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EFFECT OF COLD GAS INHALATION ON CARDIAC RATE IN MAN AT DEPTH.(U)
DEC 76 E T FLYNN, J M ALEXANDER, B HOKE
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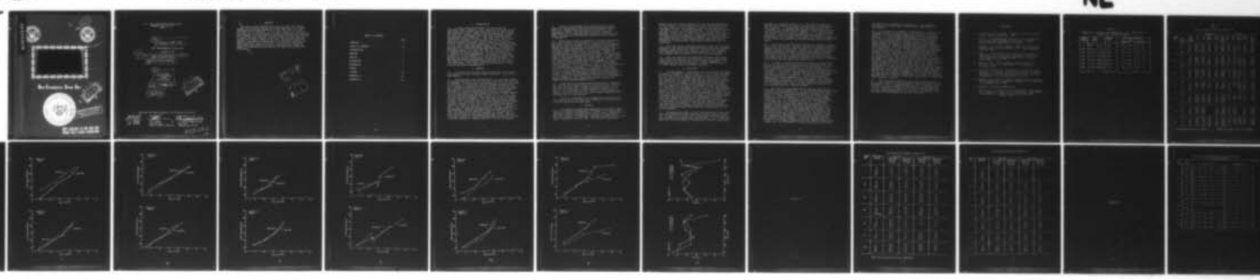

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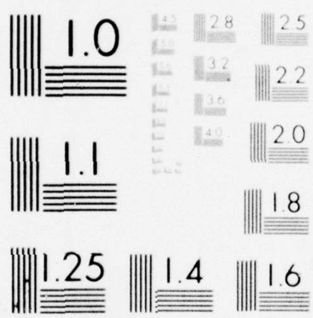

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NAVY EXPERIMENTAL DIVING UNIT

U.S. Navy Experimental Diving Unit
Panama City, Florida
32401

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NAVY EXPERIMENTAL DIVING UNIT

REPORT 13-76

(6) Effect of Cold Gas Inhalation on Cardiac Rate in Man at Depth.

(9) A Preliminary Study,

(10)
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J.M./Alexander,
B./Hoke
D.L./Jackson

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ABSTRACT

Two Navy divers breathed first warm and then cold helium-oxygen mixtures while performing graded exercise on a bicycle ergometer at simulated depths of 0, 200, 400, 600, 800, 850, and 1000 feet of seawater. In all cases, heart rate increased in proportion to the increase in oxygen consumption with exercise. When compared with warm gas control values, no consistent changes in heart rate were apparent in either subject during cold gas inhalation through a depth of 800 feet. At 850 and 1000 feet, however, both subjects demonstrated a significant reduction in exercising heart rate on cold gas. The potential mechanisms underlying these changes in cardiac rate and their impact in terms of cardiovascular performance and exercise tolerance are discussed.

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I. INTRODUCTION

1.1 In 1969, Rawlins and Tauber (7) noted that the increased thermal capacity of the inspired gas mixture during deep dives would greatly accelerate the loss of heat through the respiratory tract. Under certain circumstances of depth and work load, respiratory heat loss might actually exceed the metabolic heat production. They also noted that more intense and extensive cooling of the respiratory tract would occur during passage of the inspired gas into the lungs, possibly leading to thermal injury of the respiratory muscosa. In July, 1970 a study was undertaken at the Experimental Diving Unit to verify these theoretical predictions. Two subjects breathed 0.5-7.1°C helium-oxygen mixtures during exercise at successive depths of 0, 200, 400, 600, 800, 850 and 1000 feet of seawater during the course of a 28 day saturation dive. In addition to other measurements, the results of which are reported in detail elsewhere (4), the precordial electrocardiagram was recorded continuously during each exposure. This was done following the suggestion by Raymond (8) that the development of intrathoracic hypothermia might alter cardiac rate and rhythm. This report describes the results of these electrocardiographic measurements.

2. METHODS

2.1 A 28 year old U.S. Navy First Class diver and a 36 year old Royal Navy diving officer served as subjects. Both were in good health.

2.2 The experiments were performed in a dry pressure chamber at simulated depths of 0, 200, 400, 600, 800, 850, and 1000 feet of seawater. At each depth, the experimental protocol consisted of an initial 15 minute rest period, followed successively by two 7 minute work periods at 30 and 60 watts and two six minute work periods at 90 and 120 watts on a Monark bicycle ergometer. The exercise sequence was performed first with the subject breathing a mixture of helium-oxygen at ambient chamber temperature and then breathing the same mixture at 0.5 - 7.1°C. The gas mixtures were prepared automatically by an Airco Mixmaster located outside the chamber. The gases were cooled by passage through a 200 foot double coil of high pressure copper tubing immersed in an ice/brine slurry and then supplied to the subject through a battery of four Voit Titan II second stage demand regulators linked in parallel to a Collins Double J respiratory valve. For the warm gas control studies, the heat exchanger was bypassed. Inspired gas temperature was measured with a YSI model 520 rapid acting thermistor placed in the respiratory valve and oriented to face the incoming gas stream. The gas mixtures and inspired gas temperatures used at each depth are contained in Table 1. The gas mixtures were selected to provide a partial pressure of oxygen close to 0.3 Ata at all depths.

2.3 Pressure fluctuations within the respiratory valve during the respiratory cycle were recorded continuously by means of a Statham model 38ID pressure transducer. Peak inspiratory negative and expiratory positive pressures encountered by the subjects under the various conditions of depth, workload, and inspired gas temperature are contained in Appendix A.

2.4 Mixed expired gas was collected in Douglas bags during the final 5 minutes of the initial 15 minute rest period, during the final two minutes of the seven minute work periods and during the final minute of the six minute work periods. Samples of mixed expired gas for analysis were drawn into 100 cc glass syringes sealed with 3 way plastic stopcocks and lubricated with a film of dilute lactic acid. Samples of inspired gas for analysis were obtained from the high pressure supply line using similarly prepared syringes. At depth, both samples were passed through the chamber wall via needle valves and were analyzed for oxygen and carbon dioxide content outside the chamber using a Beckman model F-3 paramagnetic oxygen analyzer and a Beckman model LB-1 or IR 315 infrared carbon dioxide analyzer. At the surface gas samples were analyzed using the microschloander technique. The volume of expired gas remaining in the Douglas Bag after sampling was measured in a 120 liter Tissot gasometer and corrected for syringe sample volume. At depth, an empirically derived correction factor was applied to the observed spirometer temperature to compensate for the effect of increased pressure on the alcohol thermometer. Oxygen consumption ($\dot{V}_{O_2}$) during each exercise period was computed using standard equations (6).

2.5 Heart rate was recorded continuously from the output of two metal disc electrodes placed on the precordium. Reported rates are the mean values observed during the course of the expired gas collections. Linear regression equations were fitted to the relationship between heart rate and oxygen consumption during exercise at each depth and gas temperature using the technique of least squares.

2.6 Core body temperature was recorded continuously during each exposure with a YSI model 401 thermistor inserted into the rectum 10 cm beyond the anal verge.

3. RESULTS

3.1 The results of these measurements are contained in Tables 2 and 3 and depicted graphically in Figures 1-7. Least square regression equations relating heart rate to oxygen consumption at each depth and gas temperature are contained in Appendix B. Under each condition, heart rate increased linearly with increasing oxygen consumption (r=0.96-0.99). The observed differences between warm and cold gas breathing at the various depths were: (1) an increase in heart rate at all levels of exertion during cold gas inhalation in one subject (J.M.) at 200 feet and (2) a decrease in heart rate during exertion in both subjects during cold gas inhalation at 850 and 1000 feet. At 1000 feet, the decrease in heart rate in subject J.M. was apparent only during the heavier levels of exertion. Examination of these results for statistical significance by an analysis of variance was not undertaken because of the limited subject population and the variability of experimental conditions as outlined below (C_f discussion).

3.2 The slope of the regression relating heart rate to oxygen consumption was essentially unchanged during cold gas inhalation through a depth of 850 feet (Fig. 8). At 1000 feet, however, both subjects demonstrated a marked reduction in the slope of this response during inhalation of the cold helium-oxygen.

3.3. With the exception of occasional premature ventricular contractions at rest and light exercise, no ventricular arrhy-thmias were noted during the course of these experiments. The tracings were not detailed enough to ascertain whether atrial or nodal rhythms without aberration occurred.

4. DISCUSSION

4.1 The development of bradycardia during hyperbaric exposures in certain individuals is well known (9). Thus it was anticipa-ted that the change in ambient pressure and gas density as well as the lowering of gas temperature would influence heart rate. The intention of the original experimental design was to analyze the results both in terms of depth and gas temperature factors. However, during the conduct of the experiments it was found that the PI_{O_2} could not be held absolutely constant throughout all the depths with automatic gas mixing, and that the inspira-tory resistance of the demand value varied greatly between depths, increasing to very high values at 800 - 1000 feet. Since the effect of these variables on the depth dependent changes in heart rate could not be acertained, the overall influence depth was not considered and the analysis of gas temperature effects was con-fined to a comparison of warm and cold responses at each individual depth. At each depth, both the PI_{O_2} and the degree of inspiratory resistance were essentially identical for both warm and cold gas exposures. This type of analysis had the important advantage of comparing cold gas values with warm gas controls obtained several hours earlier on the same day of the 28 day exposure.

4.2 No appreciable effect of cold gas breathing on heart rate could be discerned through a depth of 600 feet, with the excep-tion of subject J.M. at 200 feet, whose heart rate was greater than control values during cold gas inhalation. It is known that emotional factors produce an acceleration of cardiac rate which persists into moderate exercise (1). The 200 foot exposure was the first time either subject breathed the cold gas mixture under pressure. It is possible that the greater heart rate in subject J.M. represented some degree of apprehension concerning the outcome of this initial exposure. It is unlikely that his change in cardiac rate was indicative of an effect of cold gas per se, since a similar response was not observed in the other subject at that depth or in subject J.M. himself subsequently at 400 or 600 feet despite the greater thermal stress at those depths.

4.3 At 800 feet, the data obtained were too limited to allow one to draw conclusions. Subject J.M. did not attempt a workload greater than 60 watts on cold gas because of excessively high external breathing resistance. Subject T.G. aborted the 90 watt workload prematurely because of airway obstruction by copious respiratory secretions. His struggling to continue exercise long enough to permit an adequate expired gas collection left some doubt about the validity of the heart rate/oxygen consumption relationship obtained during this work load.

4.4 At depths of 850 and 1000 feet a decrease in heart rate during cold gas inhalation was observed in both subjects. The pattern of response was different at the two depths. At 850 feet, bradycardia was apparent at all levels of exertion, but the slope of the cardiac rate response to exercise was essentially unchanged. At 1000 feet, relative bradycardia was present at all levels of exertion in subject T.G. but only at the higher levels of exertion in subject J.M. Both subjects however demonstrated a marked depression of the slope of the cardiac rate response to exercise. It would thus appear that cold gas inhalation was associated with a dual response, one associated with the absolute heart rate, the other with the sensitivity of the pacing system to increased demand.

4.5 The source of the bradycardia at 850 and 1000 feet is presumably cardiac hypothermia. In the isolated heart preparation, a decrease in temperature of the perfusing solution has been shown to produce a pronounced decrease in the cardiac rate (5). Similarly a linear decrease in heart rate with falling body temperature has been observed in intact dogs during induced hypothermia (2). In the present series of experiments cooling of the heart may have occurred in two ways: (1) through a generalized fall in core body temperature secondary to the negative thermal balance induced by cold gas breathing or (2) through the development of localized hypothermia within the thorax due to a failure of the nasopharynx to adequately warm the inspired gas. The first mechanism does not appear to be supported by the data (Tables 3-4). Rectal temperatures were not consistently lower than warm gas control values at times when bradycardia was manifest. Intense localized cooling of the thoracic viscera, however, is strongly suggested by the sensation of discomfort experienced by the subjects deep in the epigastrium, the development of copious respiratory secretions, and the fall in expiratory flow rates (4). An esophageal thermistor probe would have allowed better quantitation of this effect.

4.6 If bradycardia at depth is accompanied by a conpensatory increase in cardiac stroke volume, the slowing of the heart would be of little practical importance in terms of exercise capacity. If, on the other hand, bradycardia is accompanied by a fall in cardiac output, tissue oxygen consumption would have to be maintained by an increase in the arterio-venous oxygen content difference. In this situation, the maximum oxygen uptake, and therefore maximum work capacity of the diver would be reduced. There is indirect evidence which suggests that compensation for a cold induced bradycardia by an increase in stroke volume may occur. In the isolated heart preparation perfused with cold solutions and regulated to the same end-diastolic volume, bradycardia is accompanied by a decrease in systolic volume and an increase in stroke volume (5). In the hypothermic dog, both cardiac output and oxygen consumption decreased in cooling, but the relative changes in these two variables were approximately the same, so that the arterio-venous oxygen difference did not change appreciably (3). While this latter situation is not strictly analogous to the relative performance of a warm and cold heart at the same level of oxygen consumption, it is suggestive that the cardiac output may remain appropriate to the level of metabolic demand, despite cardiac cooling. From a practical standpoint, it is clear that both of our subjects were capable of completing six minutes of very hard exercise ($\dot{V}_{O_2}$ = 2.6 and 2.9 L/min STPD respectively) at 1000 feet while breathing cold gas.

4.7 The conclusions reached in this report are tentative as they are based on results obtained in two subjects in a pilot experiment. They are presented here in order to attract attention to a potential problem in deep diving. Further study in a larger population is indicated to confirm the existance of a cold gas induced bradycardia, to elucidate its mechanism, and to determine its significance in exercise tolerance.

REFERENCES

1. Astrand, P.O. and K. Rodahl. Textbook of Work Physiology. p. 167, McGraw - Hill, Inc., 1970.

2. D'Amato, H. Cardiovascular Functions in Deep Hypothermia. In the Physiology of Induced Hypothermia. NAS/NRC Publication 451, Washington, D.C., 1956.

3. Hegnauer, A.H. and H.E. D'Amato. Oxygen Consumption and cardiac output in the hypothermic dog. Am. J. Physiol. 178: 138, 1954.

4. Hoke, B., J.M. Alexander, E.T. Flynn, and D. Jackson. Respiratory heat loss during deep helium-oxygen diving. Fifth symposium on underwater physiology. Freeport, Grand Bahama Island, 1972.

5. Marshall, J.M. Cardiac output in Medical Physiology, Eleventh Edition, P. Bard, Editor. C.V. Mosby Co., St. Louis, 1961.

6. Otis, A.B. Quantitative relationship in steady state gas exchange. In Handbook of Physiology, Section 3, Volume 1, Respiration. W.O. Fenn and H. Rahn, editors. American Physiological Society, Washington, D.C. 1964.

7. Rawlins, J.S.P. and J.F. Tauber. Thermal balance at depth. Fourth Symposium on Underwater Physiology. C.J. Lambertsen, ed. Academic Press, 1971.

8. Raymond L. Personal Communication.

9. Salzano, J., D.C. Rausch, and H.A. Saltzman, Cardiorespiratory response to exercise at a simulated sea water depth of 1,000 feet. J. Appl. Physiol. 28: 34-41, 1970.

Table 1

Composition, Density, and Temperature of the Inspired Gas Mixture at the Various Depths

Depth (Feet)	Gas Mixture	Density g/l	Inspired Gas Temperature (°C)	
			Warm Gas	Cold Gas
0	28% O_2 72% He	0.48	25.0 - 31.4	0.6 - 4.4
200	4.3% O_2 95.7% He	1.47	23.7 - 29.3	0.8 - 4.3
400	2.3% O_2 97.7% He	2.43	19.2 - 27.8	0.5 - 1.3
600	1.6% O_2 98.4% He	3.38	27.2 - 30.7	0.8 - 1.6
800	1.2% O_2 98.8% He	4.34	23.7 - 29.6	0.5 - 3.9
850	1.1% O_2 98.9% He	4.58	23.0 - 30.1	4.6 - 5.1
1000	1.1% O_2 98.9% He	5.33	30.3 - 32.3	4.9 - 7.1

Table 2

Cardiac Response to Exercise in Subject J.M.

Depth (Ft)	$P_{I_{O_2}}$ (mm Hg)	Work Load (Watts)	Warm Gas T_I (°C)	Warm Gas T_R (°C)	Warm Gas $\dot{H}_R$ (Watts)	Warm Gas Heart Rate	Warm Gas $\dot{V}_{O_2}$ L/min STPD	Cold Gas T_I (°C)	Cold Gas T_R (°C)	Cold Gas $\dot{H}_R$ (Watts)	Cold Gas Heart Rate	Cold Gas $\dot{V}_{O_2}$ L/min STPD
	201	0	25.0	37.2	27	82	.536	4.4	–	21	84	.454
		30	28.0	37.3	43	112	1.087	3.4	37.6	36	103	.998
0	To	60	29.6	37.3	68	131	1.755	2.9	37.6	54	127	1.435
		90	30.2	38.2	91	152	2.024	1.6	38.0	70	133	1.703
	204	120	30.9	37.8	150	172	2.770	0.6	38.0	79	144	1.834
	227	0	24.9	36.7	34	62	.428	3.1	37.2	54	83	.413
		30	28.1	36.7	61	86	1.051	1.6	37.2	114	97	.940
200	To	60	28.5	36.8	68	100	1.327	1.2	37.2	139	104	1.173
		90	28.9	36.9	105	120	2.033	0.8	37.2	154	121	1.663
	228	120	29.3	37.2	141	144	2.468	0.8	37.2	182	144	2.289
	227	0	20.3	37.0	46	73	.392	1.3	37.0	82	65	.391
		30	24.8	36.8	83	92	1.052	1.3	36.8	157	91	1.096
400	TO	60	25.8	36.8	105	105	1.486	1.3	36.8	196	99	1.339
		90	27.3	37.0	151	124	2.024	1.3	36.8	295	119	1.979
	229	120	27.8	37.5	154	139	2.502	1.3	37.0	416	139	2.599
	229	0	27.2	36.8	66	71	.455	1.6	37.0	143	80	.520
		30	28.7	36.8	97	84	.876	1.4	36.8	283	90	1.178
600	TO	60	28.7	36.8	150	94	1.342	1.2	36.7	278	98	1.219
		90	29.1	36.8	193	118	1.680	1.2	–	376	114	1.615
	234	105	–	–	–	–	–	1.0	–	447	122	1.828
	233	0	25.6	37.2	64	73	.415	0.9	36.7	115	77	.326
		30	27.8	37.2	147	85	1.409	0.5	36.5	297	90	1.043
800	TO	60	28.5	37.2	162	98	1.399	0.7	35.9	359	96	1.317
		90	28.9	37.3	182	113	1.531	–	–	–	–	– **
	238	120	29.6	37.3	248	139	2.161	–	–	–	–	–
	227	0	24.6	36.3		76	.375	5.1	36.0		59	.408
850	TO	30	27.9	36.4		96	1.149	4.6	36.0		85	1.005
		60	29.5	36.5		117	1.589	4.6	36.0		103	1.698
	238	90	30.1	36.6		133	1.926	4.6	36.0		123	2.060
	255	0	30.3	35.6	44	66	.385	6.2	36.2	154	73	.465
		30	31.2	35.6	112	93	1.041	4.9	36.1	391	100	1.310
1000	TO	60	31.9	35.7	153	116	1.720	5.5	36.0	488	107	1.624
		90	31.9	35.9	197	146	2.032	5.5	35.9	778	126	2.641
	258	120	32.3	36.0	296	151	3.102*	–	–	–	–	–

*Aborted prematurely due to dyspnea

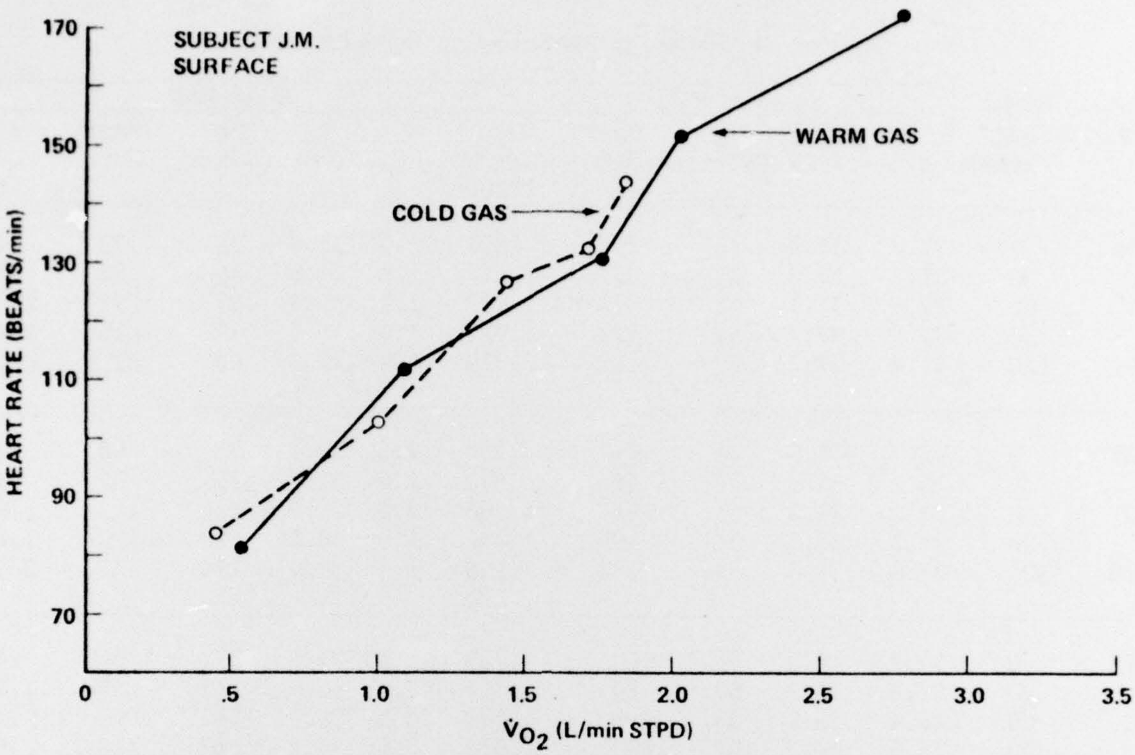
**Remaining exercise levels not attempted

Table 3

Cardiac Response to Exercise in Subject T.G.

Depth (Ft)	PI_{O_2} (mmHg)	Work Load (Watts)	Warm Gas T_I (°C)	T_R (°C)	$\dot{H}_R$ (Watts)	Heart Rate	$\dot{V}O_2$ L/min STPD	Cold Gas T_I (°C)	T_R (°C)	$\dot{H}_R$ (Watts)	Heart Rate	$\dot{V}O_2$ L/min STPD
	191	0	31.2	37.0	22	79	.450	2.3	35.8	35	77	.484
		30	31.2	37.0	31	86	1.119	1.6	36.6	46	86	1.351
0	TO	60	29.8	37.0	42	99	1.677	1.1	36.6	50	97	1.444
		90	30.7	37.2	54	122	1.911	1.0	36.6	68	116	1.904
	201	120	31.4	37.2	67	142	2.320	0.9	36.7	83	130	2.105
	225	0	23.7	36.5	24	64	.354	4.3	36.7	33	68	.366
		30	26.2	36.5	39	78	.823	2.6	36.7	71	87	.961
200	TO	60	27.3	36.5	51	94	1.266	2.6	36.7	111	103	1.645
		90	28.5	36.5	91	105	1.636	1.9	36.7	126	120	1.841
	228	120	28.9	36.6	89	132	2.155	1.8	36.9	174	143	2.333
	228	0	19.2	36.3	31	60	.285	1.3	36.5	57	66	.490
		30	22.3	36.3	60	80	.764	0.9	36.5	112	85	1.025
400	TO	60	24.4	36.2	59	88	1.099	0.5	36.4	148	98	1.347
		90	25.3	36.3	92	100	1.512	0.5	36.4	182	116	1.695
	230	120	26.1	36.4	113	119	1.971	0.5	36.5	237	128	2.198
	232	0	28.9	37.1	40	78	.461	0.8	37.0	110	76	.459
		30	28.9	37.0	59	83	.804	0.8	36.8	134	82	.710
600	TO	90	30.2	37.0	71	95	1.168	0.8	36.7	188	89	1.029
		90	30.7	36.9	117	114	1.669	1.2	36.7	283	105	1.520
	235	120	30.4	37.1	154	139	2.053	1.2	36.7	328	129	1.985
	232	0	23.7	36.8	54	67	.341	3.0	36.0	132	69	.475
		30	26.3	36.5	139	80	1.270	3.9	35.9	248	83	1.147
800	TO	60	28.1	36.5	114	88	1.223	3.3	35.9	249	100	1.109
		90	28.8	36.6	154	104	1.704	2.7	35.8	613	135	2.774*
	241	120	29.5	36.7	182	120	2.120	-	-	-	-	-
	228	0	23.0	35.8	59	71	.295	5.0	36.2	122	71	.463
	TO	30	25.4	35.8	131	94	1.074	5.0	36.0	291	93	1.362
850		60	27.9	35.9	206	117	1.806	5.0	36.0	339	110	1.700
	235	90	29.4	35.9	237	143	2.101	5.0	36.0	450	131	2.084
	254	0	30.6	36.2	51	81	.422	7.1	35.8	132	75	.414
		30	31.3	36.1	75	95	1.002	6.1	35.7	288	94	1.169
1000	TO	60	31.7	36.1	112	121	1.549	6.9	35.6	332	105	1.466
	256	90	32.1	36.2	160	145	2.106	6.3	35.5	681	121	2.902

*Aborted prematurely due to dyspnea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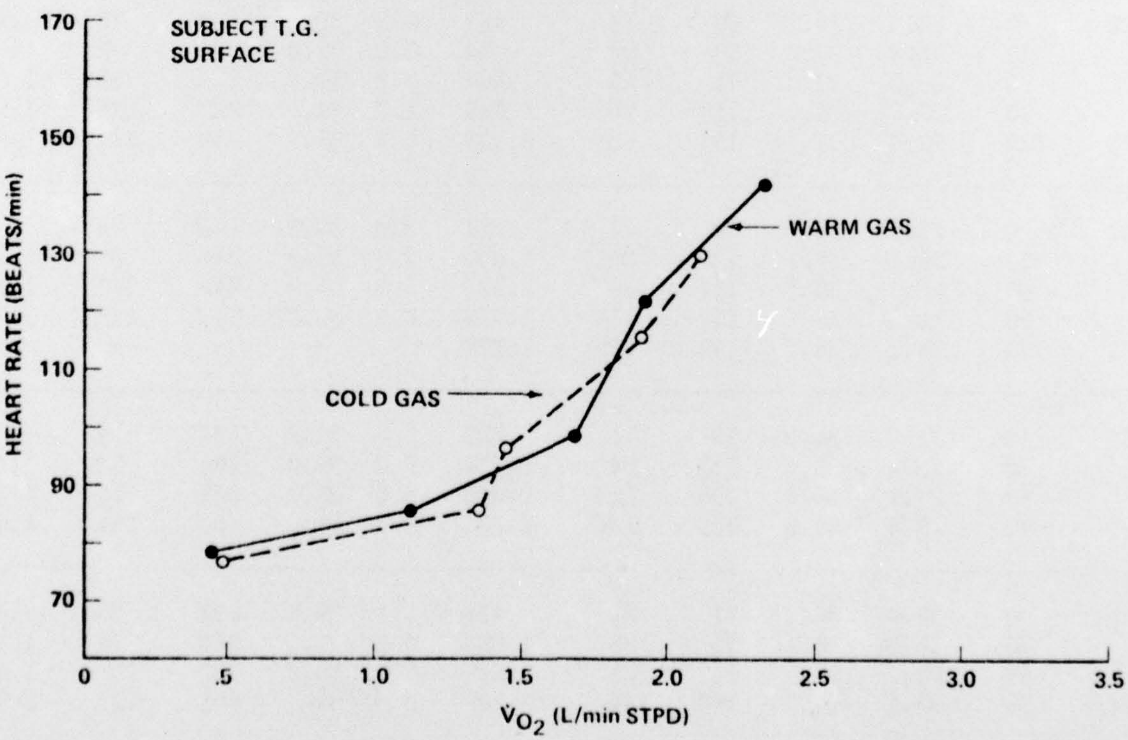
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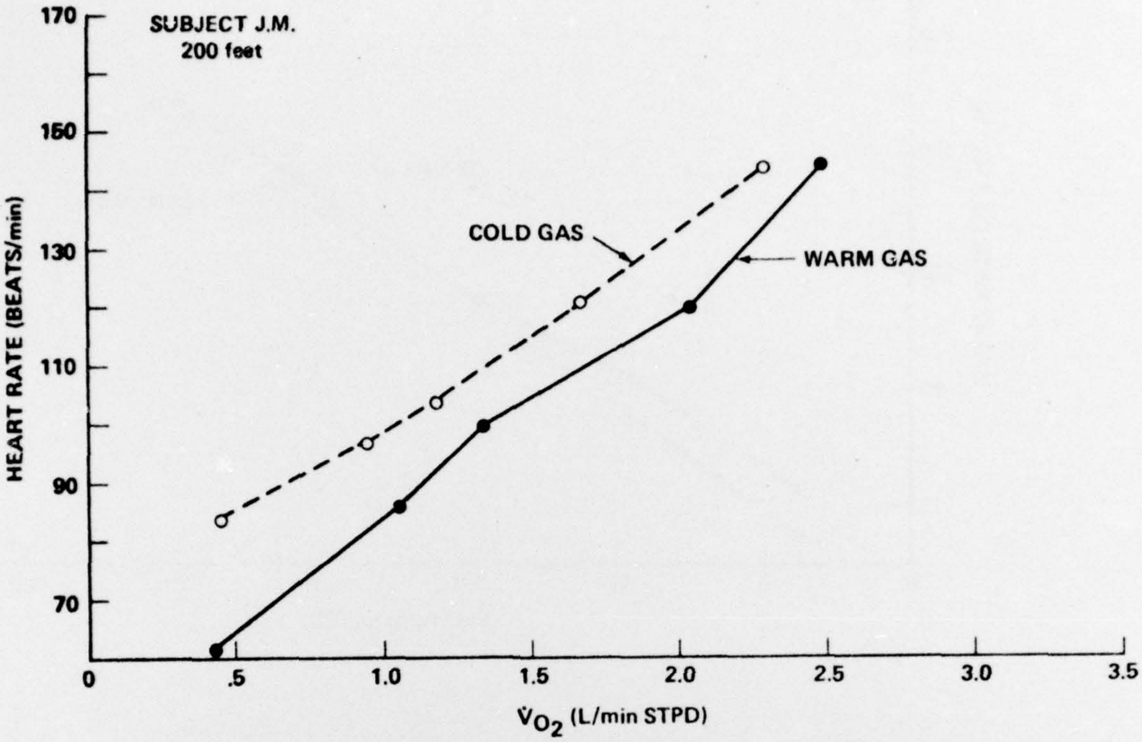
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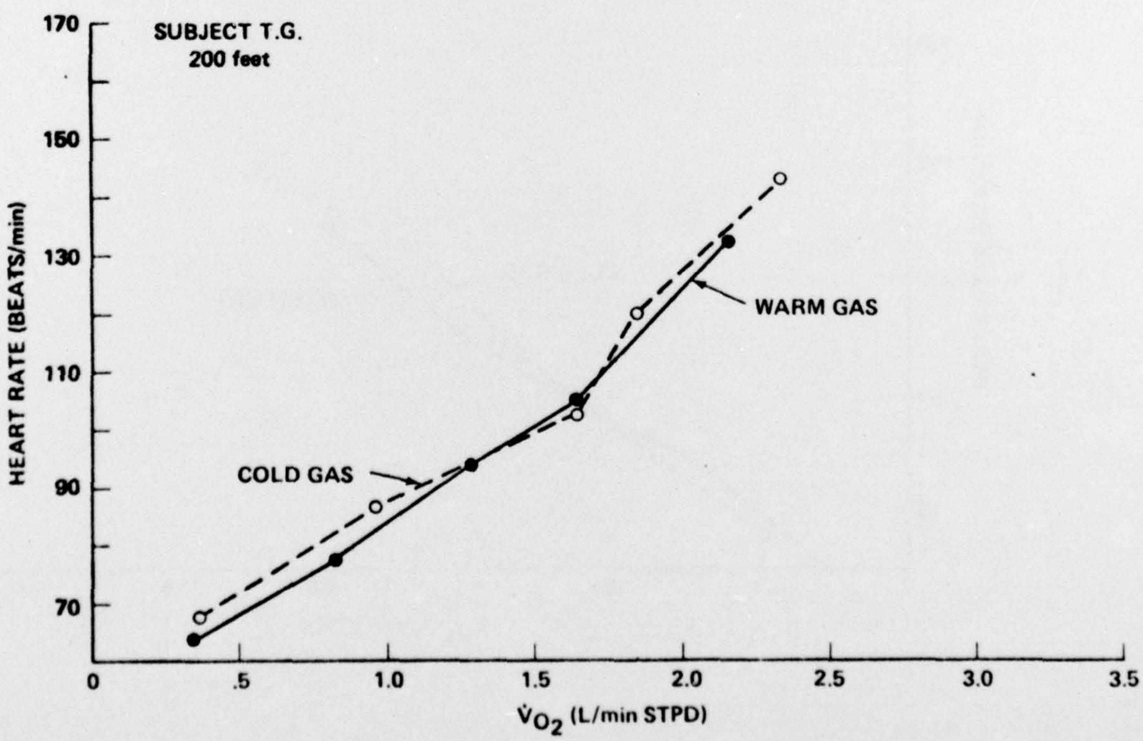
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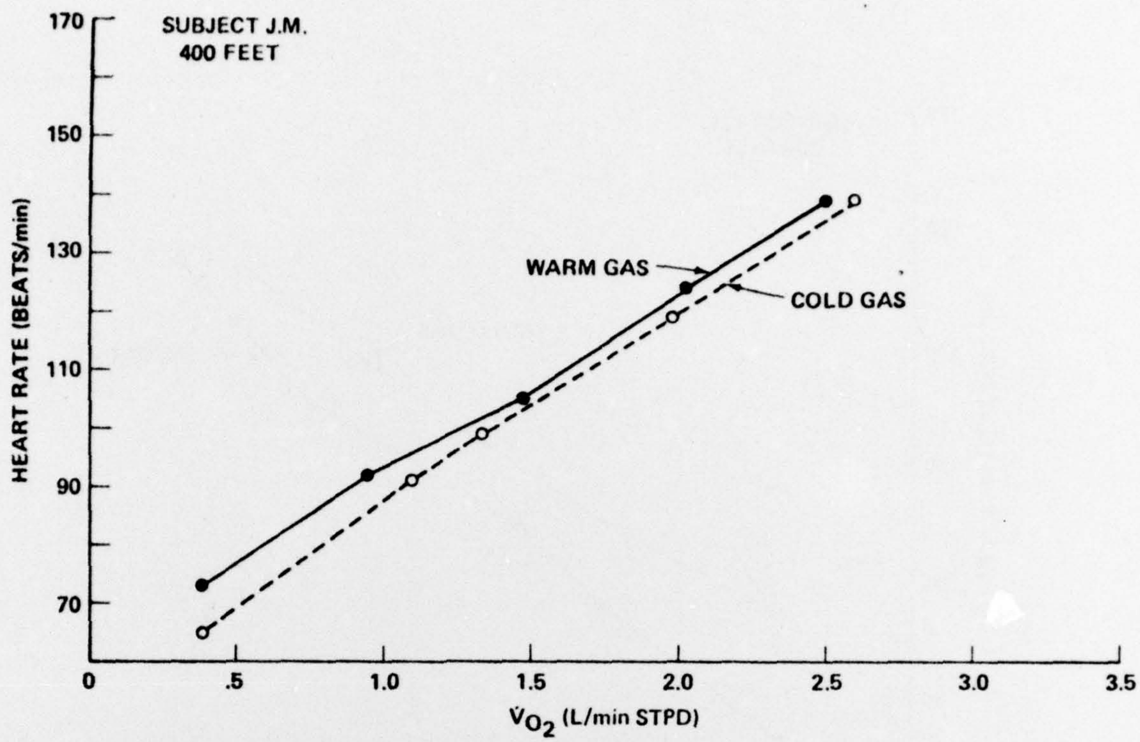
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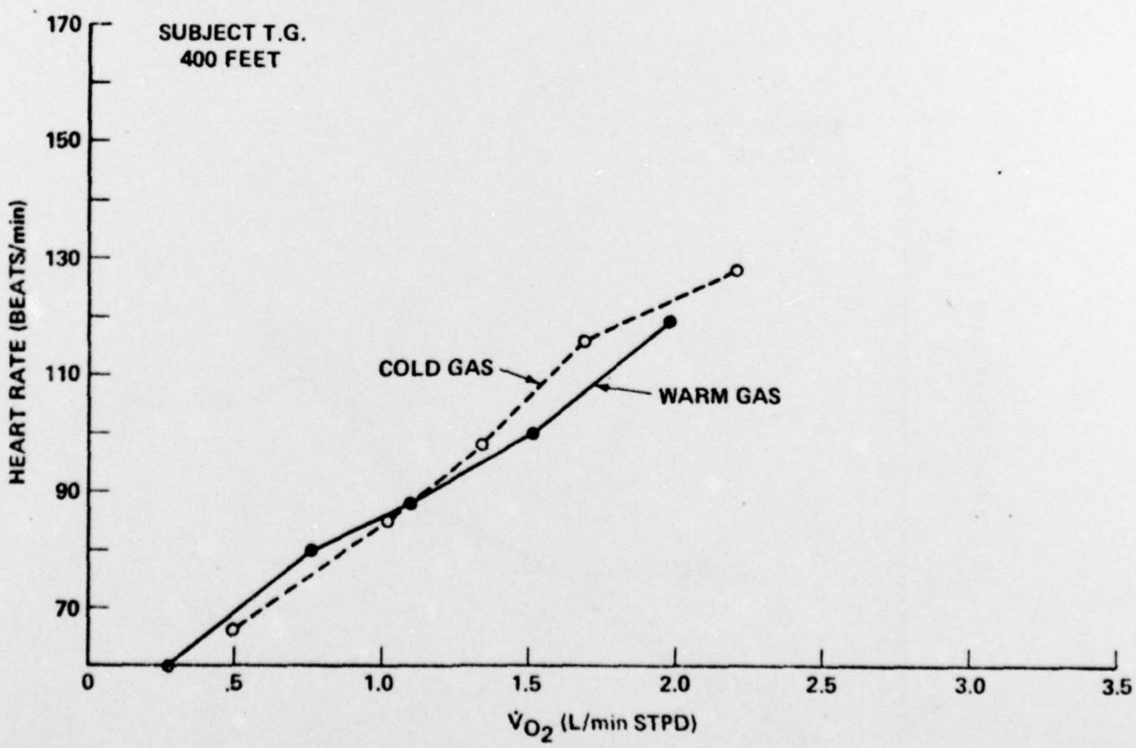
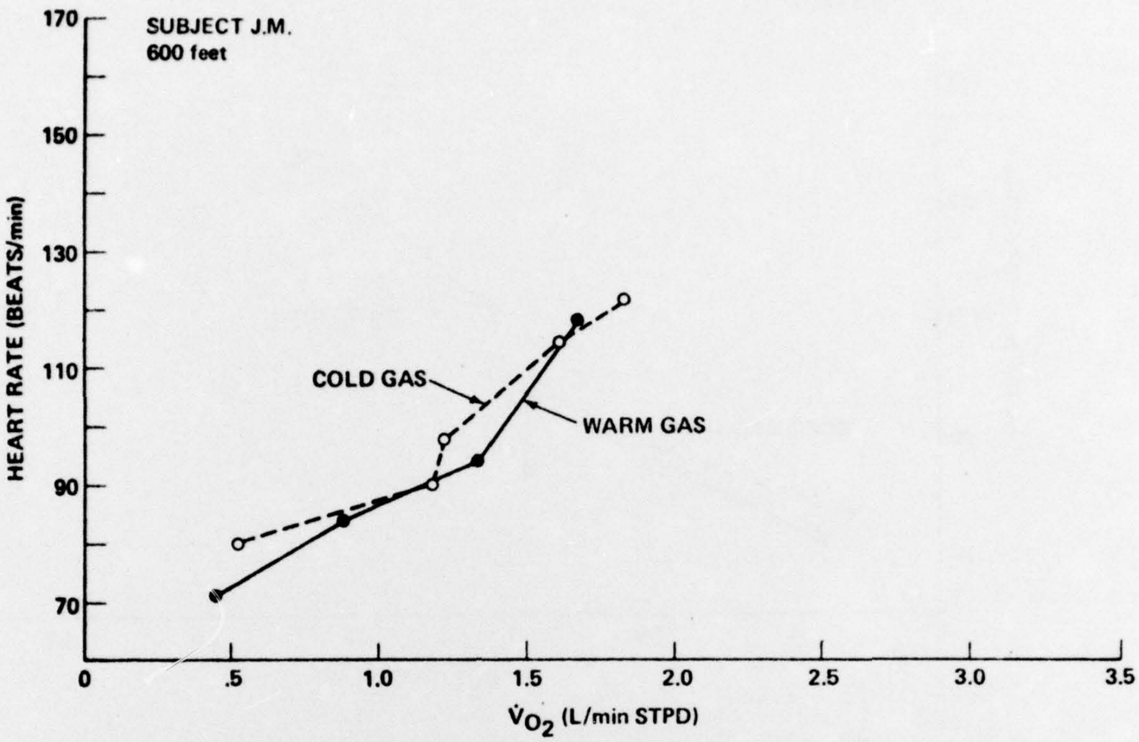
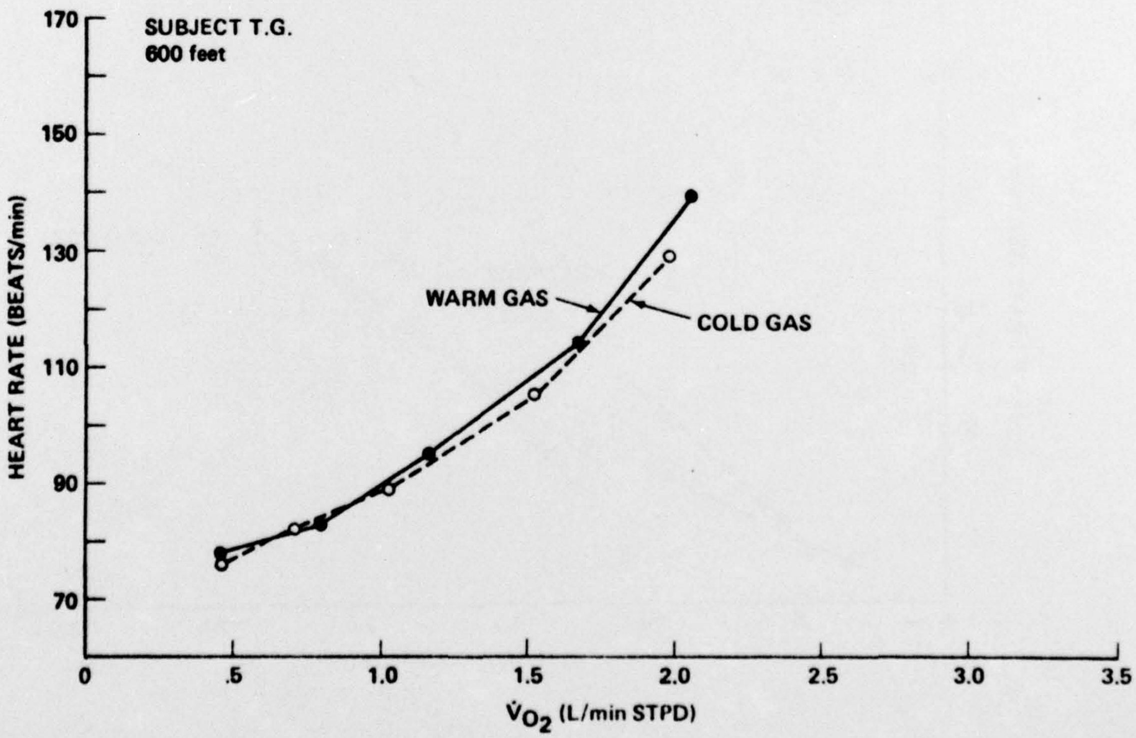
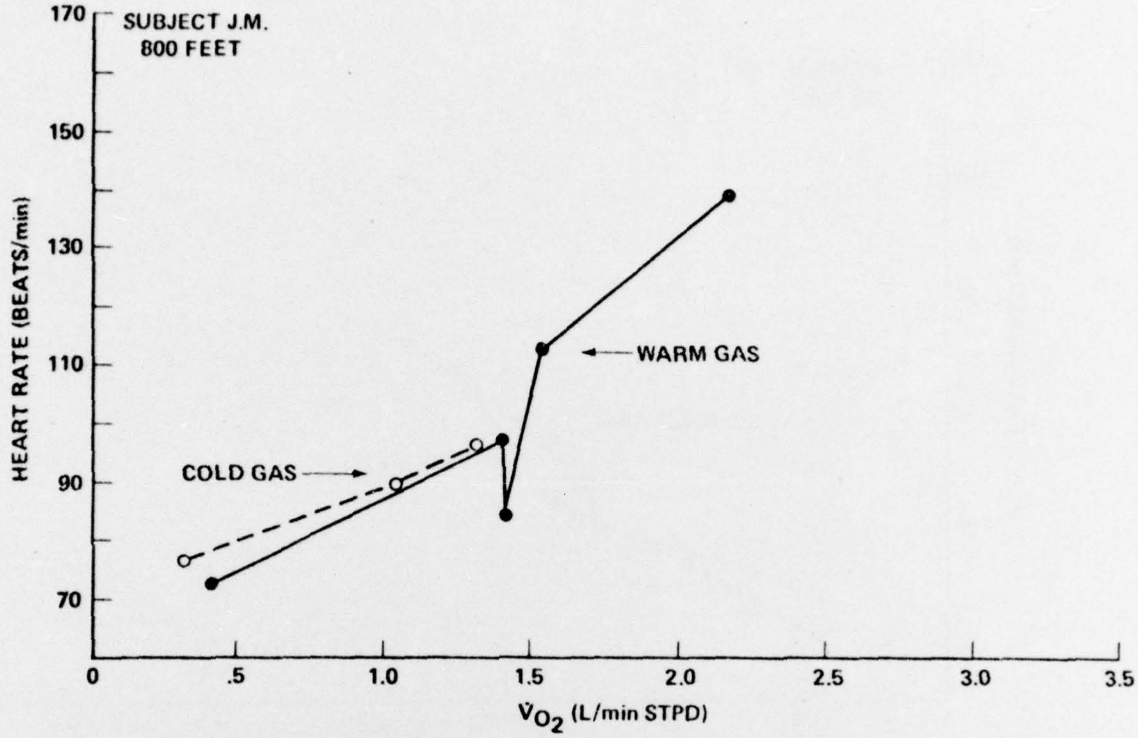
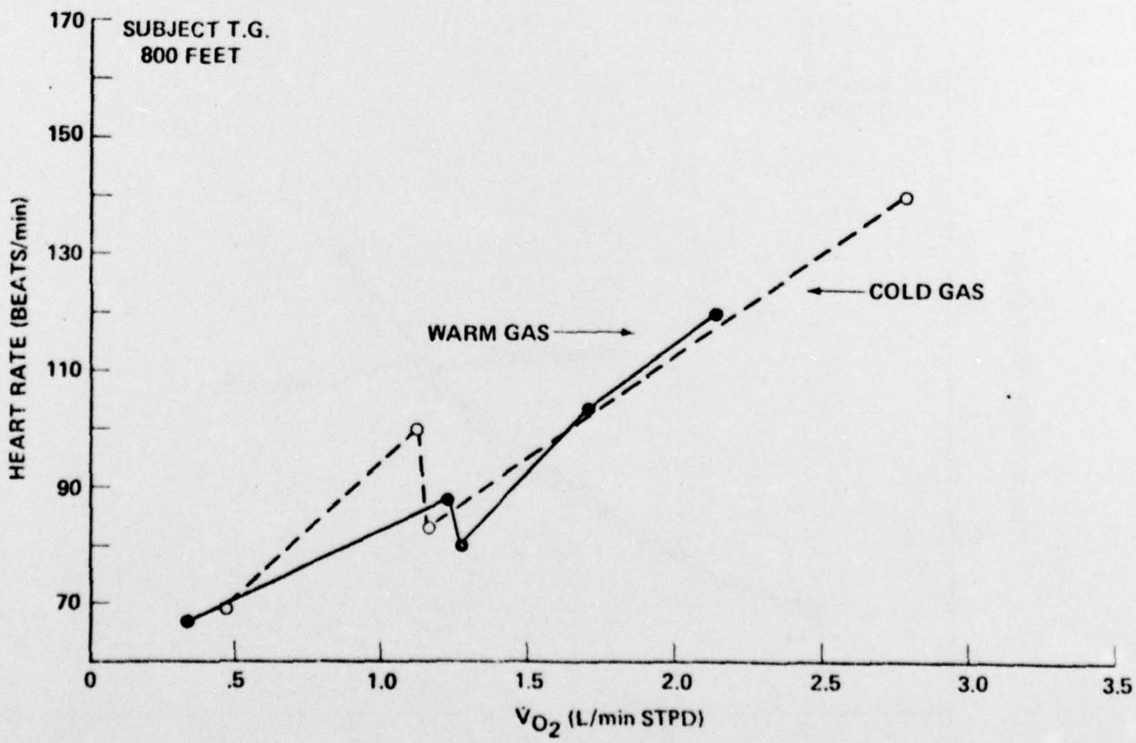
3.5
V̇O2 (L/min STPD)

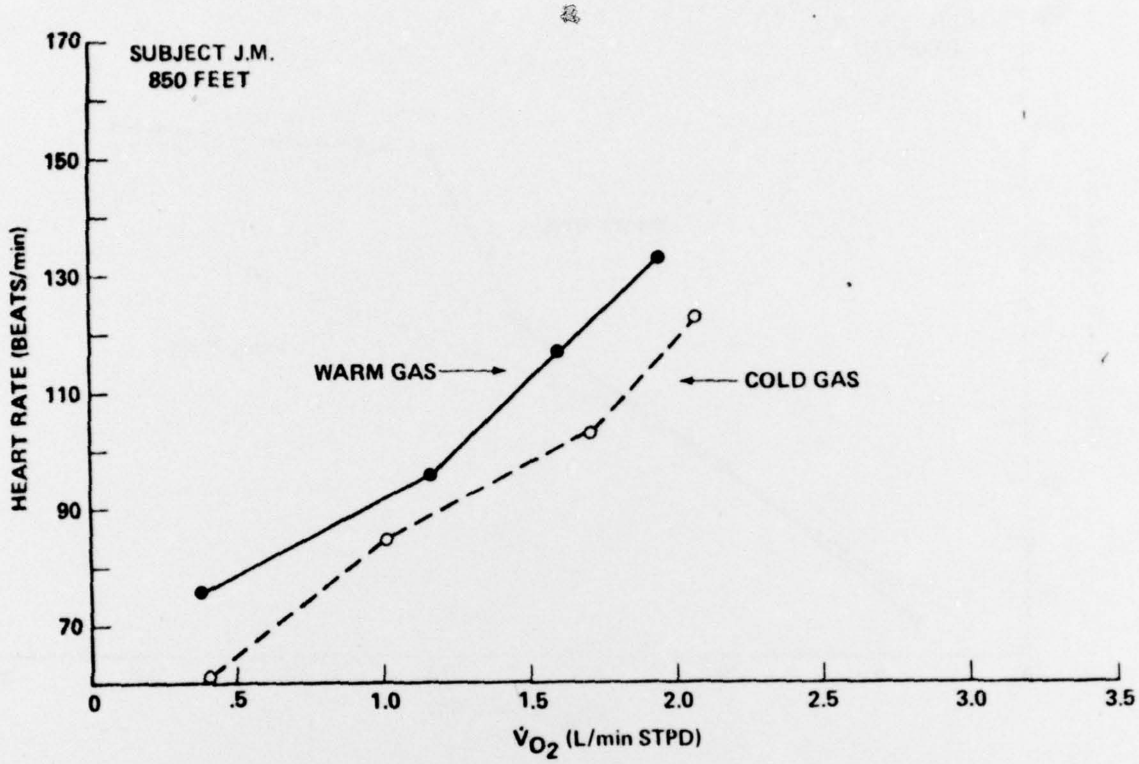

SUBJECT T.G.
400 FEET
170
150
130
110
90
70
HEART RATE (BEATS/min)
COLD GAS
WARM GAS
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
V̇O2 (L/min STPD)

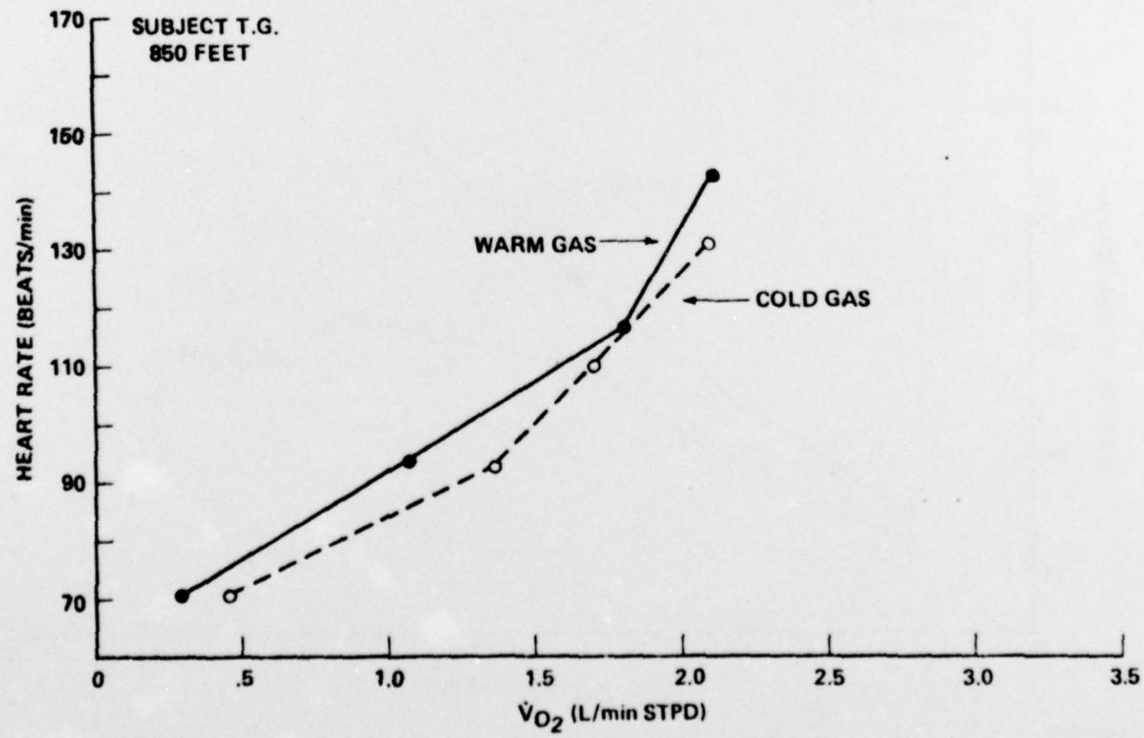

SUBJECT J.M.
600 feet
HEART RATE (BEATS/min)
COLD GAS
WARM GAS
$\dot{V}_{O_2}$ (L/min STPD)
170
150
130
110
90
70
0
.5
1.0
1.5
2.0
2.5
3.0
3.5

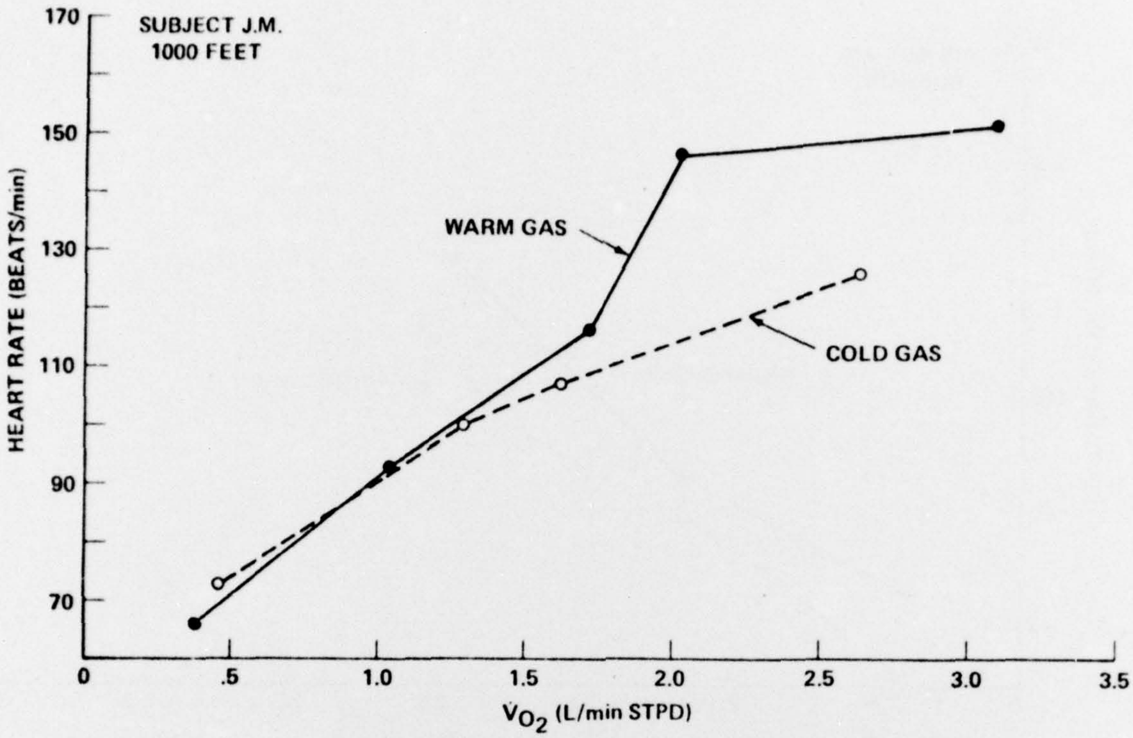

SUBJECT T.G.
600 feet
HEART RATE (BEATS/min)
WARM GAS
COLD GAS
$\dot{V}_{O_2}$ (L/min STPD)
170
150
130
110
90
70
0
.5
1.0
1.5
2.0
2.5
3.0
3.5

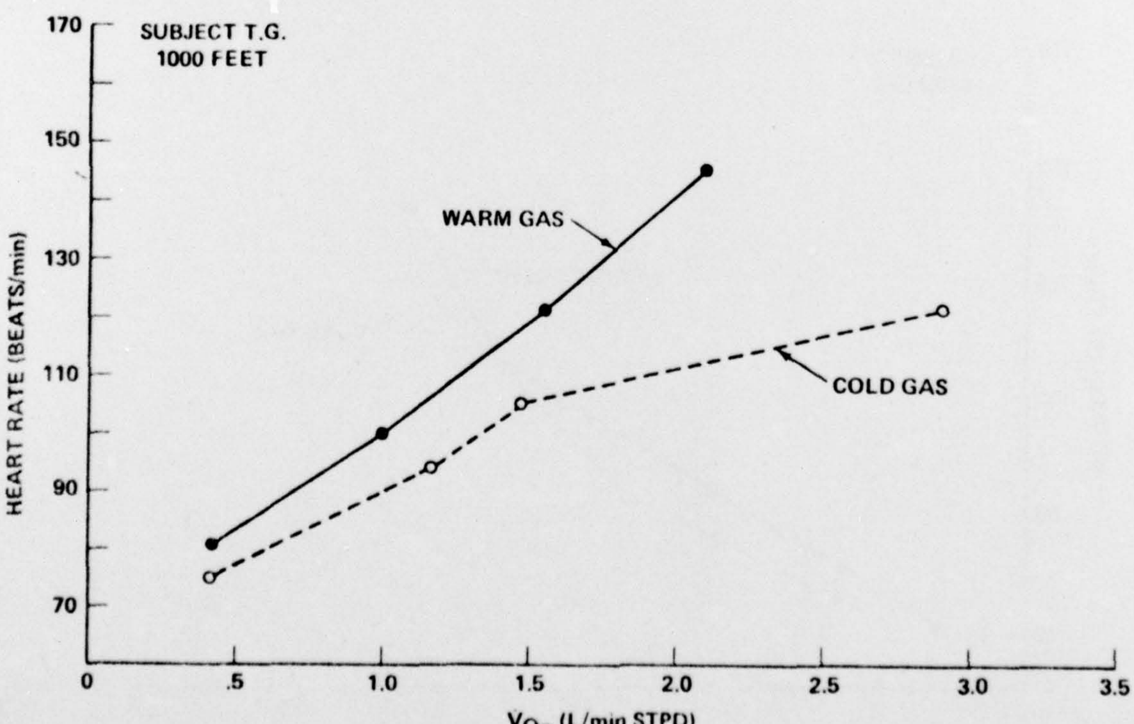

SUBJECT J.M.
800 FEET
170
150
130
110
90
70
HEART RATE (BEATS/min)
WARM GAS
COLD GAS
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
$\dot{V}_{O_2}$ (L/min STPD)

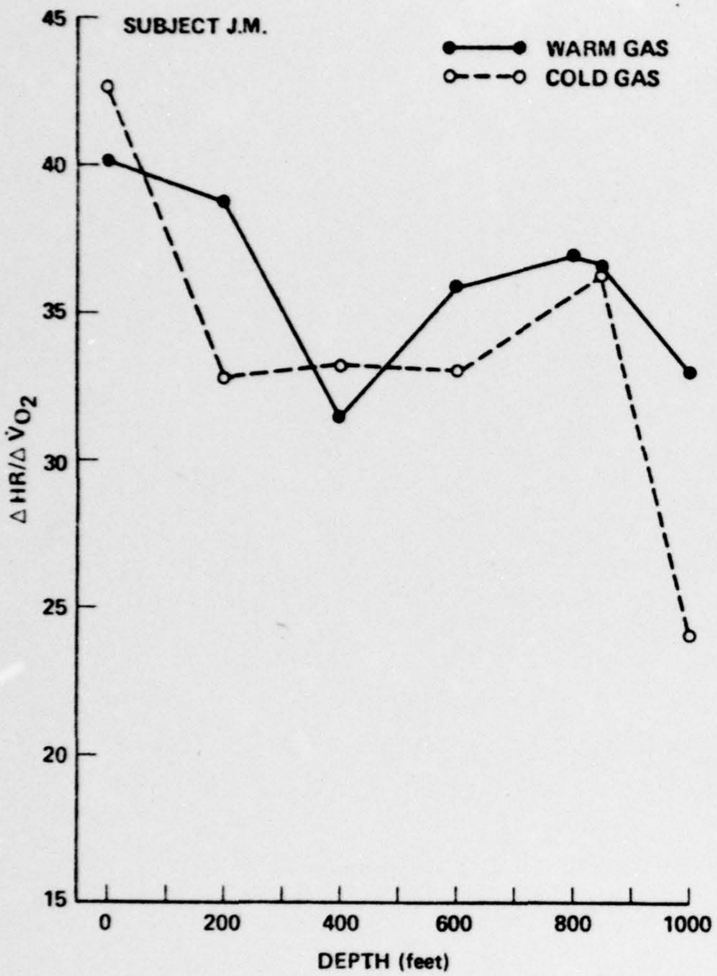

SUBJECT T.G.
800 FEET
170
150
130
110
90
70
HEART RATE (BEATS/min)
COLD GAS
WARM GAS
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
$\dot{V}_{O_2}$ (L/min STPD)

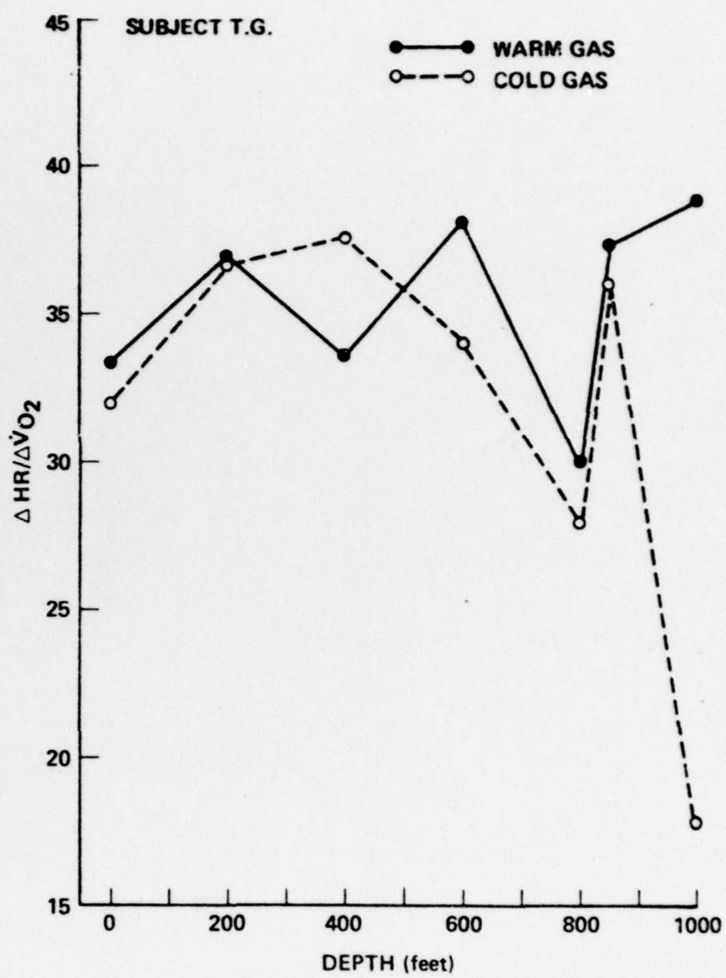

SUBJECT J.M.
850 FEET
HEART RATE (BEATS/min)
170
150
130
110
90
70
WARM GAS
COLD GAS
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
$\dot{V}_{O_2}$ (L/min STPD)


SUBJECT T.G.
850 FEET
HEART RATE (BEATS/min)
170
150
130
110
90
70
WARM GAS
COLD GAS
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
$\dot{V}_{O_2}$ (L/min STPD)


SUBJECT J.M.
1000 FEET
WARM GAS
COLD GAS
HEART RATE (BEATS/min)
170
150
130
110
90
70
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
$\dot{V}_{O_2}$ (L/min STPD)


SUBJECT T.G.
1000 FEET
WARM GAS
COLD GAS
HEART RATE (BEATS/min)
170
150
130
110
90
70
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
V_{O_2} (L/min STPD)


SUBJECT J.M.
WARM GAS
COLD GAS
Δ HR/Δ $\dot{V}O_2$
45
40
35
30
25
20
15
0
200
400
600
800
1000
DEPTH (feet)


SUBJECT T.G.
WARM GAS
COLD GAS
Δ HR/Δ$\dot{V}O_2$
45
40
35
30
25
20
15
0
200
400
600
800
1000
DEPTH (feet)

APPENDIX A

Peak Respiratory Pressures in Subject J.M.

DEPTH (FT)	WORK LOAD (WATTS)	Warm Gas		Cold Gas	
		Inhalation pressure (cm H_2O)	Exhalation pressure (cm H_2O)	Inhalation pressure (cm H_2O)	Exhalation pressure (cm H_2O)
0	0	4.7	0.5	6.0	1.0
	30	4.7	0.5	6.0	1.0
	60	5.5	1.0	7.2	2.0
	90	7.7	1.2	7.5	2.0
	120	8.0	3.0	8.0	2.0
200	0	3.7	1.0	5.5	1.2
	30	8.5	2.3	7.0	1.5
	60	10.0	2.3	7.3	2.0
	90	10.5	2.5	8.7	2.3
	120	13.5	4.3	12.0	3.0
400	0	6.2	1.0	8.0	1.3
	30	8.5	2.0	9.0	1.7
	60	9.5	2.5	10.0	2.3
	90	10.5	3.3	12.5	3.5
	120	13.8	4.3	15.5	4.5
600	0	5.0	1.0	7.0	1.3
	30	7.5	2.5	9.8	2.0
	60	10.0	2.7	10.8	2.7
	90	14.0	4.0	13.7	5.0
	120/105*	17.5	4.0	18.5	5.0
800	0	6.5	1.5	8.8	1.3
	30	9.0	3.0	-	-
	60	11.0	3.5	21.0	4.5
	90	13.5	3.5	-	-
	120	22.5	4.5	-	-
850	0	4.0	1.2	5.2	1.0
	30	6.5	2.7	10.5	1.5
	60	11.0	4.0	15.0	3.0
	90	13.5	4.5	16.0	3.5
1000	0	7.5	1.2	6.0	1.0
	30	10.0	2.7	10.0	2.0
	60	12.0	4.3	12.7	2.5
	90	17.0	5.0	14.5	4.0
	120	20.5	5.5	-	-

*Work load with warm and cold gas respectively

Peak Respiratory Pressures in Subject T.G.

DEPTH (FT)	WORK LOAD (WATTS)	Warm Gas		Cold Gas	
		Inhalation pressure (cm H_2O)	Exhalation pressure (cm H_2O)	Inhalation pressure (cm H_2O)	Exhalation pressure (cm H_2O)
0	0	2.5	1.7	4.0	-
	30	2.7	1.5	-	-
	60	3.3	1.5	-	-
	90	3.7	2.0	-	-
	120	4.7	2.3	-	-
200	0	3.7	1.0	5.3	1.3
	30	5.0	1.0	6.0	1.5
	60	6.5	1.0	6.5	1.7
	90	8.0	1.2	7.0	2.3
	120	9.5	2.0	7.7	3.3
[illegible]00	0	4.7	1.0	6.5	1.0
	30	6.7	1.0	8.0	1.5
	60	7.0	1.3	8.5	2.0
	90	8.5	2.0	9.5	2.3
	120	9.5	3.0	10.5	2.7
600	0	4.5	1.7	6.0	1.2
	30	6.0	1.7	7.5	1.2
	60	7.7	2.0	9.5	2.3
	90	9.5	3.5	10.0	2.5
	120	12.5	4.2	12.0	4.5
800	0	3.7	1.7	7.2	1.7
	30	5.0	2.2	8.7	2.2
	60	6.2	3.7	10.5	3.5
	90	7.2	4.2	25.0	6.0
	120	10.5	4.2	-	-
850	0	4.5	1.5	3.7	2.0
	30	7.5	2.5	8.7	2.7
	60	10.5	4.0	9.7	3.7
	90	13.5	4.7	11.0	4.5
1000	0	5.5	2.0	4.7	1.0
	30	9.0	1.7	7.3	2.0
	60	12.0	4.0	10.5	2.0
	90	16.0	4.5	11.0	2.5

APPENDIX B

Least Squares Relationship Between Heart Rate
And Oxygen Consumption

Depth (Ft)	Gas Temp.	Subject J.M.		Subject T.G.	
0	Warm	$HR = 40.2\ \dot{V}_{O_2} + 64.2$	r=.99	$HR = 33.4\ \dot{V}_{O_2} + 55.6$	r=.93
	Cold	$HR = 42.7\ \dot{V}_{O_2} + 63.2$	r=.99	$HR = 32.0\ \dot{V}_{O_2} + 54.6$	r=.93
200	Warm	$HR = 38.8\ \dot{V}_{O_2} + 45.6$	r=.99	$HR = 37.0\ \dot{V}_{O_2} + 48.4$	r=.99
	Cold	$HR = 32.8\ \dot{V}_{O_2} + 67.3$	r=.99	$HR = 36.9\ \dot{V}_{O_2} + 51.5$	r=.98
400	Warm	$HR = 31.5\ \dot{V}_{O_2} + 59.6$	r=.99	$HR = 33.6\ \dot{V}_{O_2} + 51.5$	r=.99
	Cold	$HR = 33.2\ \dot{V}_{O_2} + 53.4$	r=.99	$HR = 37.6\ \dot{V}_{O_2} + 47.7$	r=.99
600	Warm	$HR = 35.9\ \dot{V}_{O_2} + 52.7$	r=.97	$HR = 38.1\ \dot{V}_{O_2} + 54.9$	r=.98
	Cold	$HR = 33.0\ \dot{V}_{O_2} + 58.8$	r=.96	$HR = 34.0\ \dot{V}_{O_2} + 57.4$	r=.98
800	Warm	$HR = 37.0\ \dot{V}_{O_2} + 50.4$	r=.90	$HR = 29.9\ \dot{V}_{O_2} + 52.0$	r=.96
	Cold	- - - -	-	$HR = 27.9\ \dot{V}_{O_2} + 58.3$	r=.96
850	Warm	$HR = 36.6\ \dot{V}_{O_2} + 59.4$	r=.99	$HR = 37.3\ \dot{V}_{O_2} + 57.0$	r=.98
	Cold	$HR = 36.7\ \dot{V}_{O_2} + 45.0$	r=.99	$HR = 35.9\ \dot{V}_{O_2} + 50.9$	r=.98
1000	Warm	$HR = 33.0\ \dot{V}_{O_2} + 59.7$	r=.95	$HR = 38.9\ \dot{V}_{O_2} + 61.1$	r=.98
	Cold	$HR = 24.1\ \dot{V}_{O_2} + 65.1$	r=.99	$HR = 17.9\ \dot{V}_{O_2} + 72.1$	r=.97