $\pm$ 4.0, 47.1 $\pm$ 5.5, and 69.0 $\pm$ 9.2 liters/min.

Underwater $\dot{V}_{O_2}$, HR, and $\dot{V}_E$ were highly variable at each depth and work rate. The individual $\dot{V}_{O_2}$ ranged from a low of 1.41 (39% $\dot{V}_{O_{2max}}$) to a high of 3.89 liters/min (89% $\dot{V}_{O_{2max}}$). These work intensities range from moderate to very heavy levels. At the shallowest depth four divers reported sensations of overheating during work tests. Individual HR measures ranged from 105 to 180 beats/min at 2–4 ATA. Mean values at specific $\dot{V}_{O_2}$ indicated nonsignificant bradycardia between 2 and 4 ATA. The $\dot{V}_E$ over the three underwater work resistances ranged from 25.4 to 97.3 liters/min at 2 ATA and from 42.1 to 82.1 liters/min at 4 ATA. A consistent depth-related reduction in $\dot{V}_E$ was observed only at 2.4 kg; however, the oxygen-ventilation equivalent was invariably reduced as depth increased.

Significant differences in interpolated HR at four levels of $\dot{V}_{O_2}$ were found at only two points, yet there was a tendency for a lower HR as depth increased from 2 to 4 ATA (Table 1). In comparing the dry condition (1 ATA) to 2 ATA, however, heart rates are generally larger in the latter condition except at the highest $\dot{V}_{O_2}$. The large standard deviations indicate a substantial variability around the mean values in underwater work.

TABLE 1

INDIVIDUAL HEART RATES* INTERPOLATED FROM LAND (1 ATA) AND UNDERWATER (2–4 ATA) OXYGEN UPTAKE-HEART RATE CURVES

$\dot{V}O_2$, liters/min	Heart Rate, beats/min			
	1 ATA	2 ATA	3 ATA	4 ATA
1.5	116 ± 17.4	128 ± 17.7	122 ± 22.6	121 ± 13.8
2.0	133 ± 16.0	141 ± 15.9	134 ± 18.8	133 ± 13.4
2.5	151 ± 16.0	154 ± 13.8	147 ± 16.2	144** ± 14.4
3.0	168 ± 15.1	167 ± 12.1	159 ± 13.9	155** ± 16.0

*Means ± SD. **Significantly different ($P<0.05$) from 1-ATA value.

When the data were considered on an individual basis, as they would be under field conditions, different trends were found. Primary data points for individual interpolated heart rates at the four levels of $\dot{V}O_2$ are given in Table 2 for two representative divers. These data, together with the data of four remaining divers indicate that in 13 of 24 cases (6 divers × 4 $\dot{V}O_2$ values), the HR differences between 1 and 2 ATA exceed 10 beats/min; in 3 cases the difference exceeds 20 beats/min. In comparing data at the three depths, there are many points where HR differences exceeded 15 beats/min, the largest being 31 beats/min, and the lower HR differences were generally found at the deeper depths. Furthermore, substantial differences in HR, at the same $\dot{V}O_2$, were found between depths separated by only 10 msw.

Regression equations for the relationship between $\dot{V}O_2$ and HR are given in Table 3. A statistical test for differences between regression slopes reached significance only for the comparison between 1 and 4 ATA, but there were substantial differences in intercept between all conditions. The correlation coefficients did not exceed 0.78 and fell progressively from 1 to 4 ATA. The s_{yx} for the 1 ATA equation is 0.229, but it nearly doubles for the ocean conditions. At 3 ATA, for example, the estimated $\dot{V}O_2$ at a HR of 120 beats/min is 2.28 liters/min. With s_{yx} of 0.409 liters, 95 times out of 100 the actual $\dot{V}O_2$ would be within the limits 2.28 ± $2(s_{xy})$ or 2.28 ± 0.812 liters/min. At the remaining depths the range is larger and the probability of an accurate estimate is correspondingly lower. The position of the ocean curves (intercept) relative

TABLE 2

INDIVIDUAL HEART RATES FROM TWO DIVERS INTERPOLATED FOR FOUR LEVELS OF OXYGEN UPTAKE FROM PERSONAL REGRESSION LINES AT 1–4 ATA

Subject	$\dot{V}O_2$, liters/min	Heart Rate, beats/min			
		1 ATA	2 ATA	3 ATA	4 ATA
2	1.5	119	133	136	137
	2.0	135	143	141	142
	2.5	147	157	147	149
	3.0	161	169	153	152
3	1.5	105	128	130	108
	2.0	122	140	141	121
	2.5	138	152	151	133
	3.0	155	163	161	145

TABLE 3
CORRELATION COEFFICIENTS AND REGRESSION EQUATIONS FOR $\dot{V}O_2$, HEART RATE, AND $\dot{V}E$ IN EXERCISE AT 1–4 ATA*

Condition	r	Regression Equation (y')	x	s_{yx}*	Significant** Differences
1 ATA	0.78	$\dot{V}O_2 = 0.0109x + 0.595$	HR	0.229	D
2 ATA	0.74	$\dot{V}O_2 = 0.221x - 0.921$	HR	0.450	
3 ATA	0.54	$\dot{V}O_2 = 0.0177x + 0.150$	HR	0.409	
4 ATA	0.53	$\dot{V}O_2 = 0.0194x - 0.212$	HR	0.583	A
1 ATA	0.92	$\dot{V}O_2 = 0.0209x + 1.076$	$\dot{V}E$	0.143	C, D
2 ATA	0.79	$\dot{V}O_2 = 0.0256x + 1.070$	$\dot{V}E$	0.411	D
3 ATA	0.55	$\dot{V}O_2 = 0.0177x + 1.756$	$\dot{V}E$	0.401	A, D
4 ATA	0.84	$\dot{V}O_2 = 0.0414x + 0.335$	$\dot{V}E$	0.369	A, B, C

*Unit of s_{yx} is liters O_2/min. **Slope of regression equation for condition is significantly different ($P<0.05$): A, from 1 ATA; B, from 2 ATA; C, from 3 ATA; D, from 4 ATA.

to the curve for 1 ATA indicates that $\dot{V}O_2$ would be consistently underestimated, except during work at 2 ATA, if the 1-ATA equation were used to interpret the HR observed during work in the open sea.

Mean values for $\dot{V}E$ interpolated at four values of $\dot{V}O_2$ are given in Table 4. The $\dot{V}E$ at 2.0 and 2.5 liters/min of O_2 during dives at 4 ATA were significantly less ($P<0.05$) than the corresponding $\dot{V}E$ at 1 ATA. Mean differences between dry and shallow (2 ATA) conditions were less than 5 liters, while differences between 2 and 4 ATA did not exceed 6 liters. Individual data for Divers 2 and 3 (Table 5) indicate slightly larger differences in $\dot{V}E$ between ocean depths and 1 ATA, however. These divers were inconsistent in $\dot{V}E$ changes between 1 and 2 ATA, but they did have a tendency to progressively reduce $\dot{V}E$ as depth increased from 2 to 4 ATA.

Regression equations for $\dot{V}O_2$ estimated from $\dot{V}E$ are included in Table 3. The regression slope for 1 ATA is significantly different from slopes at 3 and 4 ATA, with large differences in intercept. Only the 4-ATA slope is significantly different from those of all remaining conditions. The s_{yx} values at 2–4 ATA are more than twice the value found at 1 ATA and similar to those of the HR analysis. The range of probable values for $\dot{V}O_2$ estimated from regression equations, at any depth, is approximately the same whether $\dot{V}E$ or HR is used in the calculation. Furthermore, the difference in slope and intercept in $\dot{V}E$ equations for 1 ATA and ocean depths

TABLE 4
INDIVIDUAL PULMONARY VENTILATION MEASURES* INTERPOLATED FROM LAND (1 ATA) AND UNDERWATER (2–4 ATA) $\dot{V}E/\dot{V}O_2$ CURVES

$\dot{V}O_2$, liters/min	$\dot{V}E$, liters/min			
	1 ATA	2 ATA	3 ATA	4 ATA
1.5	33.91 ± 5.6	31.16 ± 4.5	28.66 ± 6.3	28.83 ± 3.6
2.0	46.33 ± 6.3	42.33 ± 8.3	41.08 ± 6.8	41.00** ± 6.5
2.5	59.00 ± 6.8	54.75 ± 10.5	52.00 ± 9.2	51.58** ± 7.8
3.0	71.83 ± 8.3	69.25 ± 12.8	64.83 ± 12.8	63.33 ± 11.08

*Means ± SD. **Significantly different ($P<0.05$) from 1-ATA condition.

TABLE 5
INDIVIDUAL MEASURES OF PULMONARY VENTILATION IN TWO DIVERS INTERPOLATED FOR FOUR LEVELS OF $\dot{V}O_2$ FROM PERSONAL REGRESSION LINES

Subject	$\dot{V}O_2$, liters/min	$\dot{V}E$, liters/min 1 ATA	2 ATA	3 ATA	4 ATA
2	1.5	40.5	35.0	23.0	25.0
	2.0	57.0	57.5	50.0	50.0
	2.5	69.5	74.5	67.5	62.5
	3.0	83.0	90.0	86.0	76.0
3	1.5	31.5	37.5	36.5	27.0
	2.0	41.0	44.5	44.0	34.5
	2.5	50.5	52.0	51.5	41.5
	3.0	60.5	60.5	60.0	48.0

would enhance the error of $\dot{V}O_2$ estimation if the 1-ATA equation were used in place of a depth-specific equation, to interpret $\dot{V}E$ observed during ocean work.

DISCUSSION

Comparative studies of surface swimming and land exercise, such as running and cycling, have shown that HR is consistently lower at equivalent energy expenditures during immersion (8, 9, 18, 19). These studies, in particular the work of McArdle et al. (9), indicate that interpretation of HR recorded during swimming in terms of the HR-$\dot{V}O_2$ relationship observed in dry land exercise will lead to consistent underestimations of the work stress or $\dot{V}O_2$. Similar observations have been made when identical muscle groups are involved in the same cycling exercise in air and water (6, 20). Dressendorfer et al. (21) also studied leg cycling in water at 30°C with head-out immersion and in air at 23°C. The HR was significantly depressed 8 to 15 beats/min by immersion, even at maximal work levels that revealed no decrement in $\dot{V}O_{2max}$. Complementary results were reported by Moore et al. (10), who found consistently lower HR in leg work at specific $\dot{V}O_2$ as exercise progressed from room air to water at 16°C. Their results point to a conclusion supported by many investigations: the dry HR-$\dot{V}O_2$ relationship cannot be used to accurately evaluate the exercise HR of immersed subjects, particularly at higher $\dot{V}O_2$ in cold water. Moore et al. (10) found an error in $\dot{V}O_2$ estimates of 33% (0.5 liters/min) at HR of 125 beats/min.

The HR-$\dot{V}O_2$ relationship has also been studied under hyperbaric conditions. Several investigations have reported increased O_2-pulse, reduced HR at specific $\dot{V}O_2$, and altered HR-$\dot{V}O_2$ regression slopes in fin-swimming in a wet pot at 4 ATA (22), in open-water arm and leg work (2, 23), and in leg cycling at 31.3 and 46 ATA in He-O_2 (12, 24). Recently, Thalmann et al. (25) reported a significant pressure effect (1.45 vs. 6.79 ATA) on the HR at a $\dot{V}O_2$ of 2.5 liters/min during wet leg cycling. A consistent fall in HR-$\dot{V}O_2$ slope, with increasing pressure, was found, however, in only one of three subjects. Furthermore, they found no immersion effect, which places them at odds with other investigators (3, 6, 20, 21). Changes in the HR-$\dot{V}O_2$ relationship under hyperbaric air have been attributed to raised PO_2 and increased environmental temperature and gas density (26, 27), but static lung load has no effect (25). An additional factor in open-water studies is decreased water temperature with depth, which is compounded by wet-suit compression. Change in body position (28) and immersion have profound effects on the cardiac response to exercise, due primarily to the elimination of hydrostatic gradients that influence the circulation (3). With respect to this factor Lally et al. (7) and Fagraeus and Bennett (3) have found altered HR-$\dot{V}O_2$ relationships between dry and immersed leg and arm exercise at 1 ATA. Fagraeus and Bennett found no difference in regression slope between 1 ATA and 16–19 ATA with immersed exercise, however. In contrast, Lally et al. found erroneous $\dot{V}O_2$ estimates when the regression equation at 1 ATA-wet was used to evaluate HR at 2 ATA-wet. This discrepancy may be due to environmental temperatures to which the divers were exposed. Fagraeus and Bennett dressed their divers in dry suits, whereas Lally et al. used no protective suit in water temperatures as low as 15°C.

In the present study underwater exercise was performed for 4 min at each resistance level. This short work period was to some degree dictated by the limited air supply available in the scuba tank; preliminary studies indicated exhaustion of the tank with 6 min of heavy work at 4 ATA. To provide a safety factor, and to perform as many as three tests per dive at shallow depths, the 4-min period was selected. The possibility exists that divers did not attain a steady state in $\dot{V}O_2$ or HR by the end of the 4th min of work. Studies in our laboratory (J. Dwyer, R. King, K. Neet, 1981: unpublished observations) and reports by others clearly show that the HR-$\dot{V}O_2$ relationship is independent of steady-state attainment. Moreover, it is the same in steady-state and rapid, incremental exercise with work periods of only 1-min duration.

The present study revealed no difference in regression slope between 1 ATA-dry and 2 ATA-wet, but the standard error of estimating $\dot{V}O_2$ was doubled in the latter condition. Changes in s_{yx} indicated in Table 4 reflect a reduced probability of accurate $\dot{V}O_2$ estimations at 2–4 ATA when depth-specific regression equations are used. When the 1-ATA equation is used to estimate $\dot{V}O_2$ by HR response at 2–4 ATA, large errors result, mainly due to differences in intercept. For example, at a HR of 140 beats/min the 1-ATA equation yields a $\dot{V}O_2$ of 2.12 liters/min. The corresponding $\dot{V}O_2$ calculated with the 4-ATA equation is 2.50. Thus, evaluation of an underwater HR response with a dry-land standard produced an error of nearly 0.4 liters/min (11% $\dot{V}O_{2max}$). Due to large individual variability in HR and $\dot{V}O_2$ at depth, a larger error in estimated $\dot{V}O_2$ occurs when individual data points are used. At a $\dot{V}O_2$ of 3.0 liters/min the HR of Diver 3 was 145 beats/min at 4 ATA. According to the 1-ATA regression equation, the estimated $\dot{V}O_2$ is 2.18 and the error is 0.82 liters of O_2 (19% of individual $\dot{V}O_{2max}$). Even when the diver's own regression curve at 1 ATA is used, rather than the group curve, the error is still 0.43 liters of O_2 (10% $\dot{V}O_{2max}$). In most cases the evaluation of underwater HR by surface standards will underestimate the O_2 cost of work, and also the stress of exercise, by more than 0.4 liters/min. An exception is represented by low work rates with the 2-ATA regression equation. In this segment the $\dot{V}O_2$ would be overestimated. The alteration in the HR-$\dot{V}O_2$ curve probably reflects the heat stress experienced by four divers at this depth. Davis et al. (29) found similar HR responses at specific $\dot{V}O_2$ in water at 35°C. Some relief from the heat stress was provided by higher swim rates, which caused greater movement of water through the wet suit.

The present and previous investigations (3, 7) do not support the idea that underwater work can be evaluated by cardiac responses interpreted in surface terms. Weltman and Egstrom (5), on the basis of rank order correlations and similarities in HR response, attempted to equate underwater and land work. They suggested that the amount of work performed by divers could be assessed by HR measurements evaluated with surface standards. The degree of error in this approach was discussed above and centers on two basic physiological precepts. First, as demonstrated in surface swimming studies prior to 1969 and in subsequent hyperbaric studies, immersion per se changes the HR-$\dot{V}O_2$ relationship to the extent that a HR observed underwater represents a greater $\dot{V}O_2$ than an identical rate observed on land using the same muscle groups and motor patterns of work. Second, arm and leg work, whether they are performed wet or dry, cannot be equated on the basis of cardiac response due to basic hemodynamic differences in the two work modes (28, 30). There are indications that the work output of divers cannot be estimated by $\dot{V}O_2$ as well because of differences in mechanical efficiency (16, 31).

The accuracy of $\dot{V}O_2$ estimates from pulmonary ventilation was not found to be greater than estimates from cardiac responses. At moderately high work rates, evaluation of $\dot{V}E$ in surface standards resulted in errors in $\dot{V}O_2$ estimate of 0.49 liters of O_2 or more. Lally et al. (7) found a large difference in regression slopes between 1 ATA-dry and 2 ATA-wet but only a small immersion effect on $\dot{V}E$ at 1 ATA and no depth effect (1 vs. 2 ATA-dry). Fagraeus and Bennett (3) found no immersion effect on $\dot{V}E$-$\dot{V}O_2$ at 1 ATA. They did find a substantial depth effect at 16–19 ATA, however. These studies indicate that regression equations for shallow-immersed conditions are sufficiently different from equations for deeper immersed conditions that accurate estimates of $\dot{V}O_2$ by the former, using $\dot{V}E$ observed at greater depths, are not possible.

There are at least two reasons why $\dot{V}E$ should not be acceptable as an estimator of O_2 uptake. First, as ambient pressure and gas density increase, the $\dot{V}E$ is drastically reduced to a variable degree among individuals (2, 16, 22, 26). The $\dot{V}E$ reached at any $\dot{V}O_2$ may depend as much on the perceived work of breathing and acceptable degree of CO_2 retention as environmental variables. Remarkably, $\dot{V}E$ is not affected by variations in static lung load (25). Under specific hyperbaric conditions and work rates the ventilatory response to work may vary considerably, not only between divers at the same $\dot{V}O_2$ but also within the same diver from one dive to the next (16, 32). Second, the $\dot{V}E$ at a given $\dot{V}O_2$ will also vary between subjects, even at 1 ATA-dry, due to individual differences in anaerobic threshold (33). Even among divers with roughly the same $\dot{V}O_{2max}$ the anaerobic threshold (AT) may be different in absolute or relative terms. Thus, in working at the same percentage of $\dot{V}O_{2max}$ one diver may work aerobically, remaining below his AT, and $\dot{V}E$ will be maintained with a normal oxygen equivalency (25 liters $\dot{V}E$/liter O_2), while another diver may be forced to work anaerobically, exceed his AT, and experience hyperventilation relative to oxygen uptake. This diver will have a relatively high $\dot{V}E$, reflecting the curvilinear relationship between $\dot{V}E$ and $\dot{V}O_2$, and the ventilation equivalent may exceed 40 liters $\dot{V}E$/liter O_2. This discrepancy in ventilatory response to work points to the invalidity of the relative percentage concept in equating work stress for respiratory research purposes (33, 34). In the study of exercise ventilation, whether under normal environmental or hyperbaric conditions, work rates should be equated on the basis of AT to avoid metabolic acidosis in some subjects while others are working aerobically with normal ventilatory response.

Heart rate and pulmonary ventilation have been shown to be inadequate as estimators of $\dot{V}O_2$ during underwater work. Since HR is more easily detected and telemetered under field conditions, its use may be restricted to observing the approach of some upper limit in cardiac response. A rate of 180 beats/min in arm or leg work is probably near the HR_{max} of most divers, and as HR increases to this limit, diver activity could be curtailed or stopped. Similarly, a relative figure of 85% of HR_{max} could be used, but this requires that a diver's HR_{max} be available. Problems still arise, however, in deciding borderline cases, and it is doubtful that close regulation of divers as they work is feasible or possible with the available systems for physiological monitoring. Using cardiac response as the basis of a decision to terminate a dive or a particular activity during a dive becomes more difficult if older and younger divers are under simultaneous observation, since HR_{max} and HR response at specific $\dot{V}O_2$ are influenced by age (35). Other confounding factors that could lower HR_{max} while not significantly influencing $\dot{V}O_{2max}$ are PO_2, gas density, and combined density and pressure (27).

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Dwyer J. Estimation du prélèvement d'oxygène basée sur la réponse de la fréquence cardiaque au travail sous-marin. Undersea Biomed Res 10(2):77–87.—L'utilité d'une méthode employant la réponse de la fréquence cardiaque (FC) au travail effectué en pleine mer pour estimer le prélèvement d'oxygène ($\dot{V}O_2$) et l'effort du travail et utilisant les équations de régression générales et spécifiques à la profondeur a été examinée chez six plongeurs. Un système porté par le plongeur pour l'enregistrement des données et pour l'analyse du gaz expiré a été employé pour mesurer des réponses physiologiques au travail dans la mer. La FC et le $\dot{V}O_2$ ont été mesurées au cours de cyclage sec à 1 ATA; les mêmes mesures ont été effectuées pendant un travail variant de moderé à très sévère chez un plongeur muni de palmes nagant contre un engomètre à 2, 3 et 4 ATA. Le $\dot{V}O_2$ et la FC mesurées sous l'eau à 2–4 ATA variaient de 1, 41 à 3, 89 litres/min (39%–89% $\dot{V}O_{2max}$ observée sur terre) et 105–180/min, réspectivement. Les points des données individuelles aux trois paliers de travail à 1–4 ATA ont été employés pour calculer les coefficients de correlation *(r)* et les équations de regression. Seule une différence significative des inclinaisons des courbes a été décelée (1 ATA vs. 4 ATA), mais de grandes différences dans les intersections des courbes ont été observées pour chaque comparaison. De 1 ATA à 4 ATA, *r* a diminué de 0, 78 à 0, 53, bien que l'erreur standard de $\dot{V}O_2$ estimée par la FC (s_{yx}) a augmenté de 0, 229 à 0, 582 litres O_2. L'equation de regression pour l'exercise sec (1 ATA) a sous-estimée le $\dot{V}O_2$ sur la plupart de l'étendue du travail d'une valeur de 0, 4 à 0, 9 litres/min (11% à 25% du $\dot{V}O_{2max}$). L'exactitude de l'estimation du $\dot{V}O_2$ par la réponse cardiaque employant les équations de regression générales (1 ATA) ou spécifiques à la profondeur est insuffisante pour justifier son emploi dans la recherche ou dans les systèmes de surveillance du plongeur. Les tentatives pour estimer le $\dot{V}O_2$ par la ventilation pulmonaire ($\dot{V}E$) ont donné des résultats similaires avec plus de différences entre les inclinaisons des courbes relatives aux différentes conditions. Ces observations et celles d'autres chercheurs supportent l'hypothèse que les degrés de l'éffort du travail sous-marin ne peuvent pas être estimés ni évalués par des mesures simples de la FC faites au cours des plongées, et interpretées en fonction des standards déterminés à 1 ATA au niveau de la mer.

prélèvement d'oxygène
fréquence cardiaque
ventilation pulmonaire
exercise physique sous-marin
estimations du travail
systèmes de surveillance du plongeur

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