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Effect of In-Flight Exercise and Extravehicular Activity on Postflight Stand Tests

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Acronyms and Nomenclature

ANOVA	analysis of variance
bpm	beats per minute
BP	blood pressure
d	day(s)
DBP	diastolic blood pressure
deg	degree
EVA	extravehicular activity
G	gravity
HI_{ex}	high
hr	hour(s)
HR	heart rate
HR_{max}	maximum heart rate
L	liter
LBNP	lower body negative pressure
LO_{ex}	low
MAP	mean arterial pulse
MED_{ex}	medium
min	minute(s)
mmHg	milligrams of mercury (pressure reading)
POST	after landing
PP	pulse pressure
PRE	prior to launch
SBP	systolic blood pressure
SE	standard error
sec	second(s)

ABSTRACT

The purpose of this study was to determine whether exercise performed by Space Shuttle crewmembers during short-duration spaceflights (9-16 d) affects the heart rate (HR) and blood pressure (BP) responses to standing within 2-4 hr of landing. Thirty crewmembers performed self-selected in-flight exercise and maintained exercise logs to monitor their exercise intensity and duration. A 10-min stand test, preceded by at least 6 min of quiet supine rest, was completed 10-15 d before launch (PRE) and within four hours of landing (POST). Based upon their in-flight exercise records, subjects were grouped as either high (HI_{ex}: = 3x/week, HR = 70% HR_{max}, = 20 min/session, n = 11), medium (MED_{ex}: = 3x/week, HR = 70% HR_{max}, = 20 min/session, n = 10), or low (LO_{ex}: = 3x/week, HR and duration variable, n = 11) exercisers. HR and BP responses to standing were compared between groups (ANOVA, or analysis of variance, $P \leq 0.05$). There were no PRE differences between the groups in supine or standing HR and BP. Although POST supine HR was similar to PRE, all groups had an increased standing HR compared to PRE. The increase in HR upon standing was significantly greater after flight in the LO_{ex} group (36 ± 5 bpm) compared to HI_{ex} or MED_{ex} groups (25 ± 1 bpm; 22 ± 2 bpm). Similarly, the decrease in pulse pressure (PP) from supine to standing was unchanged after spaceflight in the MED_{ex} and HI_{ex} groups, but was significantly less in the LO_{ex} group (PRE: -9 ± 3; POST: -19 ± 4 mmHg). Thus, moderate to high levels of in-flight exercise attenuated HR and PP responses to standing after spaceflight compared.

I. INTRODUCTION

Postflight orthostatic intolerance is a consistent finding among Space Shuttle crewmembers (1, 2, 3). Fluid loading before reentry and the inflation of an anti-orthostatic lower body pressure garment (G-suit) during gravitational stress are two countermeasures to postflight orthostatic intolerance which are currently required on a routine basis (Space Shuttle Operational Flight Rules, NSTS 12820, Vol. A. Section 13: Aeromedical, 1996). However, fluid-loading alone does not completely maintain postflight orthostatic responses, even after short-duration flights (4). Seventeen crewmembers who employed the fluid loading countermeasure after spaceflights of 54 hr to 92 hr had lower standing heart rates (HR) compared to nine controls. However, the postflight standing HR of the fluid-loading subjects still was significantly greater (24%) than preflight. Further, Fritch-Yelle et al. (3) found no significant differences in plasma volume between crewmembers who became presyncopal during standing on landing day and those who did not. The anti-G-suit has been shown to increase stroke volume and cardiac output during standing (5) and to increase +Gz stress tolerance during acceleration in high-performance aircraft (6). Unfortunately its use may be detrimental during emergency egress since the G-suit severely restricts mobility during ambulation and increases the metabolic cost of walking (7). A countermeasure to postflight orthostatic intolerance is desired which would have the benefits of the G-suit without its limitations.

Current NASA flight rules require crewmembers on missions greater than 10 d to perform in-flight exercise to protect emergency egress abilities (Space Shuttle Operational Flight Rules, NSTS 12820, Vol. A, Section 13: Aeromedical: 13-57, 1996). The Shuttle flight crew (commander, pilot, and flight engineer) are required to exercise every other day during a nominal Space Shuttle mission. Mission and payload specialists are required to exercise every third day, although every other day is preferred if the work schedule allows. Although the frequency of exercise is defined, the exercise duration and intensity are not delineated.

The effect of exercise on orthostatic tolerance is somewhat controversial. In cross-sectional and training studies in ambulatory subjects, exercise capacity has been shown to have no effect, a detrimental effect, or a positive influence on orthostasis (8). After real or simulated microgravity exposure, orthostatic intolerance has been associated with reduced plasma and blood volume, increased heart rate during orthostatic stress, lower standing stroke volume and cardiac output, decreased responsiveness of the carotid baroreceptor cardiac reflex, and increased leg compliance (9). Exercise during spaceflight may serve as an effective countermeasure to each of these potential contributing mechanisms to orthostatic intolerance.

The purpose of this study was to determine the effect of self-selected in-flight exercise on the cardiovascular responses to standing after spaceflight. Secondarily, we examined pre- and postflight stand test responses of a small number of crewmembers who performed extravehicular activities (EVAs). Specifically, we hypothesized that crewmembers who performed the greatest quantity of in-flight exercise (at least three times per week for 20 minutes per session at an exercise intensity equal to or greater than 70% of age-predicted maximum HR) would have smaller changes in HR and blood pressure (BP) responses during a 10-min stand test after spaceflight than those who exercised less frequently and/or less intensely.

II. METHODS

Stand tests were performed before and immediately after spaceflights of 9-16 d by 30 astronaut volunteers, with two subjects participating twice on separate flights. Subject characteristics, including previous flight experience, are displayed in Table 1. Data from an additional four subjects who performed only EVAs in flight also were examined. None of the other crewmembers participated in EVAs during their flights. All procedures were reviewed and approved by the NASA-Johnson Space Center Institutional Review Board. Crewmembers were presented with a verbal and written explanation of all procedures and signed a statement of informed consent.

Table 1: Subject Characteristics

Group	LO_{ex}	MED_{ex}	HI_{ex}	EVA
Gender	10 males, 1 female	10 males	8 males, 3 females	3 males, 1 female
Pilot/Commander	5	8	6	0
Mission/Payload Specialists	6	2	5	4
First Time Flyers	2	4	4	0
Operational Stand Test	5	7	6	4
Research Stand Test	6	3	5	0
Age (yrs)	42 ± 2	43 ± 1	40 ± 2	48 ± 4
Flight Duration (days)	10.8 ± 0.6	11.2 ± 0.7	9.8 ± 0.4	10
Height (cm)	178.0 ± 1.8	183.2 ± 1.6	173.0 ± 4.3	175.9 ± 5.2
Preflight Weight (kg)	75.3 ± 1.3	80.5 ± 1.8	72.7 ± 5.1†§	70.8 ± 4.9
Weight Loss During Flight (kg)	-1.8 ± 0.5	-0.9 ± 0.5	-0.5 ± 0.2†	-0.6 ± 0.8

† Significantly different ($P < 0.05$) from LO_{ex} group
§ Significantly different ($P \leq 0.05$) than MED_{ex} group

Each crewmember completed a stand test 10 to 15 d before launch and within 2 to 4 hr after landing. All preflight stand tests were completed at NASA-Johnson Space Center in Houston, Texas. Postflight stand tests were conducted either at NASA-Kennedy Space Center, Florida, or at the Dryden Flight Research Center at Edwards Air Force Base, California. Crewmembers self-selected in-flight exercise regimens, and were grouped retrospectively during data analysis according to the intensity, duration, and frequency of exercise they performed.

A. Stand Test

Stand tests were performed using one of two protocols. One set of data (n = 22) was obtained using the "operational" protocol, a stand test which was routinely administered to crewmembers returning from a Shuttle mission. Subjects in this category were supine for 6 min before standing. Subjects in the second data set (n = 13) participated in a research protocol which required that they were supine for at least 30 min before standing. The distribution of crewmembers participating in each test by subject group is displayed in Table 1. All subjects were supine for the same amount of time after flight as they were before flight.

At the completion of the supine portion of each protocol, crewmembers were assisted by test operators to a free standing position with their feet approximately 15 cm apart where they remained for a period of 10 min or until signs or symptoms of pre-syncope occurred. Subjects who became presyncopal were immediately returned to the supine position, and the test was terminated. Presyncope was defined as any of the following: a sudden drop in systolic blood pressure (SBP) greater than 25 mmHg/min, a sudden drop in diastolic blood pressure (DBP) greater than 15 mmHg), a sudden drop in HR greater than 15 bpm, an absolute SBP less than 70 mmHg, dizziness, lightheadedness, or nausea.

HR was recorded from a 3-lead electrocardiogram during the last 15 sec of each min. SBP and DBP were measured by the auscultatory method by a trained technician during the last 30 sec of each minute. Mean arterial (MAP = 1/3 SBP +2/3 DBP) and pulse pressures (PP = SBP - DBP) were calculated from SBP and DBP measurements. Heart rhythm and change in BP in the finger (Finapres, Ohmeda, Inc.) were monitored continuously for signs of presyncope, but were not used for subsequent data analysis.

B. Pre- and In-Flight Exercise

Crewmembers self-selected exercise before and during spaceflight. To document the exercise performed, crewmembers recorded HR each 15 sec during their exercise sessions using a HR monitor (Vantage XL, Polar, Inc., Stamford, CN) previously validated in our laboratory and during spaceflight (10). They also maintained a written exercise log of their activities. Data files from the HR monitor were downloaded and analyzed postflight. The average HR during each exercise session was compared against the subject's age-predicted maximal HR to estimate exercise intensity. The frequency of exercise was normalized as the number of exercise sessions completed in a 7-d period.

Before flight, crewmembers wore a HR monitor during exercise sessions and maintained an exercise log for approximately 25-30 d before launch. Exercise performed by these subjects was primarily running or jogging, but also included some cycling, rowing, and swimming.

During spaceflight, crewmembers exercised primarily on a semi-recumbent cycle ergometer (Innovision, Inc., Denmark) that was specifically designed for use in microgravity. Three crewmembers on one flight performed all their in-flight exercise on experimental versions of the new flight treadmill and rower ergometer.

Crewmembers were grouped retrospectively for statistical analysis based upon their in-flight exercise routines. Subjects in the high exercise group (HI_{ex}) exercised at least three times per week at an average exercise intensity greater than 70% of age-predicted maximum HR for an average of at least 20 min per session. Subjects in the medium exercise group (MED_{ex}) exercised at least three times per week at an average exercise intensity less than 70% of age-predicted maximum HR for an average of at least 20 min per session. Subjects in the low exercise group (LO_{ex}) exercised less than three times per week and their exercise intensity and duration varied. Of the three subjects who performed in-flight exercise on the prototype treadmill and rower, two were in the MED_{ex} group and one was in the LO_{ex} group.

Of the four subjects in the EVA group, three subjects performed only EVAs. A fourth subject on this flight performed EVAs and one cycle exercise session.

C. Fluid Loading

It is a NASA flight rule that crewmembers consume approximately one liter of water and eight salt tablets, or some other approved isotonic drink solution, during the two hours before Shuttle landing as a countermeasure to orthostatic intolerance (Space Shuttle Operational Flight Rules, NSTS 12820, vol. A, Section 13: Aeromedical: 13-57, 1996). Crewmembers also are allowed to consume fluid on the crew transport vehicle as they return to the clinic for medical testing. Crewmembers are requested to report the fluid and salt tablets they've ingested during their in-flight fluid loading procedure as well as the fluid ingested after landing before the administration of the stand test at the medical testing facility.

D. Statistical Analyses

The last 2 min of data in the supine posture were averaged to represent the HR and arterial BP values in that position. Because not all subjects were able to complete the entire 10 min of standing postflight, data from minute seven of standing in all subjects were used as the standing value which represented 97% of all participants.

Statistical comparisons were made only between the LO_{ex}, MED_{ex}, and HI_{ex} groups. Due to the relatively small sample size of the EVA group, their results are reported separately without statistical comparison. Time completed during the upright portion of the stand test before and after flight was analyzed using a three-by-two analysis of variance (ANOVA) design with groups as the non-repeated measure factor and time as the repeated measure factor. HR and BP data pre- and postflight were analyzed using a two-by-two-by-three ANOVA design in which group was the non-repeated measure factor and time and posture were the repeated measure factors. The change of HR and BP from supine to standing was analyzed by using a two-by-three ANOVA design in which group was the non-repeated measure factor and time was a repeated measure factor. Tukey's Honest Significant Difference test was used for post-hoc comparisons. All analyses were completed using STATISTICA for the MacIntosh (Statsoft, Inc., Tulsa, OK), and statistical significance was accepted at $P = 0.05$. All values are reported as mean ± standard error (SE).

III. RESULTS

A. Subject Characteristics, Exercise, and Fluid Ingestion

The three groups did not differ in age, height, or flight duration (Table 1). The preflight body weight of the HI_{ex} group was significantly less than that of the other two groups. The MED_{ex} group consisted entirely of male crewmembers and the LO_{ex} group included one female, while the HI_{ex} group included three females. Postflight body weight was significantly less than preflight only in the LO_{ex} group. The change in body weight in the LO_{ex} group from pre- to postflight was significantly greater than in the HI_{ex} group but not significantly different from the MED_{ex} group.

Before flight, the three groups of subjects did not differ in mean exercise HR and duration per exercise session, but were significantly different in the frequency with which they exercised (Table 2). The HI_{ex} group exercised significantly more frequently than the LO_{ex} group but not the MED_{ex} group.

Table 2: Pre- and In-Flight Exercise

	LO_{ex}		MED_{ex}		HI_{ex}		EVA
	PRE	IN	PRE	IN	PRE	IN	PRE
Ex. Frequency (times/week)	2.6 ± 0.4	1.7 ± 0.3	3.1 ± 0.6	4.4 ± 0.2†	4.1 ± 0.5†	4.2 ± 0.2†	4.1 ± 1.0
Ex. Duration (min/session)	35.8 ± 2.7	30.1 ± 4.4	32.7 ± 3.3	29.6 ± 3.2	35.3 ± 3.0	31.0 ± 2.6	42.4 ± 18.7
Mean HR (bpm)	146 ± 5	124 ± 5*	142 ± 6	109 ± 3*	148 ± 5	134 ± 2§	139 ± 18

* Significantly different ($P \leq 0.05$) from PRE † Significantly different from LO_{ex} group
§ Significantly different ($P \leq 0.05$) than MED_{ex} group

None of the groups significantly altered their exercise frequency or their exercise duration from preflight to in-flight. However, the mean in-flight exercise HR was significantly lower than the preflight mean HR in the MED_{ex} and LO_{ex} groups and tended to be lower ($P = 0.06$) in the HI_{ex} group.

The mean in-flight exercise HR in the HI_{ex} group was significantly higher than that of the MED_{ex} group and tended to be higher than in the LO_{ex} group ($p = 0.09$). The HI_{ex} group exercised at 74.4 ± 0.7%, the MED_{ex} group exercised at 61.5 ± 1.8%, and the LO_{ex} group exercised at 69.6 ± 2.4% of age-predicted maximum HR. Although the average duration of the exercise sessions was not different among the three groups, the HI_{ex} and MED_{ex} groups completed a greater number of exercise sessions and exercised for a greater total time per week than the LO_{ex} group.

Crewmembers consumed similar amounts of fluid during their in-flight fluid loading protocol (LO_{ex}: 1.31 ± 0.09 L; MED_{ex}: 1.41 ± 0.14 L; HI_{ex}: 1.45 ± 0.10 L). Crewmembers consumed either water with 8-10 salt tablets, or an isotonic drink solution (chicken consommé or Astroade). Crewmembers also consumed similar amounts of fluid, primarily water, after landing and before the administration of the stand test (LO_{ex}: 0.70 ± 0.12 L; MED_{ex}: 0.93 ± 0.15L; HI_{ex}: 0.71 ± 0.21 L).

B. Stand Test Tolerance Time

The stand test time was not different between the three groups before and after flight. Further, there was no significant change in stand test time from pre- to postflight for any of the groups. All subjects were able to complete the entire 10 min of standing before flight. After flight, one subject in the LO_{ex} group (9%), two subjects in the MED_{ex} group (20%), and one subject in the HI_{ex} group (9%) became pre-syncopal before the completion of the 10 min of standing. Mean postflight stand test times were 9.5 ± 0.5, 9.4 ± 0.4, and 9.8 ± 0.2 min in the LO_{ex}, MED_{ex}, and HI_{ex} groups, respectively.

Of the four subjects who reported signs and symptoms of presyncope which resulted in early test termination during the postflight stand test, two subjects reported general weakness, one reported nausea and vomited, and one reported lightheadedness. All four subjects who became presyncopal had falling BP at presyncope from initial standing. However, the decline in standing BP was not rapid and did not meet the criteria for test termination. HR initially increased in each subject as BP fell, but decreased immediately before presyncope in three of the four. All four subjects were mission or payload specialists. Two were first-time flyers and two were on their second flight. Two had military aviation backgrounds. None of the presyncopal subjects were female.

Table 3: HR and BP Responses to Standing (Mean ± SE)

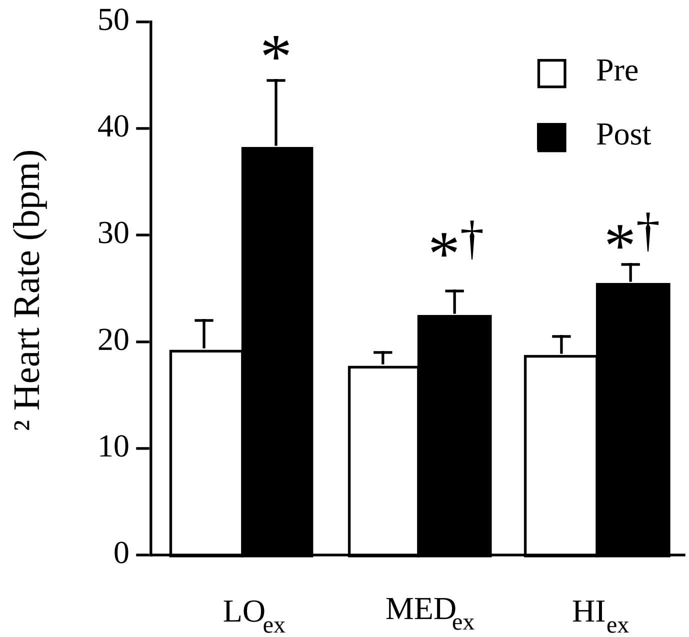
		LO_{ex}		MED_{ex}		HI_{ex}	
		Supine	Stand	Supine	Stand	Supine	Stand
HR (bpm)	Pre	59 ± 3	78 ± 4#	54 ± 4	71 ± 4#	56 ± 2	74 ± 3#
	Post	63 ± 1	99 ± 6*#	60 ± 4	83 ± 5*†#	61 ± 2	86 ± 3*†#
SBP (mmHg)	Pre	113 ± 3	112 ± 3	114 ± 3	106 ± 3	115 ± 4	109 ± 5
	Post	119 ± 3	110 ± 4#	120 ± 3	110 ± 4#	119 ± 5	114 ± 5
DBP (mmHg)	Pre	73 ± 2	79 ± 2	74 ± 3	76 ± 3	71 ± 3	75 ± 4
	Post	77 ± 2	87 ± 2*#	80 ± 2	82 ± 3	78 ± 4*	86 ± 4#
MAP (mmHg)	Pre	86 ± 2	90 ± 2	87 ± 3	86 ± 3	86 ± 3	87 ± 4
	Post	91 ± 2	95 ± 2*	94 ± 2*	91 ± 3	92 ± 4*	95 ± 4*
PP (mmHg)	Pre	41 ± 2	33 ± 3	40 ± 1	30 ± 2#	44 ± 3	34 ± 3#
	Post	42 ± 2	23 ± 4*#	40 ± 3	28 ± 3#	41 ± 2	28 ± 2#

* Significantly different from PRE † Significantly different from LO_{ex} group # Significantly different than supine

C. Heart Rate

Preflight supine and standing HR and the HR change from supine to standing did not differ between groups (Table 3). After spaceflight, supine HR was not different from preflight in any group, but standing HR was elevated significantly above preflight standing HR in all groups.

The postflight standing HR in the LO_{ex} group was significantly greater than that of either the MED_{ex} or HI_{ex} groups, which did not differ from each other. The change in HR from supine to standing was significantly greater in the LO_{ex} group (36 ± 5 bpm) after flight than either the MED_{ex} (22 ± 2 bpm) or HI_{ex} groups (25 ± 2 bpm), which did not differ from each other (Figure 1).



* Significantly greater increase than preflight ($P < 0.05$). † Significantly less increase than LO_{ex}.

Figure 1: Increase in HR from supine to standing in all the exercise groups pre- (open bar) and postflight (solid bar).

D. Systolic Blood Pressure

Supine and standing SBP did not differ between groups before flight and were not different among groups after flight (Table 3). Preflight standing SBP was not significantly different than supine SBP in all groups, but after spaceflight SBP decreased significantly from supine to standing in the MED_{ex} and LO_{ex} groups. There was no significant change in SBP from supine to standing after flight in the HI_{ex} group. However, the SBP change from supine to standing was not different among the groups before flight and was not significantly changed in any group after flight.

E. *Diastolic Blood Pressure*

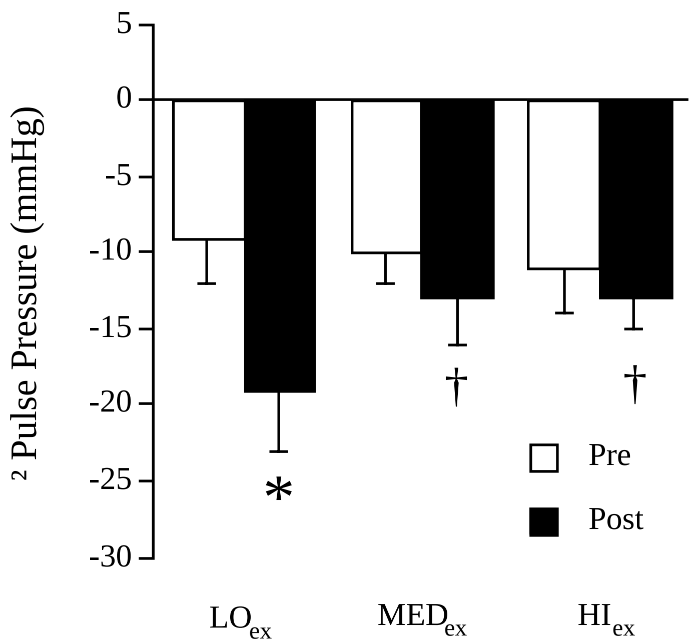
Supine and standing DBP were not different among any of the groups before flight (Table 3). Postflight supine DBP increased significantly from preflight in the HI_{ex} group and tended to increase (P = 0.06) in the MED_{ex} group but not in the LO_{ex} group. Postflight standing DBP was elevated significantly above preflight in the HI_{ex} and LO_{ex} groups and tended to increase (P = 0.08) in the MED_{ex} group. DBP was unchanged from supine to standing preflight, but after spaceflight increased significantly from supine to standing in the HI_{ex} and LO_{ex} groups. However, the change in DBP from supine to standing was unaffected by spaceflight in any group.

F. *Mean Arterial Pressure*

Supine and standing MAP did not differ between groups before flight (Table 3). Postflight supine MAP increased significantly from preflight in the HI_{ex} group and in the MED_{ex} group and tended to increase (P = 0.08) in the LO_{ex} group. Postflight standing MAP was elevated significantly above preflight in the HI_{ex} and LO_{ex} groups but only tended (p = 0.10) to increase in the MED_{ex} group. MAP did not change from supine to standing either before or after spaceflight, and the change in MAP from supine to standing was unaffected by spaceflight in any group.

G. *Pulse Pressure*

Supine and standing PP were not different among groups before flight and were not different in either the HI_{ex} or MED_{ex} groups after flight (Table 3). Although the postflight supine PP was similar to preflight in the LO_{ex} group, the standing PP was significantly less after flight than preflight. Standing PP was not different after spaceflight in the MED_{ex} and HI_{ex} groups. PP decreased significantly from supine to standing in all groups both pre- and postflight, except in the LO_{ex} group preflight in whom it only tended to decrease (P = 0.06). There was no change in the PP response from supine to standing after flight compared to preflight in the HI_{ex} and MED_{ex} groups (Figure 2), but the response was significantly greater postflight than preflight in the LO_{ex} group (-19 ± 4 vs. –9 ± 3 mmHg).



* Significantly greater decrease than preflight ($P < 0.05$). † Significantly less decrease than LO_{ex}.

Figure 2: Decrease in PP from supine to standing in all three exercise groups pre- (open bar) and postflight (solid bar).

H. EVA Group

Subjects in this group (n = 4) were all crewmembers from the same flight and appear similar in height, weight, and flight duration to the other three groups (Table 1). However, the mean age of this group (48 ± 4 yr) appeared higher than the other three groups. This group of subjects was composed of crewmembers who had made a minimum of two previous flights. One crewmember was a veteran of four previous missions.

The preflight exercise habits of this group appeared similar to those of the MED_{ex} and HI_{ex} groups (Table 2) in duration, frequency, and mean HR. During their mission, two crewmembers performed two EVAs, and two crewmembers performed three EVAs. The average length of each EVA was 383 ± 22 min. The mean HR during EVA was 108 ± 12 bpm, approximately 62 ± 6% of age-predicted maximal HR for these crewmembers. Only one crewmember performed any additional exercise. This crewmember performed very low-intensity cycle exercise for 90 min but did not wear a HR monitor.

EVA crewmembers appeared to have consumed more fluid and salt tablets than the crewmembers in the other groups. Before landing, EVA crewmembers consumed an average of 1.58 ± 0.20 L of fluid with 12 salt tablets each. The mean consumption for all other crewmembers was 1.39 ± 0.06 L of fluid and 9.3 ± 0.9 salt tablets. Further, EVA crewmembers consumed an average of 1.26 ± 0.42 L of fluid from the time of landing to the performance of the stand test but other crewmembers consumed only an average 0.79 ± 0.10 L of fluid during transport from the landing site to the data collection facility.

Preflight, all EVA crewmembers completed the 10-min stand test. Preflight HR and BP data from this group appeared quantitatively similar to data from the other three groups (Table 4). On landing day, all EVA subjects completed the 10-min stand test. Supine HR appeared unchanged from preflight but standing HR was elevated. The mean change in HR from supine to standing (27 ± 10 bpm) in the EVA crewmembers was quantitatively similar to the MED_{ex} and HI_{ex} groups. The change in BP from supine to standing in the EVA group appeared similar to the other three groups preflight and appeared to be more similar to the LO_{ex} and MED_{ex} groups postflight. However, the resting SBP (134 ± 3 mmHg) in the EVA group was higher postflight than in any of the other groups. The DBP and MAP appeared to be similar to the other three groups before and after spaceflight. However, the change in PP from supine to standing after flight most closely resembled the response observed in the LO_{ex} group.

Table 4: HR and BP Responses to Standing (Mean ± SE) in EVA Group Only

		All (n=4)		Without Veteran Flyer (n=3)	
		Supine	Stand	Supine	Stand
HR (bpm)	Pre	60 ± 6	72 ± 9	63 ± 8	76 ± 12
	Post	62 ± 5	89 ± 10	64 ± 6	99 ± 3
SBP (mmHg)	Pre	115 ± 6	104 ± 3	112 ± 7	106 ± 3
	Post	134 ± 3	123 ± 6	133 ± 4	119 ± 6
DBP (mmHg)	Pre	74 ± 1	73 ± 2	74 ± 1	73 ± 3
	Post	83 ± 3	86 ± 3	80 ± 0	85 ± 4
MAP (mmHg)	Pre	88 ± 2	83 ± 3	87 ± 2	84 ± 3
	Post	99 ± 1	98 ± 2	98 ± 1	96 ± 2
PP (mmHg)	Pre	41 ± 6	31 ± 2	38 ± 8	37 ± 7
	Post	53 ± 3	33 ± 1	54 ± 4	35 ± 9

IV. DISCUSSION

This study, the first to document in-flight exercise practices of Space Shuttle crewmembers in relation to their postflight HR and BP responses to standing, has resulted in a significant finding. Crewmembers who exercise at least three sessions per week and 20 min per session (HI_{ex} and MED_{ex}) during spaceflight had lower HR and PP responses to postflight standing compared to crewmembers who exercised less than three times per week (LO_{ex}). Additionally, crewmembers who exercised at an intensity level which elicited greater than 70% of age-predicted maximum HR for 20 min three or more times per week (HI_{ex}) were better able to maintain their SBP and increase their DBP from supine to standing after spaceflight.

Beginning with early experiences in the Mercury program, it has been well documented that many crewmembers are subject to orthostatic intolerance after spaceflight (11). Recent investigations have documented that this problem persists after Space Shuttle missions. Standing HR was significantly elevated and the maintenance of mean arterial blood pressure was compromised after spaceflights as short as 2 to 8 d (4). Further, 13% of crewmembers could not complete a 5-min stand test (12), and 25% could not complete a 10-min stand test (2, 3) after Shuttle flights of less than 15 d. Five out of ten crewmembers could not tolerate a complete lower body negative pressure (LBNP) ramp test to -60 mmHg after Shuttle missions of 6 to 14 d although all were tolerant before microgravity exposure (13). Recently, Buckey et al. (1) reported that 60% of the payload specialists participating in the SLS-1 and -2 Spacelab flights were unable to tolerate a 10-min stand test. Although the mechanisms involved have not been identified clearly, postflight orthostatic intolerance has been associated with reduced plasma and blood volume (12), lower standing stroke volume (1, 11, 12), inability to increase total peripheral resistance (1, 3, 12), decreased vasoconstrictor responsiveness with standing (12), decreased responsiveness of the carotid baroreceptor cardiac reflex (2, 14), and possibly decreased in-flight variability of HR and BP (15).

The effect of exercise on orthostatic tolerance after bed rest, an analogue of spaceflight, is unclear. The combination of exercise and orthostatic stress appears to have a beneficial effect on post-bed rest orthostatic tolerance. One of two subjects who performed chair exercise during a 24-d bed rest maintained pre-bed rest tilt tolerance (16), and subjects who performed upright exercise or supine exercise against LBNP maintained tilt tolerance to a greater degree than subjects who performed no exercise (17). However, similar results have not been shown consistently in subjects who performed exercise in the supine position (16, 18), a position used to simulate exercise during spaceflight. The +Gz tolerance of subjects who performed two 30-min periods of supine cycle exercise daily at 68% of maximal oxygen uptake during a 14-d bed rest was reduced to a similar degree as subjects who performed no exercise (19). Also, when subjects who were bed rested for 30 d performed intense interval exercise twice daily, with exercise intensities alternating between 40% and up to 90% of maximal oxygen consumption, tolerance to 60-deg head-up tilt was not different from control subjects (20). However, in a recent investigation, LBNP tolerance was maintained in subjects performing a single bout of intense exercise 24 hr before the cessation of a 16-d bed rest (21).

A. Plasma Volume

Plasma volume loss has been consistently observed after spaceflight (11) and bed rest (22). A maintenance of plasma volume in crewmembers returning from spaceflight may attenuate the increased HR, decreased venous return, and reduced stroke volume observed during postflight standing (1, 12). In bed rest, when subjects performed either twice daily 30-min bouts of supine aerobic cycle exercise at 68% of $VO2_{max}$ (22) during a 14-d bed rest or an supine intense interval cycle exercise twice a day 5 d/week during bed rest during a 30-d bed rest (24), plasma volume loss was prevented. In the present study, the in-flight exercise performed by MED_{ex} and HI_{ex} groups may have attenuated the plasma volume loss, partially reflected in decreased body weight loss in these two groups after spaceflight and may have contributed to a lower standing HR response than in the LO_{ex} group.

Even if in-flight exercise attenuated plasma and blood volume loss, one might still expect to see changes in HR and BP responses to standing after spaceflight. In bed rest investigations of 24 hr (25) to one week (26), intravenous fluid loading at the end of bed rest to restore plasma volume improved but did not restore orthostatic responses to pre-bed rest levels. Also, when plasma volume was maintained with supine exercise, orthostatic tolerance was not maintained (19, 20). Similarly, although the HR response to standing in crewmembers who completed the current Space Shuttle fluid loading protocol immediately before reentry was significantly less than the response in those who did not fluid load, their postflight HR response still was greater than the preflight response (4). These studies suggest that the restoration of plasma volume only partially restores the cardiovascular responses to standing after spaceflight. However, plasma volume status has not been correlated with orthostatic tolerance on landing day (1, 3).

B. Lower Body Compliance

Increased leg or lower body compliance results in greater venous pooling, decreased venous return, and the earlier onset of presyncope in some subjects (27). However, increased leg compliance has not been consistently observed after spaceflight (1, 11) or bed rest (22). A recent investigation which employed a stand test similar to the one used in this investigation after spaceflights of similar duration suggested that there was no postflight increase in leg compliance during standing although 60% of its subjects became presyncopal on landing day (1).

Despite a lack of increase in leg compliance after short-duration spaceflight, it is possible that blood pooling may be enhanced in different locations in the lower body. Splanchnic blood flow normally decreases by 40% and splanchnic vascular resistance increases by 45% as the cardiovascular system adjusts to the head-up posture (28). This vasoconstriction accounts for approximately 30% of total adjustment by the peripheral vasculature to maintain MAP (29). Savilov et al. (30) found that ambulatory subjects with poor orthostatic tolerance had a larger sequestering of blood in the abdominal region during LBNP than those who tolerated the stressor. Similarly, after a 120-d bed rest, blood was sequestered in the abdomen during LBNP although vasoconstriction was evident in this region before bed rest (30). It is possible that splanchnic pooling increases with standing after spaceflight and that in-flight exercise may attenuate or prevent this response. Exercise is well known to produce both splanchnic and renal vasoconstriction (27); repetitive and moderately intense exercise may be effective in maintaining this vasoconstrictor response during spaceflight.

C. Cardiac Atrophy and Mechanics

Recent data from Levine et al. (31) suggest that changes in cardiac mechanics and function during bed rest may have a significant impact on cardiac responses to standing. Subjects in a 14-d bed rest study who performed no exercise countermeasures had a 5% decrease in cardiac mass, a decrease in left ventricular distensibility, and an increase in the slope of the left ventricular Starling relationship. This would result in an accentuated fall in stroke volume for a given decline in venous return and could contribute to post-bed rest orthostatic intolerance. Similar data were reported by these authors after short-duration spaceflight. Levine et al. (31) suggested that these cardiac changes may have occurred as a result of decreased cardiac work during bed rest. Decreased cardiac work, as indicated by lower HR and BP, also has been reported during spaceflight (15). Levine et al. (31) speculated that exercise at 75% of maximum HR for 90 min/d may be necessary to counteract such changes in cardiac performance. In the present study, the crewmembers in the HI_{ex} and MED_{ex} groups may have performed enough exercise to ameliorate some of this decline in cardiac function as potentially reflected in their relatively preserved HR and PP responses during postflight standing. Perhaps the addition of a simulated orthostatic stress during in-flight exercise through LBNP or centrifugation may further increase cardiac work and assist in the maintenance of cardiac muscle mass and function.

D. Baroreceptor Function

Previous investigations have shown an impairment of the carotid-cardiac baroreflex after Shuttle missions as short as 4-5 d (14). In these subjects, the slope, range, and operational point of the reflex were all reduced on landing day relative to preflight. These results were duplicated in missions of 8-14 d, and the reduction in the operational point of the baroreflex was correlated with reduced standing arterial pressures after spaceflight (2). Acute intense exercise at the end of a 16-d bed rest has been shown to increase the sensitivity and operational point of the carotid-cardiac baroreflex to restore baroreflex function and reduce post-bed rest orthostatic intolerance (21). Although no subjects in the present study exercised at intensities equivalent to those in the bed rest study by Engelke et al. (21), the performance of regular exercise throughout the duration of the mission may have attenuated the changes in baroreflex function which have been reported previously in bed rest (32, 33) and spaceflight investigations of similar duration (2).

E. EVA Only Group

In the EVA group after spaceflight, the mean change in HR from supine to standing was quantitatively similar to the change in HR in the MED_{ex} and HI_{ex} groups. However when examining the individual data from these subjects, differences between crewmembers became apparent. One of the crewmembers was a veteran of four previous Shuttle flights. This crewmember's responses were most similar to those of the HI_{ex} group, and may have been influenced by a selection for increased tolerance with respect to prior aviation and spaceflight experience (3) or decreased HR to orthostatic stress response with older age (34).

When examining the data from the other three EVA crewmembers, the postflight stand test responses most closely resembled those responses seen in the LO_{ex} group. The postflight change from supine to standing in HR (35 ± 8 bpm) and PP (-19 ± 5 mmHg) of these three subjects was similar to the LO_{ex} group. Interestingly, a similar observation had been made previously when examining the HR response during submaximal exercise in these crewmembers on landing day. Crewmembers in the EVA and LO_{ex} groups had greater increases in submaximal HR during upright cycle ergometry after spaceflight when compared to preflight than crewmembers in the MED_{ex} and HI_{ex} groups (35). Data from this investigation and these preliminary exercise study results suggest that the performance of EVAs only, although physically and mentally fatiguing, does not protect against cardiovascular deconditioning during spaceflight.

F. Limitations

Spaceflight investigations are typically very difficult to control due to the wide variety of crew assignments and other experiments which are performed during each Shuttle flight as well as crew preferences for different activities (36, 14). In this study, the preflight and in-flight exercise routines were not controlled but self-selected. Therefore, it is difficult to extrapolate with certainty our results to a specific exercise protocol. Future investigation of specific exercise countermeasures is indicated. However, as an indication of the possible influence of different in-flight exercise regimens on the postflight stand test response in the same subjects, we examined the data of the two subjects who participated in this investigation during two different missions. One subject performed exercise in flight, which placed him in the LO_{ex} group for one flight and in the MED_{ex} group for another. As a subject in the LO_{ex} group, his HR response to standing increased from 17 bpm preflight to 34 bpm postflight. However, as a subject in the MED_{ex} group his HR response was unchanged from pre- to postflight (18 vs. 18 bpm). The second subject performed exercise at an intensity level to place her in the HI_{ex} exercise group for both of their missions and had no change in HR response to standing pre- to postflight after either mission (17 vs. 18 bpm; 20 vs. 22 bpm).

This investigation also was limited by our inability to strictly control pre-landing fluid loading regimens. All Shuttle crewmembers participate in some form of fluid loading, based primarily on personal preferences. Crewmembers consume more or less fluid based upon palatability of the fluids, feeling of well-being before reentry, previous experiences with fluid loading, and the advice of other crewmembers. However, in the present study it appears that crewmembers in each group consumed similar amounts of fluid.

Additionally, although four of the subjects became presyncopal postflight, the 10-min stand test used in this investigation was not designed as a test of orthostatic tolerance. It is often assumed that elevated HR and decreasing BP during standing after flight can be used as an indicator orthostatic tolerance, but this has not been conclusively proven (22). A more appropriate orthostatic testing protocol would take all subjects to pre-syncope before and after spaceflight and use more sensitive measurement techniques.

A final limitation of this study design was that the subjects could not be randomly assigned to the three exercise groups. Despite differences in preflight physical activity patterns, the preflight stand test responses of the three groups were not different. However, it remains possible that differences in preflight exercise habits may have influenced postflight stand test results.

V. Summary

In summary, moderate aerobic exercise in-flight seemed to attenuate the elevated standing HR and decreased PP typically observed in crewmembers after spaceflight. However, the performance of EVAs did not lead to similar results. In-flight aerobic exercise may prevent plasma volume loss, maintain cardiac mechanics, reduce splanchnic pooling, and maintain the carotid-cardiac baroreflex function, all of which may contribute to postflight orthostatic intolerance. Further studies are required to examine these mechanisms.

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13. ABSTRACT *(Maximum 200 words)*
The purpose of this study was to determine whether exercise performed by Space Shuttle crewmembers during short-duration spaceflights (9-16 d) affects the heart rate (HR) and blood pressure (BP) responses to standing within 2-4 hr of landing. Thirty crewmembers performed self-selected in-flight exercise and maintained exercise logs to monitor their exercise intensity and duration. A 10-min stand test, preceded by at least 6 min of quiet supine rest, was completed 10-15 d before launch (PRE) and within four hours of landing (POST). Based upon their in-flight exercise records, subjects were grouped as either high (HIex: = 3x/week, HR = 70% HRmax, = 20 min/session, n = 11), medium (MEDex: = 3x/week, HR = 70% HRmax, = 20 min/session, n = 10), or low (LOex: = 3x/week, HR and duration variable, n = 11) exercisers. HR and BP responses to standing were compared between groups (ANOVA, or analysis of variance, $P < 0.05$). There were no PRE differences between the groups in supine or standing HR and BP. Although POST supine HR was similar to PRE, all groups had an increased standing HR compared to PRE. The increase in HR upon standing was significantly greater after flight in the LOex group (36 ± 5 bpm) compared to HIex or MEDex groups (25 ± 1 bpm; 22 ± 2 bpm). Similarly, the decrease in pulse pressure (PP) from supine to standing was unchanged after spaceflight in the MEDex and HIex groups, but was significantly less in the LOex group (PRE: -9 ± 3; POST: -19 ± 4 mmHg). Thus, moderate to high levels of in-flight exercise attenuated HR and PP responses to standing after spaceflight compared.

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