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RESULTS OF SKYLAB MEDICAL EXPERIMENT M171 -- METABOLIC ACTIVITY

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ABSTRACT

The experiment was conducted to establish whether man's ability to perform mechanical work would be progressively altered as a result of exposure to the weightless environment of space flight. The Skylab crewmen exercised on a bicycle ergometer at workloads approximating 25, 50, and 75 percent of their maximum aerobic capacity. The physiological parameters monitored were respiratory gas exchange, blood pressure, and vectorcardiogram/heart rate. The results of these tests indicate that the crewmen had no significant decrement in their responses to exercise during their exposure to zero gravity. Immediately after the flight, however, all crewmen demonstrated an inability to perform the programed exercise with the same physiological effectiveness as they did both before flight and in-flight. The most significant changes were elevated heart rates for the same workload and oxygen consumption (decreased oxygen pulse), decreased stroke volume, and decreased cardiac output at the same oxygen consumption level. It is apparent that some adaptive changes in physiological function must have occurred in flight, but these did not become evident until the crewmen attempted to readapt to the one-g environment.

The results of the third manned Skylab mission (Skylab 4) are presented and a comparison is made of the overall results obtained from the three successively longer Skylab manned missions. The Skylab 4 crewmembers' 84-day in-flight respones to exercise were no worse and were probably better than the responses of the crewmen on the first two Skylab missions. Indications that exercise was an important contributing factor in maintaining this response are discussed.

As stated previously, an immediate postflight readaptation period was observed in all crewmen during which a decrement in response to exercise was evident. This period was of a short duration, was not intensified by the duration of the mission, and resulted in no lasting

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effects. It appears that the observed responses are a result of a decreased venous return caused by an altered fluid balance/blood volume state as well as a possible reduction in vascular tone of the venous system.

INTRODUCTION

When the metabolic activity experiment was first submitted for consideration in the proposed medical investigations associated with the Skylab Program, it was hypothesized that man's ability to do work would be compromised as a result of exposure to the weightless environment of space flight. At that time ground-based bed rest studies were the only data to support this hypothesis (1, 2, 3, 4). Exercise response tests conducted on some of the Gemini crewmen about this same time indicated trends but showed no statistically significant alterations postflight as compared to preflight. The Gemini Program postflight tests were conducted approximately 24 hours after splashdown when the crews returned to J. F. Kennedy Space Center. It was not until the Apollo Program that we were able to document a significant decrement in the crews' postflight response to excerise (5, 6, 7). During the Apollo Program, operational constraints were modified to permit postflight medical testing of the crew on board the recovery aircraft carrier within two to eight hours after splashdown. Twenty of the 27 Apollo crewmen tested exhibited a statistically significant decrease in their tolerance for exercise. Although this response was reversible within 24 to 36 hours, it became obvious that man could not be committed to long-duration space flight until the magnitude and time course of these changes could be established and the underlying physiological mechanisms understood. The eventual acceptance of the M-171 metabolic activity experiment for all three Skylab Missions provided us with an opportunity to attempt to do this. The primary objective of the experiment was to determine whether man's metabolic effectiveness in doing mechanical work was progressively altered by exposure to the space environment. The secondary objective was the evaluation of the M-171 bicycle ergometer as an in-flight crew personal exerciser.

The results of the first (Skylab 2) and second (Skylab 3) manned missions have been reported in detail previously (8, 9). This manuscript will report the results of the third (Skylab 4) manned mission and then attempt to summarize what has been learned from all three Skylab Missions about the physiological response to exercise during and after periods of 28 days, 59 days, and 84 days of weightlessness.

MATERIALS

A detailed description of the experimental hardware has been reported (8). The main items of hardware associated with the performance of the M-171 experiment are shown in figure 1 and include the bicycle ergometer, the metabolic analyzer, and the experiment support system. The experiment support system supported common and special requirements of a number of medical experiments. It provided data management with event time and subject and test identification, and regulated power for these experiments. It also provided visual readouts and controls for the blood pressure measuring system and the vectorcardiograph/heart rate system.

The ergometer is a hand- or foot-driven electromechanical bicycle-type exercise device designed to allow a test subject to exercise in the zero-g environment. A restraint system consisting of a shoulder and waist harness and foot restraints was developed, but the upper torso harness was found ineffective and was discarded during Skylab 2. The foot restraints were most effective and upon the recommendation of the first crew, modified wrap-around handlebars were installed by the Skylab 3 crew (fig. 2). Although these were, in general, well accepted by the crewmen some preferred to put their hands on the ceiling or to place padding between their head and the ceiling.

In the manual work-load mode of control of the ergometer, which was utilized in the conduct of the M-171 experiment, a continuous range of 25 to 300 watts was available. The loading of the erogmeter was independent of the pedalling rate - between 50 to 80 cycles/minute. In addition to being the M-171 experiment stressor, the ergometer was the principal device for personal exercise during the mission.

A ground support calibration system consisting primarily of a torque motor, torque sensor, and power computer was developed to provide accurate calibration of the ergometer prior to installation in the workshop. Additionally, electronic calibration was performed prior to each in-flight test.

The metabolic analyzer consists of a rolling seal dry spirometer for the measurement of volume, a mass spectrometer for the measurement of the four respiratory gases and an analog computer to calculate minute volume, oxygen consumption, carbon dioxide production, and respiratory exchange ratio. Figure 3 is a functional schematic of the metabolic analyzer.

End-to-end calibrations utilizing a hand pump and known gas mixtures were performed prior to installation of the metabolic analyzer in the

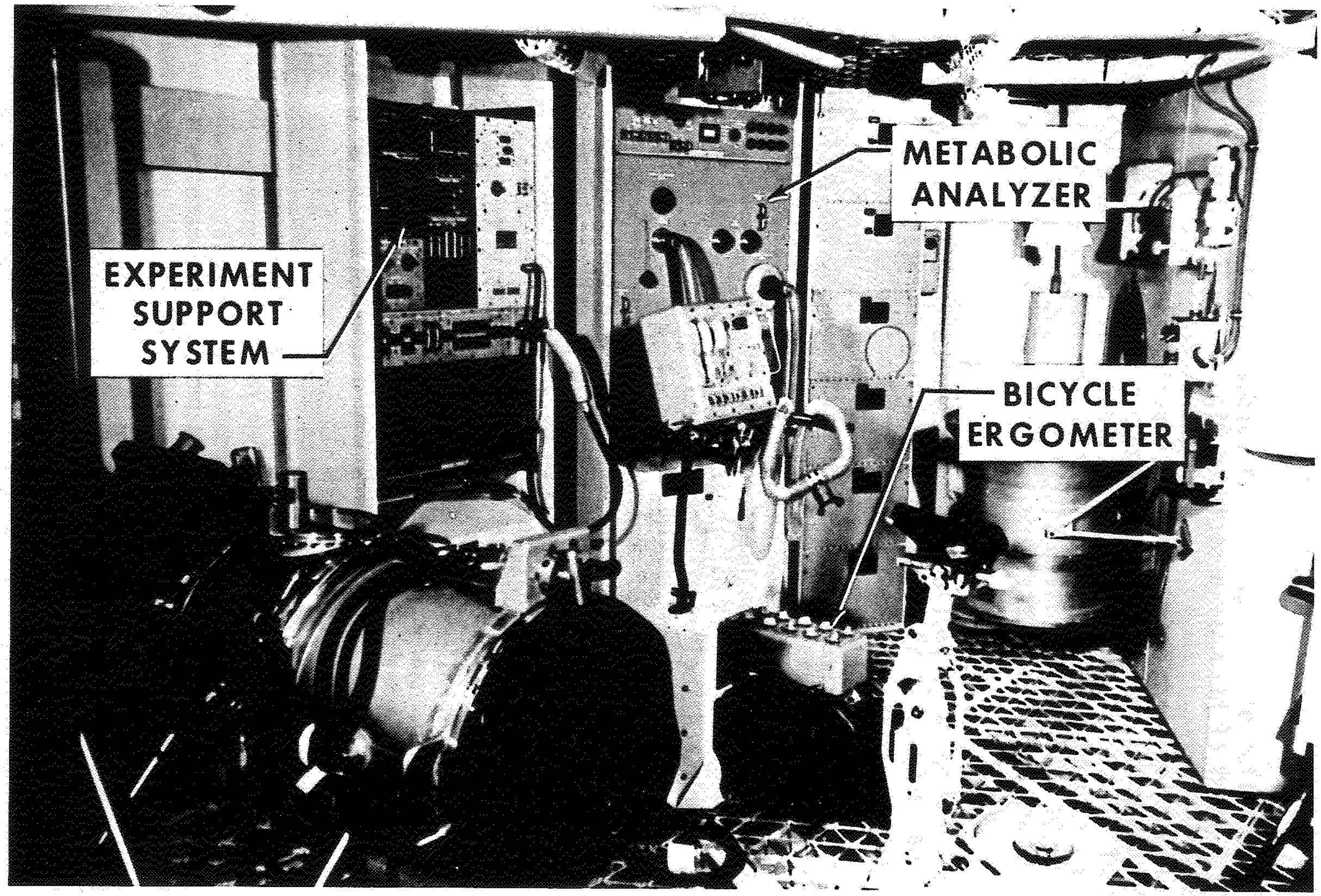


Figure 1. Skylab in-flight experiments.

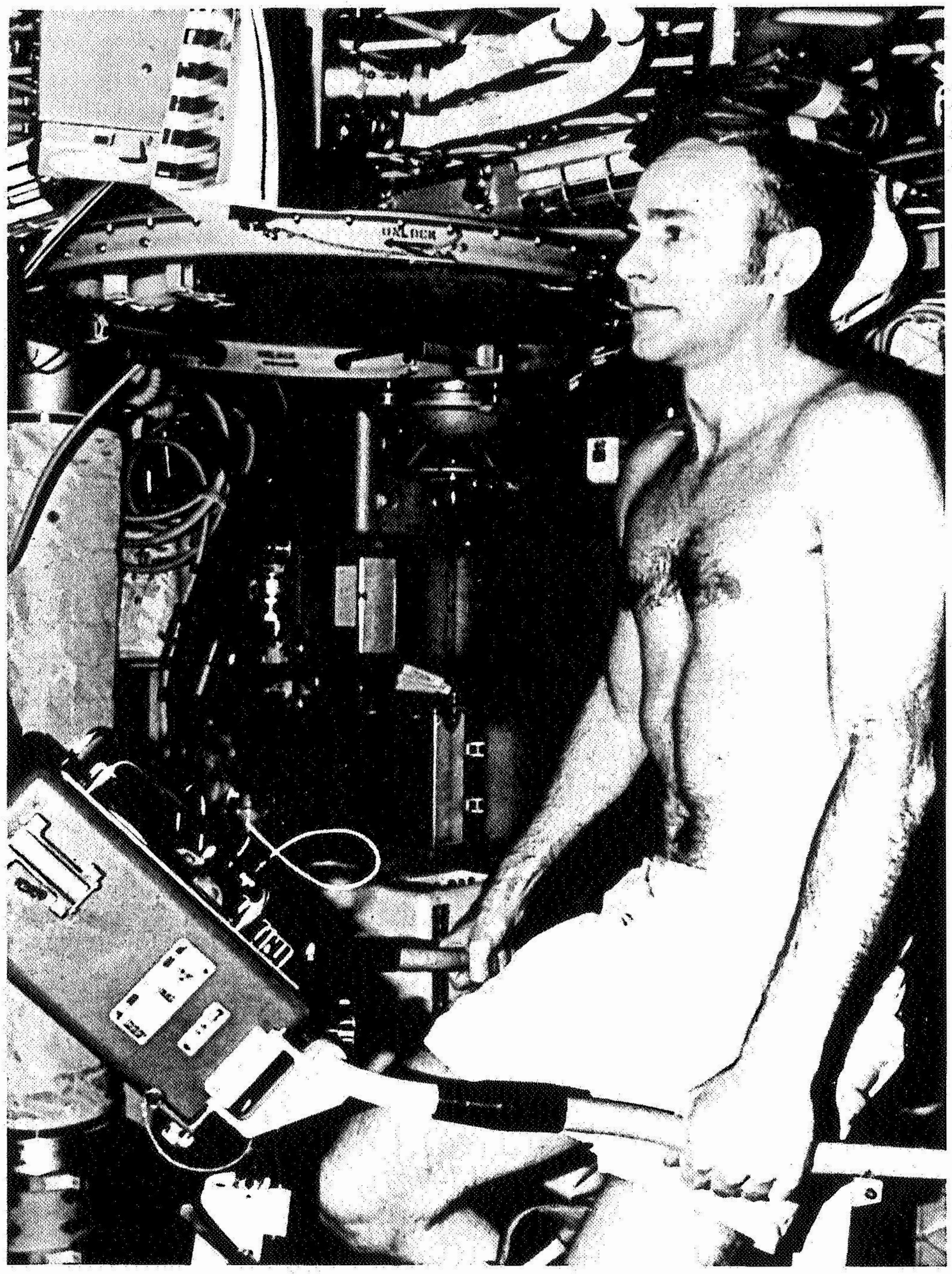


Figure 2. M-171 ergometer restraint methods.

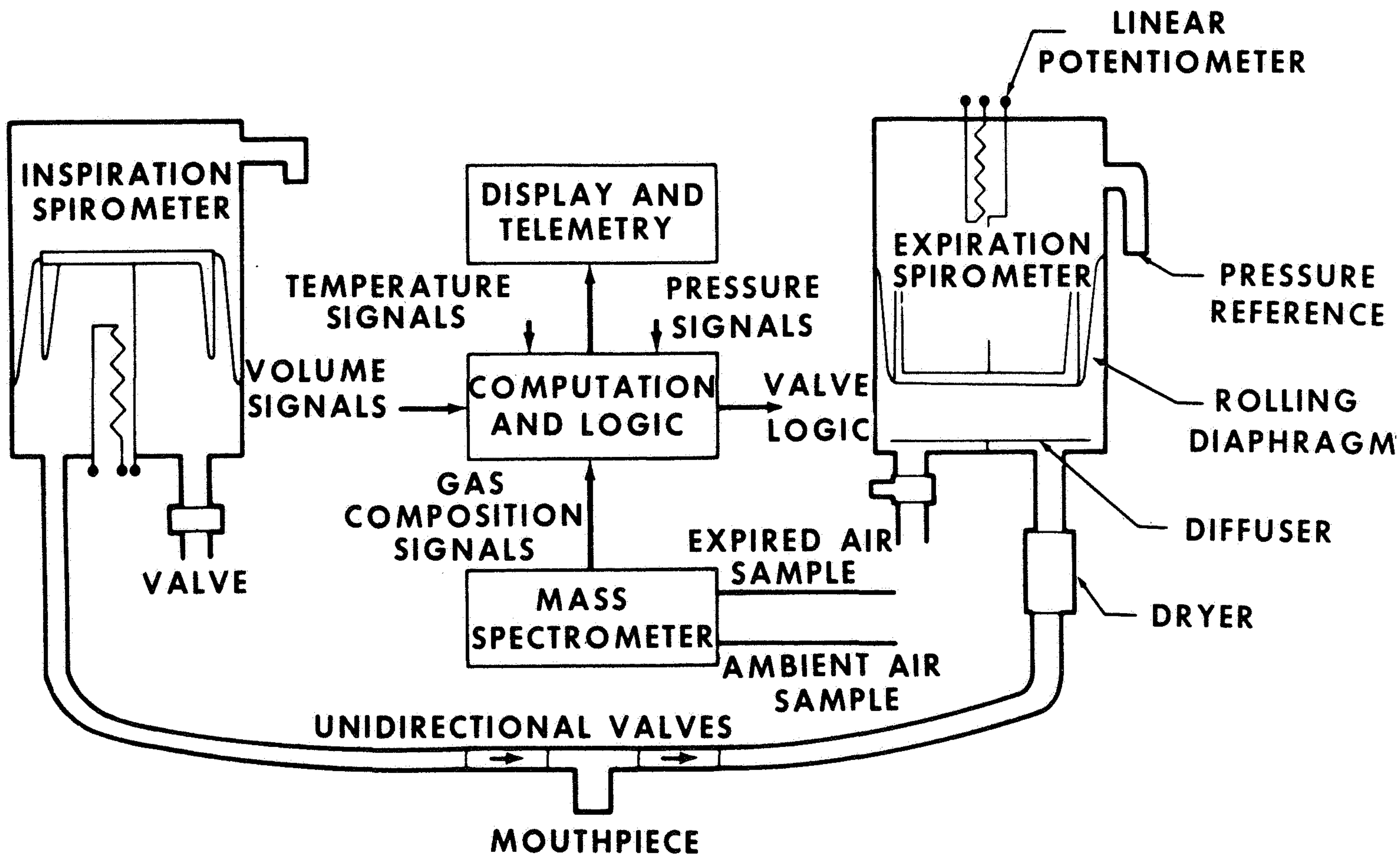


Figure 3. Schematic for respiratory gas analyzer.

workshop and during activation of the workshop at the beginning of each mission. No change in calibration was evidenced throughout the entire program.

METHODS

The experiment protocol, as shown in table I, consisted of measuring metabolic expenditures during rest and calibrated exercise. Each crewman's aerobic capacity was determined at approximately 12 months and again at six months prior to launch. Based upon these tests, a three-step workload protocol was established as follows:

- After obtaining a five-minute resting metabolic rate, the crewman exercised on the bicycle ergometer at fixed work levels approximating 25, 50, and 75 percent of his maximum oxygen uptake ($\dot{V}_{O_2}$ max) for a period of five minutes at each level.

- This was followed by a five-minute recovery period.

- The experiment protocol was scheduled to be repeated every 5 to 6 days by each crewman during all three Skylab Missions.

The acquisition of significant baseline data for each crewman was implicit in our experimental approach. Each subject served as his own control.

The physiological measurements (table II) which were made during the conduct of the experiment were oxygen consumption ($\dot{V}_{O_2}$), carbon dioxide production ($\dot{V}_{CO_2}$), minute volume ($\dot{V}_E$), vectorcardiogram/heart rate, and blood pressure. These measurements, with the exception of the vectorcardiogram/heart rate, were updated every minute. Heart rate was updated every 5 beats but only minute averages were utilized in the analysis of M171 data. Environmental conditions, ergometer work load and vectorcardiogram were measured continuously during each experiment run. An oral body temperature was obtained prior to each test. During the preflight and postflight tests single breath cardiac output (10, 11), vibrocardiographic and carotid pulse measurements were made. The derived respiratory data included respiratory exchange ratio, oxygen pulse, and mechanical and pulmonary efficiency. The derived cardiovascular data were mean arterial pressure, pulse pressure, and in the preflight and postflight tests, total peripheral resistance, A-VO_2 difference, and stroke volume. Not all of these derived data have been reduced and analyzed at this time.

In performing the M-171 experiment, each Skylab 4 crewman had eight preflight baseline tests, six spaced at approximate monthly intervals

TABLE I. M171 EXPERIMENT PROTOCOL

Time	Exercise Protocol
5 minutes	Rest
5 minutes	25 Percent of Maximum $\dot{V}_{O_2}$
5 minutes	50 Percent of Maximum $\dot{V}_{O_2}$
5 minutes	75 Percent of Maximum $\dot{V}_{O_2}$
5 minutes	Recovery

Legend:

Performed by each of three Crewmen

Five times in 28-day mission
Eight times in 59-day mission
Twelve times in 84-day mission

TABLE II. M-171 PHYSIOLOGICAL MEASUREMENTS

Raw Data	Derived Data
Ergometer Work Level (Watts)	Respiratory
Respiratory	Respiratory Exchange Ratio
Oxygen consumption	Oxygen pulse
Carbon dioxide production	Pulmonary efficiency ($\dot{V}_E/\dot{V}_{O_2}$)
Minute volume	Mechanical efficiency ($\dot{V}_{O_2}$/Watt)
Cardiovascular	Cardiovascular
ECG/VCG	Mean Arterial pressure
Systolic/Diastolic blood pressure	Total Peripheral Resistence
*Cardiac output	Arterial-Venous Oxygen Difference (A-$\dot{V}_{O_2}$)
*Vibrocardiogram	Stroke Volume
*Carotid Pulse	

*Preflight and Post flight only

ECG = Electrocardiograph
VCG = Vectorcardiograph

over a 6-month period prior to launch and two additional tests at 15 and 5 days before flight. The first six baseline tests were conducted by the crew on themselves utilizing the one-g trainer. The last two baseline tests were conducted in the Skylab Mobile Laboratories by the principal investigators who subsequently performed the postflight tests in the Skylab Mobile Laboratories onboard the recovery ship. Each crewman was tested approximately every 6 days during the 84-day mission for a total of 12 tests per man.

As a result of the experience gained from the Gemini and Apollo programs, a concerted effort was made during the planning for Skylab to perform the postflight tests on the crew as soon as possible after splashdown. To insure the best possible comparison between the preflight and postflight experiment data with those obtained in-flight the Skylab Mobile Laboratories were outfitted with a set of M-171 experiment instrumentation and transported intact to the recovery ship. Postflight, eight M-171 tests were conducted on each crewman: at recovery and on days 1, 2, 3, 5, 11, 17 and 31 following recovery. Prior to the Skylab 4 launch and based on data obtained from the first two Skylab manned missions, the principal investigators decided to perform preflight and postflight tilt ergometry exercise tests (30° from horizontal) on the crew in an attempt to better understand the previously observed postflight decrements in response to exercise. Since the recovery medical testing day was already excessively long, we elected to substitute the supine/upright ergometry testing for the standard M-171 protocol. The standard protocol was conducted on the day after recovery and on all subsequent postflight test days. The protocol used for the modified test on the day of recovery, consisted of five minutes supine rest, five minutes upright rest, five minutes upright exercise, five minutes supine exercise and five minutes supine recovery. The exercise level used was identical to the first level of work (25 percent maximum) of each crewman's standard M-171 protocol. This modified protocol was accomplished 15 and 5 days preceding launch, on recovery day, on the first day after recovery prior to M-171 standard protocol, and on 17 and 31 days post recovery.

RESULTS OF SKYLAB 4

The next three tables (tables III, IV, V) summarize the Skylab 4 results for the Commander, Scientist Pilot, and Pilot, respectively, utilizing the physiologic variables which were routinely monitored during all performances of the M-171 experiment. Resting, level-3 exercise, and recovery mean values are presented for each variable during the three phases of the mission. Those values outside the preflight 95 percent confidence levels are marked with an asterisk. The values

TABLE III. SKYLAB 4 M171 DATA SUMMARY

Commander

VARIABLE	PREFLIGHT $\overline{X}$	IN-FLIGHT $\overline{X}$	POSTFLIGHT $\overline{X}$
Heart Rate (bpm)			
Rest	66	66	76*
Level 3	157	152	163
Recovery	112	87*	109
$\dot{V}_{O_2}$ (l/min STPD)			
Rest	.237	.283*	.203*
Level 3	2.26	2.20	2.14
Recovery	.603	.632	.717
$\dot{V}_{CO_2}$ (l/min STPD)			
Rest	.234	.301*	.187*
Level 3	2.14	2.13	2.05
Recovery	.721	.776	.839
SBP (mm Hg)			
Rest	96	97	106
Level 3	192	195	195
Recovery	149	131	170
DBP (mm Hg)			
Rest	67	59*	72
Level 3	71	56*	67
Recovery	66	61*	78
$\dot{V}_E$ (l/min BTPS)			
Rest	8.90	11.79*	9.27
Level 3	64.43	62.04	60.04
Recovery	25.98	24.65	29.18

Key:

* = Outside the 95% confidence limit
STPD = Standard temperature, pressure dry
bpm = Beats per minute
BTPS = Body temperature, pressure saturated
$\dot{V}_{O_2}$ = Oxygen consumption
$\dot{V}_{CO_2}$ = Carbon dioxide production
$\dot{V}_E$ = Minute volume
SBP = Systolic blood pressure
DBP = Diastolic blood pressure

TABLE IV. SKYLAB 4 M171 DATA SUMMARY

Scientist Pilot

VARIABLE	PREFLIGHT $\bar{X}$	IN-FLIGHT $\bar{X}$	POSTFLIGHT $\bar{X}$
Heart Rate (bpm)			
Rest	64	62	74*
Level 3	164	166	167
Recovery	104	92*	102
$\dot{V}_{O_2}$ (l/min STPD)			
Rest	.269	.289	.263
Level 3	3.07	3.01	3.00
Recovery	.676	.745	.763
$\dot{V}_{CO_2}$ (l/min STPD)			
Rest	.255	.279	.221
Level 3	2.88	3.03*	2.91
Recovery	.791	.982*	.893
SBP (mm Hg)			
Rest	127	119*	123
Level 3	204	200	198
Recovery	186	174	189
DBP (mm Hg)			
Rest	84	74*	78*
Level 3	55	52	51
Recovery	66	61	63
$\dot{V}_E$ (l/min BTPS)			
Rest	7.51	9.98*	10.33*
Level 3	84.18	97.24*	102.69*
Recovery	24.6	31.44*	34.07*

Key:

* = Outside the preflight 95% confidence limit
STPD = Standard temperature, pressure,dry
bpm = Beats per minute
BTPS = Body temperature, pressure saturated
$\dot{V}_{O_2}$ = Oxygen consumption
$\dot{V}_{CO_2}$ = Carbon dioxide, production
$\dot{V}_E$ = Minute volume
SBP = Systolic blood pressure
DBP = Diastolic blood pressure

TABLE V. SKYLAB 4 M171 DATA SUMMARY

Pilot

VARIABLE	PREFLIGHT $\overline{X}$	IN-FLIGHT $\overline{X}$	POSTFLIGHT $\overline{X}$
Heart Rate (bpm)			
Rest	54	53	65*
Level 3	147	147	156*
Recovery	114	91*	118
$\dot{V}_{O_2}$ (l/min STPD)			
Rest	.238	.283*	.253
Level 3	2.86	2.59*	2.63*
Recovery	.849	.754	.849
$\dot{V}_{CO_2}$ (l/min STPD)			
Rest	.216	.247	.222
Level 3	2.72	2.65	2.68
Recovery	1.22	1.08	1.08
SBP (mm Hg)			
Rest	115	115	125*
Level 3	204	200	213
Recovery	188	186	204
DBP (mm Hg)			
Rest	72	64*	74
Level	60	51*	59
Recovery	65	60	69
$\dot{V}_E$ (l/min BTPS)			
Rest	6.69	8.47*	10.73*
Level 3	98.51	90.61*	95.12
Recovery	40.97	34.77*	45.02

Key:

* = Outside the preflight 95% confidence limit
STPD = Standard temperature, pressure dry
bpm = Beats per minute
BTPS = Body temperature, pressure saturated
$\dot{V}_{O_2}$ = Oxygen consumption
$\dot{V}_{CO_2}$ = Carbon Dioxide production
$\dot{V}_E$ = Minute volume
SBP = Systolic blood pressure
DBP = Diastolic blood pressure

for each test data point in the case of resting values were based on the average of the entire five minute period. The exercise values were based on the average of the last three minutes of the five minute period and the recovery values were those obtained for the second minute during the five minute recovery period.

As can be seen in the case of the Commander, significant changes observed in-flight were decreased recovery heart rate, decreased resting, exercising, and recovery diastolic blood pressure and increased resting minute volume, oxygen consumption and carbon dioxide production. Postflight, the Commander exhibited a significant elevation in resting heart rate and decreases in both resting oxygen consumption and carbon dioxide production.

The in-flight response of the Scientist Pilot showed a decreased recovery heart rate and increased ventilation not only during rest but during exercise and recovery. Additionally, decreases in resting systolic and diastolic blood pressures were observed as well as increased carbon dioxide production during both exercise and recovery. Postflight, the Scientist Pilot demonstrated significant elevation in resting heart rate and in resting, exercising, and recovery ventilation accompanied by a decreased resting diastolic blood pressure.

The in-flight response of the Pilot was similar to the other crewmembers in that he also exhibited a significant reduction in both recovery heart rate and diastolic blood pressure as well as an increase in resting minute volume. Unlike the others, though, he had a significant decrease in exercising oxygen consumption and exercising minute volume. The significant changes observed in the Pilot's postflight response were elevated resting and exercising heart rates, systolic blood pressure, and resting minute volume. The decreased oxygen consumption observed in-flight in the Pilot during exercise remained so during the immediate postflight test period.

Because of the immense quantity of data, we elected to report the mean values obtained during the various phases of the mission. However, this type of presentation precludes following transients and/or trends in these data. Using only the Pilot's data, the individual plots representative of the most common significant alterations seen in the Skylab 4 crew will be presented. The rest of these pertinent data are presented in the appendix. Figure 4 deals with alterations in heart rate. All three crewmen displayed a decreased in-flight recovery heart rate. Additionally, all crewmen exhibited a significantly elevated resting and exercising heart rate immediately postflight Figure 5 is a plot of the ventilation response. All crewmen exhibited a significantly elevated in-flight resting minute volume which continued

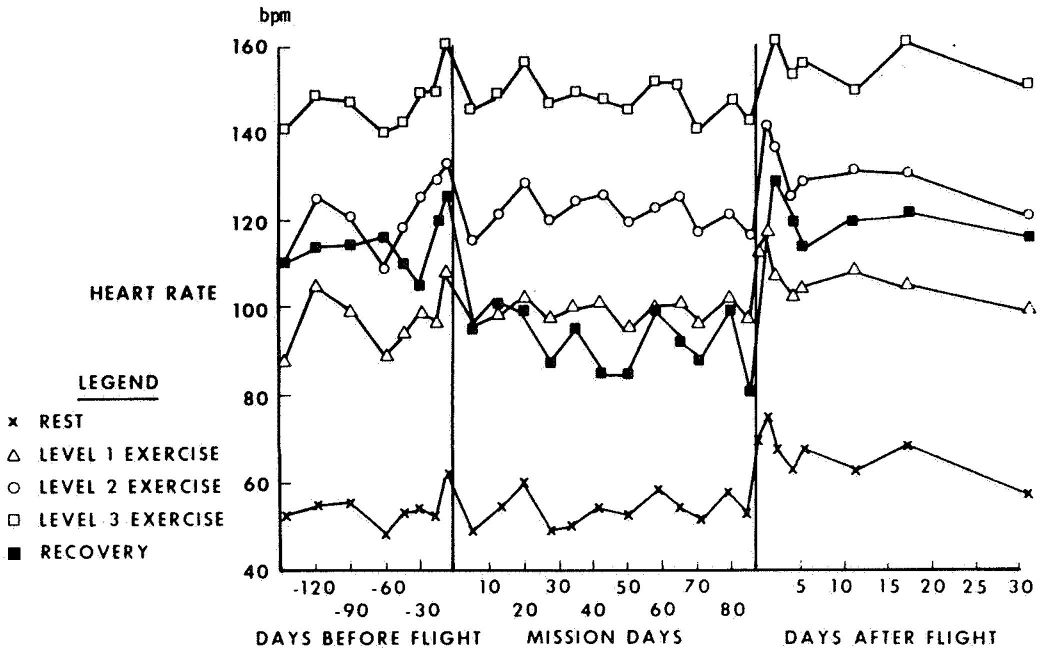


Figure 4. Heart rate, Skylab 4 Pilot.

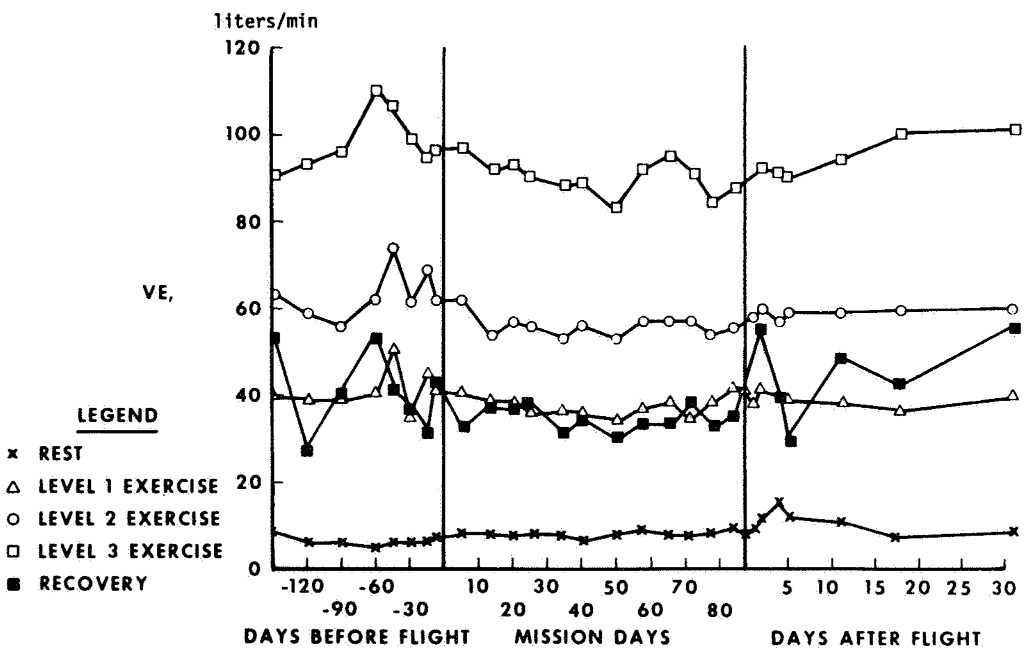


Figure 5. $\dot{V}_E$, Skylab 4 Pilot.

during the postflight testing for both Scientist Pilot and Pilot. Figure 6 shows the decreased in-flight, resting and exercising diastolic blood pressure pattern observed in all Skylab 4 crewmen.

Figures 7 and 8 show the results of the preflight and postflight cardiac output and stroke volume measurements. As stated previously, the first standard M-171 protocol was done on the first day after recovery. On that day only the Commander exhibited a decrease in cardiac output (41 percent) and stroke volume (41 percent); these values showed a prolonged but gradual increase back toward normal and both parameters were within 15 percent of normal by 31 days after recovery. The cardiac output values for the Scientist Pilot and Pilot were slightly increased over preflight while their stroke volume values were slightly decreased. The cardiac output and stroke volume levels of the Scientist Pilot gradually increased from the first day after recovery to 31 days postflight when both of these levels were significantly increased over preflight values. The Pilot showed a slight downward trend in cardiac output after the first day following recovery but his postflight stroke volume showed no particular trend. As would be expected based on the cardiac output and stroke volume data, the Scientist Pilot and Pilot had no change in their $A\text{-}V_{O_2}$ differences while the Commander exhibited an increased $A\text{-}V_{O_2}$ difference of about the same percent magnitude as his observed reduced cardiac output. The interpretation of these results will be addressed later in conjunction with the results from the Skylab 2 and Skylab 3 missions.

The tilt ergometry studies demonstrated that resting heart rate increased when subjects were placed upright from the supine position. Preflight, the average increase was from 54 to 61 beats per minute (12.6 percent) while in the immediate postflight period the increase was from 65 to 83 beats per minute (27 percent). Thus, not only was the resting level slightly increased in the supine position postflight but the change in heart rate when positioned upright was significantly greater. The late postflight values were similar to preflight.

Figure 9 summarizes the response of Skylab 4 crewmen during the 25 percent maximum exercise in the supine and upright positions. For data comparison, the six tests obtained on each crewman were categorized into preflight, immediate postflight, and late postflight periods. During preflight tests there was very little change in exercising heart rate when the subject was placed supine after five minutes in the upright position. Preflight mean supine and upright values were exactly the same at 103 beats per minute while the immediate postflight change was only from 117 beats per minute to 114 beats per minute. For

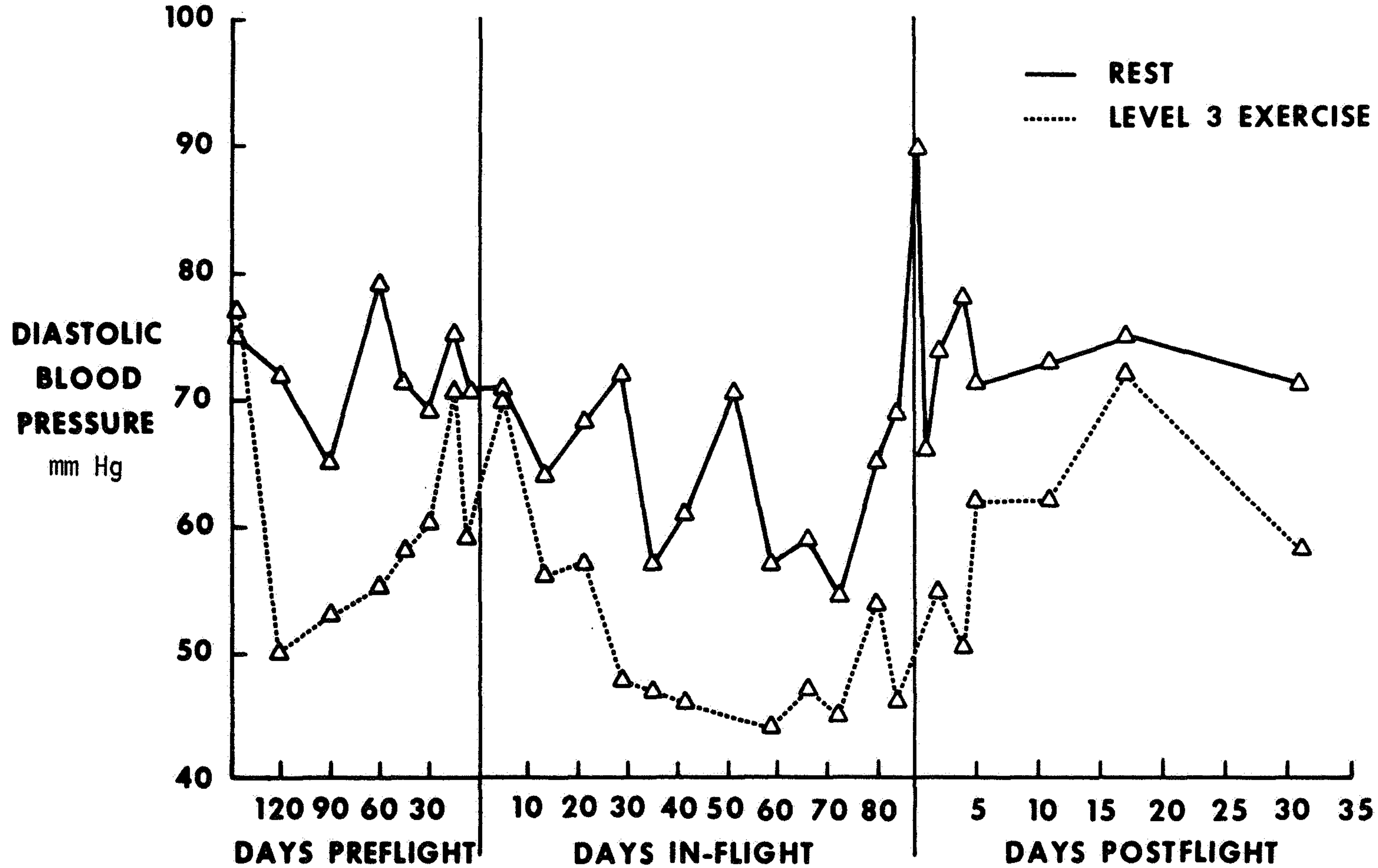


Figure 6. Diastolic blood pressure; Skylab 4 Pilot.

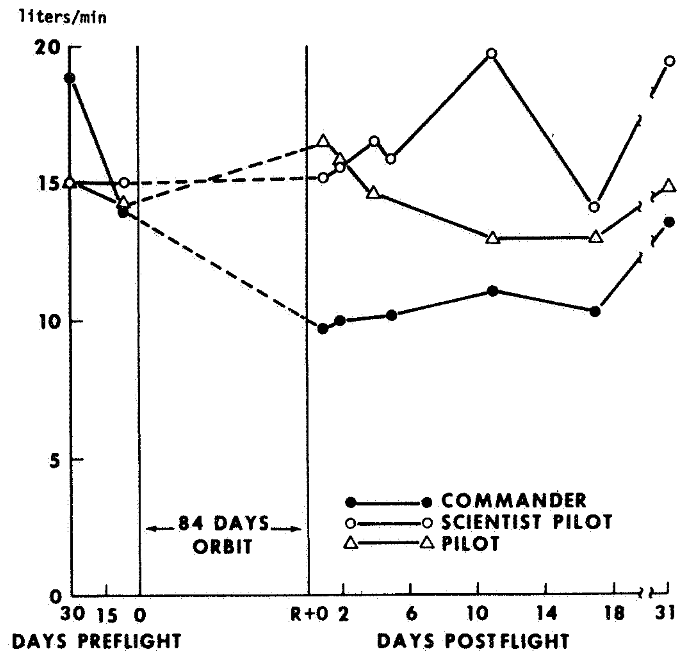


Figure 7. Cardiac output during submaximal exercise (Skylab 4).

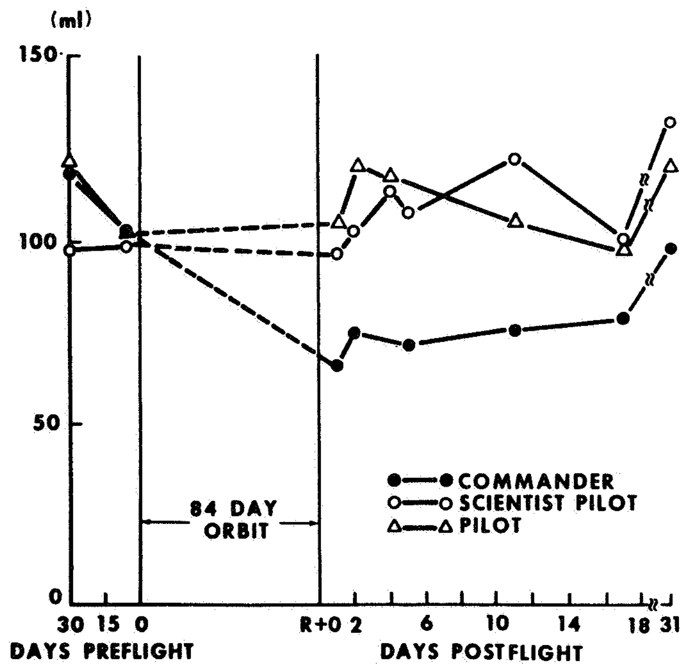


Figure 8. Mean stroke volume during submaximal exercise (Skylab 4).

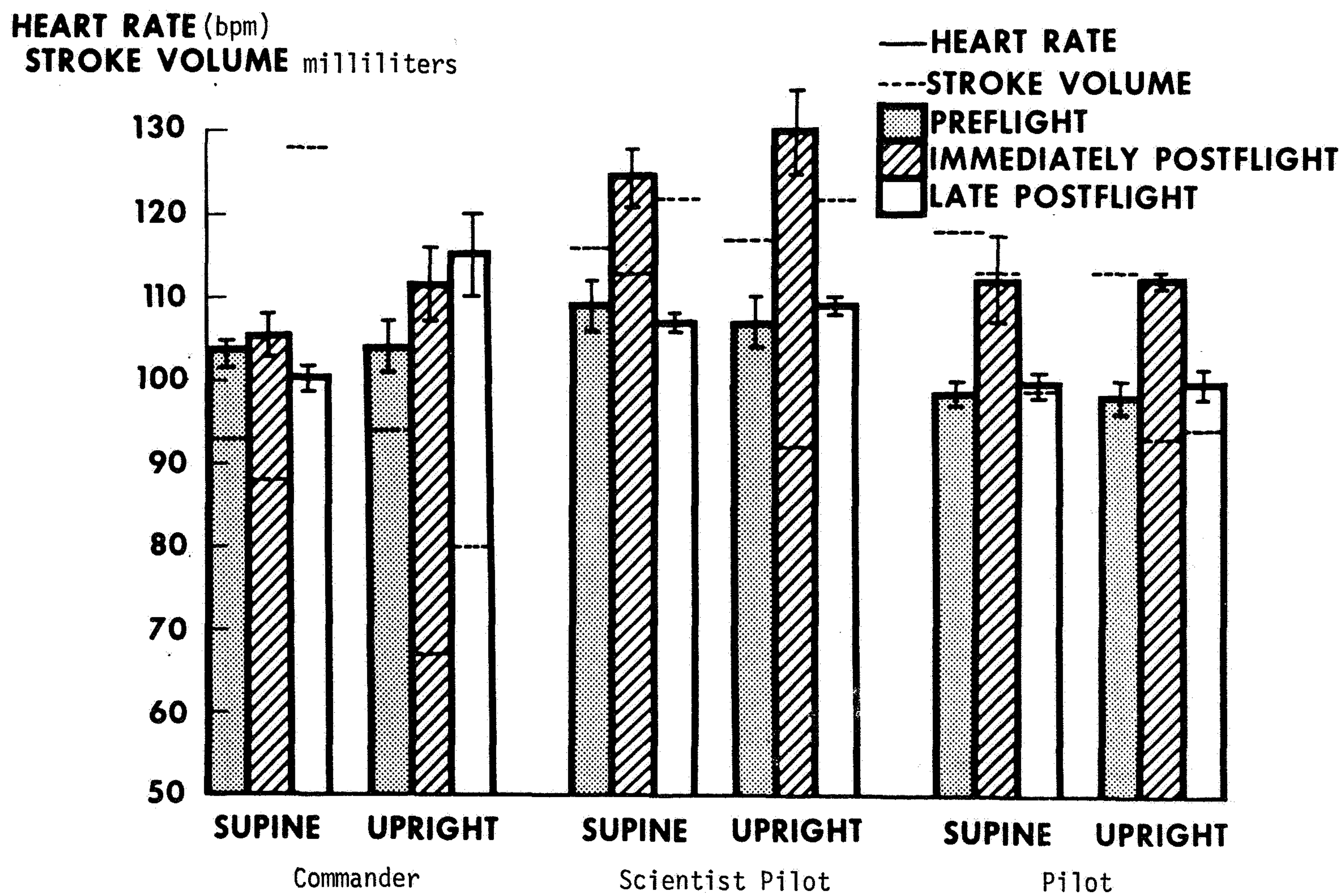


Figure 9. Skylab 4 supine ergometry (25 percent of maximum).

some yet unexplained reason the Commander exhibited a very marked response on one of his late postflight tests. All other late postflight tests were similar to baseline. On the other hand, stroke volume, as depicted by the dotted line, did show significant changes when the subject was positioned from the upright to the supine during immediate post flight exercise. Whereas the supine exercising values immediately postflight were within 5 milliliters of preflight, stroke volume decreased approximately 24 milliliters in all three crewmen upon assuming the upright position.

Table VI depicts what each Skylab crewman elected to do for personal exercise. After mission day 23 the crew reverted to negative reporting and only reported deviations from their selected protocols. As can be seen, each crewman selected a very vigorous personal exercise program which involved not only quantitative bicycle ergometry for stressing of the cardiovascular system but also the minigym, extensor springs, and "treadmill"; these exercises and exercise devices are described elsewhere (12). The latter three exercise devices were placed aboard for exercise of arm and leg antigravity muscles not adequately conditioned by bicycle ergometer exercise. These data will be further addressed when summarizing the differences in personal exercise habits of the various crewmen. Additionally, during Skylab 4 we obtained instrumented personal exercise periods on all crewmen (table VII). There had been no requirement for any instrumentation during personal exercise, however, in preflight discussions with the Skylab 4 crew they agreed to periodically instrument (vectorcardiograph/heart rate, blood pressure and metabolic analyzer) themselves. Measured heart rates and oxygen consumptions revealed that the crew had no difficulty in performing maximum levels of exercise during their personal exercise periods. Heart rates in the range of 180 to 185 beats per minute were observed during crew work loads of 240 to 286 watts. With regard to the $\dot{V}_{O_2}$ values normalized for body weight, there can be no doubt that the Skylab 4 crew did improve their physical condition during the course of the mission.

SUMMARY OF SKYLAB EXERCISE RESPONSE TESTING

Table VIII summarizes the performance of experiment M-171 during three Skylab Missions. A total of 82 tests were performed in-flight on the nine crewmen. All in-flight tests were completed as programed with the exception of the first in-flight tests on the Pilot and Scientist Pilot of Skylab 2. The Pilot's test was terminated two minutes and the Scientist Pilot's test four minutes into the third level of exercise due to ergometer restraint and environmental thermal problems.

TABLE VI. DAILY PERSONAL EXERCISE PROTOCOL SELECTED BY EACH SKYLAB 4 CREWMAN

EXERCISE	Commander	Scientist Pilot	Pilot
LEG ERGOMETRY (Watt min)	5000	8337	6000
MINIGYM (TOTAL REPETITIONS)	100	200	200
SPRINGS (TOTAL REPETITIONS)	75	0	120
TORSO ISOMETRICS (TOTAL REPETITIONS)	20	0	20
TREADMILL			
WALK (min)	10	0	0
RUN (min)	1	0	0
SPRINGS (REPETITIONS)	300	1000	100
TOE RISES (REPETITIONS)	200	200	75

TABLE VII. INSTRUMENTED MAXIMUM IN-FLIGHT ERGOMETRY

CREWMAN	MISSION DAY	WORKLOAD, Watts	$\dot{V}_{O_2}$ (liters/min)	$\dot{V}_{O_2}$ (cc/kg per min)	HEART RATE, (bpm)	$\dot{V}_E$ (liters/min)
Commander	(PREFLIGHT)		2.716	40	183	83
	21	240	3.041	45	181	106
	66	244	3.149	46.2	183	121
	79	242	2.930	42.5	184	115
Scientist Pilot	(PREFLIGHT)		3.423	48.9	183	89
	20	286	3.692	53.3	184	>142
	27	286	3.910	56.3	185	>138
	42	286	3.855	55.3	183	>150
	65	286			183	>140
	82	286	3.801	54.2	185	>147
Pilot	(PREFLIGHT)		3.182	47	183	119
	33	238	2.932	44.6	176	103
	37	230	2.932	44.2	178	137
	63	244	3.584	53.8	183	>150
	83	286	3.366	50.5	185	>150

TABLE VIII. EXPERIMENT M171 PERFORMANCE SUMMARY

	Commander	Scientist Pilot	Pilot
Skylab 2			
PREFLIGHT TESTS	5	5	5
IN-FLIGHT TESTS	6	6	7
POSTFLIGHT TESTS	8	7	9
Skylab 3			
PREFLIGHT TESTS	7	7	7
IN-FLIGHT TESTS	9	9	9
POSTFLIGHT TESTS	8	8	8
Skylab 4			
PREFLIGHT TESTS	8	8	8
IN-FLIGHT TESTS	12	12	12
POSTFLIGHT TESTS	8	8	8

Tables IX and X summarize the results for pulmonary efficiency ($\dot{V}_E$ at $2L\dot{V}_{O_2}$) or mechanical efficiency ($\dot{V}_{O_2}$ at 150 watts). The only significant changes in pulmonary efficiency in flight were observed in the Skylab 2 Pilot and the Skylab 4 Scientist Pilot. Postflight, only the Skylab 3 Scientist Pilot and Skylab 4 Scientist Pilot demonstrated a significant difference in pulmonary efficiency relative to preflight baseline. Thus, there appears to be no trend in these data that would indicate that space flight changes the pulmonary efficiency of the crews during submaximal exercise. Conversely, six of the nine crewmen demonstrated a small but statistically significant increase in in-flight mechanical efficiency and four of these six maintained this increased mechanical efficiency during the postflight test period. The exact reason for this is not known, but it might be a result of a training effect. This was unexpected in that one would expect mechanical efficiency, if changed, to decrease because of the restraint problems expected in the weightless environment.

TABLE IX. PULMONARY EFFICIENCY

$\dot{V}_E$ AT 2Liters $\dot{V}_{O_2}$

SKYLAB MISSION	TIME PERIOD	Commander $\bar{X}$	Commander SD	Scientist Pilot $\bar{X}$	Scientist Pilot SD	Pilot $\bar{X}$	Pilot SD
2							
	PREFLIGHT	51.8	3.78	59.8	3.68	59.6	2.16
	IN-FLIGHT	50.9	3.32	64.9	3.49	68.4	2.30*
	POSTFLIGHT	40.9	3.65	61.2	2.89	67.5	4.06
3							
	PREFLIGHT	57.6	7.73	49.4	3.46	56.8	3.69
	IN-FLIGHT	56.8	5.56	51.9	5.21	57.9	4.19
	POSTFLIGHT	55.3	3.66	54.8	1.96*	59.3	2.05
4							
	PREFLIGHT	54.7	3.15	48.8	1.80	60.4	2.53
	IN-FLIGHT	54.8	4.41	55.6	2.93*	62.9	3.71
	POSTFLIGHT	53.3	3.10	54.5	2.94*	62.4	2.67

*SIGNIFICANT AT $P<0.05$

$\dot{V}_E$ = Minute volume

$\dot{V}O_2$ = Oxygen consumption

SD = Standard deviation

TABLE X. MECHANICAL EFFICIENCY

$\dot{V}O_2$ AT 150 watts

SKYLAB MISSION	TIME PERIOD	Commander $\bar{X}$	Commander SD	Scientist Pilot $\bar{X}$	Scientist Pilot SD	Pilot $\bar{X}$	Pilot S
2							
	PREFLIGHT	2.07	0.09	2.07	0.22	2.10	0.069
	IN-FLIGHT	1.87	.10	1.83	.14	1.84	.05*
	POSTFLIGHT	2.05	.08	2.06	.08	2.00	.07
3							
	PREFLIGHT	2.04	0.11	2.01	0.07	2.02	0.17
	IN-FLIGHT	1.93	.08*	1.79	.27*	1.87	.07*
	POSTFLIGHT	1.93	.10	1.89	.05*	1.86	.06*
4							
	PREFLIGHT	1.96	0.09	1.94	0.05	2.11	0.11
	IN-FLIGHT	1.85	.09*	1.89	.08	1.88	.08*
	POSTFLIGHT	1.83	.05*	1.98	.10	1.90	.04*

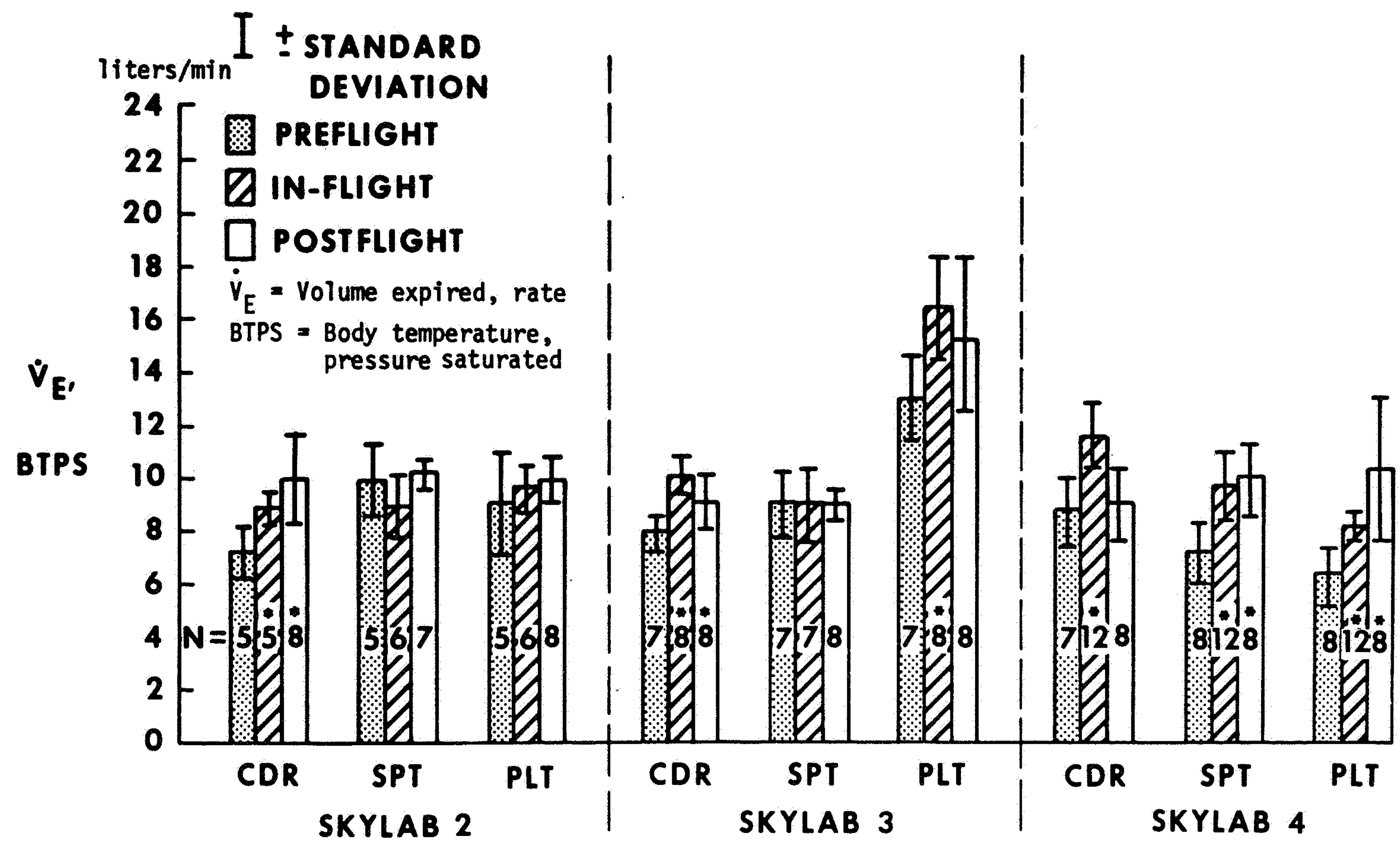
*SIGNIFICANT AT $P<0.05$

$\dot{V}O_2$ = Oxygen consumption
SD = Standard deviation

Generally, the in-flight and postflight responses to exercise by the crews of Skylab 2, 3 and 4 were similar. In-flight, some subtle, isolated differences were seen. However, there were no trends observed which would indicate a degradation in the exercise response of the crews. The Skylab 4 crew exhibited a significant in-flight decrease in recovery heart rate but not in resting (sitting position) heart rate. The Skylab 2 crew, on the other hand, exhibited decreases in both parameters while the Skylab 3 crew exhibited no changes in either. Figure 10, shows six of the nine crewmen had elevated resting ventilation in-flight which was maintained in five of these same individuals during the immediate postflight period. "Exercising" diastolic blood pressures were significantly decreased in flight in five of the crewmen while "exercising" in-flight oxygen consumption was slightly decreased in six crewmen (fig. 11 and 12).

Postflight, a significant decrement in response to exercise was noted in all crewmen. The degradation was evidenced by a decreased oxygen pulse (increased heart rate for a given oxygen consumption) as seen in figure 13. Additionally, a decreased cardiac output for the same oxygen consumption, and a decreased stroke volume were found. Significantly elevated resting ventilation was evidenced immediately postflight in both the Scientist Pilot and Pilot on Skylab 4 and the Commanders of Skylab 2 and 3.

Figures 14 and 15 summarize the cardiac output and stroke volume data for all three crews. Changes in blood flow during exercise subsequent to prolonged exposure to weightlessness were among the most consistent and striking findings of the Skylab medical experiments. The six astronauts who comprised the crews of Skylab Missions 2 and 3 exhibited large decreases in both cardiac output and stroke volume during exercise on the recovery day M-171 tests. At this time, the Skylab crewmen showed an average cardiac output deficit of 28 percent coupled with a 47 percent decline in stroke volume as compared to preflight values. For the Skylab 3 crew on the day of recovery, cardiac output was decreased by 35 percent and stroke volume was 45 percent lower than preflight. For both crews, the cardiac output values returned to within 15 percent of preflight by the second day after recovery while the stroke volume deficit required 8 to 16 days to return to within 15 percent of preflight values. However, stroke volume increased rapidly to within 80 percent of preflight during the first four postflight days. The percent changes in cardiac output and stroke volume were accompanied by changes in $A\text{-}VO_2$ differences of approximately equal magnitude but opposite direction.



*SIGNIFICANT DIFFERENCE FROM BASELINE ($p < 0.05$)

Figure 10. Resting minute volume.

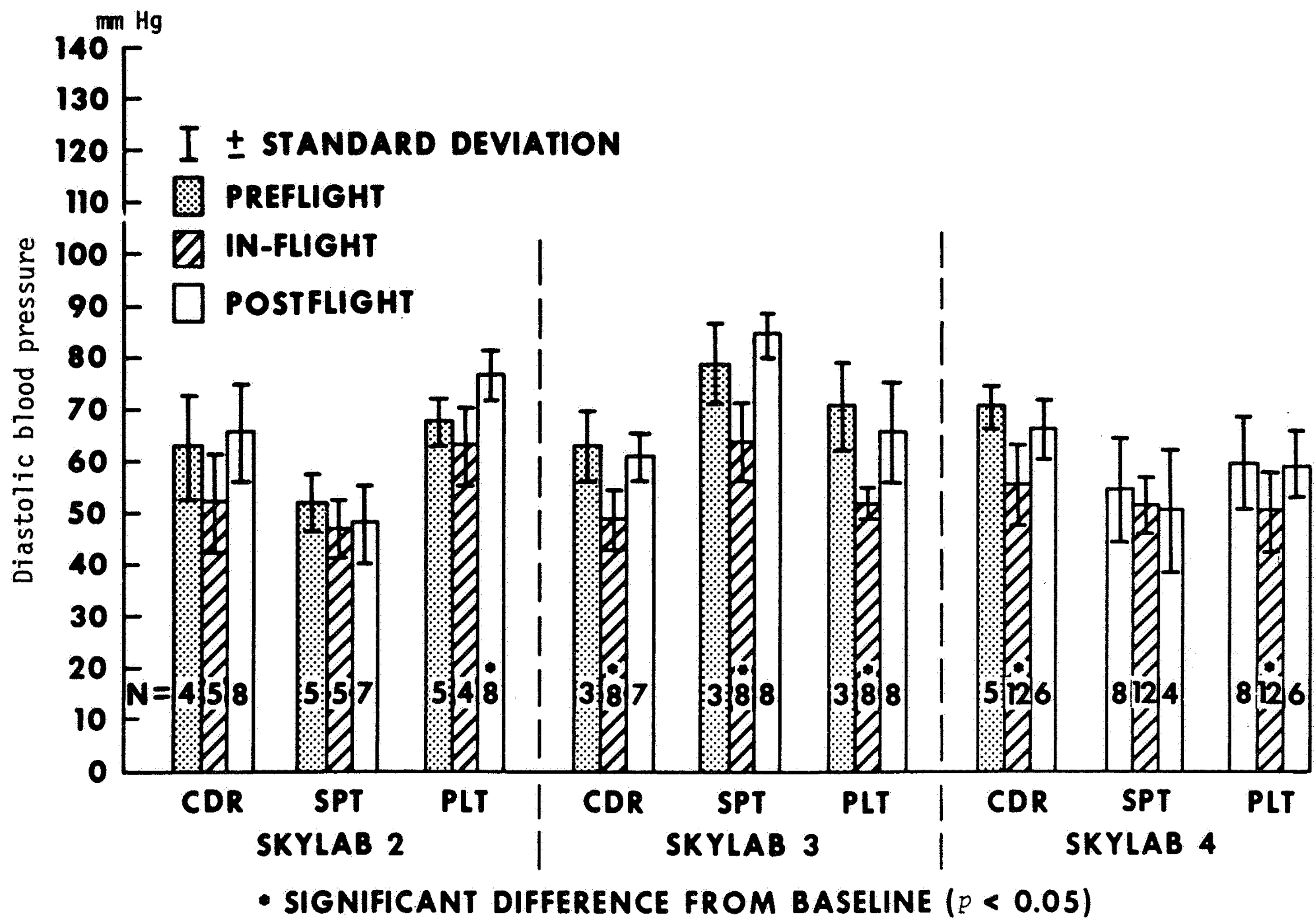


Figure 11. Diastolic blood pressure (level 3 exercise).

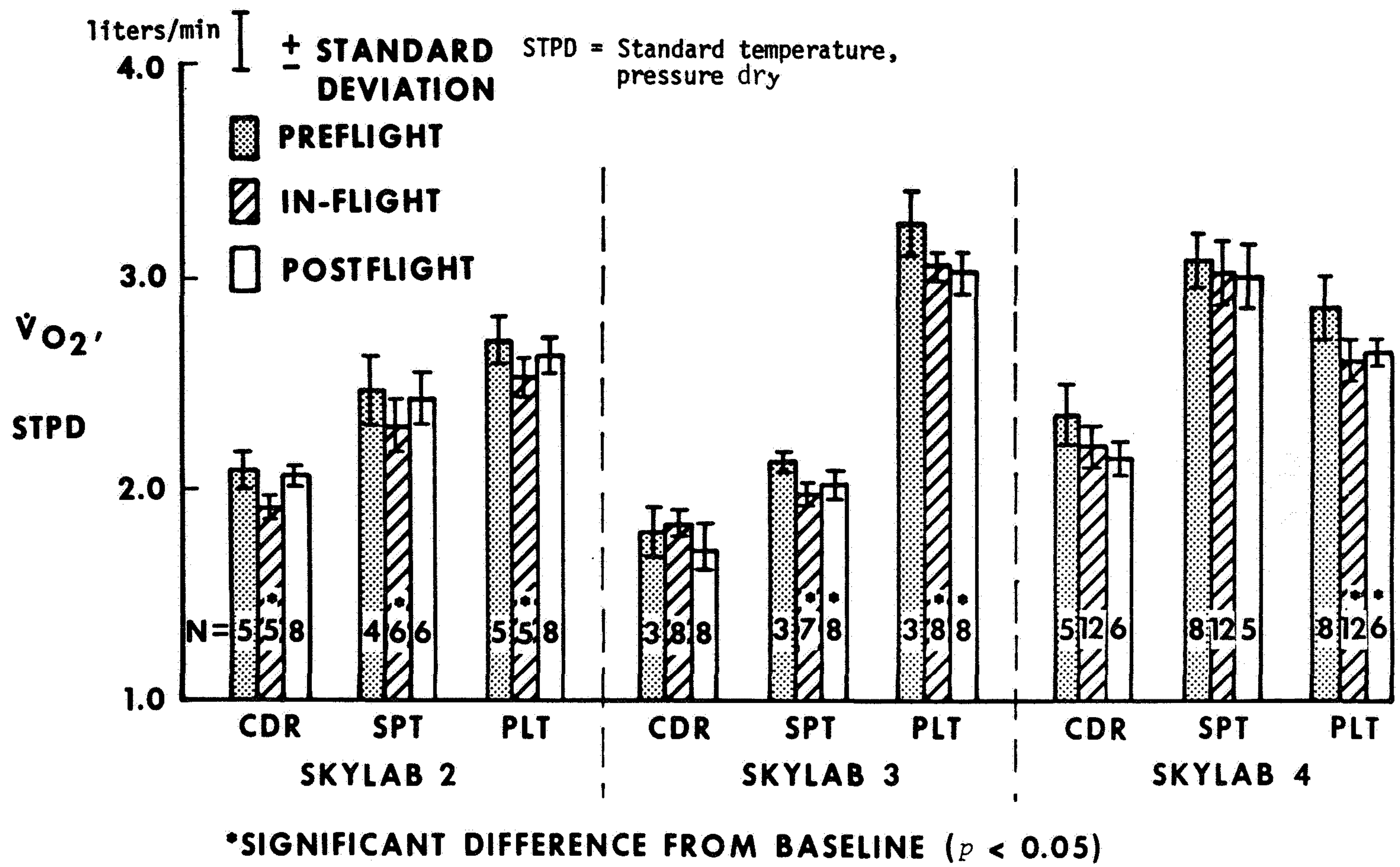


Figure 12. Oxygen Consumption, level 3 exercise.

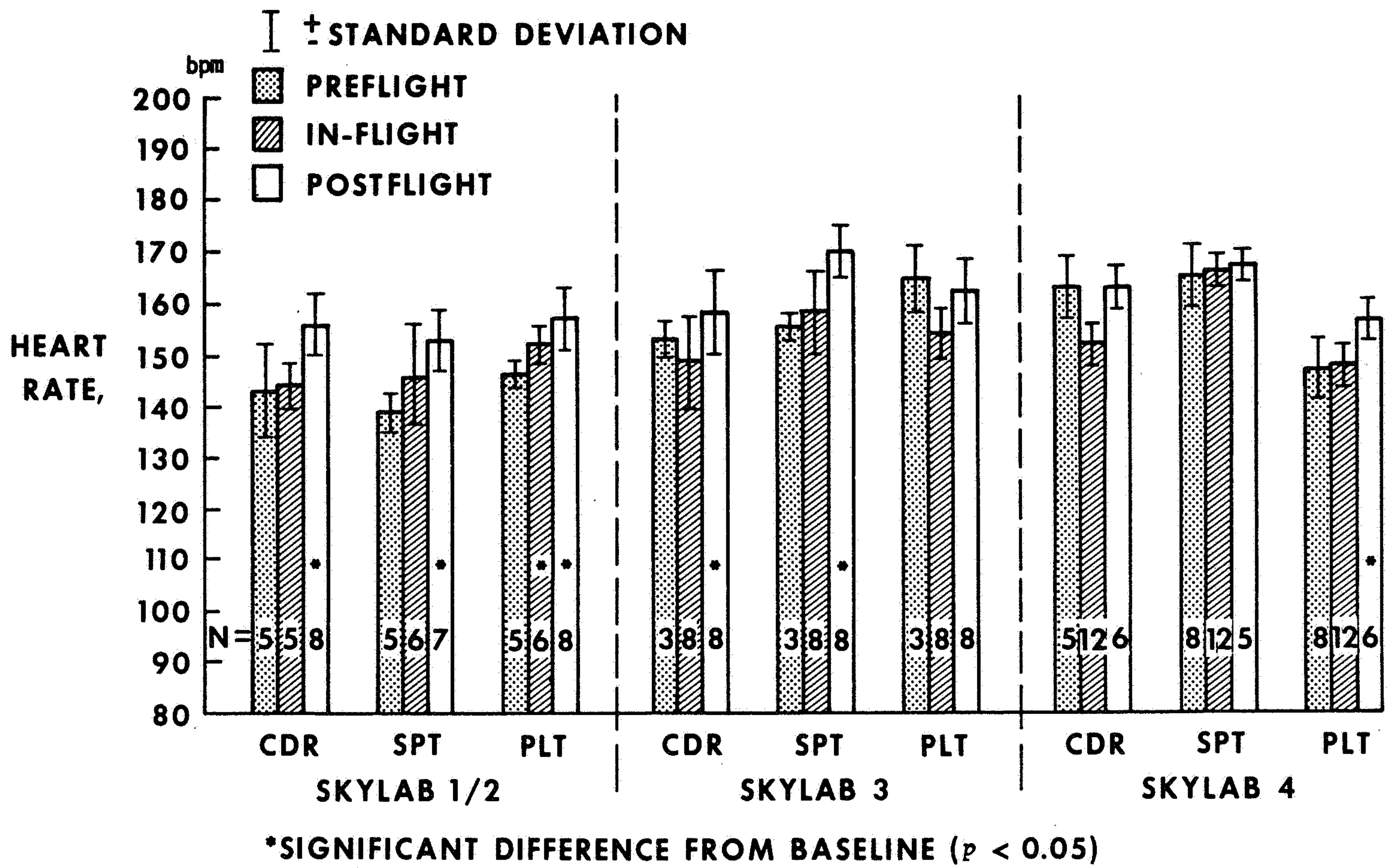


Figure 13. Heart rate, level 3 exercise.

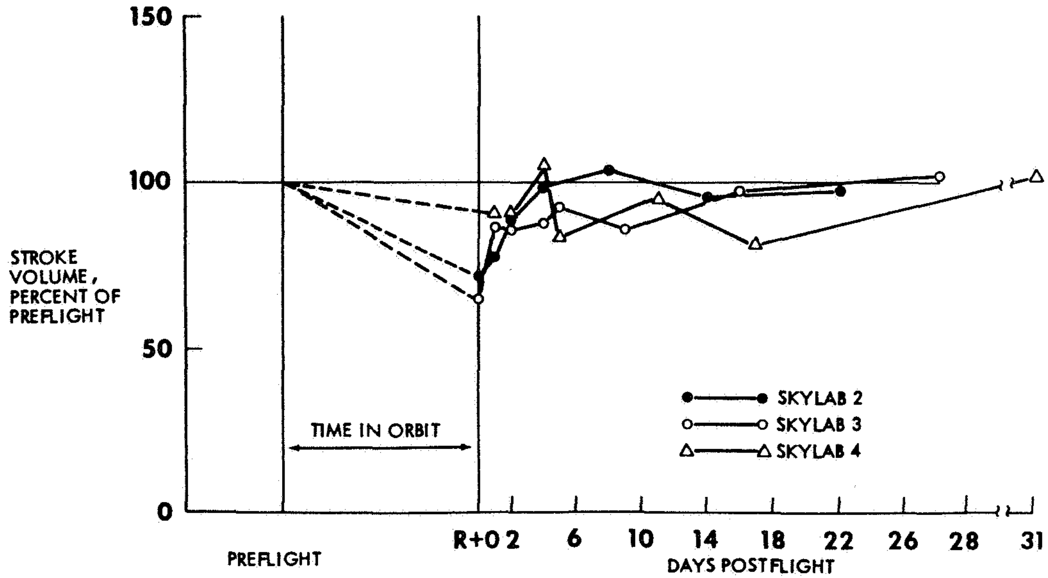


Figure 14. Cardiac output during submaximal exercise.

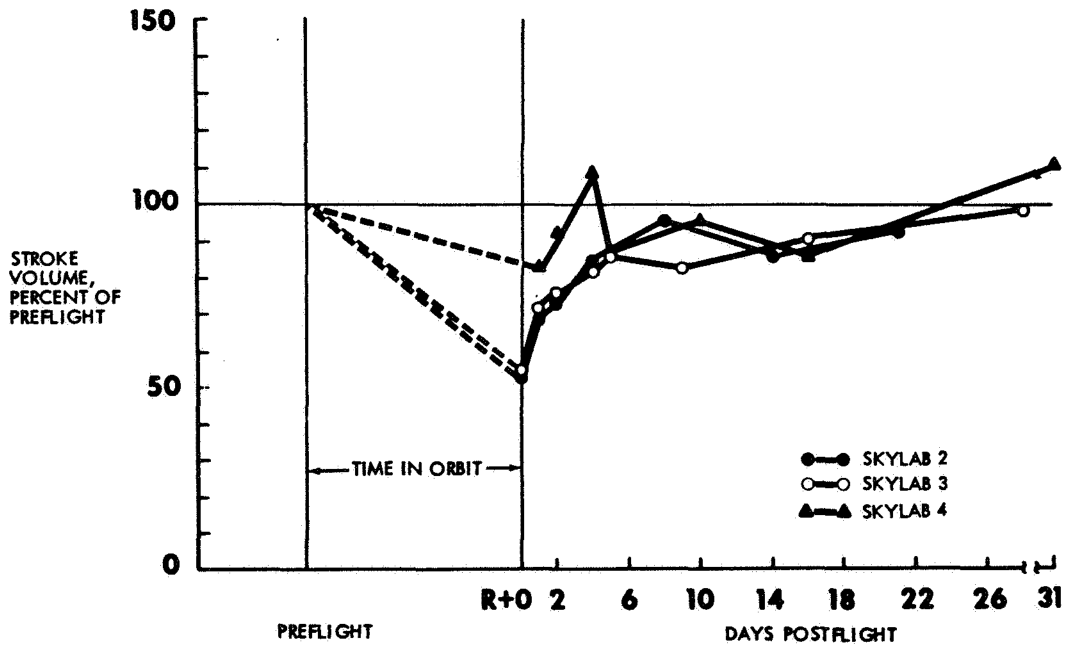


Figure 15. Stroke volume during submaximal exercise.

The present data collected on the Skylab crew would tend to implicate altered venous return as the cause of decreased cardiac output. The augmented stroke volumes noted during 30° tilt exercise reduce the likelihood that decreased myocardial function was the limiting process. Also, the rapid initial rise in both cardiac output and stroke volume over the first four postflight day would better parallel presumed readjustments in blood volume and vascular competence than would be expected if restorative processes were occuring in the myocardium.

In comparing the personal exercise levels of the various crews it becomes obvious that the amount of exercise accomplished in-flight was effective in maintaining a normal crew exercise response in-flight as well as in shortening the length of the postflight readaptation period. Table XI compares the quantitative bicycle ergometer exercise accomplished by the crews. Reference to the far right-hand column, showing these data normalized to the crewman's body weight, reveals that the Skylab 3 crew exercised about 107 percent more than the Skylab 2 crew and the Skylab 4 crew exercised 130 percent more than the Skylab 2 crew. Except for some isolated individual responses in the cardiac output and stroke volume data, all other parameters returned to normal in approximately 18 to 21 days for the Skylab 2 crew, 5 days for the Skylab 3 crew, and 4 days for the Skylab 4 crew. Based on these data there appears to be no correlation between the length of the postflight readaptation period and mission duration. It is interesting to note that the amount of exercise performed in-flight was inversely related to the length of time required postflight to return to preflight status.

TABLE XI. IN-FLIGHT QUANTITATIVE PERSONAL EXERCISE SUMMARY

SKYLAB MISSION		(1) TOTAL (watt min)	(2) DAILY avg (watt min)	(3) DAILY avg (watt min/kgm Body Weight)	
2					
	Commander	62 810	2 855	47	
	Scientist Pilot	45 307	1 618	21	31.3 avg
	Pilot	55 795	1 993	26	
3					
	Commander	228 581	3 874	58	
	Scientist Pilot	214 645	3 638	62	65 avg
	Pilot	386 193	6 545	75	
4					
	Commander	349 210	4 108	62	
	Scientist Pilot	469 420	5 523	80	72.3 avg
	Pilot	414 760	4 879	75	

(1) Includes M171 Experiment tests and personal exercise.

(2) Based on 28-day Skylab 2 mission, 59-day Skylab 3 mission, and 84-day Skylab 4 mission.

(3) Based on mean in-flight body weight.

As stated previously, the Skylab 4 results were somewhat different and are more appropriately depicted by examining the response of the individual Skylab 4 crewmen shown in figures 7, 8.

The data from the Skylab 4 Commander are similar to those seen in Skylab 2 and Skylab 3 crewmen although his return to normal was slower than the astronauts of Skylab missions 2 and 3.

The consistent postflight elevation in cardiac output and stroke volume for the Scientist Pilot of Skylab 4 may be a reflection of in-flight physical conditioning in this individual. His in-flight exercise regimen was rigorous, and it is likely that his measured preflight cardiac output and stroke volume values were not representative of his improved physical condition at the end of the orbital period. Thus, his immediate postflight values might well have been depressed and only fortuitously appeared to be the same as his preflight values. The upward trend in stroke volume during the latter days of postflight testing would seem to lend credance to the idea that his postflight "normal" levels were somewhat higher than preflight.

The results from the Skylab 4 Pilot are perhaps even more difficult to explain. His cardiac output and stroke volume values showed little or no change from preflight values during any of the postflight tests. From the first through the 17th day postflight both parameters showed a small downward trend but the overall magnitude of the trend is small enough to be of questionable significance. It is possible that his cardiovascular system was inherently nonresponsive to the weightless environment due to factors which we cannot define at this time.

The tilt ergometry testing accomplished preflight and postflight in the Skylab 4 mission demonstrated that immediate postflight supine heart rates were elevated both during rest and exercise. Although a tachycardia was observed in the upright position, the change in "exercising" heart rate was not nearly as pronounced as during rest. Both systolic and diastolic blood pressures were elevated in the upright position in at least two of the three Skylab 4 crewmen while data for the third crewman were not as clear-cut due to technical problems with the blood pressure measuring system postflight. During both the supine and upright postions reduced cardiac output was observed immediately postflight for the same stress level. However, the decrease was less in the supine position. These results on highly active crewmen cannot be directly compared with the limited studies accomplished after complete bed rest in which supine exercising stroke volumes were greatly reduced (2, 4).

The secondary objective of the M-171 experiment was to evaluate the bicycle ergometer as an in-flight exerciser for long-duration missions. Upon exposure to the weightless environment, the crews commented on a "fullness in the head" feeling and sinus problems which never really subsided. The crews have reported that the bicycle ergometer exercise provided relief from these subjective feelings, which partially explains the strong desire for the crewmen to exercise. The heavy leg exercise evidently facilitated the return of the blood to the lower extremities thus relieving their symptoms. The bicycle ergometer proved to be a very effective stressor of the cardiovascular system. If it were to be the exerciser chosen for long-duration missions, additional provision would have to be made for maintaining muscular strength in those anti-gravity muscles not adequately exercised by the bicycle ergometer.

CONCLUSIONS

Immediately postflight all crewmen showed a significant decrement in submaximal exercise response. The degradation was, in large part, evidenced by decreases in oxygen pulse, cardiac output, and stroke volume. Since similar in-flight effects were neither observed nor suspected, it is apparent that these physiological responses were a result of readaptation to one-g. Furthermore, it appears that the responses we observed resulted from decreased venous return due to re-adjustments in fluid balance/blood volume state or vascular tone. This postflight readaptation period was of short duration, was not intensified by the duration of the mission, and resulted in no irreversible effects.

Although personal exercise was not experimentally controlled during the Skylab Program, qualitative comments by the crewmen indicated that they derived some psychological benefits from these activities. In addition, given the known physiological effects of high levels of physical activity that occur in normal gravity, it would not be unreasonable to assume that in-flight exercise had a beneficial effect not only in the maintenance of a normal in-flight response to exercise and well being but also in reducing the period of time required for readaptation post flight. However, this hypothesis must be evaluated by proper experimentation. In the meantime, we will recommend exercise as a beneficial adjunct to space flight.

The successful completion of the 28-, 59-, and 84-day Skylab Missions showed that man can perform submaximal and maximal aerobic exercise in the weightless environment without detrimental trends in any of the physiologic data.

ACKNOWLEDGEMENT

Evaluation of the bicycle ergometer hardware used for the Skylab Program M171 Experiment and personal exercise showed that it was utilized approximately 248 hours in flight and the metabolic analyzer was utilized approximately 100 hours in-flight without malfunction in either device; thus, all experimental data were obtained as programed without failure. The outstanding performance of these pieces of hardware was further amplified by the successful usage of these two devices by the crewmen in their in-flight performance of 82 M171 experiment tests by and on themselves. The outstanding performance of the crewmen indicates their dedication in light of the complexity of the hardware operation and their extremely busy schedules.

This retrospective review of the successful completion of the Metabolic Activity portion of the Skylab Program experiments prompts the authors to express, here, their appreciation to the Skylab astronauts and to Mssers. R. E. Heyer, J. M. Waligora, D. J. Horrigan, H. S. Sharma, P. Schlottman of NASA-JSC and Messers. P. Schachter (Ph.D) and D. G. Mauldin of Technology Incorporated for their respective contributions and invaluable assistance in the six years of effort in design, development and performance of this experiment for Skylab. We also wish to acknowledge the counsel and encouragement of Dr. U. C. Luft of the Lovelace Foundation for Medical Education and Research.

REFERENCES

1. Cardus, D. 1966. Effects of 10 days recumbency on the response to the bicycle ergometer test. *Aerospace Med.*, 37: 993-999.

2. Hyatt, K. H., L. G. Kamenetsky, and W. M. Smith. 1969. Extravascular dehydration as an etiologic factor in post-recumbency orthostatism. *Aerospace Med.*, 40: 644-650.

3. Miller, P. B., R. L. Johnson and L. E. Lamb. 1965. Effects of moderate physical exercise during four weeks of bed rest on circulatory functions in man. *Aerospace Med.*, 36: 1077-1082.

4. Saltin, B., G. Blomquist, J. H. Mitchell, R.L. Johnson, Jr., K. Wildenthal and C. B. Champman. 1968. Response to exercise after bed rest and after training. A longitudinal study of adaptive changes in oxygen transport and body composition. *Circulation*, 38: 1-78.

5. Berry, Charles A. 1969. Preliminary clinical report of the medical aspects of Apollos VII and VIII. *Aerospace Med.*, 40: 245-254.

6. Berry, Charles A. 1970. Summary of medical experience in the Apollo 7 through 11 manned space flights. *Aerospace Med.*, 41: 500-519.

7. Rummel, J. A., E. L. Michel and C. A. Berry. 1973. Physiological response to exercise after space flight - Apollo 7 to Apollo 11. *Aerospace Med.*, 44: 235-238.

8. Michel, E. L., J. A. Rummel and C. F. Sawin. 1974. Skylab Experiment M-171 "Metabolic Activity": Results of the First Manned Mission, *Acta Astronautica*, (in press).

9. Rummel, J. A., E. L. Michel, C. F. Sawin and M. C. Buderer. 1974. Metabolic Studies During Exercise: The Second Manned Mission, *Aerospace Med.*, (in press).

10. Kim, T. S., H. Rahn and L. E. Farhi. 1966. Estimates of true venous and arterial P_{CO_2} by gas analysis of a single-breath. *J. Appl. Physiol.*, 21: 1338-1344.

11. Buderer, M. C., J. A. Rummel, C. F. Sawin and D. G. Mauldin. 1973. Use of the single-breath method of estimating cardiac output during exercise-stress testing. *Aerospace Med.*, 44: 756-760.

12. Thornton, W. and J. Rummel. 1974. Measurement and Prevention of Muscle Deconditioning on Skylab. Presented at Skylab Life Sciences Symposium, Johnson Space Center, Houston, Texas.

APPENDIX

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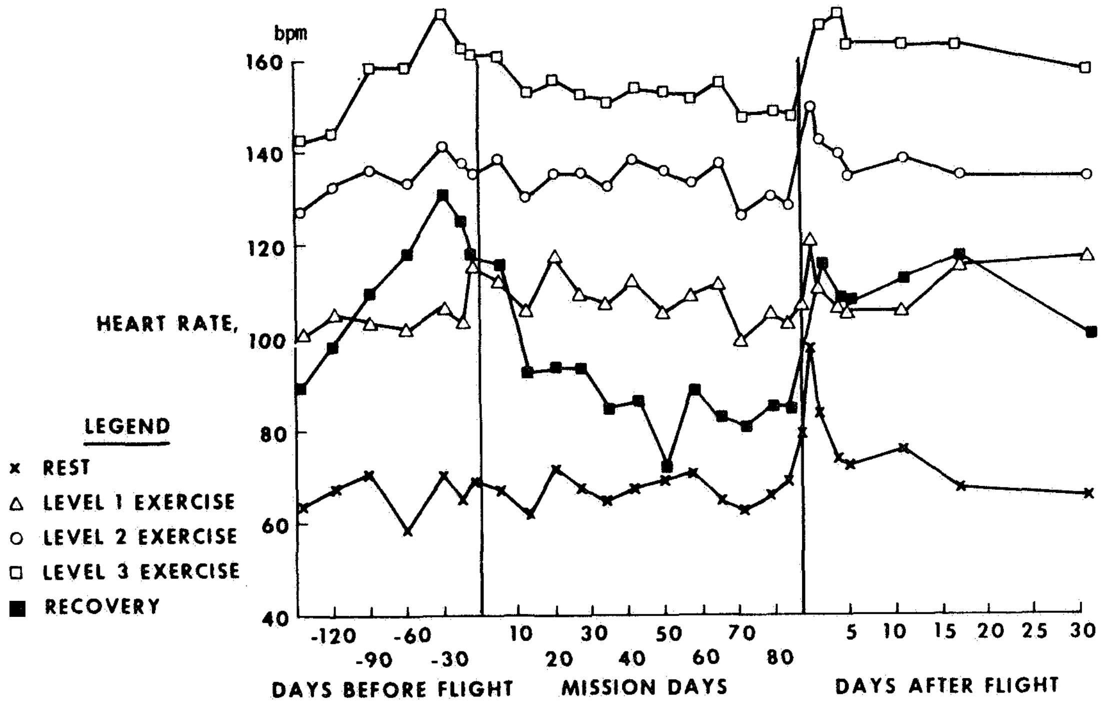

Figure 1A. Heart rate, Skylab 4 Commander.

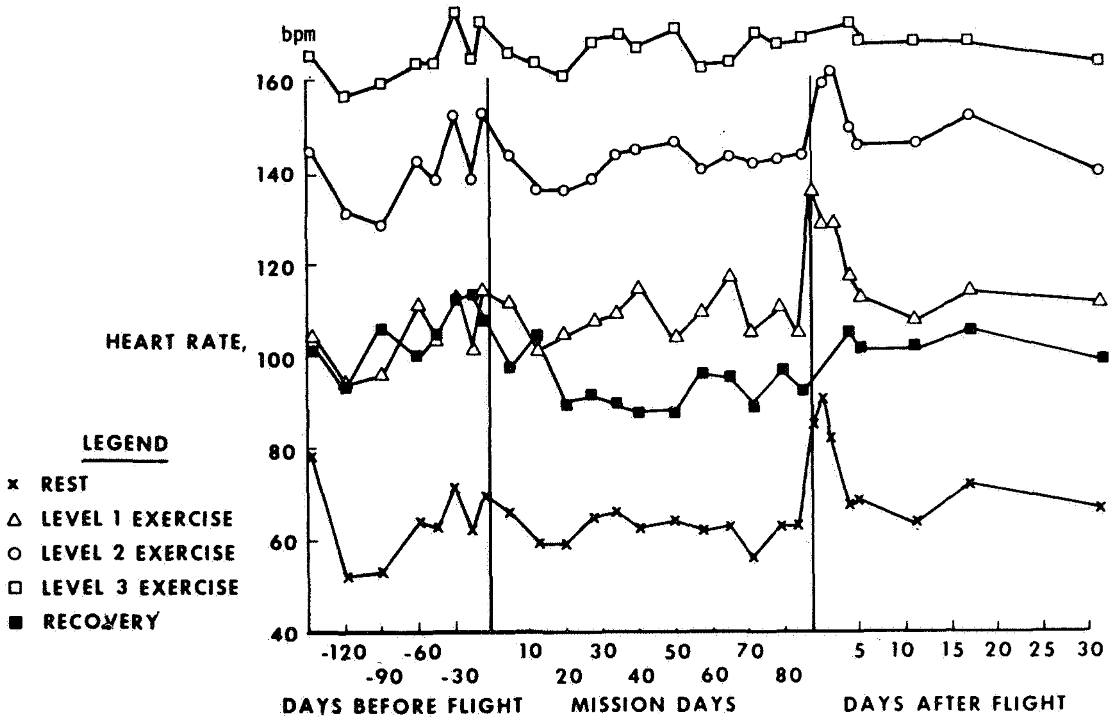

Figure 1B. Heart rate, Skylab 4 Scientist Pilot.

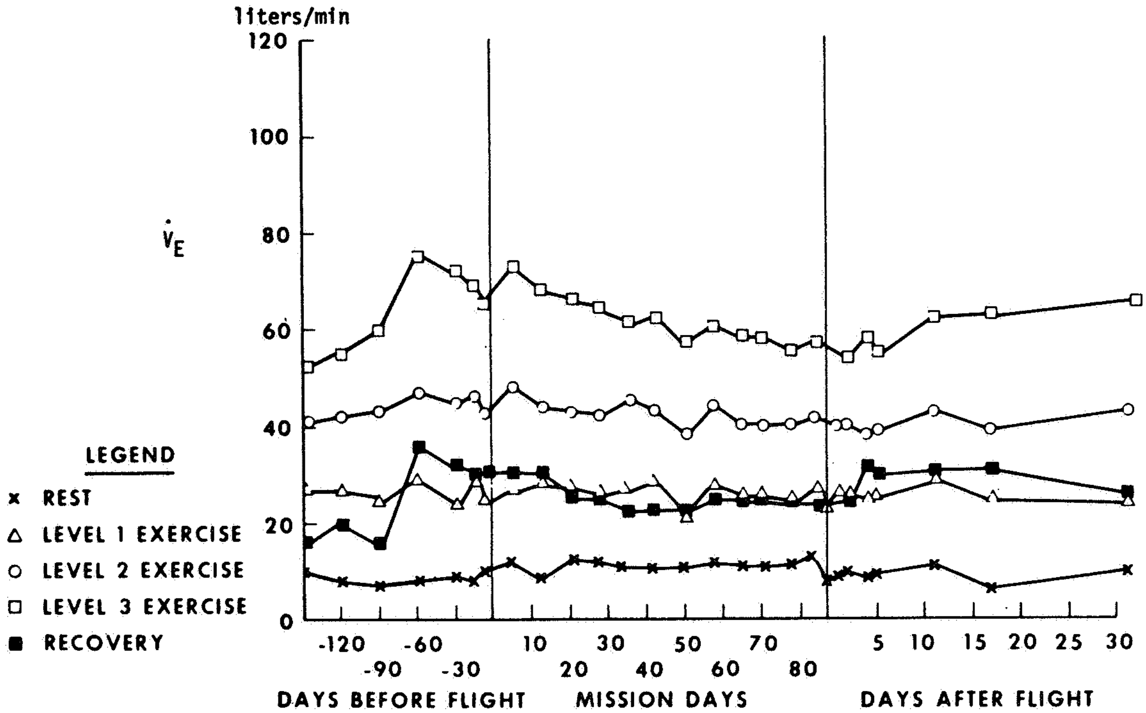

Figure 2A. $\dot{V}_E$, Skylab 4 Commander.

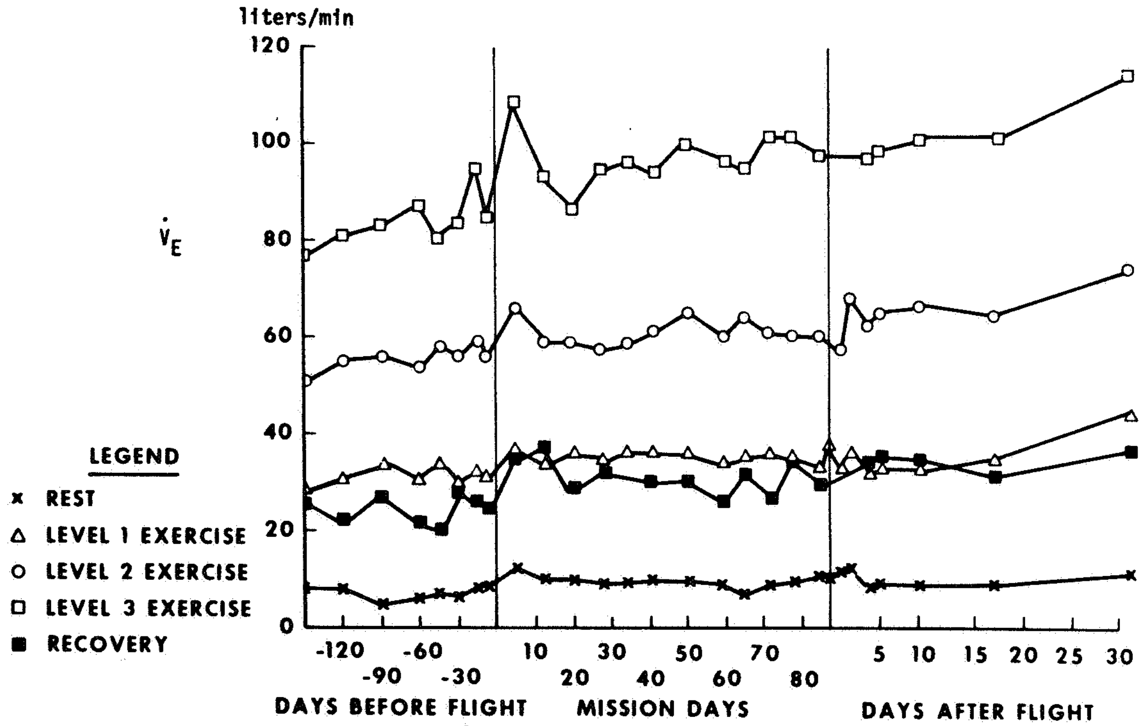

Figure 2B. $\dot{V}_E$, Skylab 4 Scientist Pilot.

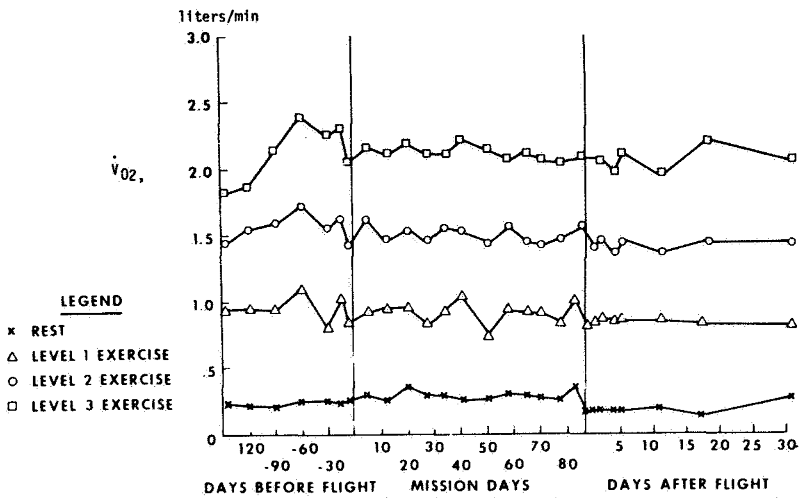

Figure 3A. $\dot{V}_{O_2}$, Skylab 4 Commander.

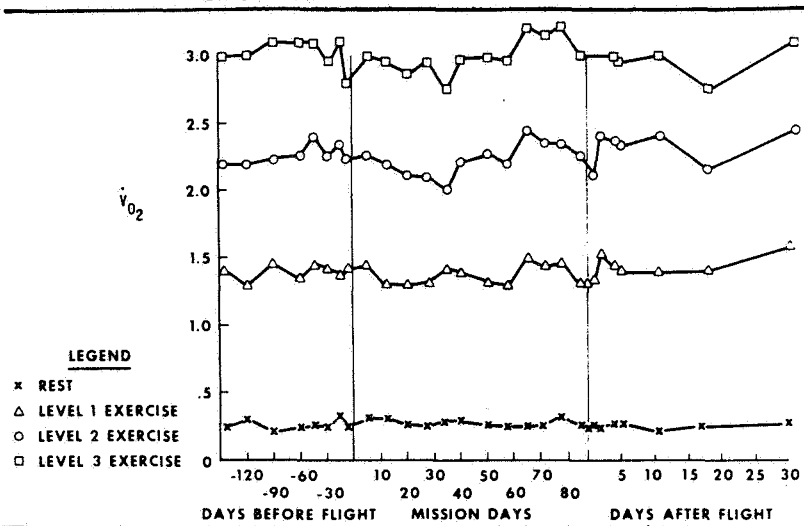

Figure 3B. $\dot{V}_{O_2}$, Skylab 4 Scientist Pilot.

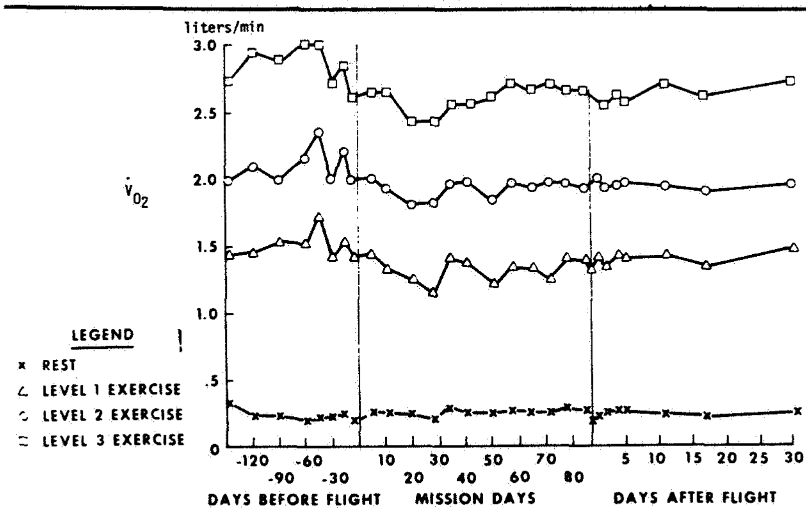

Figure 3C. $\dot{V}_{O_2}$, Skylab 4 Pilot.

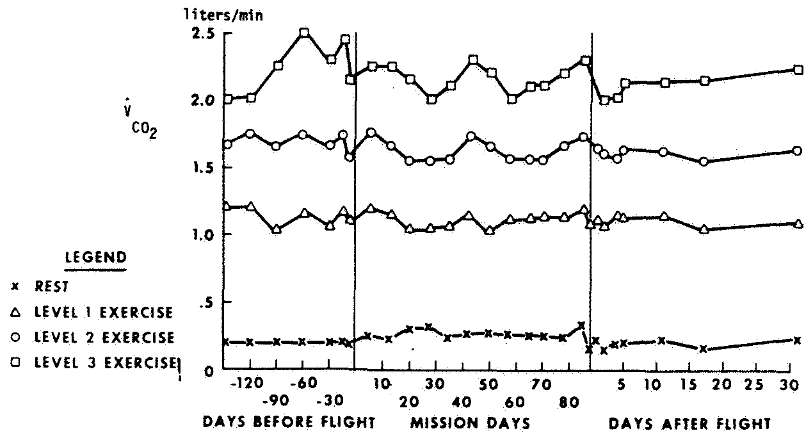

Figure 4A. $\dot{V}_{CO_2}$, Skylab 4 Commander.

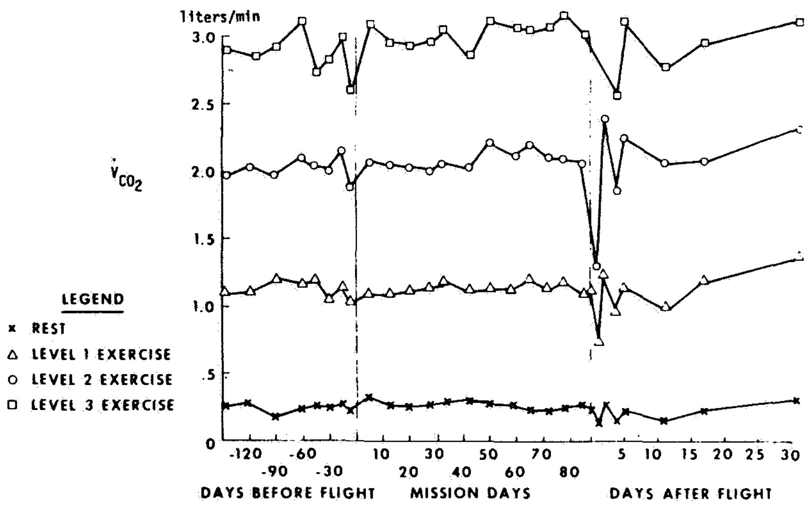

Figure 4B. $\dot{V}_{CO_2}$, Skylab 4 Scientist Pilot.

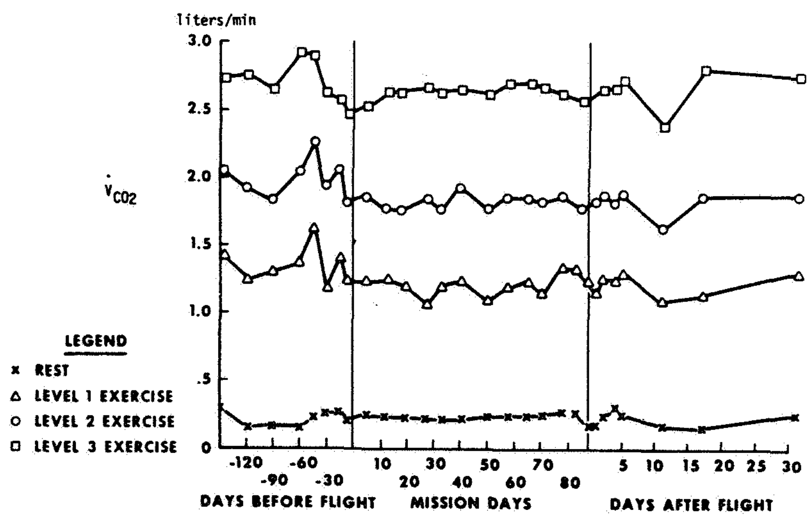

Figure 4C. $\dot{V}_{CO_2}$, Skylab 4 Pilot.

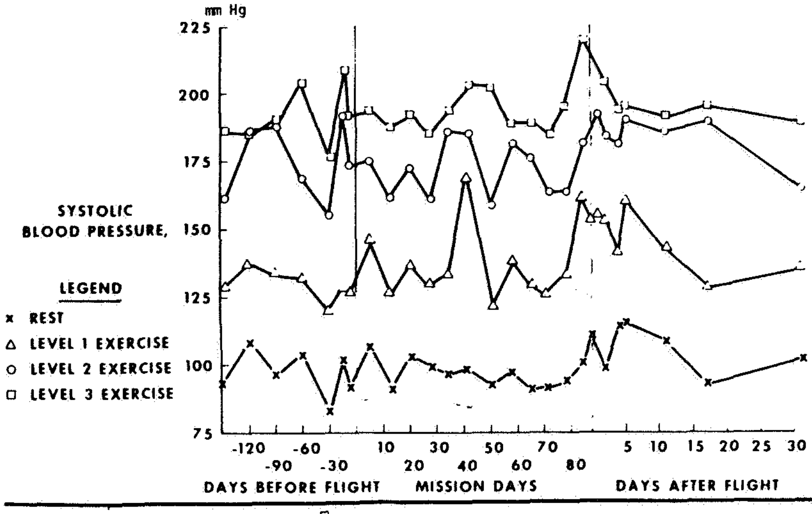

Figure 5A. Systolic blood pressure, Skylab 4 Commander.

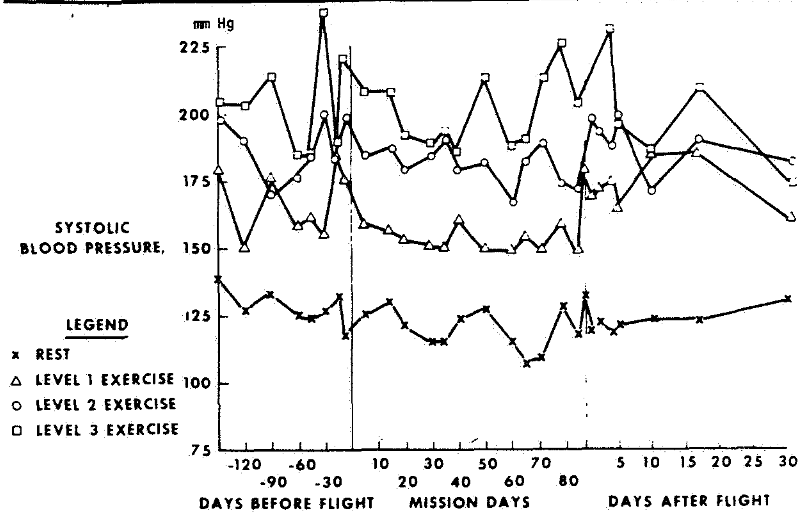

Figure 5B. Systolic blood pressure, Skylab 4 Scientist Pilot.

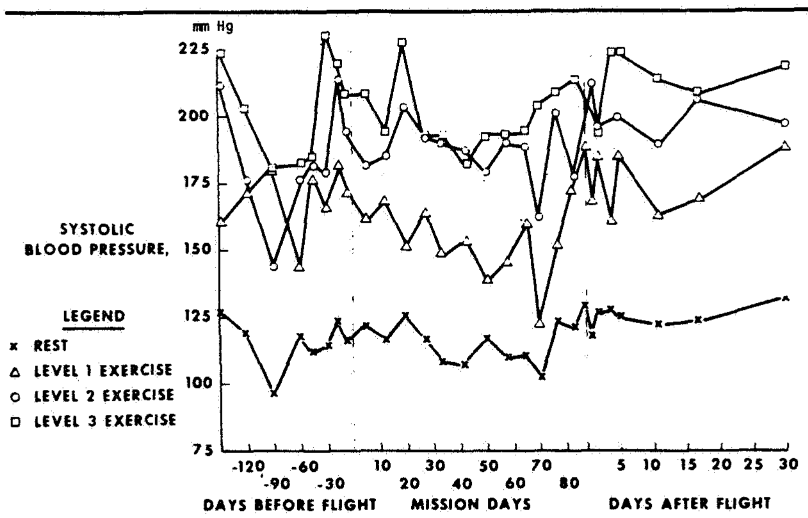

Figure 5C. Systolic blood pressure, Skylab 4 Pilot.