5.2

Exercise Countermeasures Demonstration Projects During the Lunar-Mars Life Support Test Project Phases IIa and III

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SUMMARY

The purpose of this demonstration project was to assess the compliance of crewmembers to perform exercise countermeasures similar to those planned for use during stays aboard the International Space Station (ISS) and to assess the outcomes of performing these countermeasures. During the 60-day Phase IIa project, crewmembers exercised for six consecutive days alternating between aerobic and resistive exercise, and rested on the seventh day. On the aerobic exercise days, subjects exercised for 30 minutes on an electronically braked cycle ergometer using an interval protocol. On the resistive exercise days, crewmembers performed five major multijoint resistive exercises (bench press, seated press, lat pull, squats, and heel raises) in a concentric-only mode, targeting those muscle groups and bones that are believed to be most severely affected by space flight. Subjects performed maximal efforts with each repetition. Both exercise protocols were well tolerated by the subjects, demonstrated by 98% compliance with the aerobic exercise prescription and 91% adherence to the resistive exercise prescription. After 60 days, the crewmembers improved their peak aerobic capacity by an average of 7%. Strength gains during all exercises were noted.

During the 91-day Phase III project, the frequency of the exercise countermeasures was increased to include both aerobic and resistive exercises each day for six days, with rest on the seventh day. For aerobic exercise, the cycle protocol was performed three days/week similar to the Phase IIa project. However a steady-state treadmill protocol was added on the remaining three exercise days. The same resistance exercise protocol was performed as in Phase IIa, except that the upper- and lower-body exercises were divided and performed on separate days. Three of the four subjects tolerated the aerobic exercise training well. One crewmember developed knee pain in the final third of the chamber test and did not perform further cycle or lower-body resistive exercises for the remainder of the study. The three

crewmembers who participated in all countermeasures and postchamber testing had an average increase in aerobic capacity of 14%. Of these remaining three crewmembers, one consistently refrained from resistive exercise one day per week. Strength gains were not consistently obtained during this study. These results, showing little or no change in muscle strength while demonstrating some improvement in aerobic capacity, may be consistent with an overtraining syndrome.

Taken together, the results from these two studies suggest that the prescribed aerobic and resistive exercises generally were well tolerated. However, combining both resistive and aerobic exercises with only one day of rest each week may result in a decreased benefit of strength training. Periodization of exercise protocols and/or reduction of exercise intensity or frequency may be desired to obtain optimum increases in both aerobic and resistive exercise capacities.

Introduction

Four crewmembers participated in each of two chamber tests. Phase IIa was a 60-day chamber test while the Phase III test had a duration of 91 days. Previous chamber studies were conducted in which exercise was performed, but these two projects were the first in which specific exercise prescriptions were developed for the crewmembers and the outcomes of the exercise protocols were measured. These two chamber studies served as ground-based test beds for exercise countermeasure procedure development in support of future activities for the crews of the International Space Station (ISS).

The objectives of the Exercise Countermeasures Demonstration Projects were:

1) to assist in the development and evaluation of exercise testing and prescription methods being considered for ISS; and
2) to provide realistic perturbations of carbon dioxide production and oxygen utilization as anticipated during ISS to challenge the environmental control systems.

In each project, eight crewmembers were selected for participation, four as prime and four as back-up. Crewmembers were screened for health status by means of a modified Air Force Class III Physical and a graded treadmill exercise test to volitional fatigue with 12-lead electrocardiogram. Subjects received written and verbal explanation of the procedures specific to the exercise countermeasures demonstration project and signed informed consent documents confirming their understanding and acceptance. All testing procedures and protocols were reviewed and approved by the NASA Johnson Space Center Institutional Review Board. All pre and postchamber testing, as well as prechamber training, were performed in the NASA Johnson Space Center Exercise Physiology Laboratory. Eventually, four crewmembers entered the chamber in each study and remained there for the duration of the test project. In Phase IIa, the crew consisted of three men and one woman. In Phase III, the crew consisted of two men and two women. Data presented here are from the four prime crewmembers only from each of the two chamber tests.

Phase IIa Methods

Study Overview

The characteristics of the prime crewmembers, three males and one female, were: age – 31 ± 4 years; height – 175 ± 5 cm; and body mass – 70.4 ± 10.9 kg. Prior to entry into the chamber, crewmembers completed both a graded maximal cycle exercise test to volitional fatigue and a submaximal cycle ergometer exercise protocol. Crewmembers also received training on the aerobic and resistance exercise countermeasures prior to chamber entry. At the conclusion of the chamber test, the four crewmembers repeated the maximal cycle exercise test.

During the chamber test, on alternate days the crewmembers completed the aerobic and the resistive countermeasures three times per week. In several instances, exercise was delayed or cancelled due to malfunction of the environmental control systems. Three times during the 60-day period, on days 15, 30, and 58, crewmembers completed the submaximal exercise test in place of the aerobic exercise training to assess their training status.

The aerobic exercise testing protocols chosen for this project are similar to those proposed for use in the Space Medicine Project (SMP) on the ISS as a means to monitor crew health. Similarly, the exercise countermeasures, both aerobic and resistive, were similar to those suggested for use on the ISS to maintain crew health. However, no pre to postchamber resistance exercise testing was performed during the Phase IIa test.

Maximal Cycle Exercise Test

Crewmembers completed a maximal exercise test on a cycle ergometer to quantify their individual fitness levels and to aid in the prescription of the aerobic exercise countermeasure. Data from this test were used also to develop the exercise prescription for the submaximal exercise test. Crewmembers performed the maximal cycle exercise test both before chamber entry and after chamber exit.

Crewmembers pedaled on an electronically braked cycle ergometer in the upright position at a constant pedaling cadence of 75 rpm. Expired gases were collected and analyzed using a Quinton Qplex Metabolic Cart (Quinton Industries, Seattle, WA) interfaced with a mass spectrometer (MG-1100, Marquette, Inc., Minneapolis, MN). Heart rate (HR) was monitored using a three-lead ECG configuration (Quinton Q5000 Stress Test System, Quinton Industries, Seattle, WA). The maximal cycle test began with three 3-minute stages of increasing workloads. For male subjects, these workloads were 50, 100, and 150 watts. Female subjects completed workloads of 50, 75, and 100 watts. Thereafter, for both subject groups the workload was increased in 25-watt increments each minute until volitional fatigue. Peak oxygen consumption (VO_2pk) was accepted as the mean of the last two 30-second measurements of oxygen consumption (VO_2). HR was recorded in the last 15 seconds of each minute, and Rating of Perceived Exertion (RPE; Borg's revised 10-point scale) (10) was recorded in the last 20 seconds of each stage. Systolic (SBP) and diastolic blood pressures (DBP) were measured manually by the auscultatory method in the last 30 seconds of each three-minute stage.

Submaximal Cycle Exercise Test

The submaximal cycle exercise test was prescribed individually for each subject according to the level of performance of each subject in the maximal cycle exercise test. Subjects completed three 5-minute exercise intensities of 25, 50, and 75% of VO_2pk on the same electronically braked upright cycle ergometer. Subjects recovered by cycling for five minutes at 25% of VO_2pk. The pedaling cadence was maintained at 75 rpm. Expired gases were collected as the subjects exercised using a Quinton Qplex Metabolic Cart interfaced with a mass spectrometer. HR was measured using a HR monitor (Polar Vantage XL, Polar, Inc., Stamford, CT), previously validated in our laboratory (13). HR data were saved in 15-second intervals. Means of both VO_2 and HR measured in the last two minutes of each stage were calculated. This test was performed twice prior to chamber entry and repeated on days 15, 30, and 58 of the chamber stay. Testing days were chosen to be similar to those anticipated for crewmembers aboard the ISS. Tests conducted prior to the chamber stay were performed with metabolic gas analysis. The other tests were self-administered by the subjects in the chamber without metabolic gas analysis.

Aerobic Exercise Countermeasure

Based upon the results of the VO_2pk exercise test, an exercise countermeasure (Figure 5.2-1) that has been used previously to maintain exercise capacity in bed rest subjects (4) was prescribed. This exercise protocol was performed on the same cycle used during the prechamber testing at a constant pedaling cadence of 75 rpm. Each crewmember's individual aerobic exercise prescription was preprogrammed into the cycle ergometer. HR data were recorded each 15-sec during the exercise countermeasure using a HR monitor. The data were downloaded on a weekly basis and added to each individual's database.

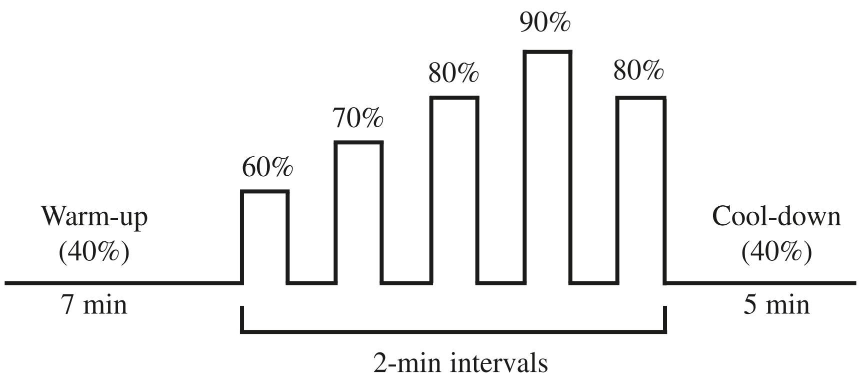

Figure 5.2-1 *Aerobic exercise countermeasure protocol*

Resistance Exercise Countermeasure

Crewmembers trained isokinetically three days per week on a computer-controlled resistive exercise device (Computerized Exercise System (CES), Ariel Life Systems, Inc., San Diego, CA). The CES consists of a single, multifunction exercise station, using passive hydraulic resistance, integrated with a laptop computer. This multifunction station allows for the performance of several multijoint exercises. Crewmembers performed bench press, seated shoulder press, lat pull, squats, and heel raises. All training was in the concentric mode only.

Throughout the study, subjects performed four sets of each exercise, one warm-up set at approximately 50% of their maximum effort followed by three sets of maximal effort with each repetition. The first week of resistance training in the chamber was treated as a familiarization period. Each day of the first week, crewmembers performed four sets of 10 repetitions of each exercise at 40°/sec with the exception of the heel raise that was performed at 15°/sec. From weeks two to nine, crewmembers performed a miniperiodization of resistance exercise within each week. The number of sets was maintained at four throughout, one warm-up and three at maximal effort, but the velocity of movement, number of repetitions per set, and amount of muscle tension developed varied across the week (Table 5.2-1). On the first day of resistance training within the week, the bench press, lat pull, seated shoulder press, and squats were performed at a slow speed (LO) of 20°/sec for six repetitions per set. The second day of training was performed at the fastest speed (HI) of 50°/sec for 12 repetitions, and the third day was performed at a moderate speed (MED) of 35°/sec for eight repetitions. Crewmembers performed the same number of repetitions for the heel raises as the other exercises, but the velocities of movement were 10°/sec on LO, 15°/sec on MED, and 20°/sec on HI. By performing maximal efforts with each repetition on each day, the subjects generated the greatest muscle forces on the first day (LO) during the slow speed of movement, the least muscle tension on the second day (HI) during the fastest movement speed, and a moderate amount of muscle tension during moderate movement speed (MED).

Table 5.2-1 *Movement velocity and repetitions for each resistive exercise day*

Movement Speed	Calf Raise		Others	
	Speed (°/sec)	Repetitions	Speed (°/sec)	Repetitions
LO	10	6	20	6
MED	15	8	35	8
HI	20	12	50	12

The torque profile for each repetition performed during the resistance training was automatically stored on the laptop computer for later analysis. Variables of interest in this demonstration project were peak torque, average peak torque, and total work. Peak torque was taken as the highest torque output from a single repetition measured in each individual set averaged across the three sets. Average peak torque was the average of the peak torque from every individual repetition from all three sets. Total work was the summation of work performed in all three sets. The data from the warm-up set and from the first week of training were not included in this analysis.

Data Analysis

All data are expressed as mean ± standard error (SE), unless otherwise noted. Although the sample size is small, the data from the aerobic exercise tests were analyzed statistically to provide objective information regarding the trends in the data. Pre- to postmaximal aerobic exercise data were statistically analyzed using dependent t-tests. Pre to postsubmaximal exercise data from the VO_2pk exercise test were analyzed using repeated measures ANOVA.

An ANOVA revealed no difference in HR at each of the workloads during the duplicate prechamber submaximal aerobic exercise tests. Therefore, the data from the two prechamber tests were averaged as a baseline measurement. Previous experience with other data sets (6) has suggested that the HR response to the higher workloads is affected most by changes in training status. Therefore, an ANOVA was performed on the HR response to the third submaximal exercise stage, 75% VO_2pk, across the four test times.

The efficacy of the resistive exercise countermeasure protocol was assessed in this project by examining the daily resistive exercise records for each subject. Peak torque, average peak torque, and total work data from the CES were calculated at early (week two), mid- (week five), and late (week eight) chamber stay. Only peak torque is reported here. Because of the varying amount of compliance within subjects, data were not statistically analyzed.

Phase IIa Results

Aerobic Exercise Countermeasure

Over the course of the nine weeks of the chamber confinement, crewmembers were prescribed to perform a total of 23 aerobic exercise countermeasure sessions. The range of compliance to this prescription was from 91 to 100% with a mean of 98 ± 4%. Two crewmembers completed all requested exercise sessions. Reasons for other crewmembers not completing all exercise sessions included work scheduling and failure of environmental control systems. Each subject attained the desired exercise intensities for this countermeasure protocol (Figure 5.2-2).

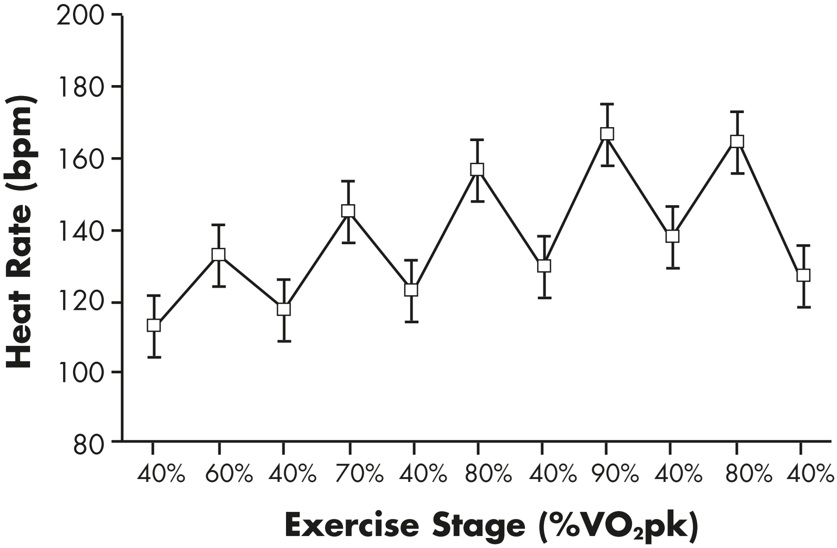

Figure 5.2-2 *Mean (± SE) heart rate response to aerobic exercise countermeasure across chamber confinement across all crewmembers*

Resistive Exercise Countermeasure

Crewmembers were prescribed to perform a total of 26 resistive exercise countermeasure sessions. The range of compliance for completing all or part of the daily resistive exercise prescription ranged from 81 to 100% with a mean of 91 ± 10%. Two subjects completed all the exercises prescribed each day, and one subject completed all the exercises on 21 out of the 26 resistance training days. No specific reason was given as to why this subject did not exercise. The fourth subject completed the upper-body exercises on 22 of the 26 resistance exercise days, but due to recurring back pain completed the squats and heel raises during only 58% of the exercise sessions. This subject had a previous history of back injury. Because of the varying amount of compliance within subjects, data were not statistically analyzed. However, visual inspection of these data suggest that crewmembers who completed the resistance exercise training exhibited increased strength across the chamber stay (Figure 5.2-3).

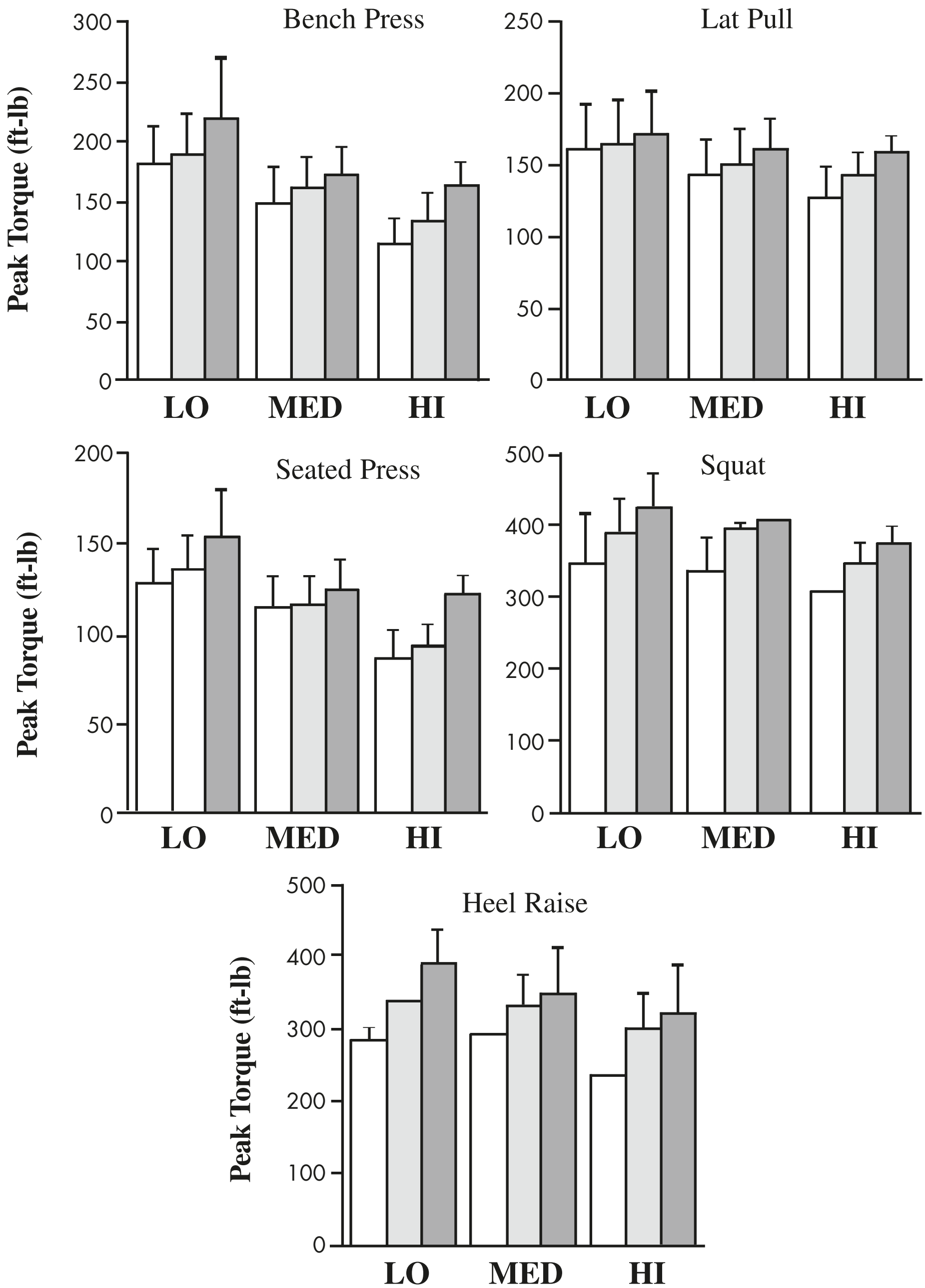

Figure 5.2-3 *Peak torque developed during bench press (n=3), seated press (n=3), lat pull (n=3), squat exercise (n=2), and heel raise (n=2) exercises across time at each training speed. Open bar is early (week 2), light gray bar is mid- (week 5), and dark gray bar is late (week 8) chamber stay.*

Pre to Postchamber Maximal Aerobic Exercise Test Results

The crewmembers' mean (± SE) VO_2pk was 2.82 ± 0.32 L/min (39.9 ± 5.5 ml/kg/min) before entering the chamber. This corresponded to a mean test time of 13.0 ± 0.5 min and a peak workload of 238 ± 22 watts. After the chamber stay, crewmembers significantly ($p < 0.05$) increased their total test time (13.9 ± 0.4 min) and the peak workload achieved (269 ± 24 watts). Although this resulted in a mean increase in VO_2pk of 7%, the improvement in VO_2 pk was not statistically significant when expressed as either absolute ($P = 0.06$) or relative ($P = 0.11$) VO_2. Mean peak HR was not changed from before (190 ± 2 bpm) to after the chamber stay (190 ± 3 bpm).

The mean submaximal HR, SBP, and DBP responses during the maximal exercise test were analyzed (Figure 5.2-4). The HR response to the first two submaximal exercise workloads was unchanged from pre to postchamber. However, the HR response at the third submaximal exercise stage was significantly less

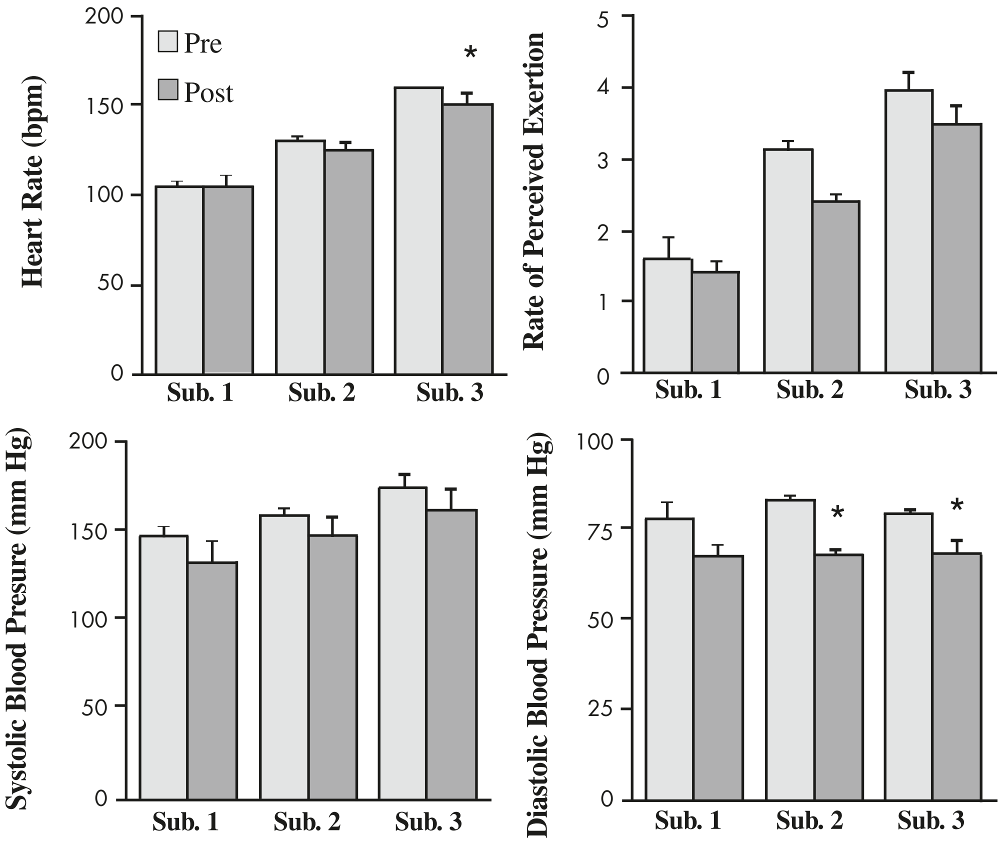

Figure 5.2-4 *Mean (± SE) heart rate, rating of perceived exertion, and blood pressure responses to submaximal exercise stages*
**Significantly different from prechamber*

($P < 0.02$) after the exercise training in the chamber (159 ± 3 vs. 149 ± 6 bpm). There was a main effect of time, pre to postchamber, on SBP, but pressures were not significantly different pre to postchamber at any particular submaximal exercise stage. The DBP during the submaximal exercise stages were significantly lower during the second (82 ± 2 vs. 67 ± 2 mm Hg) and third stages (78 ± 2 vs. 68 ± 3 mm Hg). There was also a main effect of time on the RPE reported during the submaximal exercise stages, but similar to SBP, there was no specific submaximal exercise stage in which the RPE were significantly different from pre to postchamber.

Pre- to In-Chamber Submaximal Aerobic Exercise Tests

All four prime crewmembers completed five submaximal exercise tests, two prior to and one each on day 15, day 30, and day 58 of the chamber stay. Although there was a trend ($P = 0.12$) towards a decrease in HR across time, there was no significant difference between the HR during the submaximal exercise test from prechamber to day 58 (Figure 5.2-5).

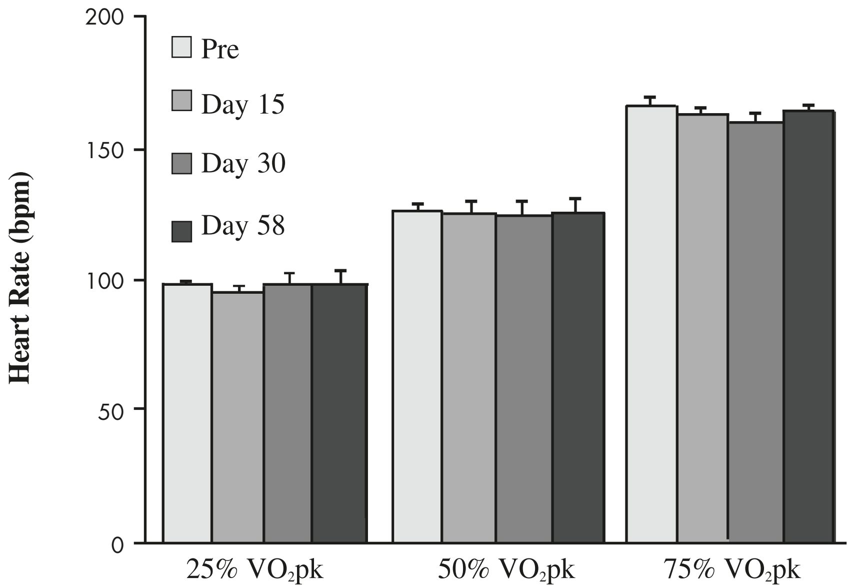

Figure 5.2-5 *Mean heart rate (± SE) during submaximal aerobic exercise tests for prime crew across chamber confinement*

Phase IIa Discussion

Maximal Cycle Exercise Test

The performance of this exercise test prior to and after the chamber stay appears to have been well tolerated. The duration of the exercise test allowed for adequate warm-up by the subject prior to reaching higher exercise intensities. All four crewmembers demonstrated an increase in peak workload achieved, total test time completed, and improvements in submaximal exercise responses during the maximal exercise test. However, the increase in VO_2pk was not statistically significant.

Submaximal Cycle Exercise Test

One crewmember showed a "classical" training response of decreasing HR at each submaximal exercise test over test times. Two subjects showed a decline in HR on days 15 and 30, but the heart rate response on day 58 was unchanged from the prechamber test. One subject showed essentially no change in HR across testing times. There was no apparent difference between the subjects in relation to their exercise prescription adherence that would explain the differences in the individual responses. All four subjects trained at the same relative exercise intensity during the aerobic exercise countermeasure.

It is interesting to note that lower submaximal HR responses were seen during the maximal exercise test after the chamber test than before it. It is possible that the active work schedules and disrupted sleep patterns of the subjects influenced the HR responses during the submaximal exercise tests in the chamber. The more rigorously controlled atmosphere of the laboratory for the VO_2pk exercise test after the chamber test had been completed may have provided for better data acquisition to assess responses to submaximal exercise intensities.

Aerobic Exercise Countermeasure

Crewmembers from previous chamber tests participated in regular exercise, but this was the first time that an exercise was prescribed for each crewmember on an individual basis with respect to the aerobic exercise protocol anticipated for use on the ISS. Further, although previous crews believed that they increased their fitness through the exercise training (15), this was the first time during the chamber studies that improvements in aerobic capacity were objectively quantified.

Crewmembers increased their VO_2pk by an average of 7% with a range of 1 to 20%. The subject who experienced the least improvement in aerobic capacity as a result of the training performed within the chamber had the highest aerobic capacity prior to the study. Conversely, the subject with the lowest aerobic capacity had the greatest improvement. From this limited data set, it appears that the performance of these exercise countermeasure protocols most benefits less fit subjects.

Resistive Exercise Countermeasure

Data from the resistive exercise countermeasure are difficult to interpret in two of the four subjects. However, it appears that muscular strength was increased in all subjects who performed the exercise requested. Improved subject motivation, increased variety in exercises performed, and more objective testing protocols may improve results from future demonstration projects.

Phase III Methods

Study Overview

The Phase III test provided an opportunity to evaluate potential exercise countermeasure and testing procedures during an even longer, 91-day chamber stay. In Phase III, two men and two women served as crewmembers with a mean (± SD) age of 34 ± 6 years, height of 173.5 ± 11.9 cm, and body mass of 68.3 ± 10.4 kg.

The testing and monitoring procedures were similar to those used in Phase IIa, except that isokinetic tests of muscle strength and endurance were added to the testing regime. Prechamber testing included maximal cycle and treadmill tests to volitional fatigue, two submaximal cycle ergometer exercise tests, training sessions for the cycle and treadmill aerobic exercise countermeasures, and two isokinetic muscular strength and endurance tests. Subjects also received two training sessions on the CES, the same resistance exercise training device used in Phase IIa. During the chamber stay, crewmembers performed the submaximal cycle exercise test biweekly on the seventh day of the week. After chamber stay, crewmembers returned to the laboratory for the maximal cycle and isokinetic strength and endurance tests.

Peak Aerobic Exercise Tests

VO_2pk was assessed in each subject on both the cycle ergometer and the treadmill. The maximal cycle test was used to prescribe exercise and to assess changes in aerobic capacity before and after the chamber test. The protocol was identical to that used during the Phase IIa testing.

The maximal treadmill test was used to aid in the prescription of the treadmill countermeasure and was performed before the chamber test. Based upon the results of the previous treadmill test performed during the subject screening and upon the feedback of the subjects, exercise intensities were prescribed individually for each crewmember. Expired gases were collected and analyzed using a Quinton Qplex Metabolic Cart (Quinton Industries, Seattle, WA) interfaced with a mass spectrometer (MGA-1100, Marquette, Inc., Minneapolis, MN). Heart rate was monitored using a three-lead ECG configuration (Quinton Q5000 Stress Test System, Quinton Industries, Seattle, WA). The test began with three 3-minute stages of increasing speed while level running (i.e., 5, 6, and 7 mph). Thereafter, the treadmill speed was held constant, treadmill grade was increased in increments of 3% until volitional fatigue. VO_2pk was accepted as the mean of the last two 30-second measurements of oxygen consumption. HR was recorded in the last 15 seconds of each minute, and RPE was recorded in the last 20 seconds of each stage. HR and VO_2 were averaged in the last minute of each submaximal exercise stage to develop a regression that would be used for the determination of the treadmill speed during the countermeasure exercise.

Submaximal Cycle Exercise Tests

Submaximal cycle tests were performed twice before and every two weeks during the chamber stay using the same protocol described in the Phase IIa test.

Isokinetic Muscle Strength and Endurance

Crewmembers were tested on three occasions: two prechamber tests and one postchamber test. Concentric and eccentric isokinetic strength of the knee, ankle, and trunk, and muscular endurance of the knee were assessed during both flexion and extension (Table 5.2-2).

***Table 5.2-2** Isokinetic testing protocols*

Joint	Mode	Speed	Reps	Range of Motion
Knee	Isometric	0°/sec	4	60°
Knee	Concentric	60°/sec	6	10 to95°
Knee	Concentric	120°/sec	5	10 to 95°
Knee	Eccentric	60°/sec	5	20 to 95°
Knee	Concentric	120°/sec	21	10 to 95°
Ankle	Concentric	30°/sec	5	-20 to 25°
Ankle	Concentric	60°/sec	5	-20 to 25°
Ankle	Eccentric	60°/sec	5	-20 to 25°
Trunk	Concentric	60°/sec	5	75 to 130°
Trunk	Eccentric	30°/sec	5	75 to 130°

All testing at the knee was performed with the subject in the upright, seated posture. Isometric testing at the knee was performed with the knee at 60° of knee flexion. Subjects performed four repetitions of five-sec maximal isometric contractions separated by one minute of rest between efforts in each specific direction of movement.

Exercise Countermeasures

The major differences in the exercise countermeasures between this study and Phase IIa were that the frequency of aerobic exercise sessions was increased from three to six days each week by adding three additional 30-minute treadmill sessions. The interval cycle exercise countermeasure was identical to the protocol used during Phase IIa. The treadmill protocol consisted of five minutes of warm-up at 40%, 20 minutes of exercise at 70%, and five minutes of cool-down at 40% of VO_2pk measured during the treadmill maximal exercise test. Treadmill and cycle ergometer exercise were performed on alternating days. In addition, the resistive exercise protocol used in Phase IIa was divided such that crewmembers performed the upper- and lower-body exercises on separate days (Table 5.2-3). Exercise countermeasures were generally performed in the order prescribed, but crewmembers were allowed to perform additional exercise based upon personal preference.

Table 5.2-3 *Schedule of exercise countermeasures*

Day of the Week	Aerobic Exercise	Resistance Exercise
1	Cycle	Upper Body
2	Treadmill	Lower Body
3	Cycle	Upper Body
4	Treadmill	Lower Body
5	Cycle	Upper Body
6	Treadmill	Lower Body
7	Rest or Submaximal Test	Rest

Scheduling of other activities, failure of environmental control systems, and personal preferences occasionally resulted in deviances from this schedule.

Beginning 30 days prior to chamber entry until the chamber exit, all subjects maintained daily exercise logs and completed activity questionnaires every two weeks. Additionally, all crewmembers monitored their exercise intensity using a HR monitor during aerobic exercise prechamber. During the chamber stay, the crewmembers continued to utilize the HR monitors during the aerobic exercise countermeasures.

Data Analysis

Data analysis for Phase III was similar to that performed for Phase IIa with respect to the common testing and countermeasures. Pre to postchamber measures of aerobic capacity were not compared statistically because only three subjects completed all these tests.

During isokinetic testing, peak torque was determined in each strength test for both extension and flexion. For data analysis of the endurance test at the knee, the first repetition was disregarded. Thereafter, total work, work at repetitions 1-3, work at repetitions 9-11, and work at repetitions 18-20 were determined from the endurance test data. The highest values obtained in each test prechamber were used for comparison to postchamber testing. All four subjects participated in these tests both pre and postchamber. Statistical comparisons of isokinetic variables were made with paired t-tests.

Phase III Results

Aerobic Exercise Countermeasures

In general, crewmembers adhered to the aerobic exercise countermeasure prescription. However, one crewmember did not participate in all in-chamber exercise due to knee discomfort experienced in the later third of the study. On two separate occasions all exercise was delayed or suspended due to environmental control concerns.

Cycle countermeasure exercise was prescribed 39 times from chamber entry to exit. As noted above, environmental control concerns impacted prescribed exercise, including one day during which exercise was cancelled altogether. Mean (± SD) compliance with the exercise prescription was 90 ± 12%, with a range from 72% in the injured crewmember to 97% in two crewmembers. The fourth crewmember completed 95% of the prescribed cycle exercise countermeasure sessions. Only one crewmember performed extra cycle exercise in addition to the prescribed cycle exercise sessions.

Treadmill countermeasure exercise was prescribed 39 times from chamber entry to chamber exit. Crewmembers ranged in compliance to this prescription from 72% in the injured crewmember to 104% in one crewmember. The other two crewmembers were 100% compliant with the prescription. Because crewmembers frequently extended the time they spent exercising on the treadmill at the end of the prescribed countermeasure, mean (± SD) duration of this exercise countermeasure was 34 ± 6 min. All crewmembers participated in at least one treadmill session in addition to that prescribed. One crewmember performed only one additional 30-minute session, but another crewmember exercised 40 additional times. This crewmember often performed treadmill walking after the cycle countermeasure session. The other crewmembers performed 6 and 17 additional treadmill exercise sessions.

Resistive Exercise Countermeasure

Overall compliance with the resistive exercise countermeasure was 88% across all four crewmembers. However, the crewmember that experienced knee discomfort did not complete lower-body resistive exercises after week 10. In addition, resistive exercise was unable to be performed for a period of five days because of electrical problems with the hardware. The problem was present again at a later time but was resolved before exercise schedules were impacted. Average compliance within crewmembers ranged from 78 to 97%.

To assess changes in strength across the length of chamber stay, peak torque developed during the performance of the LO speed exercises was examined (Figure 5.2-6). Although some crewmembers showed increased strength in individual exercises, as a group these crewmembers did not demonstrate a consistent increase in strength. Similar results were found for the HI and MED speed exercises.

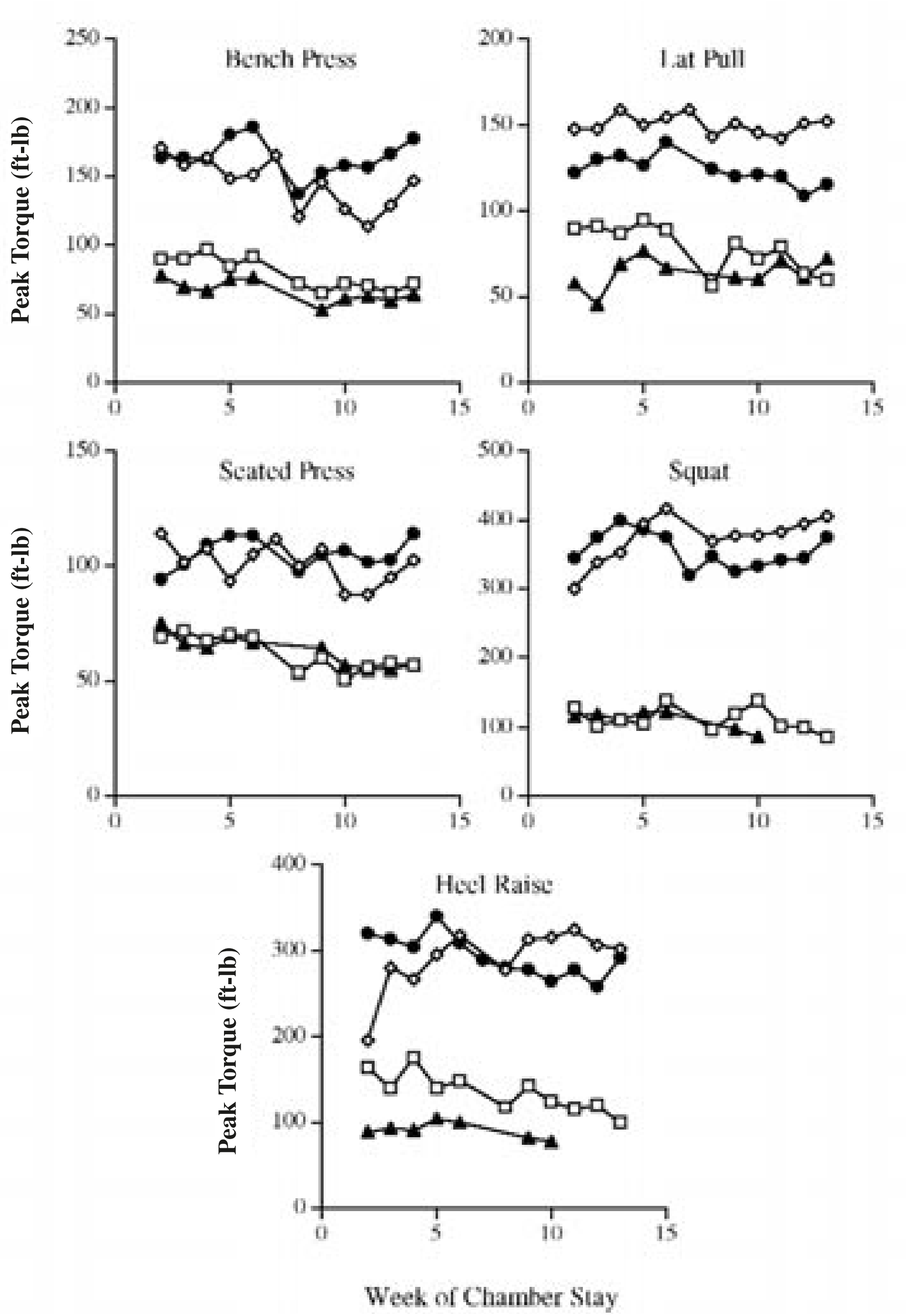

Figure 5.2-6 *Individual peak torque values obtained during isokinetic resistance exercise training at low (LO) speed of movement. Similar results were found for the HI and MED exercise speeds*

Maximal Cycle Exercise Test

Due to knee discomfort experienced by one subject, only three of the subjects participated in the postchamber cycle VO_2pk exercise test. Two of the three subjects attained higher exercise intensities (+50 watts) and longer VO_2pk test durations during postchamber testing (Table 5.2-4). VO_2pk in each of these two subjects increased by 0.5 L/min (8-9 ml/kg/min), an increase of approximately 20%. The VO_2pk of the third subject increased by 4%.

Table 5.2-4 *Mean (± SE) cycle VO_2pk exercise test results in three subjects*

	Prechamber	Postchamber
VO_2pk (l/min)	2.51 ± 0.16	2.89 ± 0.28
VO_2pk (ml/kg/min)	36.9 ± 3.4	43.2 ± 5.2
Peak Exercise Intensity (watts)	208 ± 8	242 ± 22
Total Test Time (min)	11.8 ± 0.4	12.9 ± 0.4

In the three crewmembers that completed post-chamber testing, both HR and the respiratory exchange ratio (RER) during submaximal and maximal exercise appeared to be reduced compared to prechamber testing (Figure 5.2-7).

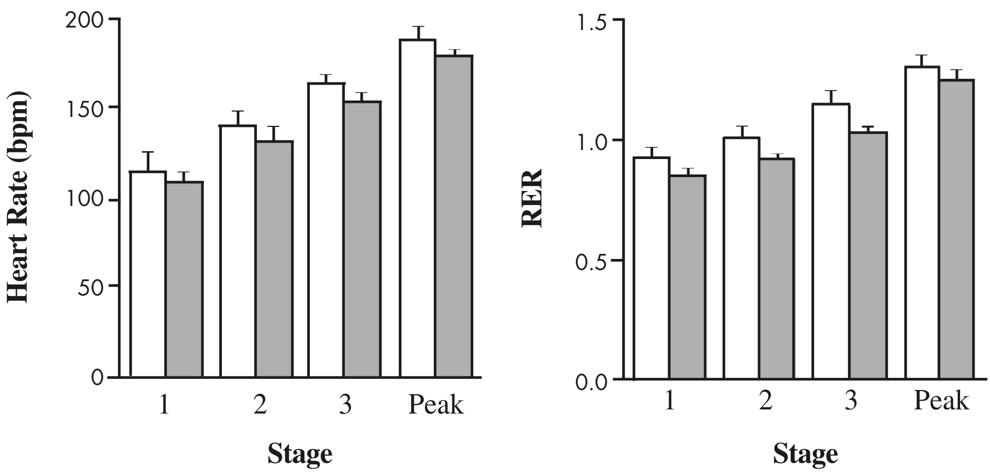

Figure 5.2-7 *Mean (± SE) HR and RER during pre (open bars) and postchamber (shaded bars) maximal cycle testing in three subjects*

Pre- to In-Chamber Submaximal Aerobic Exercise Test Results

The heart rate response during the submaximal exercise tests remained fairly constant during the first two submaximal exercise levels (25 and 50% VO_2pk) throughout the chamber stay. However, during the 75% VO_2pk exercise level, the average heart rate response decreased across the weeks of training (Figure 5.2-8).

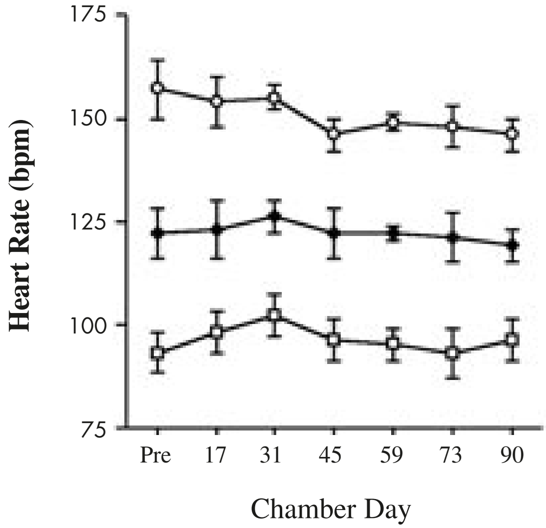

Figure 5.2-8 *Heart rate response during in-chamber submaximal exercise testing during each exercise stage at 25% (open squares), 50% (closed diamonds), and 75% VO_2pk (open circles)*

Pre to Postchamber Muscle Strength and Endurance

There was no observed difference in muscle strength during either extension or flexion at the joints tested pre to postchamber (Table 5.2-5).

Table 5.2-5 *Isokinetic strength and endurance (N-m) pre to postchamber*

Joint	Mode	Speed	Type	Movement	Pre	Post
Knee	Isometric	0°/sec	Strength	Extension Flexion	186 ± 31 92 ± 11	195 ± 29 95 ± 10
Knee	Concentric	60°/sec	Strength	Extension Flexion	157 ± 26 91 ± 14	158 ± 37 87 ± 17
Knee	Concentric	120°/sec	Strength	Extension Flexion	125 ± 21 84 ± 13	134 ± 27 81 ± 13
Knee	Eccentric	60°/sec	Strength	Extension Flexion	213 ± 44 110 ± 15	217 ± 44 104 ± 15
Knee	Concentric	120°/sec	Endurance	Extension Flexion	2,322 ± 277 1,544 ± 187	2,344 ± 302 1,323 ± 211
Ankle	Concentric	30°/sec	Strength	Extension Flexion	114 ± 17 34 ± 3	109 ± 19 32 ± 3
Ankle	Concentric	60°/sec	Strength	Extension Flexion	87 ± 23 26 ± 4	86 ± 16 26 ± 3
Ankle	Eccentric	60°/sec	Strength	Extension Flexion	155 ± 29 53 ± 5	152 ± 25 47 ± 5
Trunk	Concentric	60°/sec	Strength	Extension Flexion	215 ± 45 116 ± 15	207 ± 55 113 ± 20
Trunk	Eccentric	30°/sec	Strength	Extension Flexion	519 ± 59 126 ± 18	508 ± 77 125 ± 24

There appeared to be no change in total work performed during the knee endurance test during either extension or flexion from pre- to post-chamber stay in either group (Figure 5.2-9). Further, there was no difference in work performed at 1-3, 9-11, and 18-20.

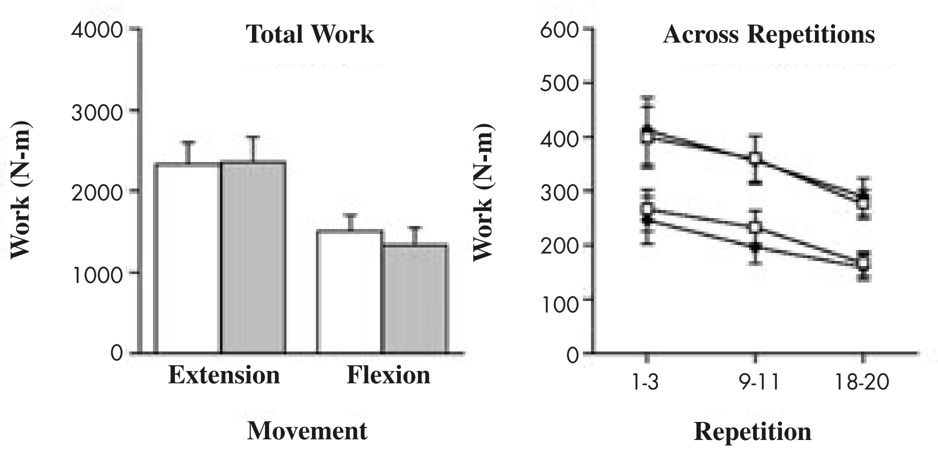

__Figure 5.2-9__ Pre (open bar) to postchamber (shaded bar) total work during knee endurance testing (120°/sec, 20 repetitions) in the four subjects. Also, pre (open squares) to postchamber (solid diamonds) sum of work performed during repetitions 1-3, 9-11, and 18-20 of knee endurance testing (120°/sec, 20 repetitions)

Phase III Discussion

Maximal Exercise Testing

Maximal exercise testing was performed prechamber stay using each exercise modality, cycle and treadmill, for which countermeasures were to be prescribed. In this way, we were able to develop modality-specific exercise prescriptions. It has been suggested that for future chamber studies and for space flight that the amount of testing should be reduced, such that only one maximal exercise test, treadmill or cycle, be performed. There are several problems with this approach:

- If the choice is made to utilize a treadmill maximal exercise test, it is likely that the protocol used for this test will be either a Bruce or modified Cunningham protocol. Both of these tests were developed for a low fit or cardiac rehabilitation population, and therefore may not be appropriate for a more physically fit group such as the astronaut corps. The profile of these protocols may not be appropriate for crewmembers to reach their "true" exercise capacity.

- It is common for VO_2pk measured on a treadmill to be 10-20% greater than the VO_2pk measured on a cycle ergometer (9). In this demonstration project, the measured VO_2pk during treadmill testing was significantly greater (19%) than that achieved during the cycle ergometry testing. Determining the desired exercise intensities for the cycle ergometer protocol using the treadmill VO_2pk value therefore would likely result in a prescription of cycle exercise intensities that may be greater than attainable by the crewmember. Conversely, using the results of a cycle ergometer test may result in the prescription of treadmill exercise intensities that are too low.
- In addition, not using metabolic data specific to the exercise modality for which a prescription is being developed would require the use of normative equations. The American College of Sports Medicine has stated that intrasubject variability of measurements of VO_2 may have a standard error of as high as 7%, and the variability of prediction equations may be even greater (10). Use of generally accepted equations may result in errors of up to 16% (16). Therefore, it would be preferable to make exercise prescriptions based upon modality-specific data obtained from the individual crewmember.

In general, maximal exercise testing was well tolerated in this group of highly motivated subjects. However, concerns with subject disqualification related to monitored changes in 12-lead EKG, whether specifically diagnostic or not, may limit the long-term use of these testing protocols as more subjects decline to participate. Therefore, it has been suggested that maximal exercise capacities be estimated from submaximal values. In our own experience, this is not desirable. Dependent upon the method used, prediction of maximal heart rates during cycle ergometer testing may range in error from -10 to +26% and prediction of maximal oxygen consumption can be ± 50% for some individual subjects.

Submaximal Exercise Testing

It was unexpected that the submaximal exercise responses during the chamber study appeared to differ slightly from the submaximal exercise responses during the postchamber maximal cycle test. While the chamber results indicated a reduction in heart rate during the chamber stay only at the highest exercise intensity (75% VO_2pk), the postchamber heart rate data was reduced at each of the three submaximal exercise levels. This difference may be due to the less stringent testing conditions during the chamber tests. This situation would be quite similar to the testing conditions during an actual space flight. At the lower exercise intensities, extraneous inputs from the environment and the self-collection of data and running the test may influence heart rate especially at the lower exercise intensities. Only at the highest exercise level may the exercise heart rate response become a true indicator of the training status.

Muscular Strength and Endurance Testing

Two methods were used to evaluate changes in muscle strength: first, the change in isokinetic resistances during the daily training sessions and second, data from the isokinetic strength tests performed before and after the chamber stay. Both sets of data in this study are consistent and support the fact that there was little increase in muscle strength during the chamber stay. When the peak torque measured during the heel raise exercise were compared with the peak torque measured during the plantar flexion portion of the isokinetic test, the values measured appear to move in similar directions from pre to postchamber in three of the four crewmembers (Figure 5.2-10). When similar comparisons were made from squat exercise and knee extension data, three of the four crewmembers displayed similar responses. These data suggest that the isokinetic testing provided valid results, but an examination of a larger database is necessary to confirm this.

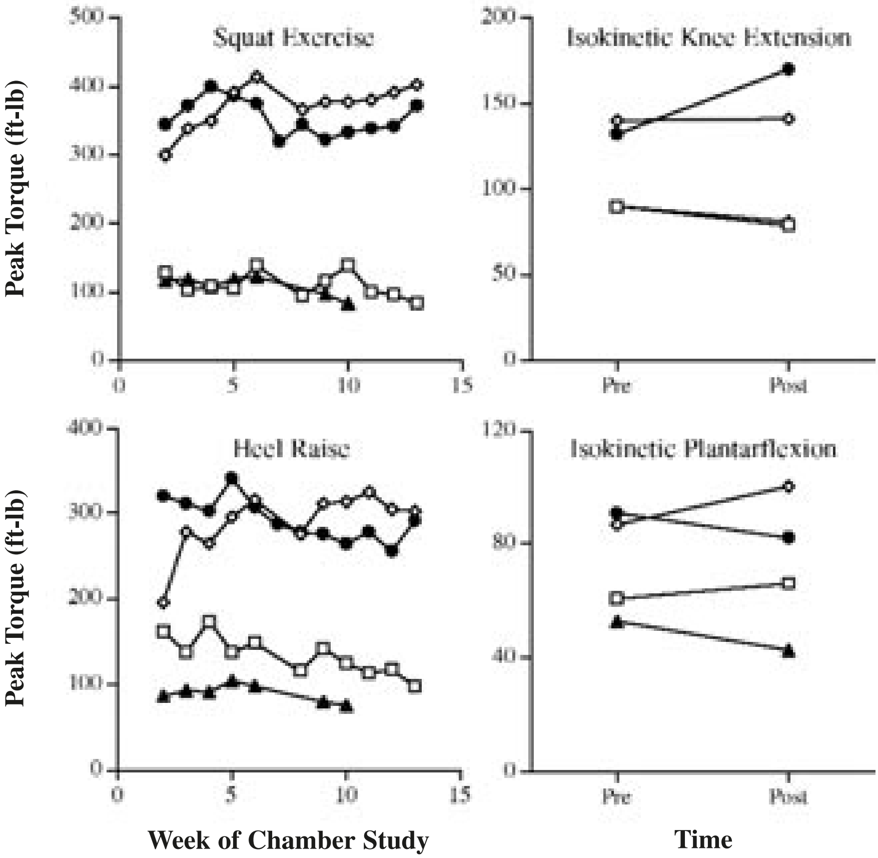

Figure 5.2-10 *Pre (open bar) to postchamber (shaded bar) total work during knee endurance testing (120°/sec, 20 repetitions) in the four subjects. Also, pre- (open squares) to postchamber (solid diamonds) sum of work performed during repetitions 1-3, 9-11, and 18-20 of knee endurance testing (120°/sec, 20 repetitions)*

Aerobic Exercise Countermeasures

The mean (± SD) time spent performing aerobic exercise protocols was 32 ± 10 min per day in these four crewmembers, ranging from 26 to 47 min across crewmembers. Therefore, crewmembers spent an average of 2941 ± 895 min exercising across the 91-day chamber stay, ranging from 2405 to 4224 min, and totaling for all four crewmembers 11,762 min. This total includes the time spent performing exercise in addition to that for performing the submaximal cycle exercise test.

The aerobic countermeasures performed in this demonstration appear to have been effective in increasing the aerobic capacity of the crewmembers. This suggests that these countermeasures also may be effective in preventing the decrements in aerobic capacity observed following space flight. Although similar interval exercise protocols have been effective during 5, 14, and 30-day bed rest studies (4, 6, 7, 17), only data from space flight studies will confirm this. Compared to the Phase IIa study, treadmill exercise was added and the frequency of exercise increased from three to six times per week. In the three subjects who completed both pre and postchamber testing, the average in increase in VO_2pk was greater in Phase III, but it is not possible to predict with certainty whether the fourth subject would have exhibited a similar improvement.

The interval protocol for the cycle ergometer and the continuous protocol for the treadmill were chosen to train for different tasks. The interval protocol with its high intensity stages was chosen to maintain high exercise capacities, involving both aerobic and anaerobic energy systems, in case high intensity work was required either during flight or immediately after flight. The continuous protocol was chosen to maintain work endurance for long periods of effort, which might be required during extravehicular activities (EVA) or intravehicular activities (IVA) while during flight or during extraterrestrial exploration. While the crewmembers found these protocols to be challenging at first, they expressed a desire for an increased variability in the protocols prescribed to reduce any staleness experienced in the repetition of these protocols over a long period of time. In addition, consideration must be given for future LMLSTP studies, as well as space flight countermeasures, to develop a periodization protocol to decrease the likelihood of overtraining, which may have been observed in one Phase III crewmember.

Although both cycle and treadmill exercise countermeasures were prescribed equally in number, when crewmembers chose to exercise longer or more frequently than prescribed, they chose to perform treadmill exercise. Only one crewmember on a single occasion performed an additional exercise session on the cycle ergometer. This preference also has been reflected in the performance of exercise during long-duration space flight. Postflight debriefs with U.S. astronauts who lived aboard the Russian space station, Mir, revealed a strong preference for treadmill exercise. Reasons given for this preference included desire to ambulate, positive feelings from the compression of the harness restraint system during treadmill exercise, and less boredom experienced during the performance of treadmill exercise. Perhaps the addition of virtual reality or computer games linked to the performance of exercise will improve the desire to exercise on both the cycle, treadmill, or during participation in any other exercise modality.

Interestingly, the crewmember that performed the greatest total volume of exercise was the one who showed no improvement in VO_2pk from pre- to post-chamber. These data suggest that there was no additional benefit from performing exercise greater than that prescribed. However, this crewmember performed primarily low-level (walking) exercise in addition to the daily exercise countermeasures. It could be argued that this crewmember was the one who participated in the greatest amount of exercise prior to chamber entry, but the in-chamber exercise was of substantially greater intensity. It is more likely that this subject was not experiencing sufficient rest between high-intensity bouts of exercise such that performance on the maximal cycle ergometer test was unchanged from prechamber and/or declined as the end of the chamber stay approached (5). This subject reported increased fatigue as the demonstration project neared completion and began to decrease the amount in excess of the exercise prescription. In addition, similar to the crewmember that experienced knee discomfort, this crewmember also had consistent decreases in muscle strength by the end of the study as suggested by decreased peak torques during isokinetic training.

The interval protocol on the cycle ergometer was prescribed because it was felt that the prescription of such a varied and high intensity protocol for the treadmill, while not an issue during LMLSTP, may be problematic during space flight. The loss of gravitational forces during cycle ergometry is unlikely to result in significant alterations in metabolic responses to cycle exercise. For example, in our experience, it does not appear that heart rate responses to cycle exercise during short-duration space flight are significantly different from that experienced during normal gravity (11), primarily because the mass of the body is supported during both normal and micro-gravity. In contrast, during treadmill exercise in normal gravity the body mass must be supported, but this is not the case during exercise in the microgravity environment. The z-axis component of treadmill exercise during microgravity exposure is wholly dependent upon the loading system that restrains the subject. During Skylab, Space Shuttle, and Mir missions, whole-body loading of the crewmembers has been accomplished through the use bungee cords, or a spring-based system in line with bungee cords, attached to a torso harness system. The design of these systems has been such that the loading carried by the crewmember is distributed similarly to that when carrying a large backpack, with the load placed on the hips and shoulders. This type of loading has been reported to be uncomfortable such that crewmembers typically load to a level of only one-half to two-thirds of their body weight. Thus, crewmembers may vary their loading dependent on their comfort levels. As a result, the exercise responses to treadmill exercise at a specific belt speed may vary depending upon the amount of loading, and the attainment of a specific metabolic load equivalent to normal gravity ambulation may require high treadmill speeds which may not be practical for treadmill construction (size of motor required, wear on treadmill parts, etc.) or may be unsafe for crewmembers. Although treadmill running in microgravity at different loads has yet to be systematically investigated, Boda and co-workers (1) have reported that metabolic loads can be attained during treadmill exercise with the body in the horizontal position using lower-body negative pressure that approximates the metabolic loads encountered during normal upright treadmill exercise. In this configuration, the interval exercise protocol during bed rest has been successfully employed (6, 7, 17).

Resistive Exercise Countermeasure

The resistive exercise countermeasure prescribed in this chamber test was similar to that used during Phase IIa. Crewmembers performed the same exercises in Phase IIa and Phase III, but in Phase IIa all the resistance exercises were performed each of three days during the week. In contrast, during Phase III the exercises were divided into upper- and lower-body exercises and performed on different days such that crewmembers were performing resistance exercise six days per week. During Phase IIa, this countermeasure appeared to improve strength in three of the four crewmembers. This was not true in Phase III. Crewmembers had inconsistent changes in strength during Phase III, as evidenced by strength training records, which was manifested in no change in strength or endurance between pre- to post-chamber measurements made during isokinetic testing. An explanation of the divergent results from the two studies may be that the manner in which the training was performed by the crewmembers differed. In Phase IIa, crewmembers completed their resistive exercise training with minimal rest between sets (~two min). In Phase III, crewmembers increased the rest period between sets, often performing other tasks and duties while resting from the previous test. The rest periods of the Phase III crew may not have been optimal for the development of muscle strength through resistive exercise training. Future protocols will address this issue.

In addition, there may be some degree of incompatibility of strength and aerobic training that could have a negative effect on strength development. However, the majority of the studies that have demonstrated this effect have employed high volumes and intensities of both strength and endurance training (2). In the Phase IIa crewmembers this may not have been problematic. Although the in-chamber exercise was at a greater level than that in which crewmembers usually engaged, the frequency was similar to that which has been shown to result in little interference in strength development (8). However, the increase in total exercise volume (resistance and aerobic) employed during Phase III may have been sufficiently greater than Phase IIa so as to induce some overtraining (2). Perhaps a periodization of both strength and endurance training may alleviate this problem and result in more consistent strength gains.

Overtraining

All four crewmembers performed the cycle ergometer countermeasure protocol at the same intensity as prescribed prior to chamber entry through day 66. On day 67, the intensity of exercise was increased in all four subjects. This increase was indicated based upon the results of the submaximal aerobic exercise tests that suggested that each had increased their aerobic fitness. Three of the four crewmembers tolerated this increase well, but the fourth reported minor discomfort in the left knee following the performance of this increased workload.

The peak workload for the injured subject increased from 165 to 174 watts. The peak HR attained during this exercise countermeasure session was 177 bpm, similar to that attained during the prechamber protocol practice session (176 bpm) and to that attained during the first two exercise sessions upon chamber entry (171 and 173 bpm). The cause of the knee discomfort in this subject was unclear, but the subject performed the first, less intense protocol for the subsequent cycle ergometer countermeasure session. The knee discomfort appeared not to lessen, and therefore cycle ergometer exercise was discontinued.

The inability of the crew surgeon to perform a physical examination with this subject interfered with our ability to determine the cause of knee discomfort in this subject. In our opinion it is unlikely that this small increase in peak exercise intensity is responsible. However, since this subject was not highly physically active prior to chamber entry, it is possible that the subject was nearing a point of overtraining and that the increase in workload accelerated this process. This indicates the need to allow a longer period of lower intensity, or active rest, for the subjects periodically when performing these countermeasures across a long period of time. Allowing crewmembers a week of less intense countermeasures every three weeks may reduce the incidence of such problems. It is difficult to reach this conclusion though since this is the first report of this nature under these conditions.

OVERALL CONCLUSIONS AND SIGNIFICANCE

These LMLSTP studies have allowed preliminary evaluation of potential exercise testing and countermeasure procedures. Lessons learned from these projects may be applied to space flight with the important consideration that training responses in a 1-g environment may not be exactly representative of space flight; exercise in the chamber projects were intended to increase exercise capacity, while exercise countermeasures in a microgravity environment are intended to maintain overall conditioning. Additionally, exercise performed within the constraints imposed by microgravity (e.g., subject loading during treadmill exercise) or with the actual flight hardware may provide a different training stimulus. Further, thresholds for training and over training may differ between the two conditions and vary among the target organ systems. Data collected during actual space flights will be required to provide the final confirmation of our countermeasure programs.

The data collected during these chamber studies also must be considered extremely preliminary due to the small number of subjects. In many cases, appropriate statistical analyses could not be performed due to the limited sample size.

With these considerations, preliminary observations from these studies are:

- The aerobic and resistive countermeasures tested in these projects provided a training stimulus when performed on separate days (Phase IIa). Further work is needed to explore a possible negative effect on strength training when aerobic exercise was performed on the same day as resistive training (Phase III).
- Most crewmembers preferred treadmill exercise over cycle exercise. This has been reported also by long-duration space flight crews. However, due to effects of microgravity on treadmill exercise loading, exercise prescriptions and testing protocols can be more accurately applied on a cycle.
- Compliance to our exercise prescriptions was very good, but some discontent was evident from the postchamber debriefs. Increasing the variety of exercise protocols, exercise devices and addition of virtual reality head gear or other forms of entertainment during exercise may improve exercise compliance.
- Almost all subjects reported a desire for more variety of exercise prescriptions.
- The lack of strength increase may suggest that the rest periods between sets were too long or that there was an overtraining response in the Phase III crew with the increased aerobic exercise volume. In future studies and during space flight, crew exercise time should be protected to optimize the effect of training. Also, the addition of muscle damage markers to future training studies may help to elucidate this issue.
- The exercise logging materials used in this study and the feedback from the subjects has been used in developing the computer-based flight logs currently planned for the ISS.

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ACRONYMS

ANOVA	analysis of variance
bpm	beats per minute
CES	computerized exercise system (Ariel Life Sciences, Inc.)
DBP	diastolic blood pressure
ECG	electrocardiogram
EVA	extravehicular activity
HI	high speed
HR	heart rate
ISS	International Space Station
IVA	intravehicular activity
l/min	liters per minute
LMLSTP	Lunar-Mars Life Support Test Project
LO	low speed
MED	medium speed
ml/kg/min	milliliters per kilogram per minute
RER	respiratory exchange ratio
RPE	rating of perceived exertion
rpm	revolutions per minute
SBP	systolic blood pressure
SD	standard deviation
SE	standard error
SMP	Space Medicine Project
VO_2pk	peak oxygen consumption
VO_2	oxygen consumption