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DEPARTMENT OF PHYSIOLOGY
UNIVERSITY OF HAWAII SCHOOL OF MEDICINE

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Abstract:

Eight subjects performed graded leg exercise at loads from light to forced maximal in air and totally submerged in water at 30°, 22°, and 16°C. There was no significant decrement in performance between the air and immersed environments. Heart rate, minute volume ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production had high linear correlation coefficients with imposed work load. $\dot{V}_E$ and $\dot{V}O_2$ were higher in water under all work loads and at the two lower water temperatures. Heart rate was the same at rest under all conditions, but significantly less at high work loads in 16°C water when compared to air. It is concluded that monitoring of a diver's heart rate will cause underestimation of work load in surface-equivalent terms at high loads in water of low temperature. The data confirm and extend information on underwater work to lower temperatures and higher work loads.

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INTRODUCTION

With increasing work performance by man in the sea, considerable research has involved the assessment of energy cost of underwater tasks (5,7), the effects of water temperature (5,6,7), and the simplest physiologic monitoring to provide accurate prediction of energy cost and stress level of underwater work (11). Studies of correlates of underwater work have seldom provided data for a broad range of work output and/or water temperatures below 20^{o}-25^{o}C. This investigation combines the two, concentrating especially upon the extreme case, high work output and low temperature.

METHODS

Eight healthy adult males, ranging in age from 23 to 42 years ($\bar{x} = 32.2$), served as subjects. All but one were members of the Department of Physiology, Univ. of Hawaii. The exception was a local diving instructor. All subjects but one had previous underwater experience, either SCUBA or skin diving. Table 1 summarizes the physical characteristics, lung volumes, and estimated maximal oxygen uptake ($\dot{V}_{O_2}$ max) of the subjects.

The experiments consisted of graded exercise levels performed in air and submerged in water at 30^{o}, 22^{o}, and 16^{o}C. In all cases, the subject's air source was a standard 71.2 cu. ft. SCUBA tank utilizing a double-stage, double-hose demand regulator (U.S. Divers Co., Santa Ana, California). Respiration rate (f_r) was recorded by sealing a thermistor into the regulator exhaust near the mouthpiece. Air temperature changes during expiration were transmitted to a polygraph for recording. Rectal temperature $(\overset{o}{Tr})$ was read directly from a Yellow Springs telethermometer.

Heart rate (f_h) was continously monitored on the polygraph via the attachment of two precordial Beckman electrodes to the subject.

Expired gas was collected from the regulator exhaust either into 250 liter Douglas bags or into a 350 liter Tissot respirometer. Gas samples were subsequently analyzed for CO_2 and O_2 on a Scholander micro-gas analyzer. Oxygen was also analyzed on a Beckman Oxygen analyzer. A standard diving mask was worn and insured respiration by mouth only.

An exercise machine was designed and built for use in an immersion tank (3x5x5 ft. deep). (Fig. 1) The subject, in a sitting position, pushed alternately with each leg against independent pedals. The pedals were attached, through a pulley system, to weights external to the immersion tank, where loads could be changed easily. Work was restricted to leg muscles in all trials. Weight displacement was limited by a subject's leg length, but there was room for maximal pedal swing within the tank for each subject.

During exercise trials at any given load, the subjects maintained a cadence of either sixty or one hundred strokes per minute, as detailed below. Strokes were recorded on a polygraph by means of impulses from a photocell attached to the chassis of the machine, positioned so as to be activated by the passage of the pedals through their swing. Actual weight displacement was measured in several trials on each subject.

The following regimen was adhered to during both air and submerged exercise experiments: Fig. 2 illustrates a typical recording regimen.

1) The subject sat quietly at rest, breathing from SCUBA, for five minutes. During the last two minutes, his steady-state heart rate, respiratory rate, rectal temperature, room (or water) temperature were recorded, and expired gas samples taken.

2) The subject immediately began light exercise (4.5 to 6.8 Kg./leg) at the rate of 60 strokes/min., for five minutes. The same steady-state parameters were recorded during the fifth minute.

3) Following a three-minute rest, the procedure repeated step 2) with a moderate load (9.1 - 13.5 Kg./leg).

4) The rest period was repeated, and heavy exercise (13.5 - 18.2 Kg/leg) began and proceeded for four minutes. Recordings and collections were made during the fourth minute. At the end of the fourth minute, the cadence was increased (without a break) to the forced exercise level of 100 strokes/minute for one and one-half minutes. The final gas collection occurred in the last thirty seconds of the period of forced exercise.

Three trials were performed in 23°-25°C air, both inside the empty immersion tank and outside. Two trials occurred before the submersion experiments, the third after. The schedule of experiments was such that any given subject performed the experiment, either in air or submerged, only once per week, in order to avoid any training effects (3,8). No decreases in resting heart rates were noted over the weeks of the experimental period.

During submersion experiments, the subjects were seated on the exercise machine in approximately four feet of water. Water temperature was maintained at any level within one degree centigrade by the addition of either hot water or ice.

Heart rates are expressed as steady-state levels taken from the last minute or half-minute at any work level. Work level is calculated as kilogram . meters per minute. Minute ventilation ($\dot{V}_E$) is corrected to BTPS, O_2 consumption ($\dot{V}_{O_2}$) and CO_2 production ($\dot{V}_{CO_2}$) to STPD.

RESULTS

A summary of the experimental results appears in Table 2. Under all conditions, $\dot{V}_{O_2}$, f_h, $\dot{V}_E$, $\dot{V}_{CO_2}$ were directly related to external work with linear correlation coefficients above 0.8 (Table 3). In the case of heart rate versus external work, the correlation coefficient was + 0.92 in air and reduced approximately 0.1 upon immersion, regardless of water temperature.

At rest, $\dot{V}_{O_2}$ was generally higher in water than in air, especially in 22° and 16°C water, while that in 30°C water was comparable to $\dot{V}_{O_2}$ in air. During light and moderate work, $\dot{V}_{O_2}$ was higher than in air during all immersion trials at 22° and 16°C. At the higher work levels, however, there was less difference between air and immersion trials. Similar results at submaximal work levels have been reported by Craig and Dvorak (7) for water temperatures from 35° to 25°C. Our data extend the findings to 16°C water. At the forced work level, $\dot{V}_{O_2}$ reached approximately 75% of estimated $\dot{V}_{O_2}$ max.

Ventilation followed a pattern similar to that of $\dot{V}_{O_2}$. $\dot{V}_E$ plotted against $\dot{V}_{O_2}$ (Fig. 3) yielded no significant difference, again confirming and extending Craig's work to the lower temperature.

The gas exchange ratio ($\dot{V}_{CO_2}/\dot{V}_{O_2}$) tended to increase in all trials with increased work load, indicating that a mild degree of hyperventilation may have occurred. This was especially noted at the forced work level and there is a marginally significant difference (P = approximately 0.05) at this level between air and 16°C water.

The relationship between heart rate and $\dot{V}_{O_2}$ is shown in Fig. 4. Heart rate for a given $\dot{V}_{O_2}$ was less in water than in air, particularly 22° and 16°C water. In 30°C water, heart rate averaged 14 beats/L $\dot{V}O_2$ less than in air, while in 22° and 16°C water, heart rate was 31.5 and 31.6 beats/L $\dot{V}_{O_2}$ less than air, respectively. The slopes of the regression lines were not different in any trial.

Heart rate and external work were linearly related with no significant differences between work in air and in 30° and 22°C water. At work loads above light, however, in 16°C water, there was a tendency toward lower heart rate per unit work (Fig. 5). At the forced work level, heart rate was 143 ± 4 (S.E.) in cold water vs. 157 ± 4 in air. This decrease in 16°C water is significant below the 2% level. While the intercepts are not different for the regression lines, the slopes were significantly different ($p < 0.02$). In air, the slope was 0.103 ± 0.004, and 0.08 ± 0.006 in 16°C water.

Rectal temperature did not change significantly in air, 30° and 16°C water. There was a progressive decrease in mean temperature recorded in 22°C water but this was primarily the effect of one subject who spent additional time in the water before the work trial began and violent shivering was noticeable. This subject had one of the lowest body fat estimates (9.5%).

None of the physical characteristics correlated significantly with the heart rate or $\dot{V}_{O_2}$ response to work level. Respiratory rate did not differ and correlation with external work was not high (0.63 - 0.69 for all trials). In part, this was due to the fact that the subjects generally adjusted their rate to some harmonic of the exercise cadence and regulated ventilation by altering tidal volume, and method was left to the subject. While maximal breathing capacity was not approached during this experiment, it was noted in early trials that MBC with SCUBA was reduced 31% from that attainable with a spirometer (Table 1).

DISCUSSION

This study confirms work from Craig's laboratory and extends the data to lower water temperatures and higher work loads. Under the conditions of this experiment, the ventilation equivalent ($\dot{V}_E/\dot{V}_{O_2}$) remained unchanged even at 16°C water immersion (see Fig. 3). This is in contrast to the findings of Costill _et al_. (5), who reported a decreased efficiency of breathing in 17.4°C water in subjects swimming vigorously ($\dot{V}_{O_2}$ = 3.0 L/min.). It is probable that the higher O_2 demand and decreased breathing efficiency recorded in the latter study reflects the use of more muscle mass than in the present study and those of Craig. Normal SCUBA swimming technique requires predominantly leg exercise.

Weltman and Egstrom (11) have reported from their studies that monitoring heart rate or minute ventilation allowed reasonable approximation of imposed workload in surface-equivalent terms. Craig suggested (7) that ventilation during work seemed to be somewhat greater in the coldest water tested (25°C). This was most pronounced at highest work loads. Our results confirm this, with an interesting qualification. While $\dot{V}_E$ in 30°C water was generally the equivalent of that in air at any given load, the ventilation in 22° and 16°C water was higher than in air under all work loads, particularly at the forced level. On the average, $\dot{V}_E$ was higher in 22°C water (though not significantly so) than in air or other water temperatures (see Table 2). Since Hensel and Wurster (9) have reported that frequency of discharge of facial cold receptors of the cat shows a maximum of about 25° - 27°C with lower frequencies at higher and lower temperatures, it is an intriguing speculation that the increased $\dot{V}_E$ is not only cold receptor mediated, but that there is an optimum temperature range instead of simple linearity involved. The data reported here do not contribute to a resolution of the question, however.

Of particular interest is the relationship between heart rate and work load. The data indicate that there is a significantly lower heart rate at high work levels in cold water compared to air and that the regression slopes are also different (see Fig. 5). It is possible that the peripheral vasoconstriction that occurs upon immersion in cold water (1) is maintained in 16^{o}C water even throughout the work regimen and that heart rate is depressed via baroreceptor reflex mechanisms. In this context it would appear paradoxical that resting heart rate was not significantly lower in 16^{o}C water. There was indeed, in most subjects, a bradycardia upon initial immersion in cold water, but f_h had returned to normal by the time (last 2 minutes) that the steady-state resting rate was recorded. Subjective impressions indicated that there was no cold discomfort during this period of rest as long as one remained very still. Upon initiation of exercise, however, the cold became quite apparent as the water was stirred up by leg motion. The possibility exists that, under the latter conditions, vasoconstriction became more pronounced.

A reasonable conclusion is that, under these extreme conditions, surface monitoring of diver's heart rate cannot be evaluted in surface-equivalent terms. In this experiment, at forced work levels in 16^{o}C water, such evaluation would have underestimated the work load actually imposed. At 743.3 Kg.M/min the predicted heart rate would have been 161 beats/min, whereas it was actually measured at 143 beats/min. Therefore, some caution must be urged when surface monitoring under these conditions. There was no significant decrement in ability to perform the graded work task in water compared to air, although subjective reports were that it was becoming more difficult to maintain the forced work cadence underwater at the termination of the experiment.

Studies are currently underway to determine the effects of water depths to four atmospheres absolute upon work performance at various water temperatures.

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Table 1. Mean Values for Physical Characteristics, Lung Volumes and Estimated $\dot{V}_{O_2}$ max.

	$\bar{X} \pm$ S.E.M.
Age (yrs)	32 ± 2.3
Height (cm)	172.1 ± 2.8
Weight (kg)	70.6 ± 1.7
Surf. area (m^2)	1.84 ± .05
Body fat (%)**	18.0 ± 2.3
Vital cap. (ml*)***	4753 ± 246
Resid. vol. (ml*)	1353 ± 102
max breathing cap (L/min*)	
with respirometer	224 ± 11
with SCUBA	153 ± 6
$\dot{V}_{O_2}$ max (L/min)****	2.63 ± .16

*BTPS

**Estimated by the method of Brozek _et al_. (4).

***Determined by the 3-breath method of Rahn _et al_ (10).

****Estimated by the method of Åstrand (2)

Table 2. Experimental results from exercise in air and during immersion (Means ± 1 S.E.M.).

	Air	30° H_2O	22° H_2O	16° H_2O
External Work (Kg.M/min)				
Light	188 ± 10	191 ± 11	189 ± 11	193 ± 12
Moderate	314 ± 19	315 ± 18	326 ± 22	322 ± 19
Heavy	475 ± 24	469 ± 36	466 ± 28	473 ± 34
Forced	727 ± 29	750 ± 63	711 ± 49	745 ± 58
Heart Rate (beats/min)				
Rest	84 ± 4	82 ± 6	79 ± 5	82 ± 5
Light	102 ± %	104 ± 5	100 ± 5	103 ± 4
Moderate	116 ± 6	117 ± 6	111 ± 6	113 ± 5
Heavy	136 ± 6	134 ± 6	126 ± 6	127 ± 5
Forced	157 ± 4	159 ± 5	149 ± 5	143 ± 4
Respiration Rate (breaths/min)				
Rest	9 ± 1	9 ± 1	9 ± 1	11 ± 2
Light	10 ± 2	9 ± 2	12 ± 2	13 ± 3
Moderate	12 ± 2	11 ± 2	14 ± 1	14 ± 2
Heavy	14 ± 2	13 ± 2	16 ± 1	18 ± 3
Forced	24 ± 7	22 ± 4	34 ± 6	29 ± 6
Minute Volume (L/min)				
Rest	9.6 ± 0.9	10.6 ± 0.5	15.1 ± 2.3	12.7 ± 1.0
Light	15.2 ± 1.6	19.5 ± 2.2	26.7 ± 3.5	22.6 ± 3.9
Moderate	20.8 ± 1.7	25.4 ± 3.2	35.3 ± 4.2	30.8 ± 4.3
Heavy	31.2 ± 3.9	31.3 ± 4.7	45.1 ± 4.5	42.3 ± 6.7
Forced	39.6 ± 4.0	56.7 ± 9.7	64.3 ± 6.8	54.7 ± 6.8
O_2 Consumption (L/min)				
Rest	0.36 ± .03	0.34 ± .02	0.52 ± .06	0.45 ± .04
Light	0.69 ± .05	0.86 ± .07	1.20 ± .12	1.10 ± .09
Moderate	0.97 ± .07	1.07 ± .09	1.20 ± .07	1.40 ± .12
Heavy	1.30 ± .12	1.30 ± .14	1.50 ± .15	1.60 ± .19
Forced	1.60 ± .11	2.00 ± .19	1.90 ± .15	1.80 ± .14
CO_2 Production (L/min)				
Rest	0.32 ± .02	0.31 ± .03	0.48 ± .04	0.43 ± .09
Light	0.71 ± .04	0.75 ± .04	1.07 ± .06	0.94 ± .06
Moderate	0.90 ± .03	0.98 ± .06	1.12 ± .05	1.33 ± .08
Heavy	1.30 ± .06	1.17 ± .07	1.53 ± .10	1.63 ± .08
Forced	1.60 ± .06	2.02 ± .09	1.98 ± .11	1.98 ± .08

Rectal Temperature (°C)				
Rest	37.4 ± .07	37.4 ± .10	37.6 ± .10	37.4 ± .08
Light	37.3 ± .08	37.4 ± .16	37.3 ± .16	37.3 ± .09
Moderate	37.3 ± .05	37.3 ± .12	37.0 ± .26	37.2 ± .13
Heavy	37.4 ± .08	37.3 ± .06	36.7 ± .44	37.0 ± .21
Forced	37.4 ± .04	37.3 ± .13	36.6 ± .56	36.8 ± .28

Table 3. Correlation coefficients.

	Air	30°C water	22°C water	16°C water
$\dot{V}_{O_2}$ vs. external work	+0.90	+0.90	+0.87	+0.85
$\dot{V}_{CO_2}$ vs. external work	+0.90	+0.88	+0.87	+0.86
$\dot{V}_E$ vs. external work	+0.88	+0.85	+0.84	+0.92
f_H vs. external work	+0.92	+0.82	+0.84	+0.83

Figure 1. Submersible ergometer.

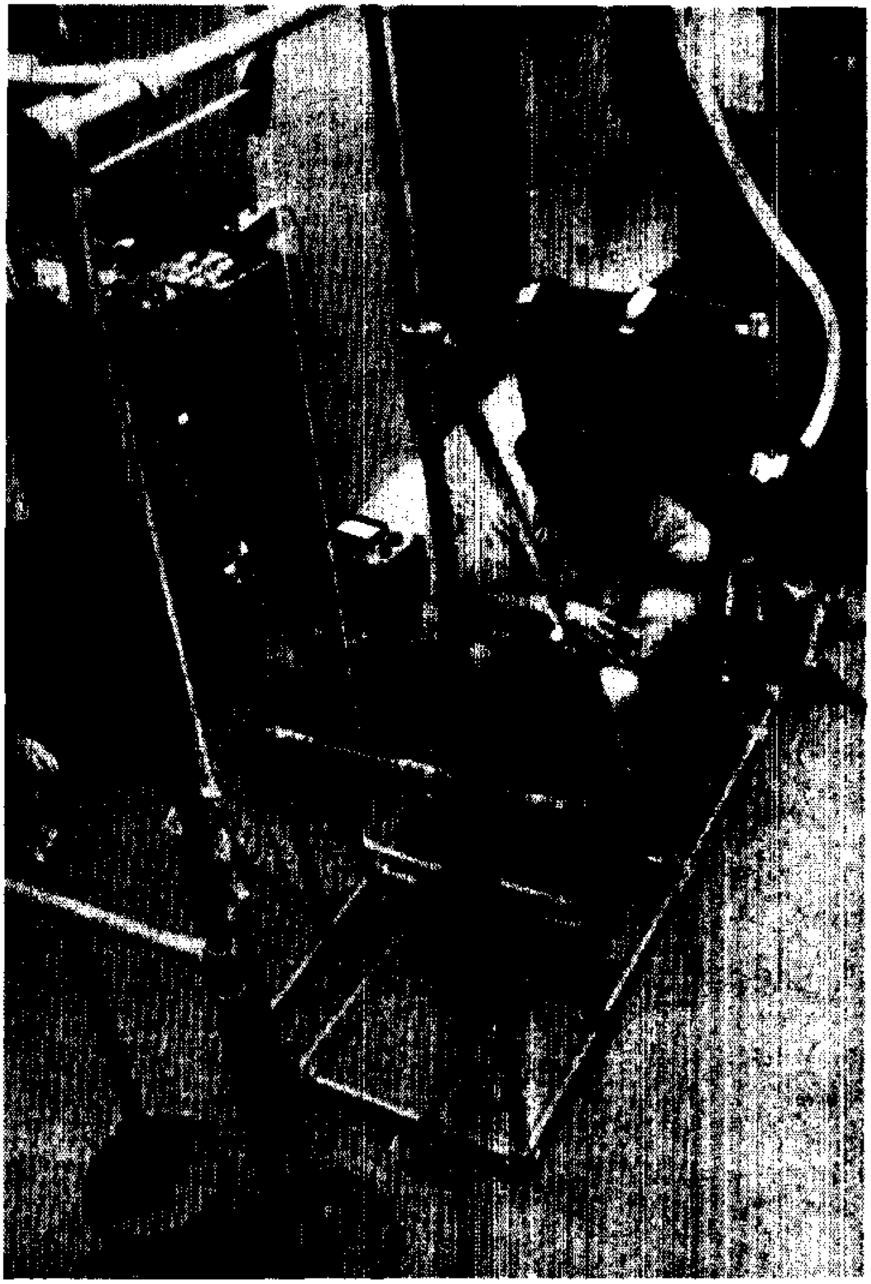


Figure 2. Experimental procedure with typical results from one subject.

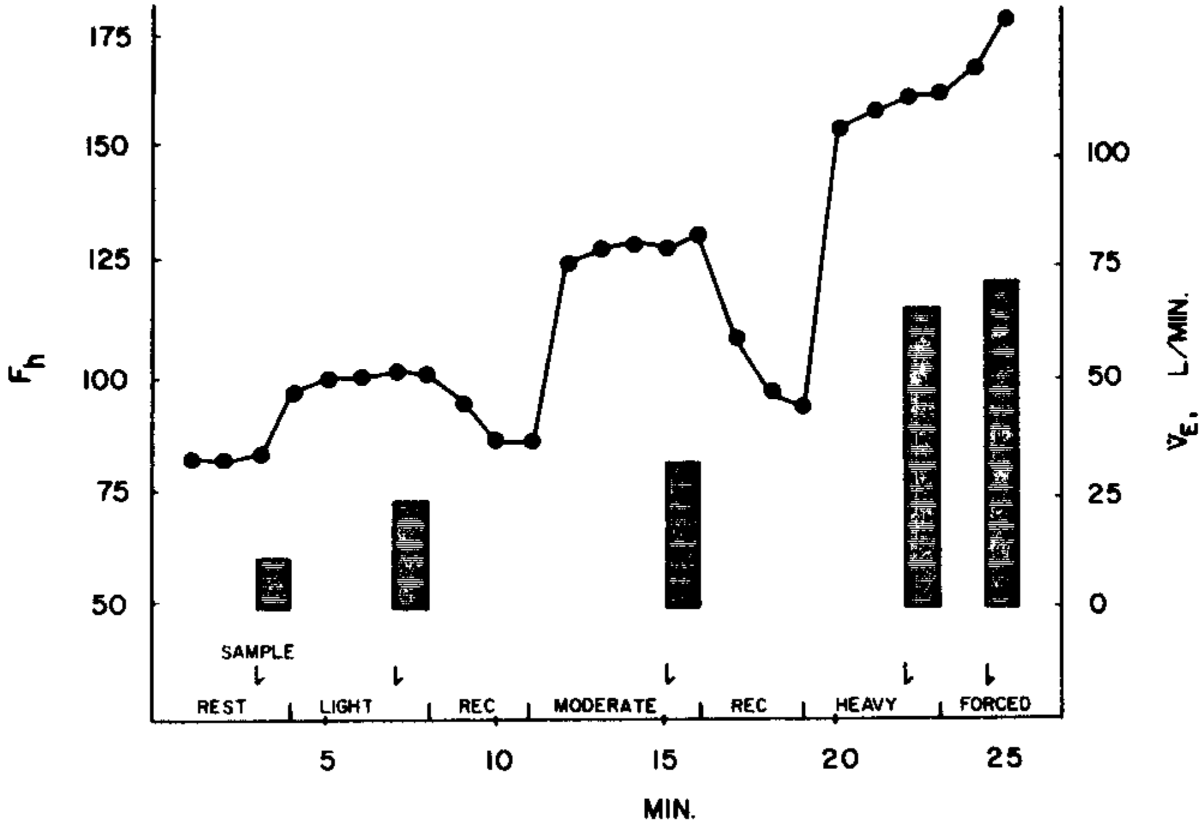

175
150
125
100
75
50
F_h
100
75
50
25
0
$\dot{V}_E$, L/MIN.
SAMPLE
REST
LIGHT
REC
MODERATE
REC
HEAVY
FORCED
5
10
15
20
25
MIN.

Figure 3. Minute ventilation versus oxygen consumption during exercise in air and submerged in 30°, 22° and $16^{\circ}C$ water.

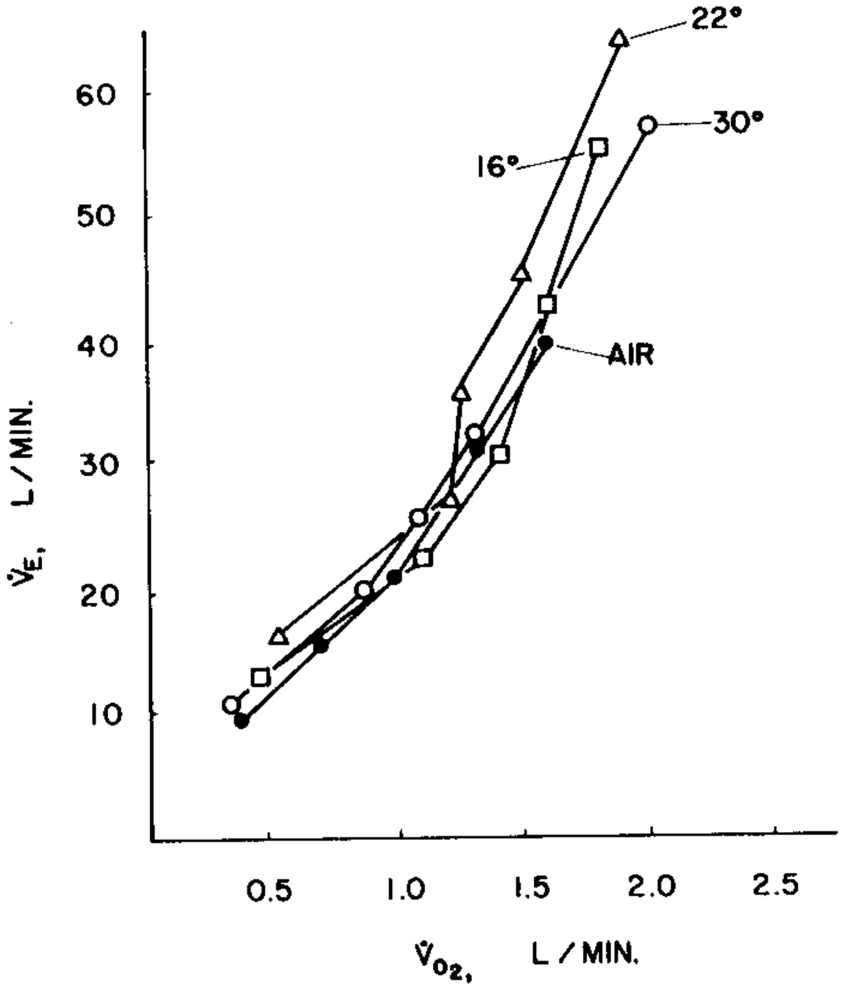

22°
30°
16°
AIR
60
50
40
30
20
10
$\dot{V}_E$, L / MIN.
0.5
1.0
1.5
2.0
2.5
$\dot{V}_{O_2}$, L / MIN.

Figure 4. Heart rate versus oxygen consumption during exercise in air and submerged in 30°, 22° and 16°C water.

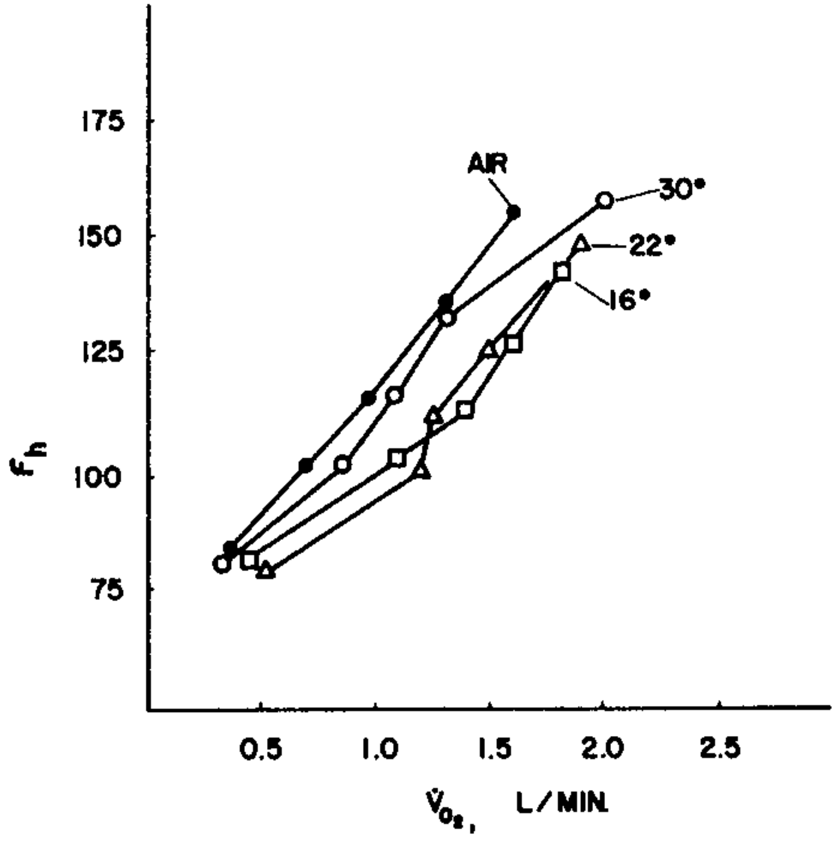
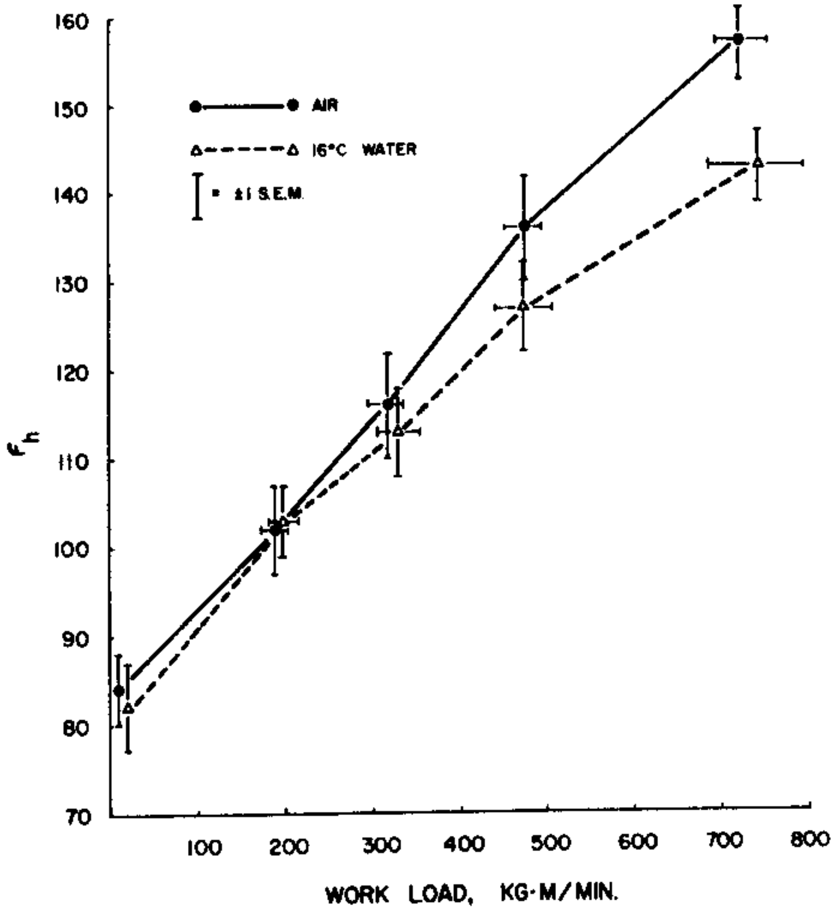

175
150
125
100
75
f_h
AIR
30°
22°
16°
0.5
1.0
1.5
2.0
2.5
$\dot{V}_{O_2}$, L/MIN.

Figure 5. Heart rate versus external work load during exercise in air and submerged in 16°C water.


160
150
140
130
120
110
100
90
80
70
f_h
AIR
16°C WATER
= ±1 S.E.M.
100
200
300
400
500
600
700
800
WORK LOAD, KG·M/MIN.

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