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CHAPTER 5

EXERCISE RESPONSE

by

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Introduction

Inherent in the successful completion of the Apollo Program was the necessity for the lunar surface crewmen to engage in long and strenuous periods of extravehicular activity (EVA). Even though reduced gravity was expected to make some tasks less arduous, reduced suit mobility and a complex timeline indicated that metabolic activity would exceed resting levels for extended periods of time. Because the type and extent of physiological dysfunction that could result from habitability in a zero-g environment had not been established, appropriate physiological tests were performed within Apollo Program constraints to ascertain whether the physiological response of the crewmen to exercise was altered as a result of space flight.

Early planning for the Apollo Program had provided that some indication of these factors would be measured in flight; however, the Apollo spacecraft fire and the resultant program redirection eliminated this capability. The next approach was to conduct only preflight and postflight exercise response studies and to assume that these findings would document any changes of cardiopulmonary status resulting from space flight. Obviously, with such an endeavor, there were circumstances that could not be experimentally controlled. First, the readaptation process would be expected to begin immediately after reentry into the Earth's gravitational field and to introduce or modify responses that might have been measured in null gravity. Additionally, required crew recovery procedures presented perturbations which precluded a well controlled experimental design; the crewmen spent variable amounts of time in a hyperthermal spacecraft while it was in the water; orbital mechanics constraints dictated recovery times which precluded assurance that postflight testing would be accomplished in the same circadian time frame in which preflight testing was performed. The influence of these conditions and that of other physical and emotional stresses could not be isolated from the response attributed to zero-g exposures. However, not attempting to provide information relating physiological responses to exercise stress would have been an unsuitable alternative for maintaining management of the medical aspect of the Apollo Program.

This section contains the preflight and postflight exercise findings. Preliminary results were summarized previously (Berry, 1969; Berry, 1970; Rummel et al., 1973).

Methods

From the many methods that have been used to conduct exercise stress tests (Bruce et al., 1965; Bruce et al., 1969; Blackburn et al., 1970; Rochmis & Blackburn, 1971; Taylor et al., 1969), the bicycle ergometer and a graded stress protocol were selected for the Apollo Program. The selection of a bicycle ergometer as the stress device (Rummel et al., 1973) was influenced mainly by the fact that it had been chosen for the Skylab exercise program. The bicycle ergometer was the only device capable of enabling quantitation of the work level and of providing a basis for experimental evaluation inflight. The Apollo experience provided a data pool and background information for the Skylab inflight exercise response testing.

A graded exercise test permitted a progressive evaluation of physiological control system response and provided a better understanding of safe stress limits. Heart rate was used for determining stress levels (Maxfield & Brouha, 1963; Burger, 1969). By maintaining the same heart rate levels before and after flight, the same relative cardiovascular stresses were imposed.

Although the exact duration of each stress level was adjusted slightly (one to two minutes) for the late Apollo missions to accomplish additional measurements, the graded stress protocol comprised exercise levels of 120, 140, and 160 beats per minute, corresponding to light, medium, and heavy work, respectively, for each individual. For the Apollo 9 and 10 missions, a stress level of 180 beats per minute was also accomplished. The entire test protocol was conducted three times within a 30-day period before lift-off. Postflight tests were conducted on recovery day, as well as 24 to 36 hours after recovery.

During each test, workload, heart rate, blood pressure, and respiratory gas exchange (oxygen consumption, carbon dioxide production, and minute volume) measurements were made. For the Apollo 15 to 17 missions, cardiac output measurements were obtained by the single-breath technique (Kim et al., 1966). Arteriovenous oxygen differences were calculated from the measured oxygen consumption and cardiac output.

Figure 1 shows an exercising control subject at the Kennedy Space Center launch facilities. This same equipment was packed and moved to the recovery ship for postflight testing.

Each preflight test was treated separately, and a mean value (Rummel et al., 1973) was computed for each subject for each mission with the crewman serving as his own control. A preflight mean and variance estimate for all Apollo crewmen was then computed, and a similar statistic was computed for the separate postflight examinations. Statistical evaluations were made by means of standard t-test criteria. Although three members of the medical operations team were tested in the same time sequence in which the crewmembers were tested, these subjects essentially served as instrumentation controls.

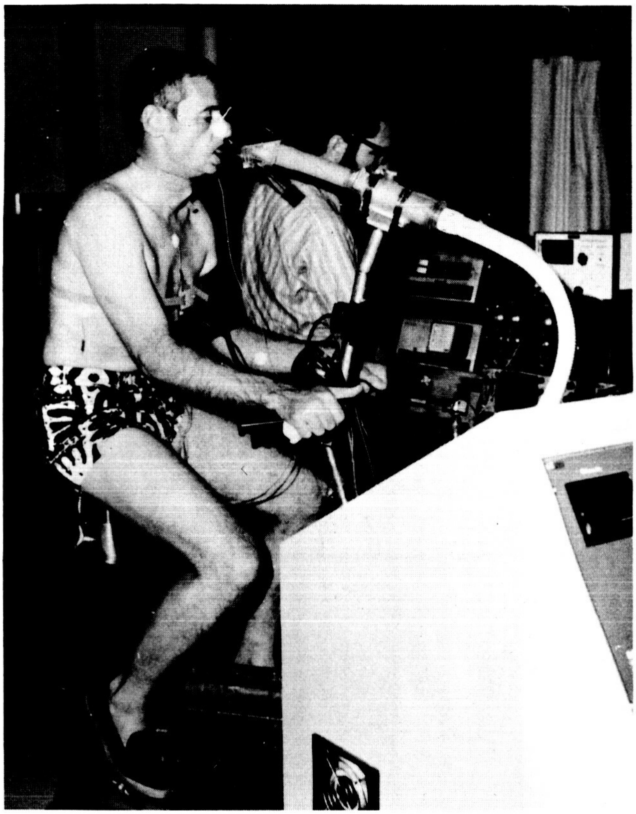

Figure 1. Control subject engaged in bicycle ergometry testing.

Results

The applicable data for each test on each crewman are given in table 1. Because these data were voluminous, only summaries and statistical considerations are presented. Testing, as noted earlier, was conducted both preflight and postflight. Test protocols were divided into three basic categories: prestress, exercise stress, and poststress.

Prestress Data

Significant changes in the sitting heart rate were observed immediately after flight; the mean difference was an approximate 16 beats per minute increase. This variable was not significantly elevated by the second postflight test (R+1). The only other significant changes observed were a slight increase in minute volume on the day of recovery and on R+1, and an increase in the resting respiratory gas exchange ratio on R+1.

Table 1

Physiological Measurements Made Before, During, and After Exercise Stress

Variable	Preflight			Day of Recovery				Day After Recovery			
	Mean	Standard Deviation	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations
Prestress Period											
Sitting heart rate beats/min	73.6	9.6	31	89.8	17.3	<0.001	27	79.3	13	NS	24
O_2 consumption l/min STPD	.279	.064	25	.291	.087	NS	20	.294	.097	NS	17
CO_2 production l/min STPD	.232	.052	12	.279	.062	NS	9	.271	.051	NS	9
Minute volume l/min BTPS	8.07	1.26	16	9.79	2.74	<0.05	11	10.0	2.57	<0.02	12
Respiratory exchange ratio	.85	.08	13	.88	.11	NS	9	.93	.08	<0.05	9
Systolic blood pressure (mm Hg)*	117	10.2	28	111	11.1	NS	24	117	9.0	NS	24
Diastolic blood pressure (mm Hg)*	78	6.3	28	79	5.8	NS	24	78	7.5	NS	24
Stress Period											
O_2 consumption l/min STPD at a heart rate of:											
120 beats/min	1.54	0.33	31	1.19	0.38	< 0.001	24	1.49	0.32	NS	21
140 beats/min	2.00	0.36	31	1.63	0.35	< 0.001	24	1.94	0.36	NS	21
160 beats/min	2.50	0.42	31	2.06	0.38	< 0.001	24	2.41	0.45	NS	21
180 beats/min**	2.98	0.50	31	2.52	0.43	< 0.001	24	2.85	0.56	NS	21

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*1 mm Hg = 133.3224 N/m^2

** Six individuals actually tested to this level—others extrapolated

NS = Not significant

STPD = Standard temperature and pressure, dry

BTPS = Body temperature and pressure, saturated

Table 1 (Continued)

Physiological Measurements Made Before, During, and After Exercise Stress

Variable	Preflight			Day of Recovery				Day After Recovery			
	Mean	Standard Deviation	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations
O_2 consumption l/min STPD at a workload of: 900 kpm/min	1.94	0.20	31	1.90	0.29	NS	23	2.09	0.33	<0.05	23
O_2 consumption l/min/kg STPD at a heart rate of:											
160 beats/min	33.1	5.6	31	28.2	6.0	<0.005	27	32.9	6.3	NS	22
180 beats/min	39.5	6.6	31	34.6	6.8	<0.01	27	39.3	7.7	NS	24
Systolic blood pressure (mm Hg) * at a heart rate of: 160 beats/min	206	22.7	31	184	30.5	<0.005	27	201	28.6	NS	27
Systolic blood pressure (mm Hg) * at 15 l/min cardiac output	170	18.0	09	173	35.8	NS	09	180	32.7	NS	09
Diastolic blood pressure (mm Hg) * at a heart rate of: 160 beats/min	089	9.5	31	080	11.8	<0.005	27	084	19.2	NS	–
Mean arterial pressure (mm Hg) * at 15 l/min cardiac output	111	15.0	09	109	17.5	NS	09	114	18.2	NS	09
Minute volume (l/min BTPS) at an O_2 consumption of 2.0 l/min STPD	52.4	7.7	31	54.7	8.8	NS	24	54.3	8.6	NS	22

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*1 mm Hg = 133.3224 N/m^2

Table 1 (Continued)

Physiological Measurements Made Before, During, and After Exercise Stress

Variable	Preflight			Day of Recovery				Day After Recovery			
	Mean	Standard Deviation	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations	Mean	Standard Deviation	Probability Level	Number of Observations
				Stress Period (Continued)							
Cardiac output (l/min) at a heart rate of: 160 beats/min	23.2	5.5	09	14.7	3.9	<0.001	09	21.6	4.8	NS	09
Arteriovenous O_2 difference, volumes percent, at a heart rate of: 160 beats/min	14.4	1.6	07	13.6	1.4	NS	07	12.5	2.9	NS	07
Arteriovenous O_2 difference, volumes percent, at an O_2 consumption of 2.0 l/min STPD	11.6	1.9	09	12.9	2.2	NS	08	13.1	2.7	NS	07
				Poststress Period							
Heart rate beats/min	121.9	12.0	26	128.7	13.0	NS	18	122.3	11.9	NS	13

Exercise Stress Data

Several significant changes for this period were noted after flight. The relationship between heart rate and oxygen consumption (0_2 pulse) was significantly altered at all heart rate levels, whether evaluated on an absolute basis (liters per minute) or corrected for body weight (liters per minute per kilogram). There were no significant changes in the oxygen required for a given workload immediately after flight, although a small increase was noted during the R+1 examination.

Both the systolic and diastolic blood pressures attained at a given heart rate level were significantly decreased immediately after flight but returned to normal by R+1. There were no significant changes in the relationship between blood pressure and levels of oxygen consumption or cardiac output.

The interrelationships of respiratory parameters (0_2 consumption per minute volume and 0_2 consumption per CO_2 production) indicated no significant changes immediately after flight. Results of the R+1 examination indicated that minute volume increased minimally.

A statistically significant decrease of large magnitude (–36 percent), was noted after flight in the cardiac output at a heart rate of 160 beats per minute. This variable had returned to preflight levels by the time of R+1 examination.

Poststress Data

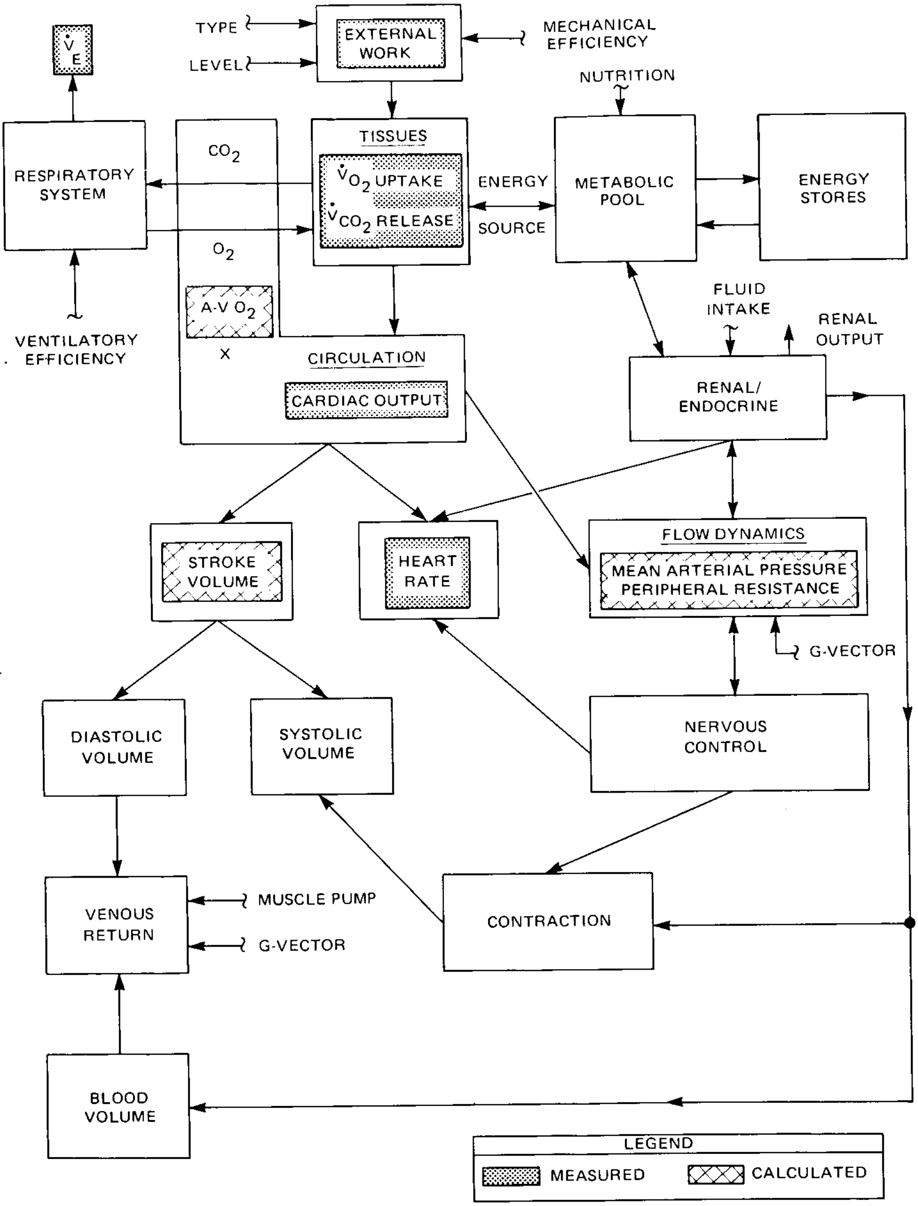
Only heart rate data collected during the second minute of recovery are presented. None of the measured variables changed significantly after the flight.

Discussion

The basic physiological processes involved in the response to increased metabolic activity are shown in figure 2. This discussion is an attempt to put available data into perspective with these principles. Those parameters that are measured or indirectly calculated are also indicated in the figure.

The external work in Apollo exercise stress testing always consisted of bicycle ergometer pedal resistance of a known level. Because respiratory gas exchange was measured, changes in mechanical efficiency or the amount of oxygen required for a given work level could be evaluated. A workload of 150 watts was selected for evaluation because this level of stress was attained by all Apollo astronauts during exercise testing. The preflight and immediate postflight mean oxygen consumption values were almost identical, an indication that there had been no basic change in mechanical efficiency. Utilizing the average resting oxygen consumption rate of 0.279 liter per minute, the mechanical efficiency is calculated to be approximately 26 percent. Other investigators have reported efficiencies of 30 percent (Whipp, 1970), 21 percent (Wasserman et al., 1967), 20 percent (Henry & DeMoor, 1950), 24 percent (Davies & Musgrove, 1971), 23 percent (Christensen et al., 1960), and 24 percent (Åstrand & Rodahl, 1970). Thus, the mechanical efficiency measured on the Apollo crewmen agrees with other bicycle ergometer studies.

The efficiency of respiratory gas exchange required to support the metabolic activity of the tissues was evaluated by studying the oxygen consumption/minute volume



$\dot{V}_E$ = pulmonary rate

$\dot{V}_{O_2}$ = O_2 utilization rate

$\dot{V}_{CO_2}$ = carbon dioxide production rate

A-V O_2 = arteriovenous O_2 difference

Figure 2. Physiological mechanisms associated with increased metabolic activity.

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relationship, which has been called the ventilatory equivalent for oxygen. At a rate of two liters per minute oxygen consumption, no significant change in the resulting minute volume was observed. The value of 2.62 liters minute volume per 100 cm^3 of oxygen consumption agrees with previously reported values of 2.7 (Higgs et al., 1967), approximately 2.5 (Hermansen & Saltin, 1969), and 2.2 to 2.5 liters (Cunningham, 1963). Cunningham (1963) reviewed fourteen studies in which this relationship was evaluated.

The circulatory responses required to support increased metabolic activity are striking and involve a complex system of varying physical properties and feedback control loops. Oxygen consumption requirements are equal to the cardiac output times the arteriovenous oxygen difference (A-V 0_2). Although the relationship between oxygen consumption and cardiac output (and thus a change in A-V 0_2 difference) appeared to change in some individuals, the overall means for the nine subjects indicated no significant changes (table 1). The absolute preflight values for cardiac output are approximately 20 to 25 percent greater than previously reported (Åstrand et al., 1964; Ekblom et al., 1968; Hermansen, 1970; Gilbert & Auchincloss, 1971) for this level of exercise. However, an evaluation of cardiac output/heart rate relationships indicated highly significant decreases in stroke volume immediately after flight. This decrease had returned to normal at the R+1 examination. These interrelationships explain the significant reduction in oxygen pulse (0_2 consumption/heart rate relationship) immediately after flight. The reduced cardiac output for the same heart rate may be responsible for the significant reduction in systolic and diastolic blood pressure immediately after flight.

The mechanism responsible for the reduced stroke volume is unknown and cannot be evaluated from the available data. The possible alternatives are a decrease in the systolic volume caused by myocardial contraction changes or a decrease in diastolic volume caused by decreased venous return. Changes in the latter could be caused by changes in the circulating blood volume, by redistribution of blood volume to the lower extremities, or by both of these mechanisms.

Based on the above physiological responses to exercise measured after space flight, it can be assumed that there was no significant change in mechanical or respiratory efficiency. Heart rate was significantly elevated for the same oxygen consumption; when coupled with a reduced stroke volume, increased heart rate maintained the same cardiac output/oxygen consumption relationship. The decreased cardiac output for the same heart rate could explain the observed reduced pressure in the systemic arteries. However, two points need to be considered. First, this general statistical response is different in some individuals, and the possibility of separate or different mechanisms operating in these separate cases should be recognized. For instance, some crewmen appeared to have had changes in peripheral resistance. Thus, each individual must be evaluated on the basis of his own particular response. Second, these responses were measured after recovery in a temporal and physical environment that was not controlled with sufficient precision to enable definition of the physiological response directly associated with the zero-g exposures.

These studies were extremely beneficial in assuring the success of the Apollo Program and have provided alternative hypotheses for inflight study during the Skylab missions.

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