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EFFECTS OF PRIOR PHYSICAL EXERTION ON TOLERANCE TO HYPOXIA, ORTHOSTATIC STRESS, AND PHYSICAL FATIGUE

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16. Abstract

Ten healthy men, 20-35 years old, were tested for tolerance to hypoxia, orthostatic stress, and physical fatigue after a period of rest and, on another occasion, after a period of physical exertion. Exertion consisted of four 10-min periods of pedal ergometry; each period consisted of a 30-watt (W) load imposed for 2 min, 60 W for 4 min, and 100 W for 4 min. Testing included a 100-min exposure to an oxygen/nitrogen gas mixture equivalent to 3658 m of altitude, 2 min of lower body negative pressure (LBNP) at -40 torr differential pressure, and 6 min of 50 W pedal ergometry. Psychomotor testing was conducted during hypoxic exposure. Although some statistically significant ($p \leq 0.05$) physiological decrements were associated with prior physical exertion, psychomotor performance and mentation were not significantly affected. In this study, prior physical exertion produced no adverse effects on physiological tolerances, mentation, or psychomotor performance.

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EFFECTS OF PRIOR PHYSICAL EXERTION ON TOLERANCE
TO HYPOXIA, ORTHOSTATIC STRESS, AND PHYSICAL FATIGUE

Introduction.

Pilot error is a primary cause of about 74 percent of all general aviation accidents (5), and about 38 percent of all air carrier accidents (4). Fatigue has been recognized as one of the underlying causes of pilot error (4,6,12,13). The Federal Aviation Administration (FAA) recognizes that fatigue has an adverse effect on safe pilot performance. The FAA has, therefore, set limits on flight time for air carrier flight crews.

The National Aeronautics and Space Administration (NASA)/FAA voluntary aviation safety reporting system, which became operational in 1976, allows air transport crews to report performance decrements that could be related to fatigue (9). Since 1976, 426 reports have been received of incidents possibly related to fatigue. When 77 of these were analyzed in detail, 75 were deemed to reflect substantive and potentially unsafe situations.

Difficulties in the measurement and definition of fatigue have been pointed out (1,11,12). Some of the factors which contribute to fatigue include: heavy physical exertion; complex, intense, and protracted psychomotor work; desynchronosis with displaced or lost sleep; monotony and protracted immobility; environmental factors such as temperature, humidity, noise, vibration, and barometric conditions; poor or insufficient nutrition; age; and chronic or acute medical conditions (9,12).

According to the NASA/FAA study (9), the factors most frequently cited by aircrews as being responsible for fatigue were duty time, flight time, number of flight segments, and number of duty days. Preduty activity was cited as another factor of concern (9).

The purpose of our study was to determine the presence and degree of adverse effects of physical exertion on pilots' tolerance for hypoxia, orthostatic stress, and physical fatigue and on psychomotor and mental performance. For this study, physical exertion consisted of four 10-min periods of pedal ergometry with 5 min of rest after each. Each ergometry period consisted of continuously pedaling at 50 revolutions per min for 2 min at a load of 30 watts (W), 4 min at 60 W, and 4 min at 100 W.

Methods.

Subjects. The participants were ten paid, healthy male volunteers, 20-35 years old. After a thorough briefing, each subject signed a standard consent form. The subject then underwent medical examination, consisting of a medical history, a standard 12-lead electrocardiogram (ECG), a spirogram, and a measurement of hemoglobin (Hb) concentration. Next, a combination psychomotor and mentation test was taken twice by the subject for practice. This test consisted of 20 pages of simple addition and subtraction problems (20 per page) to be answered true or false. The subject was instructed to make a checkmark within the correct answer block provided for each problem. Also, the checkmark was supposed to be made so that it would not touch any of the block's boundary lines. Each answer block measured 9 mm by 20 mm. The three scoring elements were time (min) for test completion, arithmetic errors, and eye/hand coordination errors. The arithmetic score was the number of incorrect answers per min. The eye/hand coordination score was the number of block boundary violations per min. Previous experience showed that the learning curve for this test starts leveling off by the fourth test. Any residual learning differences were accounted for in randomization of experimental order.

The subject then entered the experiment chamber for an equipment and protocol training session. Next, he was seated upright in our lower body negative pressure (LBNP) box (8) which contained a pedal ergometer. After adjusting seat height and pedal distance, the subject practiced one 10-min period of pedaling with timed load segments as described earlier. For the next 30 min he breathed an hypoxic gas mixture equivalent to that of a 3658 m mean sea level (MSL) altitude. The gas mixture was administered through a partial face mask which covered both the subject's nose and mouth. For practice, the subject took the psychomotor test two more times during hypoxic exposure.

After completing hypoxic exposure, the subject underwent a practice orthostatic tolerance test. This consisted of a 2-min exposure to an LBNP of -40 torr differential pressure. After that the subject practiced a final pedaling exercise at a 50-W load for 4 min. This completed the training session. The subject was disqualified from further participation if, during that session, his heart rate (HR) exceeded 150 beats per min (bpm) during the 10 min pedaling load, his arterial oxyhemoglobin saturation (HbO_2) fell below 80 percent during hypoxic exposure (10), or consciousness was not maintained during LBNP exposure. The subject was also disqualified if his monitored single-lead ECG showed evidence of ischemia or arrhythmia at any time during the training session. The subjects' mean age was 25.5 $\pm$ 1.4 years, mean height was 69.3 $\pm$ 0.7 cm, mean weight was 176.0 $\pm$ 1.8 kg, and mean Hb concentration was 15.4 $\pm$ 0.2 gm percent.

Protocol and Measured Variables. Each subject participated in one experiment per week for 2 consecutive weeks. The experimental protocol is outlined in Table I. Each subject ate breakfast prior to arriving at 0830. His body temperature was measured while he filled out a health questionnaire. Next, he took one timed psychomotor test as a learning refresher. He was then taken to the experiment chamber, and three ECG electrodes were attached to his chest. After voiding his urine, his body weight was measured. Next, the subject was seated in the LBNP box, a blood pressure (BP) cuff was placed on his right arm and the ECG cable was connected to monitoring and recording equipment. He then underwent the four 10-min periods of pedal ergometry. After completing these, the subject exited the box, voided his urine, and his body weight was again measured. A directional Doppler sensor for measuring temporal artery blood flow velocity (TAFV) was attached to his temple at this time. He was reseated in the LBNP box, and loosely sealed in it. The subject's BP cuff was repositioned, the ECG cable reconnected, and an ear oximeter positioned for subsequent monitoring and measurement of HbO_2. After 10 min of control measurements while the subject breathed ambient air, the face mask was positioned for the start of a 100 min exposure to the altitude-equivalent (3658 m MSL) hypoxic gas. During this hypoxia period, five of the timed psychomotor tests were taken consecutively by the subject. A 5 min-rest period followed each psychomotor test. At the end of the hypoxic exposure period, the face mask was removed, and shortly after HbO_2 reequilibration, the ear oximeter was removed. Tightening adjustment of the subject's waist seal preceded LBNP testing of orthostatic tolerance. After 8 min of control measurements, the subject underwent LBNP of -40 torr for 2 min. The subject's waist seal was then loosened for comfort during subsequent pedal ergometry, and a breathing

TABLE I. Experimental Protocol

Time (min)	Activity
0	Subject arrives
	Health check
15-30	Refresher psychomotor test
30-60	Body weight measurement
	Instrumentation of subject
	EXERCISE PHASE
60-70	Ergometry
70-75	Rest
75-85	Ergometry
85-90	Rest
90-100	Ergometry
100-105	Rest
105-115	Ergometry
	END EXERCISE PHASE
115-135	Body weight measurement
	Additional instrumentation of subject
135-145	Resting control measurements
145	HYPOXIA BEGINS
150-165	1st psychomotor test
165-170	Rest
170-185	2nd psychomotor test
185-190	Rest
190-205	3rd psychomotor test
205-210	Rest
210-225	4th psychomotor test
225-230	Rest
230-245	5th psychomotor test
245	HYPOXIA ENDS
245-250	Removal of ear oximeter
250-258	Pre-LBNP control measurements
258-260	LBNP (-40 torr)
265-275	Ergometry
275-280	Sensors removed
	Body weight measurement

valve was positioned for quantitative collection of expired air. The subject then pedaled at 30 W for 2 min and 50 W for 6 min. Expired air was quantitatively collected during the last 2 min of the 50-W load for measurement of pulmonary ventilation ($\dot{V}_E$) and oxygen uptake ($\dot{V}O_2$). After completing this ergometry, all sensors were removed, the subject exited the box, voided his urine and a final measurement of body weight was obtained. After completing a questionnaire concerning symptoms during the LBNP, the subject departed.

The subject returned one week later at 0830 for the second experimental session. To compensate for any effects of experimental order, half of the subjects underwent the four 10-min periods of pedal ergometry in the first experiment, and the other half in the second experiment. In the control experiment, the subjects remained at seated rest during the 10-min periods otherwise occupied by pedal ergometry. The data were statistically compared (Student's paired t test (15)) on the basis of preceding physical exertion versus preceding rest. Statistical significance was set at a probability value of $p \leq 0.05$.

During the four 10-min periods of pedaling, the HR and ECG were monitored, and HR and BP were measured during the last min of each 100-W load. Specific variables measured during hypoxic exposure consisted of: HR using a single-lead ECG; BP using auscultative manometry; HbO_2 (14); and TAFV (12). These variables were also measured during the last min of each of the five psychomotor tests conducted during hypoxic exposure. With the exception of HbO_2, these variables were subsequently measured during the LBNP test of orthostatic tolerance. These variables, as well as $\dot{V}_E$ and $\dot{V}O_2$, were measured during the last 2 min of the final ergometry test of physical fatigue tolerance. All gas volume data were normalized for differences in body size by expressing them as volume per kg of body weight. The CM_5 single-lead (2) was used to monitor and record the ECG and HR. During hypoxic exposure, a digital readout of HbO_2 was monitored for any indication of hypoxemia. The experiment was terminated if HbO_2 fell below 80 percent. The pulsatile signal of TAFV was monitored during hypoxic exposure and subsequent LBNP testing for any flow-reversal indication of approaching syncope (7). Criteria for immediate termination of the experiment were: strong subjective symptoms of impending syncope (lightheadedness, nausea, and visual grayout, tunneling or blackout) accompanied by hypotension and bradycardia, ECG evidence of ischemia or arrhythmia, and TAFV approaching zero.

Simple hand signals for "everything is OK," "subjective distress is present," and "stop the test" were taught to each subject for communication purposes while he was using the face mask or breathing valve. Subjects were continuously observed; a staff physician with emergency re scitation equipment was always available on a standby basis.

Tolerance to hypoxia was assessed on the basis of adequate HbO_2 maintenance and psychomotor test performance. Orthostatic tolerance was assessed on the basis of maintaining adequate cardiovascular function and useful consciousness during applied LBNP. Physical fatigue tolerance was assessed on the basis of quantitative shifts in cardiorespiratory functions during the final 50-W pedal ergometry load.

Results.

Table II summarizes the changes in physiological variables during the

TABLE II. Initial Pedal Ergometry (Physiological Data)

		E_1	R_1	E_2	R_2	E_3	R_3	E_4	R_4
SBP (torr)	$\overline{X}$	164.8*	116.0	162.3*	114.7	156.9*	113.1	157.8*	113.8
	SE	3.8	3.0	3.7	2.2	3.2	2.6	2.7	2.6
DBP (torr)	$\overline{X}$	62.2	60.2	62.2	57.5	60.9	58.3	62.5*	58.1
	SE	2.3	1.9	1.4	1.9	1.6	2.0	1.4	1.8
PP (torr)	$\overline{X}$	102.6*	55.8	100.2*	57.2	96.0*	54.7	95.4*	55.7
	SE	4.9	3.6	3.3	3.0	3.3	3.2	3.1	2.8
AP (torr)	$\overline{X}$	96.4*	78.5	95.5*	76.5	92.9*	76.6	94.2*	76.7
	SE	1.8	1.7	1.8	1.5	1.6	1.7	1.3	1.7
HR (bpm)	$\overline{X}$	120.5*	69.5	119.9*	67.1	120.0*	66.9	117.5*	67.7
	SE	3.9	3.5	4.1	2.7	4.7	3.5	4.3	3.5

$\overline{X}$ = Mean   SE = Standard error of the mean
SBP = Systolic blood pressure
DBP = Diastolic blood pressure
PP = Pulse pressure
HR = Heart rate
AP = Mean arterial pressure, calculated as the value of DBP + 1/3 PP
* = Statistically significant ($p \leq 0.05$) displacement of the ergometry value as compared to the corresponding resting value of the control experiment
bpm = Beats per min
$E_{1,2,3,4}$ = Last min of first, second, third, and fourth pedal ergometry periods
$R_{1,2,3,4}$ = Last min of first, second, third, and fourth resting periods of the control experiment

10-min ergometry periods and during the corresponding resting periods of the control experiment. The workloads were sufficient to produce statistically significant changes in all physiological variables, except diastolic blood pressure (DBP) that was significantly changed only during the fourth 10-min ergometry period. The four ergometry periods produced visible sweat in all subjects. Weight (water) loss caused by the four periods of exertion averaged 0.37 kg, and was significantly greater ($p < 0.001$) than the 0.12 kg weight loss of the corresponding rest periods of the control experiment.

Between the end of the fourth ergometry period, and the end of prehypoxia control measurements, each subject rested for 30 min. Of the physiological variables measured during the preceding ergometry, all had returned to pre-exertion resting levels except HR, which showed a small but significant ($p = 0.028$) elevation of 6.6 percent over the average control value of 62.1 bpm.

Table III summarizes the data from the five psychomotor tests taken by each subject during hypoxic exposure. The subject's error scores obtained from each test during hypoxic exposure after exertion were expressed as percent of the corresponding error scores obtained after rest in the control experiment. Although the data indicate a general trend of increased arithmetic errors, none of the increases was statistically significant.

Table IV summarizes the physiological data obtained during the last min of each psychomotor test taken during hypoxic exposure. The values for each physiological variable during the psychomotor testing and hypoxic exposure after ergometry were expressed as percent of the corresponding values obtained in the control experiment. As shown in Table IV, the HbO_2 data indicate that the hypoxia during psychomotor task performance was as well tolerated after exertion as after the corresponding rest periods of the control experiment. By similar comparison, neither HR nor pulse pressure (PP) was reduced. However, small but statistically significant decreases did occur in one of the mean systolic blood pressure (SBP) values, three of the mean DBP values, and all five of the mean arterial pressure (AP) values associated with prior exertion.

Table V summarizes the physiological data obtained during LBNP testing of orthostatic tolerance. All of the subjects easily tolerated the 2 min of LBNP. With the exception of barely perceptible transient lightheadedness in two subjects during the onset of LBNP, symptoms were absent. The physiological data in Table V indicate the absence of any adverse effects related to physical exertion. The only statistically significant difference was in SBP, which fell less during LBNP after physical exertion than after rest.

Table VI presents the physiological data obtained during the last 2 min of the final pedal ergometry test. There were no adverse effects related to the initial physical exertion.

Discussion.

These results indicate only negligible effects of four 10-min substantial ergometry loads on altitude-equivalent hypoxia, orthostatic and physical fatigue tolerances, and psychomotor performance at a simulated altitude of 3658 m.

Tolerance to Altitude-Equivalent Hypoxia. When a person undergoes hypobaric altitude exposure, the ambient air partial pressure of oxygen (PO_2), the pressure on the surface of the body, and the density of the respired air are reduced. The breathing of an altitude-equivalent hypoxic gas mixture at ground level in this study duplicates only the first of these three hypobaric conditions. The aviation

TABLE III. Psychomotor Test Data (During Hypoxic Exposure)

		PmT_1 (% of Cont.)	PmT_2 (% of Cont.)	PmT_3 (% of Cont.)	PmT_4 (% of Cont.)	PmT_5 (% of Cont.)
A	$\overline{X}$	176.0	136.0	109.1	122.0	88.2
	SE	50.0	25.9	16.1	18.7	14.9
E/H	$\overline{X}$	171.9	127.3	84.3	144.0	160.9
	SE	43.8	26.3	20.2	36.1	29.2

$\overline{X}$ = Mean   SE = Standard error of the mean
A = No. of arithmetic errors per min of total test time
E/H = No. of eye/hand coordination errors per min of total test time
$PmT_{1,2,3,4}$ = First, second, third, fourth, and fifth psychomotor tests
% of Cont. = % of control value

TABLE IV. Physiological Data (During Psychomotor Testing and Hypoxic Exposure)

		PmT_1 (% of Cont.)	PmT_2 (% of Cont.)	PmT_3 (% of Cont.)	PmT_4 (% of Cont.)	PmT_5 (% of Cont.)
SBP	$\overline{X}$	96.2	96.7	97.9	97.5	95.8*
(torr)	SE	2.5	1.9	1.8	1.2	1.1
DBP	$\overline{X}$	95.2	91.0*	93.7*	92.5*	95.7
(torr)	SE	2.5	2.2	2.3	1.6	2.2
PP	$\overline{X}$	97.9	102.6	101.4	102.4	96.4
(torr)	SE	5.5	4.2	3.1	3.7	1.8
AP	$\overline{X}$	95.6*	93.9*	95.9*	95.1*	95.7*
(torr)	SE	1.8	1.7	1.7	0.7	1.5
HR	$\overline{X}$	102.6	100.3	96.9	98.3	96.1
(bpm)	SE	3.6	2.7	1.8	1.9	2.2
HbO_2	$\overline{X}$	100.8	101.4	101.4	101.0	102.0
(%)	SE	1.3	1.3	1.0	1.1	1.1

$\overline{X}$ = Mean   SE = Standard error of the mean
SBP = Systolic blood pressure
DBP = Diastolic blood pressure
PP = Pulse pressure
HR = Heart rate
AP = Mean arterial pressure, calculated as the value of DBP + 1/3 PP
HbO_2 = Oxyhemoglobin saturation
bpm = Beats per min
$PmT_{1,2,3,4,5}$ = First, second, third, fourth, and fifth psychomotor tests
* = Statistically significant ($p \leq 0.05$) displacement of the experimental value as compared to the corresponding value of the control experiment

TABLE V. Orthostatic (LBNP) Test Data

		SBP (torr)			DBP (torr)		
		Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100	Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100
E	$\overline{X}$	114.1	108.8	95.4 *	61.9	63.3	102.5
	SE	1.6	2.0	1.1	1.9	1.8	2.2
C	$\overline{X}$	117.1	106.5	91.0	62.9	63.5	100.7
	SE	2.9	2.9	1.1	2.0	2.4	1.6

		PP (torr)			AP (torr)		
		Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100	Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100
E	$\overline{X}$	52.2	45.5	87.3	79.3	78.5	99.0
	SE	2.0	2.6	3.4	1.5	1.4	1.0
C	$\overline{X}$	54.1	43.0	79.5	81.0	77.8	96.0
	SE	3.2	3.0	2.3	1.8	2.1	1.1

		HR (bpm)			TAFV (cm/s)		
		Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100	Pre-LBNP	LBNP	$\frac{\text{Pre-LBNP}}{\text{LBNP}}$ X100
E	$\overline{X}$	61.8	70.4	114.0	5.5	4.5	80.8
	SE	3.6	4.3	2.2	0.6	0.6	3.1
C	$\overline{X}$	62.3	72.8	115.7	5.8	5.0	86.7
	SE	3.5	5.2	2.1	0.5	0.4	3.3

$\overline{X}$ = Mean SE = Standard error of the mean
E = Experiment in which hypoxia, orthostatic and physical fatigue tolerance testing were preceded by four 10-min pedal ergometry periods
C = Control experiment in which hypoxia, orthostatic and physical fatigue tolerance testing were preceded by four 10-min rest periods
SBP = Systolic blood pressure
DBP = Diastolic blood pressure
PP = Pulse pressure
HR = Heart rate
AP = Mean arterial pressure, calculated as the value of DBP + 1/3 PP
TAFV = Temporal artery blood flow velocity bpm = Beats per min
* = Statistically significant ($p \leq 0.05$) displacement of the experimental value as compared to the corresponding value of the control experiment

TABLE VI. Final Ergometry Test Data

		SBM (torr)	DBP (torr)	PP (torr)	AP (torr)	HR (bpm)
E	$\overline{X}$	133.7	59.7	74.0	84.3	92.3
	SE	3.6	2.2	3.8	2.1	3.1
C	$\overline{X}$	135.5	63.0	72.5	87.2	90.5
	SE	2.0	1.1	2.3	1.0	3.2

		TAFV (cm/s)	$\dot{V}O_2$ (ml/min/kg)	$\dot{V}_E$ (ml/min/kg)	f (rpm)	V_T (ml/kg)
E	$\overline{X}$	5.3	11.6	267	18.9	15.0
	SE	0.6	0.6	19.4	1.7	1.6
C	$\overline{X}$	6.0	11.5	259	17.4	15.9
	SE	0.5	0.7	17.0	1.6	1.8

$\overline{X}$ = Mean   SE = Standard error of the mean
SBP = Systolic blood pressure
DBP = Diastolic blood pressure
PP = Pulse pressure
HR = Heart rate
AP = Mean arterial pressure, calculated as the value of DBP + 1/3 PP
TAFV = Temporal artery blood flow velocity
$\dot{V}O_2$ = Oxygen uptake
$\dot{V}_E$ = Pulmonary ventilation
f = Respiratory frequency
V_T = Tidal volume
bpm = Beats per min
rpm = Respirations per min
E = Experiment in which hypoxia, orthostatic and physical fatigue tolerance testing were preceded by four 10-min pedal ergometry periods
C = Control experiment in which hypoxia, orthostatic and physical fatigue tolerance testing were preceded by four 10-min rest periods

environment contains all three. Whether or not the inclusion of all three hypobaric elements in this study would have produced different results is not known.

Although the psychomotor data (Table III) obtained during hypoxic exposure indicated a trend of decreased performance due to physical exertion, none of the effects was statistically significant. It is interesting to note that the greatest percent increase in the arithmetic and eye/hand coordination errors occurred in the first of the five tests after physical exertion. Thereafter, arithmetic performance showed a general trend of improvement.

The physiological data (Table IV) obtained during psychomotor testing and hypoxic exposure reflect small but statistically significant residual effects of the initial physical exertion. The observed decrements in SBP, DBP, and AP in the experiments with prior physical exertion, as compared to prior rest, might be construed as residual vasodilation, because both PP and HR (reflecting blood flow) remained generally undiminished. As reflected by corresponding HbO_2 data, oxygenation was not differentially affected by prior physical exertion. Circulatory accommodation to altitude-equivalent hypoxia after physical exertion of this degree appears to be quite adequate.

Orthostatic Tolerance. Each subject underwent the LBNP test in this study 143 min after cessation of the fourth 10-min exercise period. The data in Table V indicate that prior physical exertion caused no subsequent adverse effects on orthostatic tolerance. Whether or not an abbreviated exertion-recovery time would have altered the observed orthostatic tolerance is unknown.

Physical Fatigue Tolerance. The final ergometry load of 50 W for 6 min was experienced by each subject 152 min after cessation of the preceding fourth 10-min ergometry period. As indicated by the data in Table VI, the efficiency of physiological functions during this final test was not adversely affected by prior physical exertion. The data in Tables II and VI suggest that, immediately after the fourth 10-min ergometry period, a load of 50 W for only 6 min would probably have been more efficiently managed by the "opened" circulation than by the "less opened" circulation of extensive preceding rest. However, in this same context, maximum aerobic capacity would probably have been greater if assessed after extensive rest than after the fourth 10-min ergometry period.

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