Artificial Gravity as a Countermeasure to Spaceflight Deconditioning: The Cardiovascular Response to a Force Gradient

by

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Submitted to the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degree of
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Abstract

Before intermittent short-arm centrifugation can be tested as a countermeasure to space deconditioning, a number of ground-based studies must be conducted to determine the effects of a gravity gradient both on normal subjects and individuals undergoing bed rest. This investigation focused on determining several of the cardiovascular effects of a gravity gradient on normal subjects. The purposes of the investigation were to answer the following questions: 1) how cardiovascular performance measures change with G level and duration of stimulation, 2) how do cardiovascular parameters change during force gradient stimulation as compared to their response to standing in 1 G, and 3) what levels of force gradient stimulation promote significant cardiovascular regulation? It was hypothesized that G levels of 1 and less at the feet would produce few cardiovascular changes in normal subjects. This investigation will enable future researchers to more precisely outline centrifuge studies necessary on individuals undergoing bed rest treatments as models for spaceflight deconditioning. The hope is that a SAC may someday be used in space to keep the cardiovascular system stimulated to minimize orthostatic intolerance.

Eight subjects, four men and four women, participated in one control and three rotation trials on a horizontal short-arm centrifuge (SAC) such that the Gz levels at the feet were 0.5, 1.0, and 1.5. Trials consisted of 30 min. of supine rest, 1 hour of rotation (or in the control, 30 additional min. of rest and 30 min. of standing), and a final 30-minute rest period. Measurements of heart rate, calf impedance, calf volume, and blood pressure were obtained. Post-trial analysis explored the relationships between the physical characteristics of the subjects, rotation time, G level, and the cardiovascular parameters measured. Most measured cardiac parameters suggest that rotation levels causing 1.0 G at the feet or less produced regulatory responses not significantly different from continuous supine rest. In addition, the cardiovascular responses to SAC rotation with 1.5 G at the feet were statistically similar to standing, at least for a comparison based on 30 min. The primary effects of 1.5 G were an elevated diastolic pressure, increased heart rate, and increased calf volume. While some cardiovascular changes were found to be correlated to gender, mass, and height, their influence was considered minor. Most importantly, since standing intermittently during bed rest trials has been shown to decrease orthostatic intolerance and rotation at 1.5 G was found here to be similar to standing, short-arm centrifugation should be considered as a possible countermeasure to cardiovascular space deconditioning. Rotation durations on the order of 30 min. may be required for promotion of sufficient cardiovascular regulation in inactive subjects.

Thesis Supervisor: Dr. Laurence R. Young
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Dr. Steve Burns, MIT Division Health Sciences and Technology -- ECG
Dr. Andrew Taylor, Hebrew Rehabilitation Center -- Minnesota Impedance Cardiograph
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We are the children of gravity. We can't touch it or see it. But it has guided the evolutionary destiny of every plant and animal species, and has dictated the size and shape of our organs and limbs. Every bone and muscle is aligned to maximize mobility in 1 G.

-- Dr. Ralph Pelligra, NASA Ames
INTRODUCTION

The Case for Artificial Gravity

Living in a weightless environment often produces physiological changes referred to as space adaptation syndrome (SAS). The effects of SAS have been well documented (Grymes 1995; Convertino and Sandler 1995), and generalized symptoms are listed in Table 1 (Sander, et al. 1995). Changes in the skeletal and cardiovascular systems are particularly alarming. 1-2% of bone mass is lost per month in space (Sandler 1995). This is a critical problem affecting long-term spaceflight. Issues related to loss of orthostatic tolerance are also of concern. Astronaut faintness during reentry or during an emergency landing on earth or another planet is a real danger caused by cardiovascular deficiencies.

Table 1. Space Adaptation Syndrome Effects

<table>
<thead>
<tr>
<th>Anorexia</th>
<th>Decreased Exercise Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nausea</td>
<td>Muscular Incoordination</td>
</tr>
<tr>
<td>* Motion Sickness</td>
<td>Muscle Atrophy</td>
</tr>
<tr>
<td>* Disorientation</td>
<td>Fluid Shift</td>
</tr>
<tr>
<td>Restlessness</td>
<td>Dehydration</td>
</tr>
<tr>
<td>Sleeplessness</td>
<td>Weight Loss</td>
</tr>
<tr>
<td>Fatigue</td>
<td>* Gastrointestinal Disturbances</td>
</tr>
<tr>
<td>Lethargy</td>
<td>Renal Calculi</td>
</tr>
<tr>
<td>Immune System Degradation</td>
<td>Reduced Plasma Volume</td>
</tr>
<tr>
<td>* Demineralization of Bones</td>
<td>Reduced Blood Volume</td>
</tr>
<tr>
<td>* Loss in Bone Mass</td>
<td>* Cardiac Arrhythmias</td>
</tr>
<tr>
<td>Spine Length Increase/Pain</td>
<td>Tachycardia</td>
</tr>
<tr>
<td>* Decreased G Tolerance</td>
<td>Hypertension</td>
</tr>
<tr>
<td>* Postflight Syncope</td>
<td>* Hypotension</td>
</tr>
</tbody>
</table>

* May cause an emergency situation in flight.

Current countermeasures against SAS include exercise, the Russian Penguin suit, fluid loading, diet modification, lower body negative pressure (LBNP), preflight adaptation training, drugs, and electrical muscle stimulation. The primary inflight exercises practiced in the Russian and American space programs are use of a cycle ergometer, running on a treadmill, and resistance training. These maintain aerobic capacity and do a somewhat sufficient job of maintaining muscular strength. Similar to the exercise training is the Penguin suit, an elasticized garment that requires extra force to be exerted for normal movements. Fluid loading in-flight corrects for plasma volume loss and helps prevent disorders such as renal stone formation (Heer, et al. 1995). Fluid loading prior to reentry is intended to help maintain orthostatic tolerance during the large reentry G forces (up to 2 G). The potential of diet modification as a countermeasure has not fully been explored, but it can only attenuate some of the effects of SAS. Current ground-based
research on the use of LBNP is showing promise (Güell 1995); however, few in-flight studies of LBNP as a countermeasure to orthostatic intolerance have proven its effectiveness. At the moment, preflight adaptation training may consist of occasional flights in the KC-135 (to experience 0 G), underwater training, acceleration G profiles similar to Shuttle launch, and exposure to disorienting vestibular stimuli in the JSC Pre-Adaptation Trainer. However, a formal preflight adaptation program does not exist. No psychological preflight training is currently practiced either. Promethazine, for motion sickness, is the most advanced pharmacological countermeasure in place today. Altered pharmacokinetics and pharmacodynamics in microgravity have prevented most drug treatments available on Earth from being applied as countermeasures to SAS in space (Vernikos 1995). Electrically stimulating the muscles has been practiced for years by the Russians to prevent atrophy and has met with some success (Convertino and Sandler 1995).

While current countermeasures attack many aspects of space deconditioning, not one preserves bone density. Orthostatic tolerance and muscular strength are not totally sustained either. Russian cosmonauts have made extensive use of the Penguin Suit and exercise countermeasures for durations longer than one year, but they cannot walk unassisted for at least 48 hours after landing. Russell Burton, Chief Scientist at the U.S. Air Force School of Aerospace Medicine (USAFSAM), stated the problem nicely when he said (1989), “The Occupational Safety and Health Association would probably not allow employees to work in such a hazardous environment on earth, so why should it be permitted in space?” The failure of existing therapies for dealing with the debilitating effects of long duration weightlessness may call for artificial gravity (AG) as the only way to prevent SAS.

Why do we need something as extreme as artificial gravity (AG) when we can allow the astronauts to recuperate when they return? That question may be valid for short-term flights and even space station missions, but for long-term explorations such as a Mars venture certain additional considerations merit use of the extreme countermeasure. Current technology dictates that a Mars trip will require at least two years in microgravity because “the diverse capabilities of such energy sources as the dilithium crystals used on the U.S.S. Enterprise are as yet unavailable to NASA” (Grymes 1995). Providing astronauts with AG on the trip to Mars could produce several benefits. The gravity level of Mars is only 37.5% of Earth’s. No one has ever lived in microgravity for one year and returned to a gravity environment without medical treatment available. AG would maintain the astronauts' ability to perform emergency extravehicular activities (EVA’s), prevent bone fractures, and maintain the pilots' ability to perform their duties. Also, adaptation time to the Mars environment might decrease if 0.375 G could be provided prior to a Mars landing. Thus, few of the precious days on Mars would be wasted due to astronauts' limited functionality. Finally, it is not inconceivable that someday humans will live in space for many years, in orbit, on a Mars base, or on a lunar base. The effects of living in the partial gravity
environment of the moon (0.16 G) or Mars are unknown. AG may need to be provided even on the surface. The challenge is to determine what kind of AG (what G level and for how long in the context of this paper) is necessary in any of these situations.

Performing AG research has been difficult at best because the human 1 G requirements are unknown and all experiments on Earth are subject to a 1 G force. Critical studies that have been conducted pertaining to the physiological effects of AG are summarized in Appendix A. They are categorized according to the rotation environment or purpose of study. Some general observations can be made. Most of the experiments were conducted long before acquisition of the current knowledge of SAS. Usually, a handful of subjects were tested, making the validity of the findings questionable. In addition, many of the tests were not comprehensive and varied considerably so that comparisons are nearly impossible. Still, the results of these studies, the fact that bed rest can approximate the physiological effects of microgravity exposure (for some but not all major body systems), and recent orthopedic research indicate that it is not just the G force that maintains the human system but the activities carried out in the G force (Schneider, et al. 1993). That different activities stimulate different body systems seems to be clear as well. The conclusions of the intermittent stimulation investigations, added to the knowledge that humans sleep horizontally each night with no ill effects, imply that humans do not require constant exposure to gravity along the vertical axis of the body. As a final observation, each of the studies in Appendix A is concerned with only a specific aspect of AG, usually intermittent or constant exposure. While some suggestions have been made (Kotovskaya, et al. 1977; Workshop on the Role of Life Science in the Variable Gravity Research Facility 1988; Burton 1989), an overall research approach to determine the physiological AG requirements for long-term spaceflight is decidedly absent.

Before deciding what research is necessary to determine the physiological requirements for AG, a comprehensive set of questions must be compiled. As complete a list as possible is shown in Table 2. Note that only questions necessary to provide AG for long-term spaceflight are listed. Many more could be added if the entire physiological response to force levels were desired. These questions include those that must be answered for both AG provided by a rotating spacecraft and AG provided by a short-arm centrifuge (SAC) in a nonrotating spacecraft.

Motivation

As mentioned previously, one of the methods of providing artificial gravity to astronauts is by using short-arm centrifugation in space. This would most likely occur via intermittent stimulation on a SAC since a space crew would not be likely to live and work in a small volume, as would be the case if short-arm centrifugation were applied by spinning the entire spacecraft. Before a SAC can be tested as a countermeasure in space, a number of ground-based studies must
be conducted to determine the effects of a gravity gradient both on normal subjects and individuals undergoing bed rest, a treatment that mimics microgravity exposure.

Table 2. Questions Regarding the Physiological Requirements for Artificial Gravity

| 1. How much time in 1 G is necessary to maintain normal physiological status? |
| 2. What activities in 1 G keep humans fit? |
| 3. Since the activities we perform in a gravitational field stimulate us, then passive exposure to rotational G during sleep is of little benefit. Is there a best time of day to provide 1 G? |
| 4. Should 1 G be provided in a lump sum or intermittently during a day? |
| 5. If exposed to the microgravity environment for a period of time, how long does reconditioning via AG take, or can it be done at all? |
| 6. Does exposure to G levels greater than 1 decrease the total stimulation time? |
| 7. What is the relationship between the steady-state physiological response and the G level? |
| 8. What is the character of the physiological transient response to a G level? |
| 9. What is the relationship between the G-level physiological response and age, gender, fitness, etc.? |
| 10. What is the physiological response to a G gradient along the body? |
| 11. The effects of motion sickness caused by angular cross-coupling in a rotating environment on the general body system can be determined by comparing the response of subjects who have lost vestibular function to that of normal subjects. After this knowledge is gained, how can it be applied to reduce the severity of or eliminate the detriments of rotational motion sickness in a normal person? |
| 12. Does the Coriolis stimulation of the rotating environment affect physiological responses? |
| 13. What is the best way to adapt to a rotating environment? |
| 14. Burton cites data implying that animals can adapt to increased G environments while maintaining adaptation to 1 G (1989). Can a human maintain adaptation to two G levels for a period of time without experiencing major side effects from transition between the two levels? |
| 15. If partial gravity could only be provided because of engineering/cost concerns, how much more stimulation time is necessary, or can partial gravity exposure be beneficial at all? |
| 16. How similar are adaptation and physiological responses to a rotating environment on earth to those caused by a rotating environment in space? |

This investigation focused on determining several of the cardiovascular (CV) effects of a gravity gradient on normal subjects. Specifically, one purpose of the investigation was to determine how cardiovascular performance measures change with G level and duration of stimulation. Additional questions considered were: (1) how do cardiovascular parameters change during force gradient stimulation as compared to their response to standing in 1 G, and (2) what "safe" levels of force gradient stimulation promote significant cardiovascular regulation? In essence, partial answers to questions 7-10 in Table 2 were sought. As a result of previous research in this area and physical principles, it was hypothesized that G levels of 1 and less at the feet would produce few cardiovascular changes in normal subjects.

This research will enable future investigators to more precisely outline centrifuge studies necessary on individuals undergoing bed rest treatments as models for spaceflight deconditioning.
The added benefit is increased knowledge about gravitational physiology. The hope is that a SAC may someday be used in space to keep the cardiovascular system stimulated to reduce the likelihood of orthostatic intolerance, among other effects.

Background

A consequence of short-arm centrifugation is a force, or gravity, gradient along the body. Centrifugal acceleration, $a$, obeys the law

$$a = r \omega^2,$$

(1)

where $\omega$ is angular velocity and $r$ is the radius. Thus, a body subjected to a constant angular velocity on a SAC will experience a different force at each location along its longitudinal, or $z$, axis. The following equation can be used to calculate $G$ level, were $\omega$ is in rpm and $r$ is in meters:

$$G \text{ level} = \frac{r \left( \frac{2\pi \text{ rad}}{1 \text{ rev}} \frac{1 \text{ min}}{60 \text{ s}} \right)^2}{9.81 \text{ m/s}^2}.$$

(2)
Figure 1 displays curves for G level along a body for various angular rotation rates. As specified by question 10 in Table 2, the effect of the variation in force on humans has not been completely characterized.

Obviously, no centrifuge on Earth can subject a body to less than 1 G in three-dimensional space. Rather, a centrifuge rider is subjected to the vector sum of the centrifugal force and Earth's gravity. In general, studies conducted on centrifuges refer only to the G level along the rotation radius. In addition, since a force gradient exists, experimenters often refer to the G level in SAC studies as being the force felt at the feet. For example, a rotation rate of 22.3 rpm will cause a G level of 1 at the feet of a 1.8 m person whose head is placed at the center of rotation. The same rotation rate will only produce 0.80 G in a person 1.5 m tall whose head is at the center of rotation as well. The force component felt through the x-axis of a supine person, gravity, is generally considered of negligible importance to the results (of studies such as the present where subjects are horizontally supine) because the height of the x-axis hydrostatic column is small compared to the z-axis column and most major systemic blood vessels are aligned with the body's z-axis (Breit, et al. 1996).

Standing under the influence of normal gravity creates a pressure gradient along the z-axis of the body. The normal hydrostatic pressure relation is given by

\[ P = \rho g z + P_0, \]

where \( \rho \) is density, \( g \) is normal gravitational acceleration, \( z \) is the height from a reference level, and \( P_0 \) is the reference pressure. For rotation on a centrifuge the pressure relation becomes

\[ P = \frac{1}{2} \rho \omega^2 (z^2 - z_0^2) + P_0, \]

with \( z \) now representing the distance along the radius. If the heart is considered to be at the reference level, with a mean arterial pressure of 100 mmHg, then Figure 2 compares the pressure gradients induced by standing and rotation at 0.5, 1.0, and 1.5 G in a 1.8 m person. While supine, the arterial pressure over the body is much more uniform than any of the curves in Figure 2.

Before discussing the mechanisms responsible for orthostatic intolerance and how to prevent the condition, several CV variables and relations should be defined. Cardiac output (CO) is the volume of blood pumped out of the heart per unit time. It is calculated by

\[ CO = SV \times HR, \]

where HR is the heart rate and SV is the stroke volume, the volume of blood pumped out of the heart with each beat. The pulse pressure, PP, the difference between and systolic and diastolic pressures, can be directly related to SV through

\[ PP = \frac{SV}{C_a}, \]
where $C_a$ is the arterial capacitance. Unlike SV, $C_a$ is a relatively invariant to stresses induced on the body. Generally, one of the fundamental functions of CV regulation is to maintain cardiac output at a level sufficient to sustain perfusion to the brain and to maintain pressure in the circulatory system. Mean arterial pressure can be found using
where $P_S$ is the systolic pressure and $P_D$ is the diastolic pressure.

Alterations in posture or the gravity environment create increased pressure in the lower body which leads to venous pooling in legs. A postural example that demonstrates this is the transition to standing after being supine for a period of time. Hypergravity conditions will also cause venous pooling. If the increased blood flow to the periphery is not regulated, venous return to the heart is impeded. This leads to decreased cardiac output, decreased blood pressure, and eventual syncope, the classic sign of orthostatic intolerance. Orthostatic tolerance is normally maintained by compression of leg veins through local regulation and baroreflex-mediated sympathoexcitation and vagal withdrawal.

The primary mechanisms related to cardiovascular responses to orthostatic stress that will be discussed here are autonomic control of the cardiovascular system and the baroreflex response. For a further discussion of CV regulatory mechanisms the reader is referred to Blomqvist (1983) or Churchill and Bungo (1997). Autonomic control of the CV system is mediated by sympathetic and parasympathetic innervation. The parasympathetic system innervates the heart via the vagus nerve and acts to reduce heart rate. In the context of the present experiment, activation of the sympathetic system increases heart rate, increases contractility of the heart, and causes vasoconstriction. The arterial baroreflex is a mechanism for regulating arterial pressure by sensing pressure in the arteries and responding with changes in control of cardiac output or peripheral resistance to achieve a desired CV set-point. The pressure sensors, termed baroreceptors, are found in the aortic arch and a region of the neck called the corotid sinus. In the case of the present study, the baroreceptors will sense a decrease in arterial pressure when the body transitions from supine rest to an orthostatic stress. The baroreceptors will then normally cause the following changes, among others, to occur: a decrease in vagal activity, an increase in sympathetic activity to all portions of the CV system, arteriolar and venular vasoconstriction (increasing total peripheral resistance), and an increase in heart rate.

When astronauts return to the gravity environment of Earth from a stay in space, the cardiovascular regulatory mechanisms that prevent excessive blood pooling in the legs do not function properly. It is for this reason that 9 to 64% (depending on the particular study) of astronauts fail a 10 min. standing test after return to Earth (Buckey, et al. 1996). According to recent studies, the major hemodynamic defect related to orthostatic intolerance resulting from spaceflight is a lack of vasoconstriction in the lower limbs (Buckey, et al. 1997). Total peripheral resistance does not rise adequately. Changes in the baroreflex sensitivity have not been confirmed (Arbeille, et al. 1997; Buckey, et al. 1996) so sympathetic circulatory control alterations are suspect. In a simplified explanation, current theory believes these alterations in the CV regulatory system occur as a result of disuse in space. In a sense, the CV reflexes "have not been practicing."
It has been suggested that standing intermittently could be an effective countermeasure to
the orthostatic intolerance seen in SAS (Vernikos 1994). A study was performed in which subjects
were exposed to four days of -6° head-down bed rest interrupted by 15-minute periods of standing.
Two conditions, standing 8 times per day (2 hours total) and standing 16 times per day (4 hours
total), were tested. Orthostatic tolerance was assessed by 30 min. of 60° head-up tilt. Presyncope
indicated failure of the test. Standing 8 times per day partially prevented and standing 16 times per
day completely prevented orthostatic intolerance. To stand in space, a gravity field would need to
be created. This paper investigates SAC rotation as the mechanism for providing the gravity field.

Several studies have investigated the effects of a gravity gradient on the cardiovascular
system. Shulzhenko and Vil-Viliams (1992) monitored the orthostatic intolerance during 3-day dry
immersions (another analog of microgravity exposure) of 4-6 subjects who were intermittently
exposed to rotation on a 2 m-radius centrifuge. Orthostatic function was assessed by time
tolerance to rotation on a 7.25 m centrifuge at +3 Gz. In one study, subjects experienced 40-60
min. of 0.8, 1.2, or 1.6 G two to three times daily. As compared to pre-dry immersion,
orthostatic tolerance decreased 18%, 7%, and 1%, respectively, at the end of the three days. The
control decrease was 21%. When water and salt supplements were added and the experiment was
repeated for the 0.8 and 1.2 G levels, the orthostatic tolerance only decreased 7% and 1%,
respectively. The same experimenters conducted a 28-day trial with the following time profile: 7
days of no-exposure dry immersion, 7 days with 40-60-minute blocks of 0.8, 1.2, or 1.6 G 2-3
times daily, 7 days with periodic supine bicycle ergometer training, and 7 days with SAC rotation
combined with bicycle ergometry for 60 min. twice daily. It was found that after the first 7 days,
orthostatic tolerance had decreased by 56%. After 28 days, orthostatic tolerance was 8% less than
normal. While this last experiment clouds the issue because of the combined interventions, the
combination of the three trials proves that rotation at hypergravity attenuates loss of orthostatic
tolerance due to physiological microgravity analogs.

Cardús (1993a, 1993b) performed a study on six men with measurements of general
cardiovascular signals for one hour durations on a 2 m-radius SAC. G levels of 0.5, 1.0 (with
only 3 subjects in this case), and 1.5 at the feet were tested. Time profiles for the trials included a
30-minute supine rest period, one hour of rotation, and a final 30-minute rest period. The
experimenters observed few cardiovascular changes for G levels below 1 at the feet. Cardiovascular alterations did occur for G levels in the 1-1.5 range. Above 1.5 G, cardiovascular changes became more dramatic, with 2 G inducing syncope in some subjects. Figure 3 displays
some of the results of the experiment for three rotation rates. It should be noted that the authors
used rates of 17, 20, and 24 rpm to produce estimated G levels of 0.5, 1.0, and 1.5 G. Rotation
rates were not adjusted for subject height. No statistical comparisons were performed although it
Figure 3. The Cardiovascular Response to Short-Arm Centrifugation in Cardús's Study
Results of experiments conducted by Cardús (1993b) for 6 male subjects at three rotation rates.
(Only three subjects participated in the middle rotation rate trial). Trials consisted of 30 min. rest, 1 hour of rotation, and a final 30-minute rest period. Rotation was performed on a SAC termed the Artificial Gravity Simulator (AGS). TFI = thoracic fluid index
was noted that diastolic pressure tended to increase slightly. In addition, data were not compared to continued supine rest substituted for rotation. From Figure 3, one can see that systolic pressure changed little and diastolic pressure showed some increase as the rotation rate was raised. Heart rate increased and stroke volume decreased for the 1.0 and 1.5 G cases. Careful study shows that after the initial change in these two parameters, a small recovery took place, followed by a much larger alteration occurring at approximately 30 min. The thoracic fluid index (TFI) was measured via electrical impedance. An increase in impedance (or TFI) corresponds to a decrease in volume over the area measured. The plots show that TFI increased with rotation, especially at the higher G levels. This can be interpreted to mean that fluid was transferred from the thoracic cavity to the lower body. Note that this effect does not reach steady state in the one hour of rotation for the higher G levels.

Researchers at NASA Ames Research Center (Breit, et al. 1996) also conducted a study on eight men and seven women to compare the effects of short-arm centrifugation (with a 75% $G_z$ gradient), long-arm centrifugation (with a 25% $G_z$ gradient), whole-body tilting, and lower body negative pressure on regional cutaneous microvascular flow, mean arterial pressure, and heart rate. Stimuli were applied for only 30 s at a time, and transitions between stimuli levels were performed in 10 s without stopping the stimulus. Their investigation was limited to G levels of 1 and below (0.2, 0.4, 0.6, 0.8, and 1.0) at the feet. LBNP was found to cause the greatest relative flow reduction in the lower body. All stressors except short-arm centrifugation resulted in an increased heart rate. Head-up tilt was the only orthostatic stressor which produced a change in mean arterial pressure. The experimenters found no correlation between height and gender and the cardiovascular responses to centrifugation. Centrifugation was also found to produce the least severe vasoconstriction. Their results showed flow inconsistency among the subjects when exposed to centrifugation as opposed to the other orthostatic stressors. Vestibular stimulation was suggested a possible explanation. The experimenters concluded that centrifugation, especially using a SAC, may be disadvantageous for baroreflex stimulation because the carotid sinus is near the top of the pressure column and because they observed little heart rate change in their study.

The goals of the studies mentioned above and of the present experiment are to determine what stressors cause cardiovascular regulation sufficient enough to keep the CV system in practice. This paper details an investigation of short-arm centrifugation as a method for CV stimulation. Rotation trials at 0.5, 1.0, and 1.5 G were conducted for one-hour durations with pre- and post-stimulus supine periods. Since standing has been proposed as a countermeasure to SAS-induced orthostatic intolerance, responses to rotation were compared to those that standing produces to determine if adequate stimulation is caused by SAC rotation.
Figure 4. Subject on the MIT-Artificial Gravity Simulator (AGS)
METHODS

General

The rotation research was conducted using the MIT-Artificial Gravity Simulator (AGS) (Massachusetts Institute of Technology Man-Vehicle Laboratory), pictured in Figures 4 and 5, a 2 m-radius rotating platform with the ability to exceed 30 rpm (Diamandis 1988). Modifications to the AGS can be found in another document (Tomassini 1997). Rotation rate, subject position, and mounted physiological monitoring equipment were variable for the AGS. Subjects were placed supine on the AGS, such that the tops of their heads were at the center of rotation (made possible by the AGS's adjustable foot plate). As seen in Figure 4, the AGS is covered by a transparent (so that the experimenter could easily view the subjects) wind canopy, to prevent cooling of the subjects from wind. Linen material loosely sealed both ends of the canopy. Rotation rate was determined via a tachometer mounted on the motor (seen immediately below the AGS platform and mid-picture in Figure 4). The AGS tended to increase rotation speed as time progressed, so manual feedback was employed to maintain a constant angular speed. A video camera (Sony # PVM-122), as seen in Figure 5, was available for viewing the subjects and physiological monitoring equipment. The floor of the AGS platform and the foot plate were padded with foam for subject comfort. An emergency stop button, with the ability to stop the rotator in 15 s for G levels up to 1.5, was available for both the experimenter and subject. Rotation was commenced at a rate of less than 1 rpm/s. Generally, the target rotation rate was achieved 30 s from rotation onset.

This experiment was approved by the MIT Committee on the Use of Humans as Experimental Subjects. Appendix B contains the COUHES application, subject consent form, and subject selection questionnaire. Experimental participants were required to be in good health, have no cardiovascular abnormalities, and not to be pregnant. Subjects were asked to abstain from caffeine and alcohol intake 24 hours prior to each experimental session. In later trials, subjects were asked if they had eaten well, how much sleep they had had, and if they had taken any medications prior to each experiment. Subjects were blindfolded to prevent motion sickness induced by conflicting vestibular-visual cues. They were also instructed to move as little as possible. This was especially true while blood pressure measurements were being taken. It was made imminently clear that any head movements would induce motion sickness and would be counter-productive to the experiment. The experimenter and subject were in continuous two-way communication via radio headsets (Voice-Operated 49 MHz Two-Way Communication System, cat. no. 21-406, Radio Shack). To prevent the subjects from falling asleep, the experimenter read to them, talked with them, and played music during rest periods.
Figure 5. The MIT-Artificial Gravity Simulator (AGS)
Figure 6 shows the stimulation profiles for the four trials. Rotation trials included a 30-minute supine rest period, 1 hour of rotation, and a final 30-minute supine rest period (with the exception of the 1.0 G trial for subject D in which only 25 min. of rest followed rotation). Each subject participated in three rotation trials, otherwise termed G trials, such that the G levels at the feet during rotation were 0.5, 1.0, and 1.5. Table 3 shows the rotation rates, calculated from Equation 1, that were required for each subject to produce the appropriate G levels at their feet. A control trial for each subject was performed before the rotation trials, involving 1 hour of rest, 30 min. of standing, and a final 30-minute rest period. For each subject, only one trial was performed per day, all four trials were completed within 1.5 weeks, and the time of day of experimentation was controlled to within one hour. The protocol checklist is presented in Appendix C. Subjects performed the rotation trials in a pre-determined, semi-random order. The order for each subject is shown in Table 3. Because only eight subjects were studied and it was desired to have one man and one woman perform the same trial order, a full Latin square randomization of rotation trials could not be fulfilled. Since 1.0 and 1.5 G were likely to produce the greatest effects, it was decided to have these two levels as the two initial rates available in the partial Latin square. Subjects were not told how much time had elapsed during the trials nor were they told what G level they were experiencing.

Table 3. Biometric Characteristics and Rotation Parameters of the Subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Mean Mass (kg)</th>
<th>Blood Pressure at Rest (mm Hg)</th>
<th>Heart Rate at Rest (bpm)</th>
<th>ω for 0.5 G (rpm)</th>
<th>ω for 1.0 G (rpm)</th>
<th>ω for 1.5 G (rpm)</th>
<th>Order of G Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>F</td>
<td>22</td>
<td>166.4</td>
<td>53.0</td>
<td>110/69</td>
<td>71.9</td>
<td>16.4</td>
<td>23.2</td>
<td>28.4</td>
<td>1.0,0.5,1.5</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>19</td>
<td>175.3</td>
<td>77.8</td>
<td>117/66</td>
<td>73.8</td>
<td>16.0</td>
<td>22.6</td>
<td>27.7</td>
<td>1.0,1.5,0.5</td>
</tr>
<tr>
<td>E</td>
<td>M</td>
<td>19</td>
<td>180.3</td>
<td>97.8</td>
<td>140/76</td>
<td>66.1</td>
<td>15.8</td>
<td>22.3</td>
<td>27.3</td>
<td>1.0,1.5,0.5</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>27</td>
<td>172.7</td>
<td>67.6</td>
<td>109/71</td>
<td>73.8</td>
<td>16.1</td>
<td>22.8</td>
<td>27.9</td>
<td>1.0,1.5,0.5</td>
</tr>
<tr>
<td>G</td>
<td>M</td>
<td>26</td>
<td>190.5</td>
<td>98.4</td>
<td>116/63</td>
<td>77.5</td>
<td>15.3</td>
<td>21.7</td>
<td>26.5</td>
<td>1.5,0.5,1.0</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>27</td>
<td>182.9</td>
<td>80.6</td>
<td>115/66</td>
<td>73.9</td>
<td>15.6</td>
<td>22.1</td>
<td>27.1</td>
<td>1.5,1.0,0.5</td>
</tr>
<tr>
<td>I</td>
<td>F</td>
<td>23</td>
<td>160.0</td>
<td>73.3</td>
<td>128/70</td>
<td>80.8</td>
<td>16.7</td>
<td>23.6</td>
<td>29.0</td>
<td>1.5,0.5,1.0</td>
</tr>
<tr>
<td>J</td>
<td>F</td>
<td>19</td>
<td>160.0</td>
<td>55.3</td>
<td>106/63</td>
<td>69.2</td>
<td>16.7</td>
<td>23.6</td>
<td>29.0</td>
<td>1.5,1.0,0.5</td>
</tr>
</tbody>
</table>

For the control trial, subjects performed the supine portions on the AGS. They were allowed to sit up approximately 20 s prior to standing. The experimenter aided them in the
transition from the AGS to standing. While standing, subjects positioned their back against a wall but were allowed to place their feet naturally (as long as the angle the legs made with the wall was not too great). They were allowed to make minor movements of their legs such as shifting weight but were not required to "stand at attention." The experimenter remained at the side of the subject at all times to observe any presyncopal symptoms.

Four male and four female healthy volunteers, coded C-J, provided written consent to participate in this study, comprised of four trial sessions. The subjects had the following physical characteristics (mean ± standard deviation): age = 22.75 ± 3.6 years, height = 1.74 ± 0.11 m, mass = 75.5 ± 17.0 kg, resting blood pressure = 118/68 ± 11/4 mm Hg, and resting heart rate = 73.4 ± 4.6 bpm. Table 3 displays the individual biometric statistics for the subjects. The mean mass was the average of the masses measured on each of the four trial days. The maximum coefficient of variation for mass was 1.7%.

Calf Impedance and Volume

Calf impedance (I) was measured at 0.2 Hz with a Minnesota Impedance Cardiograph (Model 304B), pictured in Figure 7. The impedance cardiograph was utilized as an impedance plethysmograph in this experiment. Four circumferential electrical leads, as seen in Figure 8, were attached to one leg of a subject, two near the ankle and two near the knee. The leads were formed by wrapping electrode tape (Cardiograph Electrode Tape, IFM T-8001, Instrumentation for Medicine, Inc.), with electrode gel (Signa Gel, # 0341-15-25, Parker Laboratories, Inc.) applied to the electrode portion, around the limb and meeting the two ends. The impedance cardiograph leads were then clipped to the joined ends of the tape. Subjects were not required to remove hair from their calves. At times the electrode tape did not stick properly; so medical tape (Kendall Tenderskin Hypoallergenic Paper Tape, # 1914) was employed to improve attachment. The two outer leads ran a 4 mA AC current between them. The inner two leads measured the mean resistance \( Z_0 = \) \( I \) of the limb between their positions. Since the impedance cardiograph leads ran through the slip rings, calibration was verified at the AGS end of the circuit with an ordinary resistor attached between the four leads. The impedance cardiograph was accurate to within 1% for a range of up to 99.9 \( \Omega \). The impedance readings were sent to a computer (90 MHz Pentium PC) through an A/D board (Keithley Metrabyte DAS-1600), which had a input voltage range of ± 10 V and 12-bit quantization. The impedance leads could not be placed in exactly the same position for every trial, but the average standard deviation in the distance between the inner two leads was 0.87 cm. For each subject, the leads were placed on the same leg for all of the trials.
Figure 7. Minnesota Impedance Cardiograph

Figure 8. Example of Impedance Leads and Circumference Lines
The impedance data was normalized based on values averaged over 1 min. around \( t = 20 \) min. It was necessary to choose \( t = 20 \) min. as the resting value in order to compare impedance with volume. For purposes of statistical comparison, the normalized impedance values were extracted from the data at discrete times: \( t = 0, 20, 30 \) (for the rotation trials \( 30^- \) and \( 30^+ \), \( 60 \) (for the control trial \( 60^- \) and \( 60^+ \)), \( 90^- \), \( 90^+ \), and \( 120 \) min. These values were determined by averaging over the 1-min. period around the specific time. The - and + values refer to the fact that onset or cessation of a stimulus immediately produced a large change in the impedance. The - value is for the normalized impedance preceding the change, and the + value is for the normalized impedance immediately following the change. For the averages over 1 min. to find the critical points, the largest coefficient of variance was 0.99% but the majority were much lower. For statistical comparisons between trials, differences in normalized impedance between two times were compared.

In order to correlate the impedance readings with actual volumes, calf volume was measured at certain times during the trials. The volume measurements were taken from the same calf on which the impedance leads were attached. For every trial (except for the control trial with subject F), calf circumferences at 9 to 15 positions (depending on the size of the subject's leg) between the two inner impedance leads were measured with a flexible tape measure at \( t = 20 \) and 90 min. (\( t = 20 \) min. was the latest time before rotation that measurements could be taken because of the preparations required for rotation.) For some trials, additional recordings were taken at \( t = 0 \) and 120 min. Generally, the circumference measurements took less than one minute. They were accurate to within 1 mm. During that time, a subject was required to raise his leg approximately 2 cm to facilitate measurement. The circumference measurements were made 2 cm apart. To insure that the readings were acquired at the same positions within each trial, the circumferences were demarcated on the subjects' calves with water-proof marker (Crayola Classic Washable Markers, # 7808, Binney & Smith, Inc.). An example is depicted in Figure 8. For each subject, the same experimenter measured the circumferences whenever a reading was taken in all four trials. From the circumference, the radius of the calf at that position could be found via

\[
r = \frac{C}{2\pi}.
\]

Statistical methods were used to fit a third--order equation to the radius profile. An example profile is shown in Figure 9. The solid of revolution method was used to estimate a volume:

\[
V = \int_{0}^{\text{[position]}} \pi [f(x)]^2 dx,
\]

where \( f(x) \) is the equation fit for the radius profile.

The volume acquired from the circumference readings taken at \( t = 20 \) min. was considered to be the resting volume value. The maximum coefficient of variance for the 20-minute volume
readings over four trials was 1.9% but the majority were much lower. Volumes obtained within each trial were proportionally normalized by the resting value.

**Blood Pressure**

Blood pressure (BP) was recorded at 5-minute intervals with an Omron Smart-Inflate Blood Pressure Monitor (Model HEM-711), which had an arm cuff. The device was accurate to within 2% of the actual blood pressure. The subjects themselves initiated the measurement at the request of the experimenter. A BP measurement generally took 30 s from initiation. In some instances, the device would not take a reading because of subject movement. The BP measurements were monitored via the video camera. With respect to transitions between rest and stimuli, a BP reading was taken immediately after steady-state rotation or standing was achieved and immediately after complete rotator stop or return to the supine position. The pulse pressure was calculated post-hoc.

To obtain BP statistics, values were averaged over 15-min. intervals because of the limited number of data points. The reading at \( t = 120 \) min. was excluded because of suspected unreliability due to the subjects' anticipation of the end of the experiment. BP comparisons between trials were based on differences while within-trial comparisons looked at the raw values. The BP value obtained from the average of the last 15 min. of the initial supine period was considered the resting value for the subject for each trial. The mean resting BP for each subject was the average of these four measurements. The mean resting values for the subjects were then averaged, resulting in a group mean of 118/68 mm Hg.

Blood pressure was normalized based on differences because BP changes in the body seldom depend on initial pressures normally. For the purpose of normalization, the values at \( t = 25 \) min., 5 min. before rotation was initiated, were assumed to represent resting states for the individual trials. The group mean resting BP (118/68 mm Hg) became the value at resting \((t = 25\) min.) for the normalized blood pressure data for each subject. (Since the normalization was based on differences, no information was lost by using the group average for the individual normalized values at \( t = 25 \) min.) The normalized blood pressures at other times for the subjects were then calculated by adding to 118/68 the difference between their actual BP at that time and the subject's actual BP at \( t = 25 \) min. The following example will illustrate the normalization method. Subject
G had a BP of 115/63 mm Hg at t = 25 min. in 0.5 G trial. The normalized BP value at t = 25 min. for this case was set to 118/68 mm Hg. For the same trial, subject G had a BP of 110/69 mm Hg at t = 70 min. The difference between subject G's BP measurements at t = 70 and t = 25 min. was -5/6 mm Hg. This difference was then added to 118/68 mm Hg to achieve the normalized BP value for subject G in the 0.5 G trial at t = 70 min. of 113/74 mm Hg.

Heart Rate

Electrocardiograph (ECG) signals were recorded at 250 Hz (except for two of the 32 trials, in which a lower rate was employed) using a laboratory-constructed device (a human-rated differential amplifier with a gain of 1000). Two ECG electrodes were attached to the subjects subclavicular and towards the axilla. Another was mounted laterally on the abdomen. The self-adhesive electrodes (Electro Blue ECG Electrodes-Foam, catalog number AF310, LMI Medical) were prepared with electrode gel (Signa Gel, # 0341-15-25, Parker Laboratories, Inc.) prior to attachment. The ECG signal was sent through the AGS slip rings, a low-pass analog filter (Krohn-Hite model 3340) with a 60 Hz cutoff frequency and a DC gain set at 20 dB, the A/D board, and into the computer.

Instantaneous heart rate (HR) was calculated from the ECG data via peak detection using a matched filter. Appendix D contains the MATLAB® computer code used to do this. Since the subjects did not produce extremely high heart rates, it was acceptable to reduce the sampling rate of the data by 50%. The ECG data displayed typical baseline drift characteristics (low frequency noise) and in some cases extreme high frequency noise. The high frequency noise was a consequence not only of 60 Hz noise due to standard AC power supply voltage but also of AGS and subject movement. As a result, it was necessary to filter the signals. To see what frequency range the data were in, a 4096-point fast Fourier transform (FFT) of the first 10 s of data for each trial was performed. Figure 10 displays an example of the first 10 s of ECG data and its corresponding FFT. Note the large spike at 60 Hz due to standard AC power supply voltage. This spike was present in all of the ECG data. Also note the very strong frequency component near 1 Hz. This is most likely the baseline drift mentioned earlier. Since this experiment was interested only in heart rate, i.e. finding the QRS complexes, it was possible to use a very dramatic filter to eliminate as much noise as possible. The downside of the filter was to nearly eliminate recovery of P and T waves. A MATLAB® bandpass filter ("fir1") of order 100 with cutoff frequencies of 10 and 30 Hz was used to "clean up" the ECG signal. The narrow frequency range of the filter was necessary to eliminate as much noise as possible (low frequency drift and high frequency noise) while still maintaining recovery of the QRS complexes after filtering. The impulse response of the filter is shown in Figure 11. One can see that it resembles a QRS
complex, hence the term matched filter. The MATLAB® function "fftfilt" was utilized to filter the ECG data. For our example in Figure 10, we see that the filtered data contains very little noise. One can actually detect P and T waves in this case. The FFT of the filtered data is also presented in Figure 10. Power at the main noise frequencies has been eliminated.

![Figure 10. Example of Filtering of ECG Signals](image)

The top left picture shows 10 s of the original ECG signal. The top right picture displays the FFT of the original signal. Note the large spike at 60 Hz. The bottom left picture shows the filtered version of the same 10 s of ECG signal. Note that P and T waves can be seen. The bottom right picture displays the FFT of the filtered data.

Peak detection was performed by looking for local maximums over time. Because noise could still be present in the filtered data, it was necessary to define a range of possible heart rates. The range used was 40-133 bpm. While transient, extreme increases in heart rate were lost, all of the averaged HR data points were well within this range. The times between successive peaks, R-R intervals, were found by simple subtraction of the peak times. Instantaneous HR was then
calculated by inverting the R-R intervals. At this stage some noise still remained. In some cases the level of remaining noise was enough to severely alter the average heart rate, in most cases causing an elevation. Generally, the noise data points were distinguishable from the real data by having exceptionally high or low R-R intervals compared to the main portion of the data. Steps were taken to remove the remaining noise data by setting bounds on the R-R intervals. The bounds were set individually for each ECG signal and sometimes varied over the signal. The bounds used for each signal are shown in the MATLAB® codes entitled "heart*.m" in Appendix D, where * represents the individual subject code letter. Using the bounded instantaneous HR data, the average HR over 30 s and 5 min. intervals was found. Statistical analysis of HR utilized the values averaged over 5 min. HR comparisons between trials were based on differences while within-trial comparisons looked at the actual values.

Since no evidence attests that heart rate will change proportionally under the conditions of the experiment, the HR averaged over 5 min. was normalized based on differences (similar to the BP normalization). The values at $t = 25$ min. were assumed to represent resting states. The mean resting values for the subjects (the average of the resting values from the four trails) were averaged, resulting in a group mean of 73.4 bpm. This group mean resting value became the value at rest ($t = 25$ min.) for the normalized HR data for each of the subjects. (Since the normalization was based on differences, no information was lost by using the group mean for the individual normalized values at $t = 25$ min.) The normalized HR at other times for the subjects was then calculated by adding to 73.4 bpm the difference between the actual HR at that time and the subject's actual HR at $t = 25$ min.

Additional Procedures

Data were statistically analyzed using Student's t-tests for matched pairs. Unless otherwise stated, the $n$ for all comparisons was 8. The primary comparisons explored were between the following pairs of time intervals: the first half hour of rotation in the G trials and the second half hour of supine rest in the control trial (comparison I), the first half hour of rotation in the G trials and the half hour of standing in the control (comparison II), and the one-hour rotation periods at
the different G levels (comparison III). Comparisons can be made between standing and the first half hour of the rotation trials even though supine periods of different lengths precede these trials because the major transient changes in cardiac parameters during supine rest occur within the first 30 min. CV parameters change minimally from $t = 30$ to 60 min. of supine rest (or -5-6° head-down tilt bed rest) as verified experimentally (Hughson, et al. 1995; Lathers and Charles 1994) and with mathematical models (Simanonok, et al. 1994). Statistical significance was assessed at the 5% level. Additional comparisons explored how the parameters varied within trials and between resting values on different days. A multivariate analysis of variance (ANOVA) was used to explore correlations between CV responses and gender, age, height, mass, resting blood pressure, and resting heart rate.

It should be mentioned that one major deviation from the standard protocol occurred. Subject F accidentally pressed the AGS emergency stop button in the 1.0 G trial immediately after reaching steady-state rotation. Because the dynamic braking mechanism of the AGS required a 7 min. cooling period between uses, it was decided to allow the subject to remain supine for an additional 10 min. and complete the remainder of the trial. For purposes of data analysis, the first 10 min. of supine rest for subject F were generally dropped from the trial. This was assumed acceptable because CV parameters change minimally from additional rest after 30 min. and because the transient changes caused by the initiation of rotation recovered to their previous levels almost immediately after the rotator stopped.

RESULTS

General

No subject issued any major complaint from the protocol. Vestibular stimulation was experienced minutely during initial rotation and was quite apparent during deceleration. No subjects complained of any lasting motion sickness; however, some subjects requested that the blindfold be kept on for a while post-rotation. Several subjects mentioned feeling cold due to improper seal of the wind canopy. At the higher rotation rates, subjects felt almost as if the lower part of their body was standing while the upper portion was still resting. In the 1.5 G case, many subjects noticed discomfort in the legs, most often in the knees or ankles. Some reported that their feet felt "asleep." Many mentioned that their legs felt heavy. Subject J, for instance, requested that she be allowed to move her legs a little more than previously to relieve some of the discomfort. She was allowed to do so. Subject D also complained of a mild headache in the last half hour of rotation in the 1.0 G trial. No subject reported any immediate or delayed side effect after each 2-
hour trial. While the experimenter attempted to keep the subjects from knowing how much time had elapsed during the trials, many subjects were able to surmise when rotation or the experiment would end by counting the number of BP readings which were spaced 5 min. apart.

To even be able to compare different trials, it was necessary to test whether the resting cardiovascular (CV) values were different on the days of the trials. Table 4 shows the comparisons between the resting values of CV parameters for the different trials. For blood pressure, the resting value here was taken to be the average of the last 15 min. of the initial supine rest period. Note that no significant difference was found between resting calf volumes for the different trials. While the same area of the calves could not be used for the different trials, as explained previously, the resting volumes were similar enough to perform statistical comparisons.

<table>
<thead>
<tr>
<th>Matched Pair</th>
<th>Systolic BP p Value</th>
<th>Diastolic BP p Value</th>
<th>Heart Rate p Value</th>
<th>Volume p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C and 0.5 G</td>
<td>0.167</td>
<td>0.028*</td>
<td>0.010*</td>
<td>0.509</td>
</tr>
<tr>
<td>C and 1.0 G</td>
<td>0.133</td>
<td>0.264</td>
<td>0.011*</td>
<td>0.633</td>
</tr>
<tr>
<td>C and 1.5 G</td>
<td>0.764</td>
<td>0.496</td>
<td>0.345</td>
<td>0.133</td>
</tr>
<tr>
<td>0.5 and 1.0 G</td>
<td>0.879</td>
<td>0.036*</td>
<td>0.178</td>
<td>0.685</td>
</tr>
<tr>
<td>0.5 and 1.5 G</td>
<td>0.422</td>
<td>0.099</td>
<td>0.539</td>
<td>0.185</td>
</tr>
<tr>
<td>1.0 and 1.5 G</td>
<td>0.387</td>
<td>0.566</td>
<td>0.208</td>
<td>0.274</td>
</tr>
</tbody>
</table>

Resting systolic pressure (SP) seemed relatively invariant, as evidenced by the t-test results in Table 4. However, the resting diastolic pressures (DP's) for the 0.5 G trial appear to differ from those of the other trials. Since the order of the G trials was semi-randomized, the effect was not due to order. Analysis of the data shows that five of the subjects had their lowest resting DP when they participated in the 0.5 G trial. Post-hoc analysis assessing a correlation between those five subjects and body type, day of the week of the 0.5 G trial, and gender did not show a linkage. It was found that all but one who had their lowest DP for the 0.5 G trial participated in that trial last. These subjects may have guessed that this was the 0.5 G trial and were more relaxed; or they were more relaxed because it was their last trial. However, it cannot be said that this is a statistically significant correlation because an ANOVA that assessed the correlation between resting DP in the 0.5 G trial and position of the 0.5 G trial in the subject's G trial order resulted in a p value of 0.108. Simple probability expectations predict that one third of the subjects would have their lowest DP in the G trials for the 0.5 G trial. Using this fact, a Yates-corrected $\chi^2$ test ($\chi^2 = 1.78$) shows that the finding concerning resting level diastolic blood pressure is not statistically significant ($0.20 < p < 0.25$). Since BP comparisons between trials looked at differences and no evidence is known showing that a lower original BP will produce a different response, it was felt that comparisons between other trials and 0.5 G for DP were justifiable.
Table 4 also shows that the resting heart rates in the control were somewhat different than those in the other trials. Examination of the data shows that five of the subjects had their highest resting heart rate during the control trial. Since every subject performed the control trial first, it is likely that this was an order effect. Subjects could have been more relaxed for the other trials having already experienced the supine rest period at least once before. A Yates-corrected $\chi^2$ test ($\chi^2 = 4.5$) for the four trials, expecting only two subjects would show their highest HR in any trial, shows that the high HR's in the control are significant ($0.025 < p < 0.05$). Still, since HR comparisons between trials examined differences and no evidence is known showing that a higher resting HR will produce a different response, it was felt that comparisons between other trials and the control for HR were justifiable.

In order to include male and female subjects together for a complete statistical analysis, two criteria had to be satisfied. The resting cardiovascular parameters between the two genders had to be not statistically different. Also, the changes induced by a stimulus must not have been significantly different between the men and women. To compare resting values, an $F$ test was first performed to test the equality of the underlying variances of the two groups. If the variances proved equal, a two-sample $t$ test for independent samples with equal variances was performed. Table 5 shows the means, standard deviations, and $p$ values for these tests on the different cardiovascular parameters. We see that for no CV parameter does a variance inequality exist between the two genders. The $p$ values for the unpaired $t$ tests indicate that the male and female subjects did not have significant differences (at the 5% level) between their resting states.

<table>
<thead>
<tr>
<th>CV Parameter</th>
<th>Male Mean</th>
<th>Male Standard Deviation</th>
<th>Female Mean</th>
<th>Female Standard Deviation</th>
<th>$p$ Value for $F$ Test</th>
<th>$p$ Value for Unpaired $t$ Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic BP</td>
<td>122 mmHg</td>
<td>12.1 mmHg</td>
<td>113 mmHg</td>
<td>9.87 mmHg</td>
<td>0.747</td>
<td>0.284</td>
</tr>
<tr>
<td>Diastolic BP</td>
<td>67.8 mmHg</td>
<td>5.71 mmHg</td>
<td>68.0 mmHg</td>
<td>3.44 mmHg</td>
<td>0.427</td>
<td>0.950</td>
</tr>
<tr>
<td>Heart Rate</td>
<td>72.8 bpm</td>
<td>4.80 bpm</td>
<td>73.9 bpm</td>
<td>4.98 bpm</td>
<td>0.952</td>
<td>0.756</td>
</tr>
<tr>
<td>Volume</td>
<td>1941.2 cm$^3$</td>
<td>300.9 cm$^3$</td>
<td>1497.3 cm$^3$</td>
<td>239.4 cm$^3$</td>
<td>0.717</td>
<td>0.060</td>
</tr>
</tbody>
</table>

ANOVA was used to assess any correlations between gender and all of the response differences tested in the remainder of the results presentation. Only significant findings will be presented here. A correlation was found with the change in diastolic blood pressure (DP) over the first 30 min. of rotation at 0.5 G ($p = 0.002$). The raw data indicate that the women displayed less of a change in DP over the 30 min. However, no gender correlation was found with the change in DP over the hour of rotation at 0.5 G nor in any other BP changes. Since only one significant correlation arose among numerous comparisons, it is unlikely that gender is actually correlated with changes in DP. In all probability, the effects of a small number of subjects, resulting in a low
statistical power, are being observed. Some gender correlation was found with impedance changes: the $\Delta I$ due to one hour of rotation at 0.5 G ($n = 7, p = 0.046$), the immediate $\Delta I$ due to cessation of rotation at 0.5 G ($n = 7, p = 0.041$), and the $\Delta I$ due to 30 min. of standing in the control ($n = 7, p = 0.037$). Close examination of the impedance data indicates that the relationship to gender is very minor and statistical significance probably arose as a result of only having the measurements of three of the women available in the first two cases and only three men in the last case. In conclusion, combining male and female subjects for complete statistical analysis is justified.

Multivariate ANOVA was utilized to assess any correlations between the changes in the CV parameters and mass, height, age, average resting blood pressure, and average resting heart rate. The resting CV parameters were assessed in an analysis separate from the biometric characteristics of the subjects. Only significant results are reported here, and correlations with changes in CV parameters are shown in Table 6. A correlation was also found between the average resting volume (at $t = 20$ min.) and mass, with a $p$ value of 0.041.

### Table 6. Significant Correlations Between Experimental Results and Subject Resting CV Parameters and Biometric Characteristics

<table>
<thead>
<tr>
<th>Cause</th>
<th>Change in What CV Parameter</th>
<th>Correlation</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 min. of initial supine rest</td>
<td>$I$ (average)</td>
<td>mass</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td>$V$ (average)</td>
<td>average resting $SP$</td>
<td>0.038,†</td>
</tr>
<tr>
<td>30 min. of standing in the control</td>
<td>$I$</td>
<td>mass</td>
<td>$&lt;0.050$, †</td>
</tr>
<tr>
<td></td>
<td>$SP$</td>
<td>height</td>
<td>0.047</td>
</tr>
<tr>
<td>onset of rotation at 0.5 G</td>
<td>$I$</td>
<td>mass</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>mass</td>
<td>height</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>mass</td>
<td>height</td>
<td>0.022,†</td>
</tr>
<tr>
<td></td>
<td>mass</td>
<td>average resting $SP$</td>
<td>0.027,††</td>
</tr>
<tr>
<td>first 30 min. of rotation at 0.5 G</td>
<td>$DP$</td>
<td>mass</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>height</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>onset of rotation at 1.0 G</td>
<td>$HR$</td>
<td>height</td>
<td>0.038</td>
</tr>
<tr>
<td>first 30 min. of rotation at 1.0 G</td>
<td>$SP$</td>
<td>mass</td>
<td>0.029</td>
</tr>
<tr>
<td>one hour of rotation at 1.0 G</td>
<td>$SP$</td>
<td>mass</td>
<td>0.027</td>
</tr>
<tr>
<td>one hour of rotation at 1.0 G and 30 min. of supine rest following</td>
<td>$V$</td>
<td>average resting $HR$</td>
<td>0.015,†††</td>
</tr>
<tr>
<td></td>
<td>average resting $SP$</td>
<td>0.021,†††</td>
<td></td>
</tr>
<tr>
<td></td>
<td>average resting $DP$</td>
<td>0.027,†††</td>
<td></td>
</tr>
<tr>
<td>onset of rotation at 1.5 G</td>
<td>$DP$</td>
<td>average resting $HR$</td>
<td>0.002</td>
</tr>
<tr>
<td>one hour of rotation at 1.5 G</td>
<td>$DP$</td>
<td>mass</td>
<td>0.019</td>
</tr>
<tr>
<td>cessation of rotation at 1.5 G</td>
<td>$I$</td>
<td>mass</td>
<td>0.049</td>
</tr>
</tbody>
</table>

††† implies $n = 5$
Calf Impedance and Volume

The raw and normalized calf impedance measurements are shown in Appendix E. As an example, Figure 12 displays the normalized impedance plots for the four trials for subject J. Figure 13 shows the normalized calf impedance, averaged over the 8 subjects, at the specific points extracted for statistical comparison. (The data for these points are presented in Appendix E.) Some general trends can be seen in these plots. During the supine periods, impedance tended to increase exponentially. Exponential decreases were observed during standing and rotation at 1.5 G. Attempts were made to fit exponential curves to the different segments of the trials, but not enough data were available. Often, especially for rotation, a large shift in impedance was observed at the beginning or end of a stimulus. During rotation at 0.5 G, impedance increased for 5 subjects, decreased for one, and stayed roughly the same for two. During rotation at 1.0 G, impedance increased for 3 subjects and decreased for three. Those subjects who showed an
Average, Normalized Calf Impedance vs. Time

The plot shows the data points determined for statistical comparison. Normalization was proportionally based, referenced to volumes at 20 min. Vertical changes in the impedance are due to the change immediately before and immediately after stimulus onset or termination. Note that the stimulus in the G trials begins at 30 min. while standing begins at 60 min. in the control trial. Error bars represent standard error of the mean.

Figure 13. Calf Impedance Data.

An increase in impedance during 1.0 G also exhibited the same effect at 0.5 G. Also notice from Figure 12 that many data points appear to be peripheral to the main body of the curve. A majority are due to subject movement. These points were excluded when finding points for statistical comparisons. Often, a large jump in impedance occurs around \( t = 20 \) min. This was the effect of measuring calf volume, which required that a subject elevate his leg slightly. In general, the calf volume measurements caused no large change in the impedance trend. By examining the plots
closely in Appendix E, one notices that at times the impedance seems to shift suddenly. If this occurred, data either before or after the shift were excluded from statistical analyses.

It can be seen from Figure 13 that calf impedance increased nearly uniformly over the initial 30-min. supine period in each trial. The increase in impedance continued during the second half hour of supine rest in the control trial, but at a lower rate than during the first half hour. This is consistent with the actual data points in Appendix E, which show exponential increases over the hour of supine rest in the control. Note that when rotation began in the G trials, the impedance fell several percent immediately. The drop was nearly the same for the 0.5 and 1.0 G cases, 1.8% and 2.2%, respectively. The drop for 1.5 G was 3.2%. During the first half hour of rotation at 1.0 and 1.5 G, impedance seemed to decrease. The decrease for 0.5 G was minimal. The impedance for 0.5 G increased on average over the last half hour of rotation. An average increase was also observed over the last half hour of rotation at 1.0 G. However, while these increases resulted in a net increase in impedance for an hour of rotation at 0.5 G, they did not cause a large change in the net impedance over one hour at 1.0 G. Impedance clearly kept increasing over the last half hour of rotation at 1.5 G but at a slower rate than the first half hour. When transitioned from supine to standing in the control, an immediate drop in impedance was observed. Then, impedance decreased at a rate that appears similar to that for the first half hour of rotation at 1.5 G. For all of the trials, an immediate increase in impedance was observed post-stimulus. Impedance then seemed to increase to a similar normalized value in the post-stimulus supine period for all but the 1.5 G trial.

Statistical analysis of impedance assessed within-trial and between-trial comparisons using the data points for each subject taken at \( t = 0, 20, 30 \) (for the rotation trials \( 30^- \) and \( 30^+ \), \( 60 \) (for the control trial \( 60^- \) and \( 60^+ \)), \( 90^- \), \( 90^+ \), and \( 120 \) min. The first statistical test confirmed that the average (over all four trials) change from \( t = 0 \) to \( 20 \) min. for each subject was different from 0 \((p < 0.001)\). To determine whether the trials produced different impedance responses, the impedances at certain times were compared as shown in Table 7. It can be seen that impedance did not change significantly for the G trials from \( t = 20 \) to \( 30 \) min. Thus, these trials can be safely compared to each other. The impedances caused by an hour of rotation at 0.5 and 1.0 G were found to be statistically similar and that caused by 1.5 G was dissimilar to both of these. The \( p \) values comparing \( t = 90^+ \) and \( 120 \) min. generally indicate that impedance changed differently in the final supine period for the control and 1.5 G than it did for 0.5 and 1.0 G. From Figure 13, one can see that the impedance was increasing at a faster overall rate in the former two trials for this time interval. With one exception (when comparing the beginning of 0.5 to that of 1.5 G), the immediate change in impedance caused by the start or end of a stimulus was not significantly different for any of the trials. \( t \) tests were also performed to see how the impedance during the first half hour of rotation compared to what would have happened if supine rest had continued. These
comparisons, between \( t = 30^+ \) and \( 60^- \), indicate that a significant change was induced by all rotation levels. The most critical statistical test looked at how the first half hour of stimulation in all of the trials differed. Standing and \( 1.5 \) G are found to induce similar changes in impedance, and \( 0.5 \) and \( 1.0 \) G were different from standing. It is also shown that \( 1.0 \) and \( 1.5 \) G produced similar changes (decreases) in impedance over the first half hour of rotation. Thus, it is the last half hour of rotation that produced the opposite effect (net increase) when an hour of rotation was completed.

Table 7. \( p \) Values for Impedance Comparisons Between the Trials

* = statistical significance, , \( CH1 = 60^- \) for the control trial and \( CH1 = 30^- \) for the G trials, \( CH2 = 60^+ \) for the control trial and \( CH2 = 30^+ \) for the G trials, \( C = \) control trial, \( \dagger \) implies \( n = 7 \), \( \ddagger \) implies \( n = 6 \)

<table>
<thead>
<tr>
<th>Matched Pair</th>
<th>20 and 30^-</th>
<th>CH1 and CH2</th>
<th>30^+ and 90^-</th>
<th>30^+ and 60^-</th>
<th>(CH2 and 90^- in C) with (CH2 and 60 in G trials)</th>
<th>90^- and 90^+</th>
<th>90^+ and 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control and 0.5 G</td>
<td>0.473</td>
<td>0.001*,†</td>
<td>0.003*,††</td>
<td>0.825†</td>
<td>0.001*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control and 1.0 G</td>
<td>0.606†</td>
<td>0.001*</td>
<td>0.033*,†</td>
<td>0.346</td>
<td>0.116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control and 1.5 G</td>
<td>0.453†</td>
<td>0.001*</td>
<td>0.459†</td>
<td>0.234</td>
<td>0.216</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 and 1.0 G</td>
<td>0.159</td>
<td>0.276</td>
<td>0.064†</td>
<td>0.039*,†</td>
<td>0.056†</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>0.5 and 1.5 G</td>
<td>0.109</td>
<td>0.006*</td>
<td>0.002*,††</td>
<td>0.021*,†</td>
<td>0.075†</td>
<td>0.003*</td>
<td></td>
</tr>
<tr>
<td>1.0 and 1.5 G</td>
<td>0.932</td>
<td>0.105</td>
<td>0.002*</td>
<td>0.073</td>
<td>0.465</td>
<td>0.003*</td>
<td></td>
</tr>
</tbody>
</table>

Within-trial comparisons for impedance were performed as well. Table 8 shows the \( p \) values for the time comparisons. It can be seen that impedance changed significantly in all of the trials during the initial supine rest period. The drop in impedance caused by the onset of stimulation produced a value that was significantly different from the resting level in every case but standing. Thus, the immediate action of standing corrected for 40 min. of supine rest. In the G trials, the drop put the impedance far below the resting value. By the end of the standing period, impedance had fallen far below the resting value as well. Immediately after cessation of stimulation, the impedance rose to levels not different from resting levels for all trials except 1.5 G, where it was still less. In the half hour of supine rest following rotation at 1.5 G, impedance increased to a value near that at \( t = 20 \) min. For the rest of the trials, the effect of being supine again raised impedance beyond the stated resting values. Both of these findings are consistent with the final row of statistics in Table 8, showing that impedance greatly changed over the final supine period. Table 8 also indicates that all immediate impedance changes induced by the start or end of a stimulus were statistically significant. Perhaps the most important comparison is between the start (60^+ for the control trial and 30^+ for the G trials) and end (90^-) of stimulation. Here it can be seen from the significant \( p \) values that impedance decreased significantly for standing and the 1.5
The change during rotation at 1.0 G was nearly significant \((p = 0.070)\), and it was not for 0.5 G \((p = 0.565)\).

### Table 8. \(p\) Values for Impedance Comparisons Within the Trials

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>Control (&lt; 0.001)*</th>
<th>0.5 G (&lt; 0.001)* (\dagger)</th>
<th>1.0 G (&lt; 0.001)* (\dagger)</th>
<th>1.5 G (&lt; 0.001)* (\dagger)</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 and 20</td>
<td>&lt; 0.001*</td>
<td>0.001* (\dagger)</td>
<td>0.002* (\dagger)</td>
<td>0.004* (\dagger)</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and CH1</td>
<td>&lt; 0.001*</td>
<td>0.039*</td>
<td>0.003*</td>
<td>0.003*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and CH2</td>
<td>0.624 (\dagger)</td>
<td>&lt; 0.001*</td>
<td>0.002*</td>
<td>0.002*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and 90°</td>
<td>0.015*</td>
<td>&lt; 0.001*</td>
<td>0.003*</td>
<td>&lt; 0.001*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and 90°+</td>
<td>0.086</td>
<td>0.182</td>
<td>0.325</td>
<td>&lt; 0.001*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and 120</td>
<td>0.022*</td>
<td>&lt; 0.001*</td>
<td>0.003*</td>
<td>0.115</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>CH1 and CH2</td>
<td>0.009* (\dagger)</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>to see if transient response to stimulus start was sig.</td>
</tr>
<tr>
<td>CH2 and 90°</td>
<td>0.003* (\dagger)</td>
<td>0.565 (\dagger)</td>
<td>0.070</td>
<td>&lt; 0.001*</td>
<td>to see if any sig. change from start to end of stimulus</td>
</tr>
<tr>
<td>90° and 90°+</td>
<td>0.007*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>to see if change immediately after stimulus ends was sig.</td>
</tr>
<tr>
<td>90° and 120</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>&lt; 0.001*</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>

Appendix F contains the calf profiles and their associated curve fits for the subjects. The data and plots of the resulting volumes are also displayed in Appendix F. For all subjects, volume increased post-stimulus from its resting level for rotation at 1.5 G and standing. Post-stimulus volume for 0.5 G decreased from resting for six subjects. Of these six, four showed increased volume and two (subjects D and G) showed an even greater decrease in volume at \(t = 90\) min. in the 1.0 G trial. Figure 14 shows the normalized calf volume averaged over the 8 subjects for all four trials. Note that \(n < 8\) for the \(t = 0\) and 120 values.

Statistical analysis of calf volume assessed within-trial and between-trial comparisons. The first statistical test showed that the average (over all four trials) change from \(t = 0\) to 20 min. was significantly different from 0, with \(p < 0.001\). To determine whether the G levels due to rotation produced different responses, the normalized volume changes between \(t = 90\) and 20 were compared. The \(p\) values for the matched pairs of 0.5 and 1.0 G, 0.5 and 1.5 G, and 1.0 and 1.5 G were 0.063, 0.001, and 0.002, respectively. The volume change induced by an hour of rotation at 1.5 G was clearly different than that produced by the other two G levels, which were not significantly different from each other. The change during the control stimulus was not compared to the change during the G trials because volume measurements were not taken at \(t = 60\) min. The \(p\) values for the within-trial comparisons of actual volume change for the G trials are shown in...
Table 9. The volume change during rotation at 0.5 G is not significant at the 5% level, but that could be because of the dissimilar directional responses among the subjects. After the stimulus began in the 0.5 and 1.0 G trials, no calf volumes were significantly different from the resting volumes. The 1.5 G trial, on the other hand, produced significant volume changes during rotation and in the post-stimulus supine period. The statistical data confirm that the calf volumes did not recover to their resting levels in the 30 min. post-rotation in the 1.5 G trial. Incidentally, the \( p \) value for the comparison between \( t = 20 \) and 90 min. in the control is 0.032. Interpretation of this value is not trivial since standing only occurs during the second half of the time interval. However, the volumes at \( t = 60 \) min. would have undoubtedly been less than those at \( t = 20 \) min. had measurements been taken. Even greater volume changes would have resulted between \( t = 60 \)
and 90 min. than were observed between 20 and 90 min. Therefore, since the change between the latter interval was significant, the volume changes between the former time interval must have been significant as well.

Table 9. p Values for Volume Comparisons Within the G Trials

<table>
<thead>
<tr>
<th>Time Comparison</th>
<th>0.5 G</th>
<th>1.0 G</th>
<th>1.5 G</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 and 90 min.</td>
<td>0.066</td>
<td>0.295</td>
<td>&lt;0.001*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>20 and 120 min.</td>
<td>0.451,†</td>
<td>0.844,††</td>
<td>0.041*,†</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>90 and 120 min.</td>
<td>0.318,†</td>
<td>0.142,††</td>
<td>0.030*,†</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>

To determine how calf volume and impedance were related, the impedance values corresponding to the volume measurements were extracted. This data appears in Appendix G. Plots of actual volume versus actual impedance serve no purpose because the same area of the calf could not be assured for the different trials. A relationship might exist, however, between normalized values of volume and impedance. Plots showing this relationship appear in Appendix G. An inversely proportional relationship was observed for all subjects. The linear correlation coefficients are between -0.642 and -0.895. If the data points for all subjects are grouped together, as in Figure 15a, the correlation coefficient becomes -0.702. A relationship might be expected between a change in impedance and change in volume. These plots for each subject can also be found in Appendix G. An inversely proportional relationship (with correlation coefficients between -0.521 and -0.955) was noted for all subjects. While the lumped data for the comparison between changes (shown in Figure 15b) has a correlation coefficient of -0.677, the differences in the proportion and types of body materials between impedance leads on the different days make this comparison questionable. Therefore, the change in normalized impedance was plotted against the change in normalized volume. The plots are in Appendix G and Figure 15c. The correlation coefficient seen in Figure 15c is -0.704. The author considers this last analysis to be the most accurate way to determine the relationship between changes in impedance and volume. In summary, a positive change in volume will produce a negative change in impedance, in accordance with the physical principles. The linear correlation coefficient can be estimated as -0.70 ($n = 68$, $p < 0.001$).

**Blood Pressure**

The measured and normalized blood pressure data and plots for the subjects for all trials appear in Appendix H. While it is difficult to derive conclusions from the raw data, it is clear that the pulse pressure decreases over time for most subjects during rotation at 1.5 G. A pulse pressure
G data, on the other hand, clearly show that DP immediately increased and continued to increase over time as a result of rotation. Post-stimulus, DP did not seem to recover exactly to its post-stimulus level in the half hour of supine rest.
Figures 16. Average, Normalized Blood Pressure Results for the 4 Trials. Normalization was based on differences from the resting values, assumed to occur at 25 min. The vertical lines with arrows represent the onset or cessation of a stimulus. The error bars represent standard error of the mean.

Statistical analysis of blood pressure assessed within-trial and between-trial comparisons. As mentioned previously, comparisons were made between 15-minute periods, corresponding to when BP measurements were taken: (0-10), (15-25), (30-40), (45-55), (60-70), (75-85), (90-100), and (105-115) min. The average BP's at time (0-10) min. were compared to those at time (5-25) to elicit the response to 30 min. of supine rest. The $p$ values for systolic, diastolic, and pulse pressures were 0.010, 0.517, and 0.022, respectively. Thus, systolic pressure clearly changed during the initial rest period. Since diastolic pressure did not change significantly, the pulse pressure change was due to the altered systolic pressure. To determine whether the G levels produced different responses after one hour of rotation, times (75-85) and (15-25) min. were compared. The $p$ values are shown in Table 10. It was found that SP was not different over any of the G trials. The diastolic pressures caused by 0.5 and 1.0 G were similar and that caused by 1.5 G was dissimilar to both of these. The first half hour of rotation in the G trials was compared to the second half hour of the control trial to determine if the changes in BP were different from what would have occurred had supine rest continued. Table 10 shows that SP was relatively
Figures 17. Average, Normalized Systolic Blood Pressure Results for the 4 Trials. Normalization was based on differences from the resting values, assumed to occur at 25 min. The vertical lines with arrows represent the onset or cessation of a stimulus. Error bars are not present here so that the data may be seen more clearly; however, it should be noted that the SP after 25 min. of standing was not significantly different from that produced from 25 min. of rotation at 1.5 G for a comparison based on the measured BP data.

Invariant. Only 1.5 G produced a DP elevation that was significantly different from continued supine rest. The most important statistical comparison is the last in Table 10. The first half hour of rotation in the G trials is compared to standing in the control. Again systolic pressure did not
Figures 18. Average, Normalized Diastolic Blood Pressure Results for the 4 Trials. Normalization was based on differences from the resting values, assumed to occur at 25 min. The vertical lines with arrows represent the onset or cessation of a stimulus. Error bars are not present here so that the data may be seen more clearly.

change significantly. However, 1.5 G and standing were found to produce statistically similar elevations in DP, and standing was found to be different from 30 min. of rotation at 0.5 G and 1.0 G.
Table 10. *p* Values for Blood Pressure Comparisons Between the Trials

* = statistical significance

<table>
<thead>
<tr>
<th>Time Comparison: (15-25) and (75-85) min.</th>
<th>Matched Pair</th>
<th>Systolic <em>p</em> Value</th>
<th>Diastolic <em>p</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 and 1.0 G</td>
<td></td>
<td>0.484</td>
<td>0.4579</td>
</tr>
<tr>
<td>0.5 and 1.5 G</td>
<td></td>
<td>0.553</td>
<td>0.0194*</td>
</tr>
<tr>
<td>1.0 and 1.5 G</td>
<td></td>
<td>0.938</td>
<td>0.0204*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Comparison: (15-25) and (45-55) min.</th>
<th>Matched Pair</th>
<th>Systolic <em>p</em> Value</th>
<th>Diastolic <em>p</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control and 0.5 G</td>
<td></td>
<td>0.878</td>
<td>0.358</td>
</tr>
<tr>
<td>Control and 1.0 G</td>
<td></td>
<td>0.800</td>
<td>0.082</td>
</tr>
<tr>
<td>Control and 1.5 G</td>
<td></td>
<td>0.393</td>
<td>0.037*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Comparison: (75-85) and (45-55) min. in the Control with (45-55) and (15-25) min. in the G Trials</th>
<th>Matched Pair</th>
<th>Systolic <em>p</em> Value</th>
<th>Diastolic <em>p</em> Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control and 0.5 G</td>
<td></td>
<td>0.888</td>
<td>0.005*</td>
</tr>
<tr>
<td>Control and 1.0 G</td>
<td></td>
<td>0.845</td>
<td>0.011*</td>
</tr>
<tr>
<td>Control and 1.5 G</td>
<td></td>
<td>0.778</td>
<td>0.067</td>
</tr>
</tbody>
</table>

Within-trial comparisons for BP were performed as well. Tables 10-13 show the *p* values for 15-min. interval comparisons within the trials. Note that in all four trials, no significant difference was detected in SP. From the control comparisons in Table 11, one can see that the transient systolic increase, seen in Figures 16 and 17 when standing begins, lost significance when averaged over the first 15 min. of standing and eight subjects. Indeed, only the changes in diastolic pressure were significant when posture was changed. As seen in Table 11, during standing, and even during the 15-min. period following standing, diastolic pressure was significantly different from the resting level. (Figure 16 shows that it was elevated.) However, after the final 30-min. rest period, DP neared its resting value again. For 0.5 G, DP was significantly different from resting by the end of rotation and for the final supine period. The facts that the first DP measured after rotation was not different from resting and *p* = 0.013 for the comparison between times (30-40) and (75-85) min. point to an increasing DP over the course of rotation. For the 1.0 G trial, the heightened G force had now caused a significant difference (from resting levels) in DP at the start of rotation. As a consequence, no statistically significant change was observed over the course of rotation. Like the 1.0 G trial, DP was significantly different from resting during all rotation periods at 1.5 G. However, at 1.5 G, DP kept increasing significantly over the rotation time. With 1.5 G, it is seen for the first time that a statistically significant change, a large drop as evidenced in Figure 15, occurred immediately after rotation stops. Notice that for all three G trials the DP elevation did not decrease to resting levels during the final 30-min. supine period. It is clear from Tables 10-13 that any significant changes in pulse pressure, most notably
Table 11. *p* Values for Blood Pressure Comparisons Within the Control Trial

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>SP p Value</th>
<th>DP p Value</th>
<th>PP p Value</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15-25) and (45-55)</td>
<td>0.603</td>
<td>0.513</td>
<td>0.855</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (60-70)</td>
<td>0.093</td>
<td>0.007*</td>
<td>0.080</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (75-85)</td>
<td>0.570</td>
<td>0.001*</td>
<td>0.013*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (90-100)</td>
<td>0.463</td>
<td>0.001*</td>
<td>0.156</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (105-115)</td>
<td>0.795</td>
<td>0.056</td>
<td>0.296</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(45-55) and (60-70)</td>
<td>0.375</td>
<td>0.011*</td>
<td>0.054</td>
<td>to see if transient change to standing was sig.</td>
</tr>
<tr>
<td>(60-70) and (75-85)</td>
<td>0.159</td>
<td>0.960</td>
<td>0.159</td>
<td>to see if change over period of standing was sig.</td>
</tr>
<tr>
<td>(75-85) and (90-100)</td>
<td>0.943</td>
<td>0.005*</td>
<td>0.028*</td>
<td>to see if change immediately after standing was sig.</td>
</tr>
<tr>
<td>(90-100) and (105-115)</td>
<td>0.453</td>
<td>0.077</td>
<td>0.441</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>

Table 12. *p* Values for Blood Pressure Comparisons Within the 0.5 G Trial

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>SP p Value</th>
<th>DP p Value</th>
<th>PP p Value</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15-25) and (30-40)</td>
<td>0.293</td>
<td>0.377</td>
<td>0.165</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (75-85)</td>
<td>0.716</td>
<td>0.005*</td>
<td>0.055</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (90-100)</td>
<td>0.898</td>
<td>0.025*</td>
<td>0.028*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (105-115)</td>
<td>0.636</td>
<td>0.010*</td>
<td>0.080</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(30-40) and (75-85)</td>
<td>0.538</td>
<td>0.013*</td>
<td>0.188</td>
<td>to see if any sig. change from start to end of rotation</td>
</tr>
<tr>
<td>(75-85) and (90-100)</td>
<td>0.723</td>
<td>0.467</td>
<td>0.662</td>
<td>to see if change immediately after rotation was sig.</td>
</tr>
<tr>
<td>(90-100) and (105-115)</td>
<td>0.425</td>
<td>0.806</td>
<td>0.680</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>

Table 13. *p* Values for Blood Pressure Comparisons Within the 1.0 G Trial

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>SP p Value</th>
<th>DP p Value</th>
<th>PP p Value</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15-25) and (30-40)</td>
<td>0.413</td>
<td>0.010*</td>
<td>&lt; 0.001*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (75-85)</td>
<td>0.726</td>
<td>0.004*</td>
<td>0.001*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (90-100)</td>
<td>0.287</td>
<td>0.019*</td>
<td>0.118</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (105-115)</td>
<td>0.339</td>
<td>0.006*</td>
<td>0.064</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(30-40) and (75-85)</td>
<td>0.889</td>
<td>0.408</td>
<td>0.440</td>
<td>to see if any sig. change from start to end of rotation</td>
</tr>
<tr>
<td>(75-85) and (90-100)</td>
<td>0.139</td>
<td>0.264</td>
<td>0.073</td>
<td>to see if change immediately after rotation was sig.</td>
</tr>
<tr>
<td>(90-100) and (105-115)</td>
<td>0.725</td>
<td>0.076</td>
<td>0.278</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>
Table 14. *p* Values for Blood Pressure Comparisons Within the 1.5 G Trial

*SP* = systolic pressure, *DP* = diastolic pressure, *PP* = pulse pressure, sig. diff. = significantly different, * = statistical significance

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>SP <em>p</em> Value</th>
<th>DP <em>p</em> Value</th>
<th>PP <em>p</em> Value</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15-25) and (30-40)</td>
<td>0.100</td>
<td>0.013*</td>
<td>0.020*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (75-85)</td>
<td>0.784</td>
<td>0.000*</td>
<td>0.013*</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (90-100)</td>
<td>0.862</td>
<td>0.072</td>
<td>0.210</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(15-25) and (105-115)</td>
<td>0.805</td>
<td>0.023*</td>
<td>0.286</td>
<td>to see if any sig. diff. from resting</td>
</tr>
<tr>
<td>(30-40) and (75-85)</td>
<td>0.260</td>
<td>0.002*</td>
<td>0.062</td>
<td>to see if any sig. change from start to end of rotation</td>
</tr>
<tr>
<td>(75-85) and (90-100)</td>
<td>0.834</td>
<td>0.005*</td>
<td>0.008*</td>
<td>to see if change immediately after rotation was sig.</td>
</tr>
<tr>
<td>(90-100) and (105-115)</td>
<td>0.132</td>
<td>0.868</td>
<td>0.510</td>
<td>to see if change over last supine period was sig.</td>
</tr>
</tbody>
</table>

the decrease that occurs during stimulation, were due to changes in DP. In conclusion, a narrowing of the pulse pressure due to an increase in DP occurred by the end of the stimulus in all four trials.

**Heart Rate**

ECG readings were not always available at all times during the trials. On several occasions, the ECG output exceeded 10 V, saturating the A/D board. In some instances, one of the leads became detached from the subjects. Also, the headsets periodically induced noise in the ECG signal when they were in use during rotation. The filter was able to "clean" most of the ECG signals except when the noise was similar in magnitude or frequency to the QRS complexes.

Appendix I shows the plots of R-R intervals and instantaneous heart rate for the subjects. Figure 19 displays example graphs. Note that the noise in Figure 19 is hardly visible. A brief look at Appendix I reveals that in some cases the level of remaining noise was enough to severely alter the average heart rate, in most cases raising it. Also in Figure 19, notice that HR increased dramatically near the transitions from supine to stimulus and vice versa. This finding was true for most subjects during all transitions. The plots of HR averaged over 30 s and 5 min. intervals, the measured and normalized data for the 5 min. intervals, and the plots of normalized data for the individuals are shown in Appendix I.

Figure 20 displays the normalized heart rates averaged over all eight subjects. Note that each data point represents heart rate averaged over the previous 5 min. Several observations can be made from this plot. In general, heart rate decreased during the initial supine rest periods. This is seen most dramatically in the first hour of the control trial, except for a slight elevation at $t = 25$
From the plot, it appears that HR actually increased right before standing began in the control. This averaging artifact was due to the fact that subjects were allowed to have a longer transition between rest and the stimulus in the control, causing anticipation of the stimulus which increased HR. While standing, heart rate steadily increased until 25 min. of standing had occurred, at which point it began to decrease. The large increase in HR observed at the end of standing was once again an artifact of the transition. HR continued to decrease during the first half hour of rotation at 0.5 G but then increased during the last half hour. Rotation at 1.0 G caused some unusual affects in HR. The transient response (first 10 min.) was an increase. Then, HR fell to near resting level for the remainder of the first half hour of rotation. A HR increase was observed for the last half hour. Rotation at 1.5 G produced a similar effect: first increase, then decrease, and then increase (although the error bars suggest that this effect may not have been significant). However, the larger G level did not allow HR to fall back to resting levels. For all of
the G trials, the HR quickly fell to near resting levels when the subjects returned to the nonrotating state. A different post-stimulus response was seen for the control trial. HR fell far below the resting level and even below its value before standing. It then increased in the final supine period to a value somewhere near what it was pre-stimulus. In terms of gross responses, 0.5 and 1.0 G seemed to produce similar HR's over an hour of rotation. Standing and 1.5 G also were similar.

Figure 20. Heart Rate Profiles.
Each data point represents heart rate averaged over the previous 5 min. Normalization was based on differences from resting values, assumed to occur at approximately 25 min. Note that the stimulus in the G trials begins at 30 min. while standing begins at 60 min. in the control trial. The error bars represent standard error of the mean.
Statistical analysis of heart rate, with the data averaged over 5 min., assessed within-trial and between-trial comparisons. The first statistical test showed that the average (over all four trials) change from $t = 0$ to 25 min. for each subject was statistically not different from 0, but the $p$ value (0.069) suggests that heart rate actually decreased during the initial supine rest period. To determine whether the $G$ levels produced different responses after rotation, times 85 and 55 min. were compared to $t = 25$ min. The $p$ values are shown in Table 15. Heart rates at 0.5 and 1.0 G were similar to each other, and the heart rates at 1.5 G were different from the those in the 0.5 and 1.0 G conditions for both 30 min. and one hour of rotation. The first half hour of rotation in the $G$ trials was compared to the second half hour of the control trial to determine if the changes in HR were different from what would occurred had supine rest continued. Table 15 shows that 30 min. of rotation at 0.5 or 1.0 G was similar to continued rest. 1.5 G was different from continued supine rest. The most important statistical comparison in Table 15 is that between the first half hour of rotation in the $G$ trials and standing in the control. 1.5 G and standing were found to statistically similar, and standing was found to be different from 30 min. of rotation at 0.5 and 1.0 G. When comparing the transient responses, going from rest to stimulus or vice versa, the recurrent trends were again observed. Standing in the control produced a response similar to 1.5 G, both of which were different from the other two G levels. 0.5 and 1.0 G were statistically similar. The final comparison in Table 15 shows that heart rate did not change differently for any of the trials in the last 30 min.

Table 15. $p$ Values for Heart Rate Comparisons Between the Trials

<table>
<thead>
<tr>
<th>Matched Pair</th>
<th>CH1 and CH2</th>
<th>25 and 85</th>
<th>25 and 55</th>
<th>(CH2 and 85 in C) with (CH2 and 85 in G trials)</th>
<th>85 and 95</th>
<th>95 and 120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control and 0.5 G</td>
<td>&lt; 0.001*,†</td>
<td>0.096</td>
<td>&lt; 0.001*</td>
<td>0.001*,†</td>
<td>0.200,†</td>
<td></td>
</tr>
<tr>
<td>Control and 1.0 G</td>
<td>&lt; 0.001*</td>
<td>0.152</td>
<td>0.001*</td>
<td>0.005*,†</td>
<td>0.080,†</td>
<td></td>
</tr>
<tr>
<td>Control and 1.5 G</td>
<td>0.060,†</td>
<td>0.001*,†</td>
<td>0.094,†</td>
<td>0.403,†</td>
<td>0.988,†</td>
<td></td>
</tr>
<tr>
<td>0.5 and 1.0 G</td>
<td>0.243,†</td>
<td>0.756</td>
<td>0.840</td>
<td>0.897</td>
<td>0.522,†</td>
<td></td>
</tr>
<tr>
<td>0.5 and 1.5 G</td>
<td>0.023*,††</td>
<td>0.011*,†</td>
<td>0.011*,†</td>
<td>0.005*,†</td>
<td>0.157</td>
<td></td>
</tr>
<tr>
<td>1.0 and 1.5 G</td>
<td>0.014*,†</td>
<td>0.006*,†</td>
<td>0.015*,†</td>
<td>0.002*,†</td>
<td>0.221,†</td>
<td></td>
</tr>
</tbody>
</table>

Within-trial comparisons for heart rate were performed as well. Table 16 shows the $p$ values for the time comparisons. Interestingly, no changes in HR during the 0.5 and 1.0 G trials were significant. As seen in Table 16, HR changed significantly over the second half hour in the control. The increase in HR caused by standing more than made up for the drop since the HR at $t = 65$ min. was statistically different from that at 25 min. 1.5 G was the only rotation trial that
produced a significant change in HR from resting during the stimulus. All of the G trials produced HR's close to resting immediately after rotation, and the HR's did not change significantly over the last supine period. With respect to transitions, only standing in the control and rotation at 1.5 G produced immediate changes that were statistically significant.

Table 16. p Values for Heart Rate Comparisons Within the Trials

<table>
<thead>
<tr>
<th>Time Comparison (min)</th>
<th>Control</th>
<th>0.5 G</th>
<th>1.0 G</th>
<th>1.5 G</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 and 55</td>
<td>0.032*</td>
<td>0.999</td>
<td>0.680</td>
<td>0.007*,† to see if any sig. diff. from resting</td>
<td></td>
</tr>
<tr>
<td>25 and 85</td>
<td>0.002*</td>
<td>0.572</td>
<td>0.575</td>
<td>0.009*,† to see if any sig. diff. from resting</td>
<td></td>
</tr>
<tr>
<td>CH1 and 95</td>
<td>0.871</td>
<td>0.382</td>
<td>0.481</td>
<td>to see if any sig. diff. from resting</td>
<td></td>
</tr>
<tr>
<td>CH1 and 120</td>
<td>0.065</td>
<td>0.592,†</td>
<td>0.730</td>
<td>to see if any sig. diff. from resting</td>
<td></td>
</tr>
<tr>
<td>CH1 and CH2</td>
<td>&lt; 0.001*</td>
<td>0.190,†</td>
<td>0.885</td>
<td>0.014*,† to see if transient response to</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>stimulus start was sig.</td>
<td></td>
</tr>
<tr>
<td>CH2 and 85</td>
<td>0.581</td>
<td>0.284,†</td>
<td>0.607</td>
<td>0.445,† to see if any sig. change from start to</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>end of stimulus</td>
<td></td>
</tr>
<tr>
<td>85 and 95</td>
<td>0.003*,†</td>
<td>0.535</td>
<td>0.913</td>
<td>0.005*,† to see if change immediately after</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>stimulus ends was sig.</td>
<td></td>
</tr>
<tr>
<td>95 and 120</td>
<td>0.640,†</td>
<td>0.146</td>
<td>0.369,†</td>
<td>0.461 to see if change over last supine</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>period was sig.</td>
<td></td>
</tr>
</tbody>
</table>

Summary

Table 17. p Values for Comparisons

The time ranges shown are those for which the differences in cardiac parameters were compared. At the 5% significance level, it can be seen that the 0.5 and 1.0 G trials were generally not different from supine rest. Rotation at 1.5 G and standing in the control were similar. * = statistical significance † n = 7 †† n = 6

<table>
<thead>
<tr>
<th>Comparison I</th>
<th>C Rest/0.5 G</th>
<th>C Rest/1.0 G</th>
<th>C Rest/1.5 G</th>
<th>Purpose of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate: 25-55 min.</td>
<td>0.096</td>
<td>0.152</td>
<td>0.001*,†</td>
<td></td>
</tr>
<tr>
<td>Systolic Blood Pressure: 25-55 min.</td>
<td>0.878</td>
<td>0.799</td>
<td>0.393</td>
<td></td>
</tr>
<tr>
<td>Diastolic Blood Pressure: 25-55 min.</td>
<td>0.358</td>
<td>0.082</td>
<td>0.037*</td>
<td></td>
</tr>
<tr>
<td>Calf Impedance: 30-60 min.</td>
<td>0.001*,†</td>
<td>0.001*</td>
<td>0.001*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comparison II</th>
<th>C Standing/0.5 G</th>
<th>C Standing/1.0 G</th>
<th>C Standing/1.5 G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate: 25-55 min. G's, 55-85 min. Control</td>
<td>&lt; 0.001*</td>
<td>0.001*</td>
<td>0.094,†</td>
</tr>
<tr>
<td>SP: G's 25-55 min., 55-85 min. Control</td>
<td>0.888</td>
<td>0.845</td>
<td>0.778</td>
</tr>
<tr>
<td>DP: G's 25-55 min., 55-85 min. Control</td>
<td>0.005*</td>
<td>0.011*</td>
<td>0.067</td>
</tr>
<tr>
<td>Calf Impedance: 30-60 min.</td>
<td>0.003*,††</td>
<td>0.033*,††</td>
<td>0.459,†</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comparison III</th>
<th>0.5 G/1.0 G</th>
<th>0.5 G/1.5 G</th>
<th>1.0 G/1.5 G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate: 25-85 min.</td>
<td>0.756</td>
<td>0.011*,†</td>
<td>0.006*,†</td>
</tr>
<tr>
<td>Systolic Blood Pressure: 25-85 min.</td>
<td>0.484</td>
<td>0.533</td>
<td>0.938</td>
</tr>
<tr>
<td>Diastolic Blood Pressure: 25-85 min.</td>
<td>0.458</td>
<td>0.019*</td>
<td>0.020*</td>
</tr>
<tr>
<td>Calf Impedance: 20-90 min.</td>
<td>0.064†</td>
<td>0.002*,††</td>
<td>0.002*</td>
</tr>
</tbody>
</table>
Table 17 summarizes the $p$ values for primary comparisons I, II, and III for heart rate, calf impedance, and blood pressures. (In the remainder of this document, these comparisons will be referred to by their corresponding Roman numeral.) Changes in SP were not significantly dissimilar for any of the trials. Rotation at 1.5 G was similar to standing when the gross responses over 30 min. were compared (comparison II) for the other CV parameters. 1.5 G was significantly different from supine rest (I). The other two G levels were different from standing (II) but similar to supine rest (I), with the exception of calf impedance. Calf impedance in all of the G trials was significantly different from supine rest (I). The final comparison (III) shows that the lower two G levels were similar to each other and different from 1.5 G.

DISCUSSION

Major Findings

The results repeatedly affirm several conclusions. First, standing in the control and rotation at 1.5 G were similar. Second, rotation at 0.5 and 1.0 G were not significantly different from continued supine rest. These two conclusions were based on comparisons made over 30 min. periods only. Finally, one hour of rotation at 0.5 or 1.0 G produced CV responses that were significantly different from those induced by 1.5 G.

The blood pressure curves showed that pulse pressure was significantly decreased in the standing and 1.5 G cases due to an increase in diastolic pressure. A significant change was not observed for the 0.5 and 1.0 G cases. For all trials, no major change in systolic pressure was seen (comparison I). (The reader should be reminded that references are being made to systolic values at the end of 30 min. or one hour, not the transient response.) The $p$ values also showed that diastolic pressures for 0.5 G and 1.0 G were similar (III) and diastolic pressures for 1.5 G and standing were similar (II). These two groups were dissimilar to each other. The changes in blood pressure were undoubtedly a result of sympathetic activation of the cardiovascular system. The degree of activation was proportional to the level of stimulus. It can be seen in Figure 16 that the diastolic pressure continuously increased during rotation ($p = 0.002$ for the comparison between times 30 and 85 min. for 1.5 G). Also, it should be pointed out that pulse pressure did not show statistically significant differences at every time interval that DP did because of insignificant variations in systolic pressure and because PP is a derived quantity, hence its standard deviation is higher.

Heart rate decreased during supine rest, as evidenced by the first 60 min. of the control trial in Figure 20. The $p$ values in Table 17 indicate that the changes in heart rate during the 0.5 and 1.0
G trials were not different from supine rest (I) but were different from the 1.5 G trial (III) and standing (II). A large, sustained increase in heart rate, comparable to that for standing, was observed for the 1.5 G trial. These elevations in heart rate are a typical baroreflex response to a change in the pressure gradient along the body's z-axis.

The changes in blood pressure and heart rate indicate that the body was trying to maintain a constant cardiac output for standing and the high G levels in this study. Rotation and standing increase the mean arterial pressure compared to the supine state. This increase in mean arterial pressure is produced by an increase in diastolic pressure. Since the diastolic pressure increases and systolic pressure remains relatively the same, pulse pressure decreases. Through Equation 6, stroke volume decreases as a consequence. The decreased SV and increased HR combine via Equation 5 to keep CO relatively constant. Thus, it is not surprising that systolic blood pressure experienced no significant changes.

Figures 15a-c indicate that calf impedance and volume were inversely related with a linear correlation coefficient of approximately -0.70. The correlation was not expected to be perfectly linear because the data is empirical. In addition, the actual relationship between calf volume and impedance may not be perfectly linear. Tissue inhomogeneity and inter-subject variabilities certainly argue for some nonlinear component. Qualitative inferences regarding whether volume is increasing or decreasing can certainly be derived from the continuous impedance measurements. As shown in Figure 13, the control trial attests that continued supine rest increased impedance (decreased volume). For the 0.5 G trial, impedance actually increased during one hour of rotation, and the volume data support this finding. The other G trials and the standing in the control displayed an opposite effect, namely that impedance decreased (volume increased) during the stimulus. The latter was the expected effect of a +Gz force. The decrease in volume during the 0.5 G trial suggests that the effects of being supine outweighed the effects of the G force at this level. The p values in Table 17 indicate that the calf impedances caused by rotation producing 0.5 and 1.0 G at the feet were significantly different from those that would be produced by continued supine rest (I), 1.5 G (III), and standing (II). This implies that 0.5 G at least attenuated the effects of being supine. The calf impedances produced by 30 min. of 1.5 G at the feet and 30 min. of standing (II) were similar. The plateauing of the impedance curves in the G trials in the last 30 min. of rotation is likely due to sympathetically-activated vasoconstriction.

Careful study of the data reveals the existence of half hour trends for the G levels. As seen in Figure 13, for both 0.5 and 1.0 G, the average normalized impedance decreased in the first half hour and increased in the last half hour. For the lower G level, the combination over one hour resulted in a net increase in calf impedance. Impedance in the 1.5 G trial changed at a slower rate during the second half hour. It can be assumed that actual calf volume is changing inversely with these impedance changes. Eliciting similar trends from the blood pressure data is difficult.
Observations can be made from Figure 18, though. Heart rate for the 0.5 G trial continued to decrease for most of the first half hour. An elevation occurred over the last half hour. The heart rate responses to 1.0 and 1.5 G showed the increase-decrease-increase trend described previously. The transition from decreasing to increasing HR appeared to occur at approximately 30 min. The mechanism for the 30 min. trends is not entirely clear. The sustained pooling of blood in the legs may finally require additional cardiovascular regulation after 30 min. This would explain the increase in HR and decreasing rate of volume shift to the legs. However, it would not explain a volume decrease during the last 30 min. at the lower G levels. Again, this may be due to the additional cardiovascular effects caused by supine posture.

While it was unexpected that the effects of being supine would outweigh the effects of the 0.5 G level for calf volume, it was expected that 0.5 and 1.0 G at the feet would not produce a response similar to standing. Not until the G level is increased to 1.5 do the legs experience at least 1 G over most of their length. As can be seen in Figure 2, with 1.5 G at the feet the pressure over the lower portion of the body nears that due to standing. With a slightly increased mean arterial pressure, as occurs during SAC rotation, the pressures will be very similar for the two orthostatic stressors. The implication is that 1 G over most of the legs, or something that produces a pressure gradient over the lower body similar to standing, is required to achieve significant cardiovascular regulation using a SAC. The idea that hypergravity on a SAC may be required to prevent space deconditioning has been promoted by other authors as well (Burton 1989). However, this finding may not be true for subjects undergoing bed rest.

Additional Findings

The correlations between changes in CV parameters and subject biometric characteristics, as well as resting CV values, shown in Table 6 do not display consistency across the trials. It is primarily for this reason that the correlations are considered to be of negligible importance. For instance, it is highly unlikely that changes in SP could be correlated with mass for only one G trial, especially since no significant changes in SP were observed during the trial. It is reasonable that a mass, height, or age correlation might exist with some of these parameters, but the small number of subjects in the present experiment may prevent the appearance of a solid correlation across all trials. Other experimenters have observed correlations between CV changes due to standing and age (Frey, et al. 1994a; Smith, et al. 1994) and height (Smith et al. 1994). However, Breit, et al. (1996) discovered no height correlation in their orthostatic stressor experiment. One correlation shown in Table 6 is logical, that of mass and the average change in impedance during supine rest. This seems valid because the average resting volume, which is related to impedance, is correlated to mass. Also, few significant gender correlations were observed in the present experiment. Frey,
et al. (1994a) has reported gender correlations with CV changes due to 10 min. of standing, but Breit, et al. (1996) observed none. Again, the lack of a significant correlation here may be due to the small number of subjects.

Several deviations in the impedance and volume data should be discussed. The two subjects who showed a greater decrease in calf volume at 1.0 G than at 0.5 G were anomalous. The findings conflict with the impedance data for the same subjects. Most likely, measurement limitations are being observed. The impedance data for the control trial of subject H, shown in Appendix E, appears erroneous. The electrode tape becoming detached is the most probable cause.

Transient changes in the impedance curves corresponding to the onset or end of a stimulus, as shown in Figure 13, were assumed here to be due to nearly immediate changes in volume caused by transfer of blood from above the calves. This issue is controversial. Smith, et al. (1994) claim such impedance shifts are due to blood transferal but Montgomery (1997) has suggested they may be the result of changes in interstitial fluid location in the area.

The lack of any motor coordination or vestibular-induced side effects following each trial suggests that a half hour of supine rest following each stimulation period was sufficient for recovery. Had a final rest period not occurred, subjects may very well have reported vestibular-induced motion sickness phenomena. The discomfort in the legs during the 1.5 G trials was probably due to the pooling of fluid in the legs at this G level. In addition, the large centrifugal force required subjects to remain with their knees locked. Otherwise, the large force would have pushed their entire body towards the foot plate. Indeed, in the 1.5 G case, as opposed to the other G levels, subjects felt more like they were actively standing.

Some of the experimental data, heart rate for instance, have rather large standard deviations. It has been suggested that this is a result of combining male and female subjects for the statistics and not performing the experiments at the same time of day for each subject (Vernikos 1997). Since no major gender differences were found, the variation may also be due to a disparate level of alertness among the subjects. In some cases it was hard to keep the subjects awake. Often, a subject's alertness varied during the course of a trial. The claim that time of day may have affected the results could have merit, but the subjects were taken from a student population, which tends to display inconsistent diurnal rhythms.

In addition to the eight subjects presented here, two additional female subjects were disqualified from the protocol after failing to complete the control session. In both cases, orthostatic intolerance, in one case leading to vasovagal syncope, became apparent after approximately 15 min. of standing. The response was likely due to insufficient sympathetic activation precipitated by an extended period of being supine. Dehydration may have also been a complication in the syncope case. While these events were unfortunate, 10% (Smith, et al. 1994),
or more according to some researchers (Vernikos, 1997), of the population will exhibit poor orthostatic tolerance to periods of standing longer than 15 min.

**Significance of Findings**

The results of this experiment should be compared to those of Cardús's experiment (1993a, 1993b) mentioned previously. He also found no major change in systolic blood pressure. The diastolic increase seen in the present experiment was more pronounced than that seen in his and showed a definite relationship with G level. In contrast to the present experiment, Figure 3 shows that HR decreased continuously in the 0.5 G trial in Cardús's experiment. The same increase-decrease-increase trend was observed for 1.0 and 1.5 G, but Cardús's experiment had HR's that were similar in magnitude for these two G levels. His exponential increase in TFI at the two higher G levels corresponds to the exponential decrease in calf impedance observed in this experiment. Combined, the two studies show that fluid is leaving the thoracic and abdominal cavities exponentially to enter the legs. Overall, his experiment presented a larger CV response to 1.0 G. The result differences may be explained by different normalization procedures, subject population, and method of calculating the G level. Cardús normalized his data proportionally while the present experiment utilized normalization based on differences for HR and BP. Although no significant gender differences were observed, the present experiment employed more subjects, half of which were women. Finally, Cardús maintained the same rotation rate for all subjects whereas the rotation rate that would produce the correct G level at the feet was chosen for each subject here.

Additionally, it should be noted that the observed CV effects due to standing after a period of supine rest have been reported by other authors. Smith, et al. (1970, 1994) also observed increases in DP, PP, and HR as a result of standing. This fact, in addition to the similarities in responses due to rotation with Cardús's investigation, lends validity to the present data.

The author disputes the opinion of Breit, et al. (1996) that SAC rotation may not be sufficient to promote baroreflex stimulation because the pressure change produced in the upper body is minimal. Their study only rotated subjects for 30 s at the different G levels, rotation did not stop between the G levels (thus causing interaction affects in the results), and they only explored G levels at the feet of 1 and below. Rotation for only 30 s is insufficient to determine the effects of rotation on a SAC as a countermeasure and brings vestibular interactions into play, as the authors mentioned. The longer rotation time investigated in the present study clearly shows that rotation times on the order of 30 min. are required to induce sufficient cardiovascular regulation for resting subjects. Increases in heart rate and mean arterial pressure were observed here. Rotation on a SAC does not produce a large transient response, as compared to LBNP for instance, because
1) no large pressure change is present over the upper portion of body (to cause a large initial baroreflex response) and 2) it takes a while for the blood pooling in the legs to severely inhibit venous return to the heart. Still, a longer rotation time, perhaps somewhere between 30 and 60 min., should be sufficient to maintain the CV mechanisms that prevent orthostatic intolerance. With a longer rotation time, baroreflexes are stimulated when venous pooling causes a reduction in systemic arterial pressure provoked by a reduced cardiac filling pressure. Most importantly, since standing intermittently during bed rest trials has been shown to decrease orthostatic intolerance and rotation at 1.5 G was found here to be similar to standing, short-arm centrifugation should clearly be considered as a possible countermeasure to cardiovascular space deconditioning.

While significant results were obtained from the present study, it was not without limitations. First, factors such as diet, fluid intake (correlation to responses to standing shown by Frey, et al. (1994b)), sleep-wake cycles, quality and quantity of sleep, drugs, and menstrual cycles could not be controlled. Although, it should be mentioned that these variables cannot easily be controlled with astronauts either. Second, the target astronaut pool is between the ages of 28 and 63. All the subjects utilized here were younger than this range and may not have the same physiological responses as older people. In addition, blood pressure measurements may not have been entirely accurate in some cases when subjects reported that the cuff slipped down their arm (due to the centrifugal force) and they had to pull it up without the experimenter's assistance. Muscle movement during impedance and circumference measurements tended to confound results. In a few cases, taking the circumference measurements caused the impedance to shift to a different curve. In addition, it should be mentioned that subject movement during the stand test, although slight, was difficult to control. The magnitudes of volume shifts and pressure changes can be affected by muscle activity (Blomqvist and Stone 1983). Also, the volume shifts during the 1.5 G trial were so large that subjects noted visual changes in the size of their calves. The tape electrodes near the top of the calves were tight enough by the end of the experiment to visibly indent the calves in most subjects. This tightness may have hindered further volume shift to the lower legs. Finally, the reader should also be reminded that the subjects actually experienced hypergravity during all rotations and were not subjected to -6° head-down tilt (to approximate the deconditioning effects of weightlessness). Despite these limitations, it should not be forgotten that significant results were obtained across all CV parameters.
CONCLUSION

Summary

Calf impedance, calf volume, blood pressure, and heart rate were measured from eight subjects during one hour rotations on a SAC with 0.5, 1.0, and 1.5 G at the feet. The changes in cardiovascular parameters were compared to pre- and post-rotation supine periods, continued supine rest, and standing. Post-trial analysis explored the relationship between rotation time, G level, biometric characteristics of the subjects, and the cardiovascular parameters measured. Most measured cardiac parameters suggest that rotation levels causing 1.0 G at the feet or less produced regulatory responses not significantly different from continued supine rest in normal subjects. In addition, the cardiovascular responses to SAC rotation with 1.5 G at the feet were statistically similar to standing, at least for a comparison based on 30 min. The results imply that for normal subjects hypergravity may be required to prevent deconditioning in space. On the other hand, while few significant changes were observed for the lower G levels in these normal subjects, the same may not be true for bed rest subjects.

Since standing intermittently during bed rest trials has been shown to decrease orthostatic intolerance and rotation at 1.5 G was determined to be similar to standing, the results demonstrate the efficacy of short-arm centrifugation as a possible countermeasure to the cardiovascular deconditioning that occurs in space. Determining how a force gradient affects the cardiovascular system will enable future researchers to more precisely outline SAC studies necessary on individuals undergoing bed rest treatment. The hope is that a SAC may someday be used in space to keep the cardiovascular system stimulated and minimize orthostatic intolerance.

Suggested Future Research

Additional research could also performed with the data acquired for this experiment. The instantaneous change in calf impedance is available, recorded from the impedance cardiograph. This data could be used to make conjectures about blood flow rates during the trials. The effects of the G gradient on the CV parameters could be determined by comparing the data to that caused by a long-arm centrifuge, namely to answer question 10 in Table 2. In turn, these results could be compared to the effects of rotation on a centrifuge 3 m in length, which still has a G gradient although it is less than 100%. Thus, the effects of different G gradients could be determined.

With respect to cardiovascular research on the AGS, an obvious next step would be to add a mechanism for exercise while rotating. Pedaling (as on a bicycle) or deep knee bends are possibilities. After all, passive exposure to a gravity field will not counteract all of the effects of
SAS. Undoubtedly, exercise will alter the cardiovascular responses enough to reduce the required rotating time and perhaps lower the required G level to prevent deconditioning.

Computer modeling of the cardiovascular system on a SAC is a logical next step as well. Only one computer modeling study of humans on centrifuges has been conducted (Pancratz, et al. 1994). The details of the study, performed by the Biodynamic Research Corporation (BRC), are listed in Appendix A. Computer modeling research is critical because it provides a cost effective method to rule out centrifuge use scenarios and determine what actual trials should be performed. The method is also favored because it can estimate the differences between the physiological effects of ground- and space-based centrifuges. The data acquired in this study could be utilized to validate a computer model.

A bed rest study in which subjects experience -6° head-down tilt and undergo intermittent SAC rotation is suggested as an important follow-up to the present investigation. The author suggests rotation periods on the order of 30 min. With respect to how many times per day, not enough information is provided by the present experiment to make a recommendation. Certainly, several studies should be conducted which examine at this effect and how it varies with biometric characteristics.

On a more global research scale, the author feels that six categories of research are needed to answer the questions posed in Table 2: 1) computer modeling, 2) studies of simulated microgravity by bed rest or water immersion, 3) short-arm centrifuge studies, 4) long-arm centrifuge studies, 5) rotating room studies, and 6) experiments in space. Presumably, these levels would be carried out in the specified order, but certain aspects, such as adaptation research, do not require completion of research at the previous level. A detailed outline of this research strategy is presented in Appendix J. The discussion includes a recommendation for a trip to Mars using a SAC.
REFERENCES


*Newton.* International Space University, 1989.


Vernikos, Joan. Personal Communication. 21 April, 1997.


# APPENDIX A

## Previous Studies Related to Artificial Gravity

<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher(s)</th>
<th>Number of Subjects</th>
<th>Experimental Conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Computer Centrifuge Modeling</td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>Pancratz, David J., John B. Bomar, and James H. Raddin</td>
<td>2 m centrifuge with subject’s head at 1 m, used dynamic mathematical models of the vestibular and the cardiovascular system</td>
<td>- predicts static pressure of cardiovascular system on space centrifuge will be similar to that of centrifuge riders on earth</td>
<td></td>
</tr>
</tbody>
</table>

### 1 G Requirements to Maintain Conditioning

<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher(s)</th>
<th>Number of Subjects</th>
<th>Experimental Conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963-1964</td>
<td>Birkhead, N.C., et al.</td>
<td>6</td>
<td>bed rest for 24-42 days with 30 min. twice daily of upright bicycle exercise at 600 kpm/min.</td>
<td>- maintained aerobic capacity - did not prevent tilt intolerance or increased urinary calcium loss</td>
</tr>
<tr>
<td>1964</td>
<td>Birkhead, N.C., et al.</td>
<td>4</td>
<td>bed rest with 4 hours twice daily of quiet sitting</td>
<td>- resulted in minor decreases in maximal oxygen uptake - had no effect on urinary calcium loss - reduced tilt intolerance</td>
</tr>
<tr>
<td>1966</td>
<td>Birkhead, N.C., et al.</td>
<td>5</td>
<td>quiet standing for 3 hours daily during 18-24 days of bed rest</td>
<td>- reduced increased urinary calcium excretion to ambulatory levels - reduced tilt intolerance</td>
</tr>
<tr>
<td>1992</td>
<td>A.C. Ertl, A.S. Dearborn, and J. Vernikos</td>
<td>8</td>
<td>4 days -7° head-down bed rest interrupted by 15 min. of standing or walking to total 2 or 4 hours/day</td>
<td>- the stimulation attenuated but did not prevent decrease in maximal oxygen uptake</td>
</tr>
<tr>
<td>1992</td>
<td>C.E. Wade, J. Vernikos, J. Evans, and D. Ohara</td>
<td>9</td>
<td>4 hours of -6° head-down bed rest interrupted by 15 min. standing or moderate upright exercise at end of each hour</td>
<td>- standing or moderate upright exercise negated the decrease in aldosterone and plasma neurohormone levels due to head-down bed rest</td>
</tr>
<tr>
<td>1994</td>
<td>Vernikos, Joan and David A. Ludwig</td>
<td>9</td>
<td>4 days of -6° head-down bed rest interrupted by 15 min. standing 8 times daily (2 hours total)</td>
<td>- partially prevented orthostatic intolerance - had no effect on plasma volume loss or urinary calcium excretion - partially effective in preventing decrease in maximal oxygen uptake</td>
</tr>
<tr>
<td>Year</td>
<td>Authors</td>
<td>Days of -6° head-down bed rest interrupted by 15 standing 16 times daily (4 hours total)</td>
<td>Effects</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td>----------------------------------------------------------------------------------</td>
<td>---------</td>
<td></td>
</tr>
</tbody>
</table>
| 1994 | Vernikos, Joan and David A. Ludwig | - totally prevented orthostatic intolerance  
- prevented plasma volume loss  
- attenuated decrease in maximal oxygen uptake  
- had no effect on urinary calcium excretion | 
| 1994 | Vernikos, Joan and David A. Ludwig | - barely helped orthostatic intolerance  
- had no effect on plasma volume loss  
- effective in reducing the decrease in maximal oxygen uptake  
- prevented excess urinary calcium excretion | 
| 1994 | Vernikos, Joan and David A. Ludwig | - did not prevent orthostatic intolerance  
- prevented plasma volume loss and excess urinary calcium excretion  
- effective in reducing the decrease in maximal oxygen uptake | 

### Short-Arm Centrifuge (SAC) Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Details</th>
<th>Effects</th>
</tr>
</thead>
</table>
| 1965 | White, W.J., J.W. Nyberg, P.D. White, R.H. Grimes, and L.M. Finney | 1.1 m-radius centrifuge, 14 days of bed rest, 4 daily 4-G exposures (measured at the foot) of 11.2 min. each. | - totally prevented orthostatic intolerance  
- reduced increased urinary calcium output by half  
- eliminated increased urinary phosphorous output  
- had no effect on plasma volume  
- 4 G was more effective than 1 G | 
| 1965 | White, W.J., J.W. Nyberg, P.D. White, R.H. Grimes, and L.M. Finney | 1.1 m-radius centrifuge, 20 days bed rest with no countermeasures, testing during 16 days of additional bed rest, periodic 1 G or 4 G exposures with a total of 30 min. daily | - prevented further deconditioning after the 20 days of bed rest  
- 4 G was more effective than 1 G | 
| 1966 | White, P.D., et al. | 2.5 m-radius centrifuge, 4 daily exposures of 7.5 min. each of 7 G (foot level) during 10 days bed rest | - prevented orthostasis  
- failed to affect weight, plasma volume, and red blood cell loss | 
| 1970 | Cramer, D.B. and Ashton Graybiel | 3-m radius partial room, subject suspended horizontally to counteract Earth's gravity and so he could walk on the walls in partial gravity; 1 G exposure accomplished by standing up normally; pre-deconditioning for 7 days by bed rest and dry immersion; after pre-deconditioning, exposure plan: walking at 0.18 G for 2.5 hours/day for 7 days, 3 days bed rest only, 3 days walking at 0.5 G for 1 hour/day, 1 day bed rest | - pre-deconditioning decreased orthostatic tolerance by 30%, walking at 0.18 G increased it by 10-40%, walking at 0.5 G increased it by 20-45%  
- maximum strength unaffected  
- exercise tolerance decreased by 50% during pre-deconditioning and did not improve with treatments |
<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Subjects</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Cramer, D.B. and Ashton Graybiel</td>
<td>3-m radius partial room, subject suspended horizontally to counteract Earth's gravity and so he could walk on the walls in partial gravity; 1 G exposure accomplished by standing up normally; pre-deconditioning for 7 days by bed rest and dry immersion; after pre-deconditioning, exposure plan: passive 0.18 G for 2.5 hours/daily for 7 days, 1 day bed rest, walking at 0.5 G for 30 min. daily for 3 days, 1 day bed rest, walking in 1 G for 1 hour/day for 3 days, 1 day bed rest</td>
<td>- pre-deconditioning decreased orthostatic tolerance by 40-50%; passive exposure to 0.18 G helped little, walking at 0.5 G helped little, walking at 1 G eliminated orthostasis - passive exposure did not increase orthostatic and exercise tolerance as much as walking at 0.18 G had - maximum strength unaffected - exercise tolerance decreased by 50% during pre-deconditioning and improved only with 1 G walking</td>
</tr>
<tr>
<td>1973</td>
<td>Hoche, J. and Ashton Graybiel</td>
<td>3-m radius partial room, subject suspended horizontally to counteract Earth's gravity and so he could walk on the walls in partial gravity; 14 days of bed rest interrupted by 4 hours/day of exercise on normal or inclined treadmills at 0.5 G</td>
<td>- the time between exposures (simulation 2 or 3 times/day) created a significant difference in the response</td>
</tr>
<tr>
<td>1980</td>
<td>Vil-Viliams, I.F. and Ye. B. Shulzhenko</td>
<td>1.74 m radius of rotation, 1.3, 1.6, or 1.9 G 2-3 times daily for a total of 120 min. with different non-stimulation times in between during 3-day dry immersion</td>
<td>- adequate sleep levels were achieved</td>
</tr>
<tr>
<td>1988</td>
<td>Diamandis, Peter</td>
<td>2 m-radius rotating bed, 9 nights of sleep at 0-1 G at the feet</td>
<td>- cardiovascular reflexes useful in maintaining orthostatic tolerance were stimulated - 2 G's more can be sustained with a 0.1 G/s onset rate than a 1 G/s onset rate on the SAC - elevating the feet by having the person bring their knees to their chest increases the 0.1 G/s onset rate tolerance by 1 G</td>
</tr>
<tr>
<td>1992</td>
<td>Burton, R.R. and L.J. Meeker</td>
<td>1.5 m-radius centrifuge, tested G tolerances to 1 G/s and 0.1 G/s onset rates on a larger centrifuge and on a SAC</td>
<td>- control study of 3 days of dry immersion caused decrease in orthostatic tolerance of 21% - exposure to 1.3, 1.6, or 1.9 G periodically during same test caused decrease in orthostatic tolerance of 18%, 7%, and 1%, respectively</td>
</tr>
<tr>
<td>1992</td>
<td>Shulzhenko, E.B and I.F. Vil-Viliams</td>
<td>2 m-radius centrifuge, 40-60 min. blocks 2-3 times daily of 1.3, 1.6, or 1.9 G during 3-day dry immersion rest, orthostatic intolerance to 3 G was tested before and after on a 7.25 m-radius centrifuge for 5 min.</td>
<td>- control study of 3 days of dry immersion caused decrease in orthostatic tolerance of 21% - exposure to 1.3 or 1.6 G periodically with water and salt supplements during same test caused decrease in orthostatic tolerance of 13% and 4%, respectively</td>
</tr>
<tr>
<td>1992</td>
<td>Shulzhenko, E.B and I.F. Vil-Viliams</td>
<td>2 m-radius centrifuge, 40-60 min. blocks 2-3 times daily of 1.3 or 1.6 G during 3-day dry immersion rest, water and salt supplements were an added countermeasure, orthostatic intolerance to 3 G was tested before and after on a 7.25 m-radius centrifuge for 5 min.</td>
<td>- control study of 3 days of dry immersion caused decrease in orthostatic tolerance of 21% - exposure to 1.3 or 1.6 G periodically with water and salt supplements during same test caused decrease in orthostatic tolerance of 13% and 4%, respectively</td>
</tr>
<tr>
<td>Year</td>
<td>Authors</td>
<td>Type</td>
<td>Description</td>
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<tr>
<td>1992</td>
<td>Shulzhenko, E.B and I.F. Vil-Viliams</td>
<td>Centrifuge</td>
<td>2 m-radius centrifuge; time profile: 7 days of no-exposure dry immersion rest, 40-60 min. blocks 2-3 times daily of 1.3, 1.6, or 1.9 G during next 7 days. Supine bicycle ergometer training periodically during next 7 days, during next 7 days SAC rotation for 60 min. twice daily during which 600 kpm/min. of bicycle exercise was performed for ten min. three times; orthostatic intolerance to 3 G was tested before and after on a 7.25 m-radius centrifuge for 5 min. - after first 7 days, orthostatic tolerance had decreased by 56% - after the 28 trial period, orthostatic tolerance was 8% less than normal</td>
</tr>
<tr>
<td>1995</td>
<td>Greenleaf, J.E., et al.</td>
<td>Centrifuge</td>
<td>1.8 m-radius pedal-powered centrifuge. Subjects blindfolded, protocol of 1 G for 2 min., 2 min. rest, 2 G for 2 min., 2 min. rest, max. acceleration for 2 min., rest, 25% of max. rpm for 2 min., rest, 50% of max. acceleration for 2 min., rest, 75% of max. acceleration for 2 min.</td>
</tr>
</tbody>
</table>

**Long-Arm Centrifuge (LAC) Studies**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1959</td>
<td>Clark, C.C. and J.D. Hardy</td>
<td>LAC</td>
<td>Rotated for 24 hours at 2 G - only adverse symptom was “anesthesia sensation” in one hand that resolved in 2 months - exhibited positive fluid balance and doubled white blood cell count</td>
</tr>
<tr>
<td>1971</td>
<td>Green, J.A., J.L. Peacock, and A.P. Holm</td>
<td>LAC</td>
<td>Crew module 3 m by 12 m located at 22 m and freely aligned with resultant force vector, experienced 4 rpm for 12 days - adaptation and recovery occurred within two days - little motion sickness</td>
</tr>
</tbody>
</table>

**Rotating Room Studies**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>Graybiel, Ashton, Brant Clark, and J.J. Zarriello</td>
<td>Room</td>
<td>Room was 4.6 m in diameter and 2.1 m high, 2 day exposures at either 1.71, 2.22, 3.82, 5.44, or 10 rpm - mild nausea was felt at the first three rotation levels - the two highest rotation levels were highly stressful; nausea and extreme fatigue were observed - one control subject, who had lost vestibular function, only experienced problems with walking - most subjects adapted with the 2 days - readaptation was seen after cessation of rotation</td>
</tr>
<tr>
<td>Year</td>
<td>Authors</td>
<td>Description</td>
<td></td>
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<tr>
<td>------</td>
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<td></td>
</tr>
<tr>
<td>1965</td>
<td>Graybiel, et al.</td>
<td>10 rpm for 12 days, room was 4.6 m in diameter and 2.1 m high</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Bergstedt, M.</td>
<td>attempted to adapt subjects to 10 rpm by incrementally increasing the rotation rate, 2 studies tried three incremental steps over 3 days</td>
<td></td>
</tr>
<tr>
<td>1965</td>
<td>Bergstedt, M.</td>
<td>attempted to adapt subjects to 10 rpm by incrementally increasing the rotation rate, 40 incremental steps over 40 hours</td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>Graybiel, Ashton, F. Robert Deane, and James K. Colehour</td>
<td>room was 6 m in diameter and 3 m high, attempted to adapt subjects to 10 rpm by incrementally increasing the rotation rate, total rotation time lasted 25 days; started rotating at 2 rpm, every 2 days rotation rate was increased by 1 rpm until 10 rpm reached, 9 days total of 10 rpm exposure were completed</td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>Graybiel, Ashton</td>
<td>room was 6 m in diameter and 3 m high, attempted to adapt subjects to 10 rpm by incrementally increasing the rotation rate, change subjects were required to make 1000 head movements</td>
<td></td>
</tr>
</tbody>
</table>

**Space-Based Research**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>Shipov, A.A., et al.</td>
<td>turtles on Cosmos-782 were spun at 0.3 G for 19.5 days on a 0.32 m arm</td>
</tr>
<tr>
<td>1977</td>
<td>Gazenko, O.G., Ye. A. II’in, V.S. Oganov and L.V. Serova; Gurovsky, N.N., et al.</td>
<td>rats on Cosmos-936 were spun on a 0.32 m arm to achieve 1 G in space for 18.5 days</td>
</tr>
</tbody>
</table>

- onboard observer was experienced rider and required little time to adapt (no nausea) when moving into and out of the rotating environment
- subjects were extremely motion sick during the first few days
- none of the subjects had fully adapted to the environment by the end of 12 days
- lethargy and fatigue were observed
- cessation of rotation was less traumatic than the onset
- it was unclear which effects were due to rotation and which were due to confinement
- subjects all felt unfit to carry out duties of astronauts during experiment
- subjects did not adapt
- no motion sickness in subjects observed and the subjects adapted
- lethargy observed
- onboard experimenter who alternated between rotating and non-rotating environments did experience motion sickness
- 2 subjects experienced no side effects
- 1 was nauseated and lethargic
- no muscular changes were observed as being different from ground controls
- except for a depression of brain metabolism, semicircular canal stimulation, and a radial bone growth deficiency, the rats were protected from all physiological responses to spaceflight experienced by the control group on the biosatellite
Appendix B

COUHES Application, Subject Consent Form, and Subject Selection Questionnaire

Application Number 2318

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Committee on the Use of Humans as Experimental Subjects

Application for Approval to Use Humans as Experimental Subjects

PART I. DATE: 5/7/96

Title of Study: The Effect of Short-Arm Centrifugation on Human Performance and Physiology

Principal investigator: Professor Laurence Young

Department: Aeronautics & Astronautics

Room No.: 37-219

Telephone No.: 253-7759

Associated Investigators: Dawn Hastreiter 253-7509
Anna Tomassini 253-7509

Collaborating Institution(s), if applicable: none

Financial Support: NASA Grant NAGW-3958 Visual-Vestibular Interaction

Purpose of Study: The investigation is divided into two components: human performance and human physiology. Please see the following pages for discussions of the purposes of each of the components.
The Effects of Short-Arm Centrifugation on the Cardiovascular System

Purpose of Study

Exposure to microgravity causes significant physiological changes. One of the proposed mechanisms for countering these affects for long-duration missions is artificial gravity in space. Proposals include spinning the entire spacecraft or incorporating a short-arm centrifuge (SAC) into the spacecraft. Short-arm centrifugation in a non-rotating craft may ease some engineering and astrodynamic requirements. Before a SAC could be tested in space, a significant number of ground studies must be conducted to determine the effects of a gravity gradient both on a normal person and individuals undergoing treatment, such as bed rest, that produces similar physiological microgravity effects.

This study focuses on determining several of the cardiovascular effects of a gravity gradient on a normal person. Two contemporary investigations have recently been performed. Cardús (1993) performed a study on six men with measurements of general cardiovascular signals for one hour durations on a device similar to the MIT-Artificial Gravity Simulator (AGS), a short-arm centrifuge. He found that few changes were seen for G levels below 1 at the feet. Cardiovascular trends did change in the range 1-1.5 G at the feet. Above 1.5 G, cardiovascular changes became more dramatic with 2 G at the feet being near the safe physiological limit. Researchers at NASA's Ames Research Center (Breit, et al. 1996) also conducted a study on men and women to compare the effects of short-arm centrifugation, long-arm centrifugation, whole-body tilting, and lower body negative pressure on blood flow rates and baroreceptor stimulation. Their investigation was limited to G levels of 1 and below at the feet. Confirming Cardús's earlier study, few significant overall cardiovascular changes were seen below 1 G at the feet. Some baroreceptor stimulation did occur.

The purpose of this study is to extend the work of the previous researchers. Heart rate variability, heart rate, ECG signals, fluid shift to the legs, and blood pressure will be assessed in men and women for G levels at the feet up to 1.5. Determining how a gravity gradient affects the cardiovascular system will enable future researchers to more precisely outline studies necessary on individuals undergoing bed rest treatments as models for spaceflight deconditioning.
The Effect of Coriolis Forces on the Human Performance of Two-Handed Tasks While in a Rotating Environment

Purpose of Study

One of the proposed means of preventing physiological deconditioning during long-term space missions, such as traveling to Mars, is to create artificial gravity by rotating the spacecraft. However, while artificial gravity may help prevent the physiological problems induced by microgravity, the unfamiliar gravity gradients and Coriolis forces which result cause problems with motions attempted in the rotating environment (Loret, 1963; Stone, 1970; Ramsey, 1971; Lackner, 1993). Ever since the idea of rotating space vehicles evolved, studies have been conducted on the effects of artificial gravity on human performance. The studies conducted at the Pensacola Slow Rotation Room consisted of various tests to assess human performance while in a rotating environment, however, the researchers were mainly concerned with the effects on the vestibular system and the brain-stem activating system (Graybiel, Clark, and Zarriello, 1960; Clark and Graybiel, 1961; Kennedy and Graybiel, 1962; Graybiel et al., 1965; Guedry, 1962). In addition, the subjects were not oriented as they would be in an artificial gravity environment. Studies conducted by the North American Rockwell Corporation and Langley Research Center were in simulators where the subjects were rotated about an axis perpendicular to their body axis, as if in a rotating space vehicle (Stone and Letko, 1962(1), 1962(2), 1964; Piland et al., 1970; Green and Peacock 1972). Unfortunately, experiments involving complex two-handed tasks that would be affected by Coriolis forces were not conducted.

The purpose of this portion of the study is to investigate how the Coriolis forces created by rotation affect the subjects' ability to perform motor tasks requiring two-handed hand-eye coordination. The importance of two-handed tasks lies in the different Coriolis forces which must be compensated for when the two hands do not move with identical direction and speed. The motivation is that during long-term missions it is very important for astronauts to still be able to complete their required tasks efficiently while experiencing artificial gravity. Stone and Letko looked at how Coriolis forces affect the performance of simple perceptual motor skills, as did Lackner and DiZio (1994) with their experiments on the ability of subjects to point at targets while rotating. However, neither used complex two-handed tasks, and Lackner and DiZio performed their experiments in Brandeis University's rotating room with subjects in a different orientation to that of an artificial gravity environment.
PART II.

EXPERIMENTAL PROTOCOL

Please see the following comments for the two experimental protocols of the investigation.

Experimental Protocol for Human Physiology Study:

Experimental subjects will be chosen with the aid of the attached selection questionnaire. Volunteers with histories of heart conditions, loss of consciousness, respiratory disorders, and other medical conditions that contraindicate participation will be asked not to participate. Individuals with the above histories may be placed in physical danger during rotation on the MIT-Artificial Gravity Simulator (AGS). Susceptibility to motion sickness should not necessarily eliminate a volunteer for the physiological studies because it is not anticipated to be a major side effect.

The height, weight, and certain characteristic lengths of the subject will be measured. Subject height is necessary to determine what rotation rate will produce a certain G level at the feet. Subject weight will be used to determine if any correlation exists between weight and the results of the experiment. Distance measurements referenced from the top of the head, such as location of the vestibular system and heart, will also be obtained to calculate the force stimulation level of these body systems.

Subjects will be placed supine on the AGS, pictured in Figure 1, such that the top of their head is at the center of rotation. Since the AGS is of such short-radius, subjects experience a 100% z-axis force gradient along their body. All subjects will be rotated up to the experimentation speed with an onset rate no greater than 1 rpm/s. Rotation rate will be such that the equivalent G level in the plane of rotation at the subject’s feet will not exceed 1.5 G. 1.5 G at the feet corresponds to a rotation rate of 27.1 rpm and 29.7 rpm for 5-ft. and 6-ft. individuals, respectively. Rotation will last for no more than one hour. For the actual physiological trials, rotation will be preceded by at least a ten minute stationary period with cardiovascular monitoring. Also, at least a fifteen minute monitoring period will be observed after each one hour rotation.

Three cardiovascular measuring devices will be attached to the subject during the protocol: an electrocardiograph (ECG), a blood pressure monitor, and an impedance plethysmograph. The ECG will trace the heart rhythm, which will be studied afterwards for heart rate variability and any abnormalities. ECG leads will be placed near each clavicle and on one side of the abdomen. The leads have an adhesive undersurface and an attempt will be made to place them in hairless areas. Blood pressure and heart rate will be measured every five minutes by an automatic blood pressure cuff placed on the subject’s right arm. The impedance plethysmograph to be used will measure the electrical resistance in the calf. Resistance in the calf corresponds to volume in the calf. The impedance plethysmograph requires four circumferential electrodes to be placed on the subject. 4 mA of AC current at 100 kHz is passed through the outer 2 electrodes, and the resistance measurement is taken from the inner two electrodes. The Minnesota Impedance Cardiograph Model 304 B will be used for the impedance plethysmography. The device has been used for approximately 20 years for safe resistance measurements of the body. Circumferential measurements of the calf before and after trials will be used to correlate actual volume change to resistance changes. Circumference measurements will be taken at pre-administered marks on the subject’s calf. All leads from the physiological monitoring equipment are attached to slip rings in the shaft of the AGS support rod and terminate at a computer system. In addition, the leads will be well insulated for the safety of the subjects.

After testing equipment on several volunteers, actual experimental trials will begin. The protocol will require at least four sessions with each subject. We anticipate one control session consisting of approximately: one hour of supine rest on the AGS, one half hour of standing, and a final half hour of supine rest on the AGS. The three experimental runs will likely include: one half hour of supine rest on the AGS, one hour of rotation, and a final half hour of supine rest on the
AGS. Three rotation rates are anticipated for each subject, resulting in 0.5, 1.0, and 1.5 G's at the feet. Additional trials at intermediate rotation rates or durations may be requested from subjects. Trials will most likely take place on different days at the subject's convenience. From the long duration physiological measurements at different G levels, investigators hope to discover the time and force dependent cardiovascular effects of a gravity gradient.

In addition to the informed consent form for AGS rotation, experimental trial subjects will receive an outline of the trials with a statement of purpose.

**Experimental Protocol for Human Performance Study:**

The experiment will be conducted at the MIT Man-Vehicle Laboratory on a rotating platform originally designed in a previous Master's thesis project to investigate sleeping during rotation (Diamandis, 1988). (This project received COUHES approval #1688 in June of 1986.) The platform is 3 ft wide with a radius of 7 ft and has a counterweight at one end. Subjects will be rotated at 10 rpm with their head at the center of rotation. This rotation rate matches that which would be used for a 4m radius vehicle, creating a centripetal force of about 0.5G at the rim, which is a proposed design for a Mars vehicle. The head placement at the center of rotation will help prevent motion sickness.

An experiment hood will be placed above the subjects near eye-level so that they may perform their tasks while lying on the rotating platform with minimal head movement. There are various means of measuring performance, including vigilance, serial reaction, tracking, and memory tasks; however, alertness, speed, accuracy, and short-term memory capacity are considered more reliable measures of the effect of stressors (Boff and Lincoln, 1988). Speed and accuracy will be used in this study as measures of the performance of motor tasks while under the stress of a rotating environment.

Preliminary static tests will be performed to assess the learning curve for the different tasks. Preliminary tests are required since subjects naturally improve in their performance of a certain task logarithmically each time they perform that specific task. Speed and accuracy are increased by fifty percent between the first and second time a task is done. Completion time is again improved by half the previous amount the next time that task is executed, and so on. The purpose of the initial tests is to reach an asymptotic level of performance, which should occur after three to five trials, before conducting the experiments so that the effect of Coriolis forces can be differentiated from any learning process. Two different tasks will be considered: a modified Stromberg Dexterity Test and a modified Bolt Test. The original Stromberg Dexterity Test (Peacock and Green, 1971) required erect subjects to place 54 cylindrical blocks of three different colors into correspondingly colored holes that were on a flat plane in front of them using only one hand. The modified test used in this study will involve having the cylindrical blocks dispersed to the right, left, and in front of the subject while the he switches the order of the blocks using both hands. The performance of this task will be measured by time to completion of the test run. The other task being considered, the Bolt Test (Kennedy, Tolhurst and Graybiel, 1965), involves placing three washers onto a bolt and placing the bolt into a hole. Here the washers and bolts will be picked up from different locations to the left and to the right of the subject, and the finished product will be placed into a hole in front of the subject. Performance for the Bolt Test will also be measured in time to completion of the test run, which involves 30 bolts. Two test runs will be performed for each session of the chosen task. The exact task which will ultimately be performed will be determined during the preliminary learning curve study according to the reliability associated with each task.

The actual experimentation will involve a training session before rotation and test sessions during and after rotation for the task chosen during the preliminary study. Subjects will be loosely strapped onto the platform and a communication check will be made of the headsets prior to spin up. The platform will be gradually accelerated to a constant velocity of 10 rpm over a period of about 30 seconds. Two minutes will elapse before starting the tests in order to allow the subject to get accustomed to the accelerated environment. After completing two runs of the selected task, the platform will be gradually spun down to 0 rpm. Two minutes will again elapse before post-
rotation tests begin, which will be an exact repetition of the test runs performed before and during rotation. In addition, to look at adaptation to the artificial gravity environment, the subjects will be asked to do another set of pre-, per-, and post-rotation test sessions about three days following the initial testing and again five days after the second test session. Subjects will have the ability to stop rotation by pressing a button if so desired at any time, and they will be constantly monitored through a video monitor and audio communication. If the subject should try to sit up during rotation, the two quick-release safety belts would open the same circuit as the subject's emergency button and stop the platform. The emergency cessation of rotation will occur gradually, but at a faster rate than normal spin up or spin down so as to reach 0 rpm in 5 seconds.
PART III. Please answer each question below, and indicate "NA" where not applicable to your application. Positive answers should be briefly explained, with detailed information included in PART II.

1. How will subjects be obtained?
   Subjects will be volunteers recruited from the MIT community.
   Number of subjects needed? Preferably, at least 10.
   Age(s) of subjects?
   Subjects must be at least 18. Participation will be limited to subjects under the age of forty except for the Principal Investigator and trained astronauts.

2. Will women and minorities be recruited? Yes.
   If not, explain why.

3. Will subjects receive any payment or other compensation for participation?
   Subjects who are not members of the Man Vehicle Laboratory will receive compensation.

4. Will your subjects be studied outside MIT premises? No.
   If so, please indicate location.

5. Will the facilities of the Clinical Research Center be used? No.
   If so, the approval of the CRC Advisory Committee is also required.

6. Will drugs be used? No.
   Any Investigational New Drugs (IND)? No.

7. Will radiation or radioactive materials be employed? No.
   If so, your study must also be approved by the Committee on Radiation Exposure to Human Subjects. Application forms are available from Mr. Francis X. Masse, Radiation Protection Office, 20C-207, x3-2180.

8. Will special diets be used? If so, please state proposed duration(s).
   Subjects in the physiological studies will be asked to refrain from alcohol and caffeine intake for 24 hours prior to each experimentation period.

9. Will subjects experience physical pain or stress?
   Subjects may possibly feel slight, non painful pressure in their legs due to fluid shift caused by centrifugation. Some subjects may experience a headache due to fluid shift. While they will be instructed not to move their head, motion sickness may result if the subjects do not comply. Claustrophobia may be experienced by some subjects in the human performance study. Subjects can end rotation gradually and safely at any point with an emergency stop switch near their hand position.

10. Will a questionnaire be used? Yes. (Copy is attached.)

11. Are personal interviews involved? No.
    If so, include an explanation in Part II and attach an outline.

13. Does this study involve planned deception of subjects? No.

14. Can information acquired through this investigation adversely affect a subject's relationships with other individuals (e.g. employee-supervisor, patient-physician, student-teacher, co-worker, family relationships)? No.

15. Please explain how subject's anonymity will be protected, and/or confidentiality of data will be preserved.

Subjects will be coded. Only the code number will appear in any dissemination of data.

PART IV.

A. Please summarize the risks to the individual subject and the benefits, if any;

include any possible risk of invasion of privacy, embarrassment or exposure of sensitive or confidential data, and explain how you propose to deal with these risks.

1. Headaches, Pressure in the Legs
These possible effects are caused by a fluid shift in the body due to centrifugation. On initial report of a headache from a subject, an investigator will suggest relaxation techniques to relieve the headache. If the headache persists for the longer than 5 minutes, the experiment will stop. The subject also has the option of ending the experiment at any time for any reason. In previous studies of this nature, no subject elimination was reported based on these effects.

2. Nausea/Motion Sickness
Motion sickness is primarily due to sensory conflict. The subject tactually perceives himself as lying on a still bed after an initial period on the bed. Movements of the head and the resulting vestibular stimulation reveal the influence of Coriolis forces due to rotation. The canopy of the AGS is translucent and the subject sees a blurring of external objects during rotation. The consequent sensory conflict may cause nausea. For the physiological studies on the AGS, the subjects will be blindfolded and instructed not to move their head. In both experiments subjects will be told that moving their head may make them nauseous. In addition, the canopy will be covered with an opaque material for the performance studies and subjects will be asked to focus of the experiment hood (which is stationary with respect to them) and their tasks. If the subject reports intolerable motion sickness, the experiment will be stopped. The subject also has the option of ending the experiment at any time for any reason with an emergency switch.

3. Claustrophobia
Subjects in the human performance study may experience claustrophobia due to the placement of the experiment hood. Volunteers with known claustrophobia will be asked to decline participation. The subject has the option to end the experiment at any time.

4. Heart Rate Increase
Previous research has shown that rotation with G levels at the feet between 1 and 1.5 G causes increased heart rate of up to 1.75 times normal supine levels. While the increased
heart rate is no greater than that which would be experienced during aerobic exercise, medical heart conditions unknown to the subject may become evident. The heart rate of the subjects in the physiological studies will be continuously monitored. If heart rate becomes abnormally high, 1.75 times the subject's normal heart rate, the experiment will be stopped. Maximum heart rate for an individual is HR(max)= 220 - age. Subjects will also be monitored for complications for at least 15 minutes after each rotation session in the physiological studies.

5. Injury Related to Falling Off the AGS While Rotating
Serious injury could result from falling off the AGS while it is rotating. The following steps will be taken to prevent such an incident:
   a. The subject will be loosely restrained at the legs and thorax, preventing him from making sudden motions or falling off the rotating bed. The restraints will be equipped with quick release latches making it possible for the subject to escape quickly if necessary.
   b. Side railings similar to those on a hospital stretcher will be employed to contain the subject.
   c. As mentioned previously, the subject will be equipped with an emergency stop switch which will stop the AGS from rotating within approximately 5 seconds.
   d. The subject will be continuously monitored by at least one experimenter in the same room.
   e. The subject will be equipped with a 2-way headset communication system connected to the observing experimenter.
   f. Final human performance measurements will employ a video camera mounted on the AGS which may help the investigator understand the nature of any problems that arise.
   g. Finally, subjects will experience a short test ride of several minutes duration after familiarization with the equipment.

6. Skin Irritation
Subjects in the human physiology study will have seven electrodes placed on their bodies. Sufficient electrical contact with the skin requires that electrode gel be placed between the leads and skin. Also, calf volume measurements require marking the leg with a washable marker to ensure consistency of measurements. The application of gel and marker to the skin may cause minor skin irritation. However, the irritation is unlikely to be lasting.

B. Detection and reporting of harmful effects: If applicable, please describe what follow-up efforts will be made to detect harm to subjects, and how this committee will be kept informed.

All AGS studies involve multiple sessions on different days. Detection of harmful effects during exposure will occur by asking the subjects how they feel after every 15 minutes of rotation and if they wish to continue. Subjects will also have the opportunity to report any harmful effects noticed since the last exposure before commencing the next trial. In addition, all physiological studies involve a 15-30 minute monitoring period after each trial, and the human performance studies involve post-rotation tests. In the event of harmful effects, COUHES will be informed verbally or through written communication, depending on the severity of the situation.
PART V.

INFORMED CONSENT MECHANISMS:
Please send the following attachment.

The committee is mandated by the DHHS and Institute regulations to require documented informed consent. The document should be retained as a permanent record. Under certain circumstances, the committee may waive documentation. The elements of such informed consent are:

1. Consent forms should start with a statement that participation is voluntary and that the subject is free to withdraw his/her consent and to discontinue participation in the project or activity at any time without prejudice to the subject.

2. A fair explanation of the procedures to be followed and their purposes, including identification of any procedures which are experimental.

3. A description of any attendant discomforts and risks reasonably to be expected.

4. A description of any benefits to the subject that are reasonably to be expected.

5. A disclosure of any appropriate alternative procedures that might be advantageous for the subject.

6. An offer on the part of the investigator to answer any inquiries concerning the procedures.

7. There shall be no exculpatory language making the subject waive or seem to waive any rights.

8. In addition, the following statement or a comparable one (in the case of cooperating institutions) shall appear on all informed consent documents, except that in certain cases in non-biomedical disciplines, COUHES may decide that it may be omitted:

"In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.*

"I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787, if I feel I have been treated unfairly as a subject."

Consent forms used in cooperating institutions must assure that the rights of the subject are protected at least to the same degree.

*Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

These elements should be clearly stated in a document to be signed by the subject or a legally authorized representative in the case of minors or incompetent individuals. The material presented in such as document must be in clear English, easily understandable to the least educated of subjects. Where minors are involved as subjects, due consideration should be given to their
capability to give consent. The informed consent document should be signed by both the subject and parent or guardian wherever possible.

In the case of Questionnaires or Interviews, the Committee may decide that a consent form is not required if the intent is merely to obtain the requested information. However, it must be made clear to the subject that:

- Participation is voluntary.
- The subject may decline to answer any questions.
- The subject may decline further participation at any time without prejudice.
- Confidentiality and/or anonymity are assured.

In addition:

- No coercion to participate will be involved. For example, handing out or collecting questionnaires personally may be so interpreted.
- The data collected will be reported in such a way that the identity of individuals is protected.
- Proper measures will be taken to safeguard the data.

Other examples of situations in which informed consent documentation is not required include use of discarded blood, certain psychological studies involving intentional deception, or record searches and use of stored data. In a case of any deception, debriefing mechanisms must be acceptable before approval of an application may be complete. The Committee expects the investigators will notify the Committee if any adverse side effects occur.

Signature of Principal Investigator ___________________________ Date ______________

Print Full Name: Laurence Young

Signature of Department Head ___________________________ Date ______________

Print Full Name: Earll Murman

Please return this application with 3 photocopies to:
H. Walter Jones, Jr. M.D.
COUHES Chairman
E23-389
253-6787
CONSENT FORM

I have been asked to participate in a study of the effects of short-arm centrifugation on the cardiovascular system. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason. I have completed a selection questionnaire related to my medical history and understand that I should not participate in this study if I have any medical heart or respiratory conditions, if I have any medical conditions which would be triggered if I develop motion sickness, or if there is any possibility that I may be pregnant. I understand that participation in the investigation under any of the above circumstances may put me in danger. I agree to abstain from caffeine and alcohol intake 24 hours prior to each experimentation period since this may affect cardiovascular measurements. My participation as a subject on the AGS involves either testing of equipment or actual experimental trials.

Prior to rotation, I will be oriented to the MIT-Artificial Gravity Simulator (AGS) and all cardiovascular monitoring equipment. I understand that my height, weight, and certain characteristic lengths, such as location of my heart, may be measured. During rotation I may have several medical devices or leads attached to my body. These would consist of a blood pressure monitor, ECG leads, and/or an impedance plethysmograph around one of my calves. A description of how these devices will feel has been presented to me. I agree to participate in possible stationary monitoring periods before or after rotation.

Rotation on the AGS will not exceed the following parameters:
• onset rate no greater than 1 rpm/s
• G level at my feet no greater than 1.5 G
• time of rotation will not exceed 1 hour.
I understand that these are well within the safe limits for short-radius rotation. I can end rotation at my discretion by pressing the subject’s stop button, the use of which has been demonstrated to me.

I understand the following risks and the listed steps investigators have taken to minimize those risks.

1. Headaches, Pressure in the Legs
These possible effects are caused by a fluid shift in the body due to centrifugation. On initial report of a headache from a subject, an investigator will suggest relaxation techniques to relieve the headache. If the headache persists for the longer than 5 minutes, the experiment will stop. The subject also has the option of ending the experiment at any time for any reason.

2. Nausea/Motion Sickness
Motion sickness is primarily due to sensory conflict. The subject tactually perceives himself as lying on a still bed after an initial period on the bed. Movements of the head and the resulting vestibular stimulation reveal the influence of Coriolis forces due to rotation. The canopy of the AGS is translucent and the subject sees a blurring of external objects during rotation. The consequent sensory conflict may cause nausea. For the physiological studies on the AGS, the subjects will be blindfolded and instructed not to move their head. If the subject reports intolerable motion sickness, the experiment will be stopped. The subject also has
the option ending the experiment at any time for any reason with an emergency switch.

3. Heart Rate Increase
Previous research has shown that rotation with G levels at the feet between 1 and 1.5 G causes increased heart rate of up to 1.75 times normal levels. While the increased heart rate is no greater than that which would be experienced during aerobic exercise, medical heart conditions unknown to the subject may become evident. The heart rate of the subjects in the physiological studies will be continuously monitored. If heart rate becomes abnormally high, 1.75 times the subject's normal heart rate, the experiment will be stopped. Maximum heart rate for an individual is HR(max)= 220 - age. Subjects will also be monitored for complications for at least 15 minutes after each rotation session in the physiological studies.

4. Injury Related to Falling Off the AGS While Rotating
Serious injury could result from falling off the AGS while it is rotating. The following steps will be taken to prevent such an incident:
a. The subject will be loosely restrained at the legs and thorax, preventing him from making sudden motions or falling off the rotating bed. The restraints will be equipped with quick release latches making it possible for the subject to escape quickly if necessary.
b. Side railing similar to those on a hospital stretcher will be employed to contain the subject.
c. As mentioned previously, the subject will be equipped with an emergency stop switch which will stop the AGS from rotating within approximately 5 seconds.
d. The subject will be continuously monitored by at least one experimenter in the same room.
e. The subject will be equipped with a 2-way headset communication system connected to the observing experimenter.
f. Final human performance measurements will employ a video camera mounted on the AGS which may help the investigator understand the nature of any problems that arise.
g. Finally, subjects will experience a short test ride of several minutes duration after familiarization with the equipment.

5. Skin Irritation
Subjects will have seven electrodes placed on their bodies. Sufficient electrical contact with the skin requires that electrode gel be placed between the leads and skin. Also, calf volume measurements require marking the leg with a washable marker to ensure consistency of measurements. The application of gel and marker to the skin may cause minor skin irritation. However, the irritation is unlikely to be lasting.

If I am a participant in experimental trials, I tentatively agree to return for additional trials (at most 10) requested by the experimenter. However, I understand that I can withdraw from this study at any time for any reason. I understand that the likely protocol for the actual trials will consist of the following four sessions, the order of which will be determined by the experimenter:

1. control session: one hour of supine rest on the AGS, one half hour of standing, and a final half hour of supine rest on the AGS
2. one half hour of supine rest on the AGS, one hour of rotation resulting in 0.5 G's at my feet, and a final half hour of supine rest on the AGS
3. one half hour of supine rest on the AGS, one hour of rotation resulting in 1.0 G's at my feet, and a final half hour of supine rest on the AGS
4. one half hour of supine rest on the AGS, one hour of rotation resulting in 1.5 G's at my feet, and a final half hour of supine rest on the AGS.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)

Monetary compensation for those who are not members of the Man-Vehicle Laboratory will be $10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D. (MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment. I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject Code No.: _______

Experimenter _______

Date _______

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAN-VEHICLE LABORATORY

THE EFFECT OF CORIOLIS FORCES ON THE HUMAN PERFORMANCE OF TWO-HANDED TASKS WHILE IN A ROTATING ENVIRONMENT

CONSENT FORM

I have been asked to participate in a study of the effects of the forces produced by rotation on the performance of two-handed tasks. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason. I have completed a selection questionnaire related to my medical history and understand that I should not participate in this study if I have any medical heart conditions, if I have any medical conditions which would be triggered if I develop motion sickness, or if there is any possibility that I could be pregnant.

Prior to rotation, I will undergo a static training session while lying on the platform in which I will be taught and have the chance to practice the manual task which I will be asked to perform while rotating. The manual task involves simultaneous use of both my hands. After I have learned the task, a prerotation test session will be conducted. During the next portion of the experiment I will be rotated at a speed of 10 RPM, a speed well within the established safety limits, while still lying on my back. During the first few minutes of rotation while the platform comes up to speed, I will probably feel some slight dizziness. If I do become dizzy I will close my eyes and relax until the sensation goes away. After the initial start-up phase, my balance system will adapt to the constant rotational rate, and sensation of spinning should be greatly reduced. At this point I will be asked to perform the manual tasks learned in the training session. During this portion of the experiment I may experience nausea or disorientation, especially if I move my head. To reduce the possibility of nausea, a padded headrest will be provided to help reduce the amount of head movement, and all objects I will have to interact with will be in my immediate line of sight.

I will be prevented from falling off the platform by two side rails and two quick-release safety belts, one at chest level and one at my legs. I should not try to sit up or make fast head movements while rotating; if I try to sit up the safety belt at my chest will be released and will stop the rotation of the platform. My hands will be free to move within the confines of the hand rails and wind canopy. In the case of an emergency, or if I have an immediate desire to stop rotation, there will be an easily accessible stop switch (the use of which has been demonstrated to me) within arms reach which will bring the platform to a halt within approximately 5 seconds. I will be in constant communication with the experimenter through headsets and will be monitored by a video camera. If I experience unacceptable symptoms, I am free to close my eyes, ask for a break, or withdraw entirely from the experiment at any time. I understand that rotation sessions will not exceed thirty minutes and that I may be asked to come back two more times in order to investigate adaptation to artificial gravity, once three days after the initial test session, and again five days after the second test session.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)
Monetary compensation for those who are not members of the Man Vehicle Laboratory will be $10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D. (MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment.

I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject ________________________________ Date _________
Experimenter ____________________________ Date _________
References


SELECTION QUESTIONNAIRE

BIOGRAPHICAL INFORMATION:
Name: ____________________________ Age: _____ Sex: _____
Address: __________________________ Telephone: _____________
__________________________________ Occupation: ____________

PLEASE ANSWER ALL QUESTIONS TO THE BEST OF YOUR ABILITY:
1. Do you have a history of medical heart conditions (arrhythmia, heart attack, failure)? ______
2. Do you have a heart murmur that requires notification of dentist during a dental exam? ______
3. Do you have a history of seizures or epilepsy? ________________________________
4. Do you have a history of black outs? ________________________________
5. Do you have any breathing difficulties (asthma, bronchitis, emphysema)? ___________
6. Is there any possibility you could be pregnant? ______________________________
7. Do you have a history of claustrophobia? ________________________________
   Do you get claustrophobic: ☐ Very easily ☐ Sometimes ☐ Almost never
8. Do you have any medical conditions which might be triggered if you develop motion sickness? ______
   If yes, explain: ________________________________
9. Have you ever had motion sickness? ______
   If yes, about how many times? ______
   From which of the following: ☐ Car ☐ Plane ☐ Boat ☐ Game ride ☐ Other ______
   Do you become motion sick: ☐ Very easily ☐ Sometimes ☐ Almost never
   Approximately when did you last have motion sickness (Month/Year)? __________
10. Do you have any other chronic or acute medical problems which might place you in danger during this experiment? ______
    If yes, explain: ________________________________
11. Have you had extensive experience spinning (ice skating, dancing, game ride)? ______
    Did you: ☐ Like it ☐ Dislike it ☐ Feel indifferent
12. Do you have any conditions which would prevent you from having full use of both of your arms and hands? ________________________________

SUBJECT'S ASSIGNED CODE: ______
APPENDIX C

Protocol Checklist

Things to Do Prior to Placing the Subject on the AGS
1. Calibrate the impedance cardiograph.
2. Weight the subject.
3. Measure subject height.
4. Draw circumference lines on the calf, 2 cm apart.
5. Place impedance electrodes on the calf.
6. Put the foot plate at the desired height.
7. Offer the subject food and water.
8. Place appropriate counterweights on the AGS while another experimenter counterbalances.

Things to Do in Transition
1. Allow subject to climb onto the AGS via a chair. Have him position himself with his feet firmly flat on the foot plate.
2. Attach the ECG leads to the ECG electrodes.
3. Attach the impedance cardiograph leads to the electrode tape.
4. Place the BP cuff around one arm.

Things to Do During 30-minute Pre-Stimulus Period
1. Measure the circumferences immediately.
2. Have the subject initiate an BP measurement every five minutes.
3. Fix the BP unit to the side of the AGS with a clamp.
4. Measure the distance between the impedance electrodes.
5. Make sure no loose objects are on the AGS or in the path or rotation.
6. Confirm balance of the AGS with a level. If necessary change the counterweights.
7. Move several chairs over to the wall where standing will take place. (if standing trial)
8. Connect the battery to the camera and turn the power on. (if rotation trial)
9. Turn on the video monitor and adjust camera focus. (if rotation trial)
10. Blindfold the subject. (if rotation trial)
11. Mount the headset on the subject. Check for proper function and any interference with the ECG readings. If interference persists, adjust the AGS ground lead. (if rotation trial)
12. Fasten the subject's seat belt and place the safety button near their hand. (if rotation trial)
13. Measure the circumferences after the BP reading at 20 minutes
14. After the circumference measurements at 20 minutes, attach the wind canopy. (if rotation trial)
15. Attach the linen sheets to both ends of the canopy and the AGS. (if rotation trial)
16. Plug in the emergency stop relay; turn the motor power on; briefly place the controller start/stop switch in the start position. (if rotation trial)

Things to Do During Rotation Period
1. Rotate the AGS up to the desired level over 30 s using the motor controller potentiometer.
2. Immediately initiate a BP measurement when steady-state rotation is reached. Take a BP reading every 5 minutes thereafter.
3. Check to make sure the computer system is recording data.
4. After 15 minutes of rotation, ask the subject if he wants to continue the experiment.
5. Ask the subject how he feels every 10 minutes
6. Confirm the rotation rate experimentally.
7. Monitor the heart rate and BP readings for any abnormal responses and indications that the subject is too relaxed.
8. Maintain verbal communication with the subject.

**Things to Do During Standing Period**
1. Allow the subject to sit up at least 15 s prior to the transition to standing.
2. Aid the subject in transition from supine on the AGS to standing with his back against the wall, being careful of all leads.
3. Initiate a blood pressure measurement after standing is achieved and verbal verification of the subject’s well-being has been elicited. Take a BP reading every 5 minutes thereafter.
4. Offer the subject water.
5. An experimenter is required to stand next to the subject at all times and be prepared to catch the subject.
6. The subject is allowed to move his legs a bit.

**Things to Do Post-Stimulus**
1. Rotate the subject down to no movement over 30 s using the motor controller potentiometer; turn the motor controller power off.
2. Immediately initiate a BP measurement when rotation has stopped. Take a BP reading every 5 minutes thereafter.
3. Remove the wind canopy. (if rotation trial)
4. Measure the circumferences immediately after the first BP reading.
5. Remove the subject’s blindfold and headset.
APPENDIX D

Heart Rate Computer Code

% program ecg
% overhead program for calculating peak times/heart rate from the ECG data
% all 4 trials for one subject

subject='E';
dayc=1104;
day05=1119;
day10=1108;
day15=1115;

% control
% load the original file
load -ascii /usr/tmp/dawn/EGE1104.PRN;
% down sample from 250Hz to 125Hz
signal=resample(EGE1104);
sr=125; %sampling rate
min=120; %approximate number of minutes covered
[tbp, peaktime, hrtime, heartrate]=overhead(signal, sr, min, subject, 'Control');
new=[tbp 0.0];
save hrvEcont peaktime new -ascii;
save heartEcont hrtime heartrate -ascii;
figure(2)
print -dps hrEcont.ps
figure(3)
print -dps hrvEcont.ps
clear EGE1104;

% 0.5 G
load -ascii /usr/tmp/dawn/EGE1119.PRN;
signal=resample(EGE1119);
sr=125;
min=120;
[tbp, peaktime, hrtime, heartrate]=overhead(signal, sr, min, subject, '0.5 G');
new=[tbp 0.0];
save hrvE0.5 peaktime new -ascii;
save hrE0.5 hrtime heartrate -ascii;
figure(2)
print -dps hrE0.5.ps
figure(3)
print -dps hrvE0.5.ps
clear EGE1119;

% 1.0 G
load -ascii /usr/tmp/dawn/EGE1108.PRN;
signal=resample(EGE1108);
sr=125;
min=120;
[tbp, peaktime, hrtime, heartrate]=overhead(signal, sr, min, subject, '1.0 G');
new=[tbp 0.0];
save hrvE1.0 peaktime new -ascii;
save hrE1.0 hrtime heartrate -ascii;
figure(2)
print -dps hrE1.0.ps
figure(3)
print -dps hrvE1.0.ps
clear EGE1108;

% 1.5 G
load -ascii /usr/tmp/dawn/EGE1115.PRN;
signal=resample(EGE1115);
sr=125;
min=120;
[tbp, peaktime, hrtme, heartrate]=overhead(signal, sr, min, subject, '1.5 G');
new=[tbp 0.0];
save hrvE1.5 peaktime new -ascii;
save hrE1.5 hrtme heartrate -ascii;
figure(2)
print -dps hrE1.5.ps
figure(3)
print -dps hrvE1.5.ps
clear EGE1115

function [signal2]=resample(signal)
% down-samples a file by 2
signal2=zeros(1,length(signal)/2);
j=1;
    for i=1:length(signal2),
        signal2(i)=signal(j);
        j=j+2;
    end;
end;

function [tbp, peaktime, hrtme, heartrate]=overhead(signal, sr, min, subject, trial)
% overhead program for finding the peak times/heart rate from an ECG signal
% see if there is less than the specified number of minutes
min2=length(signal)/sr/60;
if min <= min2,
signal=signal(1:sr*60*min);
    min2=min;
end;

[tbp, heartrate, peaktime]=process(signal, sr, min2);
avt=30;
hrtme=(avt:avt:min2*60)/60;
figure(2)
plot(hrtme,heartrate,'.')
xlabel('Time (min)');
ylabel('Heart Rate (bpm)');
title(sprintf('Heart Rate vs. Time for Subject %c During %s Trial',subject, trial));
figure(3)
plot(peaktime(1:length(peaktime)-1),tbp,'.');
xlabel('Time (s)');
ylabel('R-R Interval Time (s)');
title(sprintf('R-R Intervals vs. Time for Subject %c During %s Trial',subject,trial));
end;

function [tbp, heartrate, peaktime] = process(signal, sr, min2)
% filters the signal, finds the QRS peaks, and calculates heart rate

t = 0:1/sr:min2*60-1/sr; % time vector

figure(1)
xo = signal(1:10*sr);
subplot(221), plot(t(1:10*sr), xo) % see the data
title('First Ten Seconds of ECG Signal');
xlabel('Time (s)');
ylabel('Voltage (V)');

% check to see what frequency range the data is in
fre = [1/4096:1/4096:1]*sr;
xfft = abs(fft(xo, 4096));
subplot(222), plot(fre, xfft);
axis([0 75 0 800]);
title('FFT');
xlabel('Frequency (Hz)');
clear xo
clear xfft

% filter the signal with a matched filter
fmin = 10; % lower cutoff frequency in Hz
fmax = 30; % higher cutoff frequency in Hz
order = 100; % filter order
wn = [fmin*2/sr fmax*2/sr];
B = firl(order, wn);
J = fftfilt(B, signal);
clear signal

% see what it looks like
subplot(223), plot(t(1:10*sr), J(1:10*sr));
title('ECG Voltage vs. Time, Filtered');
xlabel('Time (s)');
ylabel('Voltage (V)');

% see what filtered fft looks like
Y = abs(fft(J(1:10*sr), 4096));
subplot(224), plot(fre, Y)
axis([0 75 0 800]);
title('FFT of Filtered Data');
xlabel('Frequency (Hz)');
clear Y

print -dps filtering
% let's find the peaks
k=1;
peaktime=zeros(1, min2*100);
r=-1000;
for i=1:length(J),
  if i > 5*sr
    m=max(abs(J(i-5*sr:i)));
  else
    m=max(abs(J(1:5*sr)));
  end; % FIND the local maximum.
  % lockout period assumes heart rate never exceeds 133 bpm
  if ((abs(J(i)) > .25*m) & ((i-r) > .45*sr))
    peaktime(k)=t(i);
    k=k+1;
    r=i;
  end;
end;
peaktime=peaktime(1:k-1);
%clear J

% find the time between peaks
btp=zeros(1,length(peaktime)-1);
k=1;
for i=1:length(peaktime)-1,
  btp(k)=peaktime(i+1)-peaktime(i);
  if btp(k) > 1.5
    if k > 1
      btp(k)=btp(k-1);
    else
      btp(k)=0;
    end;
  end;
k=k+1;
end;
% let's find heartrate
avt=30; % number of seconds over which heart rate is averaged
hrtime=(avt:avt:min2*60)/60;
heartrate=zeros(size(hrtime));
for i=avt:avt:min2*60,
  q=find((peaktime <= i) & (peaktime >= (i-avt)));
  if length(q) > 1
    dummy=zeros(1,length(q)-1);
    k=1;
    j=0;
    for n=1:length(q)-1,
      % lockout period assumes heartrate is always greater than 40bpm
      if (peaktime(q(n+1))-peaktime(q(n))) < 1.5
        dummy(k)=(peaktime(q(n+1))-peaktime(q(n)))^(-1)*60;
        k=k+1;
      else
        j=j+1;
      end;
    end;
    dummy=dummy(1:length(dummy)-j);
    heartrate(i/avt)=mean(dummy);
  else
    100
heartrate(i/avt)=0;
end;
end;
end

% heartc.m
% overhead program for calculated heart rate at different averaging intervals
% from a known set of peak times
% allows for noise rejection

figure(1)
min2=120;
subject='C';

load 'hrvCcont' -ascii;
hprocess(hrvCcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratec15,hrvarc]=hrover(hrvCcont(1,:),min2,subject,'Control');
[hrtrateo5,hrtrateo15,hrvaro]=hrover2(hrvCcont(1,:),min2,subject,'Control',32,[30],1/(96/60));

load 'hrvC0.5' -ascii;
hprocess(hrvC0(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvC0(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover2(hrvC0(1,:),min2,subject,'0.5 G',[0],[120],[.6]);

load 'hrvC1.0' -ascii;
hprocess(hrvC1(1,:),min2,subject,'1.0 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvC1(1,:),min2,subject,'1.0 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover2(hrvC1(1,:),min2,subject,'1.0 G',[0],[120],[2/3]);

load 'hrvC1.5' -ascii;
hprocess(hrvC1(1,:),min2,subject,'1.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvC1(1,:),min2,subject,'1.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover2(hrvC1(1,:),min2,subject,'1.5 G',[0 0.005 90.0001],[30 90 120],[.6 1/(110/60) .6]);

data1=[hrtratec5' hrtrateo5' hrtratef5'];
data2=[hrtratec15' hrtrateo5' hrtratef15'];
data3=[hrvarc' hrvarf' hrvaro' hrvarf'];
% save Chr5 data1 -ascii;
% save Chr5 data2 -ascii;
% save Chr5 data3 -ascii;
save Chr5 data1 -ascii;
save Chr5 data2 -ascii;
save Chr5 data3 -ascii;

% heartd.m
figure(1)
min2=120;
subject='D';
load 'hrvDcont' -ascii;
hprocess(hrvDcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratecl5,hrvarc]=hrover(hrvDcont(1,:),min2,subject,'Control');

load 'hrvD0.5' -ascii;
hprocess(hrvD0(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvD0(1,:),min2,subject,'0.5 G',0,[120],[2/3]);

load 'hrvD1.0' -ascii;
hprocess(hrvD1(1,:),min2,subject,'1.0 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvD1(1,:),min2,subject,'1.0 G',0,
30.0001,90.0001,[30 90 120],[.6 2/3 1/(11/6)]);

load 'hrvD1.5.1' -ascii;
peaktimel=hrvD1(1,:);
load 'hrvD1.5.2' -ascii;
peaktime2=hrvD1(1,:)+3600;
hprocess([peaktimel peaktime2],min2,subject,'1.5 G');
[hrtratef5,hrtratef15,hrvarft]=hrover([peaktimel
peaktime2],min2,subject,'1.5 G');

load 'hrvDl.0' -ascii;
hprocess(hrvDl(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvDl(1,:),min2,subject,'0.5 G',0,
30.0001,90.0001,[30 90 120],[.6 2/3 1/(11/6)]);

load 'hrvDl.5.1' -ascii;

% hearte.m
figure(1)
min2=120;
subject='E';

load 'hrvEcont' -ascii;
hprocess(hrvEcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratecl5,hrvarc]=hrover(hrvEcont(1,:),min2,subject,'Control');

load 'hrvE0.5' -ascii;
hprocess(hrvE0(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvE0(1,:),min2,subject,'0.5 G',0,
[120],[2/3]);

load 'hrvE1.0' -ascii;
hprocess(hrvE1(1,:),min2,subject,'1.0 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvE1(1,:),min2,subject,'1.0 G',0,
30.0001,82.0001,[30 82 120],[.75 .75 .6 .75]);

load 'hrvE1.5' -ascii;
hprocess(hrvEl(1,:),min2,subject,'1.5 G');

% [hrtrateft5,hrtrateft15,hrvarft]=hrover(hrvEl(1,:),min2,subject,'1.5 G');
[hrtrateft5,hrtrateft15,hrvarft]=hrover2(hrvEl(1,:),min2,subject,'1.5 G',[0 30],[28 120],[1/(11/6) .5]);

data1=[hrtratec5' hrtratef5' hrtrateo5' hrtrateft5'];
data2=[hrtratec15' hrtratef15' hrtrateo15' hrtrateft15'];
data3=[hrvarc' hrvarf' hrvaro' hrvarft'];

% save Ehr5 data1 -ascii;
% save Ehr15 data2 -ascii;
% save Ehrv data3 -ascii;
save Ehr52 data1 -ascii;
save Ehr152 data2 -ascii;
save Ehrv2 data3 -ascii;

% heartf.m

figure(1)
min2=120;
subject='F';

load 'hrvFcont' -ascii;
hprocess(hrvFcont(1,:),min2,subject,'Control');

% [hrtratec5,hrtratec15,hrvarc]=hrover(hrvFcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratec15,hrvarc]=hrover2(hrvFcont(1,:),min2,subject,'Control',[0 20.001 28.001 37.001],[20 28 37 120],[2/3 .6 2/3 .6]);

load 'hrvF0.5' -ascii;
hprocess(hrvF0(1,:),min2,subject,'0.5 G');

% [hrtratef5,hrtratef15,hrvarf]=hrover(hrvF0(1,:),min2,subject,'0.5 G');
[hrtratef5,hrtratef15,hrvarf]=hrover2(hrvF0(1,:),min2,subject,'0.5 G',[0 20.001 28.001 37.001],[20 28 37 120],[2/3 .6 2/3 .6]);

load 'hrvF1.0' -ascii;
hprocess(hrvF1(1,:),130,subject,'1.0 G');

% [hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvF1(1,:),130,subject,'1.0 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover2(hrvF1(1,:),130,subject,'1.0 G',[0 40.001],[40 130],[60/95 .6]);

load 'hrvF1.5' -ascii;
hprocess(hrvF1(1,:),min2,subject,'1.5 G');

% [hrtrateft5,hrtrateft15,hrvarft]=hrover(hrvF1(1,:),min2,subject,'1.5 G');
[hrtrateft5,hrtrateft15,hrvarft]=hrover2(hrvF1(1,:),min2,subject,'1.5 G',[0 29.0001 60.0001 92.0001],[29 60 92 120],[2/3 .6 6/11 .6]);

diff1=length(hrtrateo5)-length(hrtrateft5);
diff2=length(hrtrateo15)-length(hrtrateft15);
hrtratec5=[hrtratec5 zeros(1,diff1)];
hrtratef5=[hrtratef5 zeros(1,diff1)];
hrtrateft5=[hrtrateft5 zeros(1,diff1)];
hrtratec15=[hrtratec15 zeros(1,diff2)];
hrtratef15=[hrtratef15 zeros(1,diff2)];
hrtrateft15=[hrtrateft15 zeros(1,diff2)];
hrvarc=[hrvarc zeros(1,diff1)];
hrvarf=[hrvarf zeros(1,diff1)];
hrvarft=[hrvarft zeros(1,diff1)];
data1=[hrtratec5' hrtratef5' hrtrateo5' hrtrateft5'];
data2=[hrtratec15' hrtratef15' hrtrateo15' hrtrateft15'];
data3=[hrvarc' hrvarf' hrvaro' hrvarft'];

%save Fhr5 data1 -ascii;
%save Fhr15 data2 -ascii;
%save Fhrv data3 -ascii;
save Fhr52 data1 -ascii;
save Fhr152 data2 -ascii;
save Fhrv2 data3 -ascii;

% hearthg.m
figure(1)
min2=120;
subject='G';
load 'hrvGcont' -ascii;
hprocess(hrvGcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratec15,hrvarc]=hrover(hrvGcont(1,:),min2,subject,'Control');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvGcont(1,:),min2,subject,'0.5 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvGcont(1,:),min2,subject,'1.0 G');
[hrtrateft5,hrtrateft15,hrvarft]=hrover(hrvGcont(1,:),min2,subject,'1.5 G');
data1=[hrtratec5' hrtratef5' hrtrateo5' hrtrateft5'];
data2=[hrtratec15' hrtratef15' hrtrateo15' hrtrateft15'];
data3=[hrvarc' hrvarf' hrvaro' hrvarft'];

% hearth.m
figure(1)
min2=120;
subject='H';
load 'hrvHcont' -ascii;
hprocess(hrvHcont(1,:),min2,subject,'Control');
[hrtratec5,hrtratec15,hrvarc]=hrover(hrvHcont(1,:),min2,subject,'Control');
[hrtratef5,hrtratef15,hrvarf]=hrover(hrvHcont(1,:),min2,subject,'0.5 G');
[hrtrateo5,hrtrateo15,hrvaro]=hrover(hrvHcont(1,:),min2,subject,'1.0 G');
[hrtrateft5,hrtrateft15,hrvarft]=hrover(hrvHcont(1,:),min2,subject,'1.5 G');
data1=[hrtratec5' hrtratef5' hrtrateo5' hrtrateft5'];
data2=[hrtratec15' hrtratef15' hrtrateo15' hrtrateft15'];
data3=[hrvarc' hrvarf' hrvaro' hrvarft'];
load 'hrvH0.5' -ascii;
hprocess(hrvH0(1,:),min2,subject,'0.5 G');
%[hrstratef5,hrstratef15,hrvarf]=hrover(hrvH0(1,:),min2,subject,'0.5 G');
[hrstratef5,hrstratef15,hrvarf]=hrover2(hrvH0(1,:),min2,subject,'0.5 G',[0],[120],[6/11]);
load 'hrvH1.0' -ascii;
hprocess(hrvH1(1,:),min2,subject,'1.0 G');
%[hrstrateo5,hrstrateo15,hrvaro]=hrover(hrvH1(1,:),min2,subject,'1.0 G');
[hrstrateo5,hrstrateo15,hrvaro]=hrover2(hrvH1(1,:),min2,subject,'1.0 G',[0 32.0001 55.0001],[32 55 120],[6/11 .6 6/11]);
load 'hrvH1.5' -ascii;
hprocess(hrvH1(1,:),min2,subject,'1.5 G');
%[hrstrateft5,hrstrateft15,hrvarft]=hrover(hrvH1(1,:),min2,subject,'1.5 G');
[hrstrateft5,hrstrateft15,hrvarft]=hrover2(hrvH1(1,:),min2,subject,'1.5 G',[0 35.0001 90.001],[35 90 120],[6/11 .6 6/11]);
data1=[hrstratec5' hrstratef5' hrstrateo5' hrstrateft5'];
data2=[hrstratec15' hrstratef15' hrstrateo15' hrstrateft15'];
data3=[hrvari' hrvarf' hrvaro' hrvarf'];
%save Hhr5 data1 -ascii;
%save Hhr15 data2 -ascii;
%save Hhrv data3 -ascii;
save Hhr52 data1 -ascii;
save Hhr152 data2 -ascii;
save Hhrv2 data3 -ascii;

% hearti.m
figure(1)
min2=120;
subject='I';
load 'hrvIcont' -ascii;
hprocess(hrvIcont(1,:),min2,subject,'Control');
%[hrstratec5,hrstratec15,hrvari]=hrover(hrvIcont(1,:),min2,subject,'Control');
[hrstratec5,hrstratec15,hrvari]=hrover2(hrvIcont(1,:),min2,subject,'Control',[0 60 90],[57 87 120],[6/11 .5 .6]);
load 'hrvI0.5' -ascii;
hprocess(hrvI0(1,:),min2,subject,'0.5 G');
%[hrstratef5,hrstratef15,hrvarf]=hrover(hrvI0(1,:),min2,subject,'0.5 G');
[hrstratef5,hrstratef15,hrvarf]=hrover2(hrvI0(1,:),min2,subject,'0.5 G',[0 20.01 75.0001],[20 75 120],[6/11 .6 6/11]);
load 'hrvI1.0' -ascii;
hprocess(hrvI1(1,:),min2,subject,'1.0 G');
%[hrstrateo5,hrstrateo15,hrvaro]=hrover(hrvI1(1,:),min2,subject,'1.0 G');
[hrstrateo5,hrstrateo15,hrvaro]=hrover2(hrvI1(1,:),min2,subject,'1.0 G',[0],[120],[6]);
load 'hrvI1.5' -ascii;
hprocess(hrvI1(1,:),min2,subject,'1.5 G');
%[hrstrateft5,hrstrateft15,hrvarft]=hrover(hrvI1(1,:),min2,subject,'1.5 G');
function hprocess(peaktime,min2,subject, trial)
% finds the R-R intervals from the peak times and calculates instantaneous HR
tbp=zeros(1,length(peaktime)-1);
k=1;
for i=1:length(peaktime)-1,
    tbp(k)=peaktime(i+1)-peaktime(i);
    if tbp(k) > 1.5
        if k > 1
            tbp(k)=tbp(k-1);
        else
            tbp(k)=0;
        end;
    end;
    k=k+1;
end;

% do the plot

bp=.4:.01:1.6;
bp2=40:.1:150;
if (trial(1,1:5) == 'Contr')
    tll=ones(size(bp))*60;
    tl12=ones(size(bp2))*60;
else
    tll=ones(size(bp))*30;
    tl12=ones(size(bp2))*30;
end;
t12=ones(size(bp))*90;
tl22=ones(size(bp2))*90;

figure(gcf+1)
subplot(211),plot(peaktime(1:length(peaktime)-1)/60,tbp,'.');
xlabel('Time (min)');
ylabel('R-R Interval Time (s)');
title(sprintf('R-R Intervals vs. Time for Subject %c During %s Trial',subject, trial));
hold on
sy(.4,1.6);
axis(axis)
pplot(tll,bp);
pplot(tl12,bp);
ggrid
subplot(212),plot(peaktime(1:length(peaktime)-1)/60,1./(tbp/60),'.');
xlabel('Time (min)');
ylabel('Instantaneous Heart Rate (bpm)');
title(sprintf('Instantaneous Heart Rate vs. Time for Subject %c During %s Trial',subject, trial));
hold on
axis(axis)
pplot(tll2,bp2);
pplot(tl22,bp2);
ggrid

function [heartrate2,heartrate3,hstdev2] =hrover (peaktime,min,subject,trial)
% overhead program to plot HR due to different averaging intervals

% find average heartrates for 30s, 5 min, and 15 min. intervals
[hrtime1, heartrate1, hstdev1] = hrate(peaktime, min, 30);
[hrtime2, heartrate2, hstdev2] = hrate(peaktime, min, 300);
[hrtime3, heartrate3, hstdev3] = hrate(peaktime, min, 900);

bp = 40:.1:150;
if (trial(1,1:5) == 'Contr')
    tll = ones(size(bp))*60;
else
    tll = ones(size(bp))*30;
end;
t12 = ones(size(bp))*90;

figure(gcf+1)
subplot(311), plot(hrtimel, heartratel, '.
ylabel('Heart Rate (bpm)');
title(sprintf('Heart Rate vs. Time for Subject %c During %s Trial', subject,
trial));
cur = axis;
if cur(3) == 0,
    cur(3) = 50;
end;
cur = [0 cur(2) cur(3) cur(4)];
axis(cur)
axis(axis)
hold on
plot(tll, bp);
plot(tl2, bp);
grid
subplot(312), plot(hrtime2, heartrate2, 'o')
ylabel('Heart Rate (bpm)');
hold on
axis(axis)
plot(tll, bp);
plot(tl2, bp);
grid
axis(cur)
subplot(313), plot(hrtime3, heartrate3, 'o'
xlabel('Time (min)');
ylabel('Heart Rate (bpm)');
hold on
axis(axis)
plot(tll, bp);
plot(tl2, bp);
grid
axis(cur)

function [hrtime, heartrate, hstdev] = hrate(peaktime, min2, avt)
% let's find heartrate

% avt= number of seconds over which heart rate is averaged
hrtime = (avt:avt:min2*60)/60;
heartrate = zeros(1, length(hrtime));
hstdev = zeros(1, length(hrtime));
for i = avt:avt:min2*60,
    q = find((peaktime <= i) & (peaktime >= (i-avt)));
    if length(q) > 1
        % calculate averages
        for j = 1:length(q)
            hrtime = hrtime + peaktime(j);
            heartrate = heartrate + 1;
            hstdev = hstdev + (peaktime(j) - i)^2;
        end;
        hrtime = hrtime / length(q);
        heartrate = heartrate / length(q);
        hstdev = hstdev / length(q);
    end;
end;
dummy=zeros(1,length(q)-1);
k=1;
j=0;
for n=1:length(q)-1,
  % lockout period assumes heartrate is always greater than 40bpm
  if (peaktime(q(n+1))-peaktime(q(n))) < 1.5
    dummy(k)=(peaktime(q(n+1))-peaktime(q(n)))^(-1)*60;
    k=k+1;
  else
    j=j+1;
  end;
  dummy=dummy(1:length(dummy)-j);
end;
heartrate(i/avt)=mean(dummy);
else
  heartrate(i/avt)=0;
end;
hstdev(i/avt)=std(dummy);
end;

function [heartrate2,heartrate3,hstdev2]=hrover2(peaktime,min,subject,trial,
stb,ste,cutoff)

% overhead program to plot HR due to different averaging intervals
% allows for noise rejection

% stb=times when periods of elimination of noisy data begin
% ste=times when periods of elimination of noisy data begin
% cutoff = R-R interval values in periods below which data will be eliminated

% find average heartrates for 30s, 5 min, and 15 min. intervals
[hrtime1,heartrate1,hstdev1]=hrate2(peaktime,min,30,stb,ste,cutoff);
[hrtime2,heartrate2,hstdev2]=hrate2(peaktime,min,300,stb,ste,cutoff);
[hrtime3,heartrate3,hstdev3]=hrate2(peaktime,min,900,stb,ste,cutoff);

bp=40:.1:150;
if (trial(1,1:5) == 'Contr')
  tll=ones(size(bp))*60;
else
  tll=ones(size(bp))*30;
end;
tl2=ones(size(bp))*90;

figure(gcf+1)
subplot(311),plot(hrtime1,heartrate1,'.');
ylabel('Heart Rate (bpm)');
title(sprintf('Heart Rate vs. Time for Subject %c During %s Trial',subject,trial));
cur=axis;
if cur(3) == 0,
  cur(3)=50;
end;
cur=[0 cur(2) cur(3) cur(4)];
axis(cur)
axis(axis)
hold on
plot(tll,bp);
plot(tl2,bp); grid
subplot(312), plot(hrtime2, heartrate2, 'o')
ylabel('Heart Rate (bpm)'); hold on
axis(axis)
plot(tll,bp); plot(tl2,bp); grid
axis(cur)
subplot(313), plot(hrtime3, heartrate3, 'o')
xlabel('Time (min)'); ylabel('Heart Rate (bpm)'); hold on
axis(axis)
plot(tll,bp); plot(tl2,bp); grid
axis(cur)

function [hrtime, heartrate, hstdev] = hrate2(peaktime, min2, avt, stb, ste, cutoff)
% let's find heartrate
% allows for noise rejection
% avt= number of seconds over which heart rate is averaged

count = length(stb);
hrtime = (avt:avt:min2*60)/60;
heartrate = zeros(1, length(hrtime));
hstdev = zeros(1, length(hrtime));
for i = avt:avt:min2*60,
    q = find((peaktime <= i) & (peaktime >= (i-avt)));
    if length(q) > 1
        dummy = zeros(1, length(q) - 1);
        k = 1;
        j = 0;
        for n = 1:length(q) - 1,
            % check to see if point is in noisy period
            g = 0;
            for w = 1:count,
                if ((i >= stb(w)*60) & (i <= ste(w)*60))
                    g = w;
                end;
            end;
            if (g == 0)
                % lockout period assumes heartrate is always greater
                than 40bpm
                    if (peaktime(q(n+1)) - peaktime(q(n))) < 1.5
                        dummy(k) = (peaktime(q(n+1)) - peaktime(q(n)))^(-1)*60;
                        k = k + 1;
                    else
                        j = j + 1;
                    end;
                else
                else
                    % ...
if (((peaktime(q(n+l))-peaktime(q(n))) < 1.5) &
((peaktime(q(n+1))-peaktime(q(n))) > cutoff(g)))
dummy(k)=(peaktime(q(n+1))-peaktime(q(n)))^(-1)*60;
k=k+1;
else
j=j+1;
end;
end;
dummy=dummy(1:length(dummy)-j);
heartrate(i/avt)=mean(dummy);
else
heartrate(i/avt)=0;
end;
hstddev(i/avt)=std(dummy);
end;
APPENDIX E

Calf Impedance Measurements

Measured Impedance Plots

The vertical lines with arrows represent the onset or end of a stimulus.

Subject C
Subject D

Calf Impedance vs. Time, Subject D, Control

Calf Impedance vs. Time, Subject D, 0.5 G

Calf Impedance vs. Time, Subject D, 1.0 G

Calf Impedance vs. Time, Subject D, 1.5 G
Subject E

Calf Impedance vs. Time, Subject E, Control

Calf Impedance vs. Time, Subject E, 0.5 G

Calf Impedance vs. Time, Subject E, 1.0 G

Calf Impedance vs. Time, Subject E, 1.5 G
Subject F
Subject G

Calf Impedance vs. Time, Subject G, Control

Calf Impedance vs. Time, Subject G, 0.5 G

Calf Impedance vs. Time, Subject G, 1.0 G

Calf Impedance vs. Time, Subject G, 1.5 G
Subject H
Subject I

Calf Impedance vs. Time, Subject I, Control

Calf Impedance vs. Time, Subject I, 0.5 G

Calf Impedance vs. Time, Subject I, 1.0 G

Calf Impedance vs. Time, Subject I, 1.5 G
Subject J

Calf Impedance vs. Time, Subject J, Control

Calf Impedance vs. Time, Subject J, 0.5 G

Calf Impedance vs. Time, Subject J, 1.0 G

Calf Impedance vs. Time, Subject J, 1.5 G
Normalized Volume Plots

Subject C

Normalized Impedance vs. Time, Subject C, Control

Normalized Impedance vs. Time, Subject C, 0.5 G

Normalized Impedance vs. Time, Subject C, 1.0 G

Normalized Impedance vs. Time, Subject C, 1.5 G
Subject D

Normalized Impedance vs. Time, Subject D, Control

Normalized Impedance vs. Time, Subject D, 0.5 G

Normalized Impedance vs. Time, Subject D, 1.0 G

Normalized Impedance vs. Time, Subject D, 1.5 G
Subject E

Normalized Impedance vs. Time, Subject E, Control

Normalized Impedance vs. Time, Subject E, 0.5 G

Normalized Impedance vs. Time, Subject E, 1.0 G

Normalized Impedance vs. Time, Subject E, 1.5 G
Subject F

Normalized Impedance vs. Time, Subject F, 0.5 G

Normalized Impedance vs. Time, Subject F, 1.0 G

Normalized Impedance vs. Time, Subject F, 1.5 G

Normalized Impedance vs. Time, Subject F, Control
Subject G

Normalized Impedance vs. Time, Subject G, Control

Normalized Impedance vs. Time, Subject G, 0.5 G

Normalized Impedance vs. Time, Subject G, 1.0 G

Normalized Impedance vs. Time, Subject G, 1.5 G
Subject H

Normalized Impedance vs. Time, Subject H, Control

Normalized Impedance vs. Time, Subject H, 0.5 G

Normalized Impedance vs. Time, Subject H, 1.0 G

Normalized Impedance vs. Time, Subject H, 1.5 G
Subject I

Normalized Impedance vs. Time, Subject I, Control

Normalized Impedance vs. Time, Subject I, 0.5 G

Normalized Impedance vs. Time, Subject I, 1.0 G

Normalized Impedance vs. Time, Subject I, 1.5 G
Subject J

Normalized Impedance vs. Time, Subject J, Control

Normalized Impedance vs. Time, Subject J, 0.5 G

Normalized Impedance vs. Time, Subject J, 1.0 G

Normalized Impedance vs. Time, Subject J, 1.5 G

Time (min)

Normalized Impedance
## Data at Discrete Points

### Subject C

<table>
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<th>Location</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Location</th>
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<th>Y</th>
<th>Z</th>
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Subject F

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131
Subject G

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<th>13 G</th>
<th>Control</th>
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<th>11 G</th>
<th>10 G</th>
<th>9 G</th>
<th>8 G</th>
<th>7 G</th>
<th>6 G</th>
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<td>1.00</td>
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APPENDIX F

Calf Circumference Profiles, Volume Data, and Volume Plots

Calf Circumference Profiles

Postrotation in the control implies post-standing. The \( t = 0 \) measurements were made in the erect position. The equation coefficients are arranged so that \( t = 0 \) and 20 are in the first column and \( t = 90 \) and 120 are in the second column. As mentioned previously, not every subject had calf circumferences measured at \( t = 0 \) and 120 for every trial.

Subject C

![Graphs showing calf circumference profiles for Subject C under different conditions.](image-url)
Subject D

Calf Profile, Subject D, Control

Calf Profile, Subject D, 0.5 G

Calf Profile, Subject D, 1.0 G

Calf Profile, Subject D, 1.5 G
Subject E

Calf Profile, Subject E, Control

Calf Profile, Subject E, 0.5 G

Calf Profile, Subject E, 1.0 G

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Subject F

Calf Profile, Subject F, Control

Calf Profile, Subject F, 0.5 G

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Calf Profile, Subject F, 1.5 G
Subject G

Calf Profile, Subject G, Control

Calf Profile, Subject G, 0.5 G

Calf Profile, Subject G, 1.0 G

Calf Profile, Subject G, 1.5 G
Subject H

Prerotation Radius, 20 min. (cm)

Postrotation Radius, 120 min. (cm)

Calf Profile, Subject H, Control

Prerotation Radius, Standing (cm)

Postrotation Radius, 90 min. (cm)

Calf Profile, Subject H, 0.5 G

Prerotation Radius, Standing (cm)

Postrotation Radius, 20 min. (cm)

Calf Profile, Subject H, 1.0 G

Prerotation Radius, Standing (cm)

Postrotation Radius, 20 min. (cm)

Calf Profile, Subject H, 1.5 G

Prerotation Radius, Standing (cm)

Postrotation Radius, 20 min. (cm)
Subject J

Calf Profile, Subject J, Control

Calf Profile, Subject J, 0.5 G

Calf Profile, Subject J, 1.0 G

Calf Profile, Subject J, 1.5 G
Volume Data

Volumes are in cm^3.

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Volume Plots

Calf Volume vs. Time, Subject C

Normalized Calf Volume vs. Time, Subject C

Calf Volume vs. Time, Subject D

Normalized Calf Volume vs. Time, Subject D

Calf Volume vs. Time, Subject E

Normalized Volume vs. Time, Subject E

Volume (cm³)

Time (min)

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APPENDIX G

Data and Plots for Calf Impedance-Volume Relationship

Data for Calf Impedance-Volume Relationship

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Plots for Calf Impedance-Volume Relationship

Error bars represent standard deviations.

Subject C

Normalized Impedance vs. Normalized Volume

for Subject C

\[ y = 1.0274 - 0.5296x \quad R^2 = 0.76243 \]

Change in Impedance vs. Change in Volume

for Subject C

\[ y = 0.034321 + 0.09656x \quad R^2 = 0.70385 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject C

\[ y = 0.0022323 + 0.008217x \quad R^2 = 0.73285 \]

Subject D

Normalized Impedance vs. Normalized Volume

for Subject D

\[ y = 1.0367 + 0.03525x \quad R^2 = 0.91681 \]

Change in Impedance vs. Change in Volume

for Subject D

\[ y = 0.13628 + 0.05282x \quad R^2 = 0.91681 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject D

\[ y = 0.001772 + 0.008622x \quad R^2 = 0.88671 \]
Subject E

Normalized Impedance vs. Normalized Volume for Subject E

Change in Impedance vs. Change in Volume for Subject E

Normalized Change in Impedance vs. Normalized Change in Volume for Subject E

Subject F

Normalized Impedance vs. Normalized Volume for Subject F

Change in Impedance vs. Change in Volume for Subject F

Normalized Change in Impedance vs. Normalized Change in Volume for Subject F
Subject G

Normalized Impedance vs. Normalized Volume for Subject G

\[ y = 1.7856 - 0.781323 x, \quad R^2 = 0.68405 \]

Change in Impedance vs. Change in Volume for Subject G

\[ y = 1.2498 - 0.027225 x, \quad R^2 = 0.5218 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject G

\[ y = 0.016388 - 0.63273 x, \quad R^2 = 0.51814 \]

Subject H

Normalized Impedance vs. Normalized Volume for Subject H

\[ y = 1.8775 - 0.99657 x, \quad R^2 = 0.83718 \]

Change in Impedance vs. Change in Volume for Subject H

\[ y = 0.65797 - 0.023744 x, \quad R^2 = 0.775 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject H

\[ y = 0.009682 - 0.62136 x, \quad R^2 = 0.79645 \]
Subject I

Normalized Impedance vs. Normalized Volume for Subject I

\[ y = 2.0242 \pm 1.0201 \times R^2 = 0.87174 \]

Change in Impedance vs. Change in Volume for Subject I

\[ y = 0.50413 - 0.05760 \times R^2 = 0.5525 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject I

\[ y = 0.0079313 - 0.99232 \times R^2 = 0.96133 \]

Subject J

Normalized Impedance vs. Normalized Volume for Subject J

\[ y = 1.9276 + 0.9150 \times R^2 = 0.64151 \]

Change in Impedance vs. Change in Volume for Subject J

\[ y = 0.91005 - 0.04891 \times R^2 = 0.53865 \]

Normalized Change in Impedance vs. Normalized Change in Volume for Subject J

\[ y = 0.014204 - 0.77794 \times R^2 = 0.66964 \]
APPENDIX H

Blood Pressure Data and Plots
### Measured Blood Pressure Data

Results are presented with the subject's code letter followed by an "S" or a "D" indicating systolic or diastolic BP, respectively.

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Measured Blood Pressure Plots

The vertical bars with arrows represent initiation or cessation of a stimulus.

Subject C
Subject D
Subject E

Blood Pressure vs. Time, Subject E, Control

Blood Pressure vs. Time, Subject E, 0.5 G

Blood Pressure vs. Time, Subject E, 1.0 G

Blood Pressure vs. Time, Subject E, 1.5 G

[Graphs showing blood pressure over time for different G forces]
Subject F

Blood Pressure vs. Time, Subject F, Control

Blood Pressure vs. Time, Subject F, 0.5 G

Blood Pressure vs. Time, Subject F, 1.0 G

Blood Pressure vs. Time, Subject F, 1.5 G
Subject G
Subject H
Subject I

Blood Pressure vs. Time, Subject I, Control

Blood Pressure vs. Time, Subject I, 0.5 G

Blood Pressure vs. Time, Subject I, 1.0 G

Blood Pressure vs. Time, Subject I, 1.5 G
Subject J

Blood Pressure vs. Time, Subject J, Control

Blood Pressure vs. Time, Subject J, 0.5 G

Blood Pressure vs. Time, Subject J, 1.0 G

Blood Pressure vs. Time, Subject J, 1.5 G
Normalized Blood Pressure Data

Results are presented with the subject's code letter followed by an "S" or a "D" indicating systolic or diastolic BP, respectively.

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BP, respectively.
Normalized Blood Pressure Plots

The vertical lines in the plots represent the onset or end of a stimulus. The following is the key for all of the plots.

- • Systolic, Control
- • Diastolic, Control
- □ Systolic, 0.5 G
- □ Diastolic, 0.5 G
- △ Systolic, 1.0 G
- △ Diastolic, 1.0 G
- ○ Systolic, 1.5 G
- ○ Diastolic, 1.5 G

Normalized Blood Pressure vs. Time for Subject C

Normalized Blood Pressure vs. Time for Subject D

Normalized Blood Pressure vs. Time for Subject E

Normalized Blood Pressure vs. Time for Subject F
APPENDIX I

Heart Rate Data and Plots

Plots of R-R Intervals and Instantaneous Heart Rate

The vertical lines in the plots represent the onset or end of a stimulus.
Subject C

R-R Intervals vs. Time for Subject C During Control Trial

Instantaneous Heart Rate vs. Time for Subject C During Control Trial

R-R Intervals vs. Time for Subject C During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject C During 0.5 G Trial
R-R Intervals vs. Time for Subject C During 1.0 G Trial

Instantaneous Heart Rate vs. Time for Subject C During 1.0 G Trial

R-R Intervals vs. Time for Subject C During 1.5 G Trial

Instantaneous Heart Rate vs. Time for Subject C During 1.5 G Trial
Subject D

R-R Intervals vs. Time for Subject D During Control Trial

Instantaneous Heart Rate vs. Time for Subject D During Control Trial

R-R Intervals vs. Time for Subject D During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject D During 0.5 G Trial
R-R Intervals vs. Time for Subject D During 1.0 G Trial

Instantaneous Heart Rate vs. Time for Subject D During 1.0 G Trial

R-R Intervals vs. Time for Subject D During 1.5 G Trial

Instantaneous Heart Rate vs. Time for Subject D During 1.5 G Trial
Subject E

R-R Intervals vs. Time for Subject E During Control Trial

Instantaneous Heart Rate vs. Time for Subject E During Control Trial

R-R Intervals vs. Time for Subject E During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject E During 0.5 G Trial
R-R Intervals vs. Time for Subject E During 1.0 G Trial

Instantaneous Heart Rate vs. Time for Subject E During 1.0 G Trial

R-R Intervals vs. Time for Subject E During 1.5 G Trial

Instantaneous Heart Rate vs. Time for Subject E During 1.5 G Trial
Subject F

R-R Intervals vs. Time for Subject F During Control Trial

Instantaneous Heart Rate vs. Time for Subject F During Control Trial

R-R Intervals vs. Time for Subject F During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject F During 0.5 G Trial
Subject G

R-R Intervals vs. Time for Subject G During Control Trial

Instantaneous Heart Rate vs. Time for Subject G During Control Trial

R-R Intervals vs. Time for Subject G During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject G During 0.5 G Trial
Subject H

R-R Intervals vs. Time for Subject H During Control Trial

R-R Intervals vs. Time for Subject H During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject H During Control Trial

Instantaneous Heart Rate vs. Time for Subject H During 0.5 G Trial
Subject I

R-R Intervals vs. Time for Subject I During Control Trial

Instantaneous Heart Rate vs. Time for Subject I During Control Trial

R-R Intervals vs. Time for Subject I During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject I During 0.5 G Trial
R-R Intervals vs. Time for Subject I During 1.0 G Trial

Instantaneous Heart Rate vs. Time for Subject I During 1.0 G Trial

R-R Intervals vs. Time for Subject I During 1.5 G Trial

Instantaneous Heart Rate vs. Time for Subject I During 1.5 G Trial
Subject J

R-R Intervals vs. Time for Subject J During Control Trial

Instantaneous Heart Rate vs. Time for Subject J During Control Trial

R-R Intervals vs. Time for Subject J During 0.5 G Trial

Instantaneous Heart Rate vs. Time for Subject J During 0.5 G Trial
R-R Intervals vs. Time for Subject J During 1.0 G Trial

Instantaneous Heart Rate vs. Time for Subject J During 1.0 G Trial

R-R Intervals vs. Time for Subject J During 1.5 G Trial

Instantaneous Heart Rate vs. Time for Subject J During 1.5 G Trial
Plots of Heart Rate Averaged Over Intervals

The following plots display heart rate averaged over 30 s and 5 min. intervals. The vertical lines in the plots represent the onset or end of a stimulus.

Subject C

Heart Rate vs. Time for Subject C During Control Trial

Heart Rate vs. Time for Subject C During 0.5 G Trial
Heart Rate vs. Time for Subject C During 1.0 G Trial

Heart Rate (bpm)

Time (min)

Heart Rate vs. Time for Subject C During 1.5 G Trial

Heart Rate (bpm)

Time (min)
Subject D

Heart Rate vs. Time for Subject D During Control Trial

Heart Rate vs. Time for Subject D During 0.5 G Trial
Heart Rate vs. Time for Subject D During 1.0 G Trial

Heart Rate vs. Time for Subject D During 1.5 G Trial
Subject E

Heart Rate vs. Time for Subject E During Control Trial

Heart Rate vs. Time for Subject E During 0.5 G Trial
Heart Rate vs. Time for Subject E During 1.0 G Trial

Heart Rate vs. Time for Subject E During 1.5 G Trial

Time (min)

Heart Rate (bpm)
Subject F

Heart Rate vs. Time for Subject F During Control Trial

Heart Rate vs. Time for Subject F During 0.5 G Trial
Heart Rate vs. Time for Subject F During 1.0 G Trial

Heart Rate vs. Time for Subject F During 1.5 G Trial
Subject G

Heart Rate vs. Time for Subject G During Control Trial

Heart Rate vs. Time for Subject G During 0.5 G Trial
Subject H

Heart Rate vs. Time for Subject H During Control Trial

Heart Rate vs. Time for Subject H During 0.5 G Trial
Heart Rate vs. Time for Subject I During 1.0 G Trial

Heart Rate vs. Time for Subject I During 1.5 G Trial
Subject J

Heart Rate vs. Time for Subject J During Control Trial

Heart Rate vs. Time for Subject J During 0.5 G Trial

Heart Rate (bpm)

Time (min)

Heart Rate (bpm)

Time (min)

Heart Rate (bpm)

Time (min)
Heart Rate vs. Time for Subject J During 1.0 G Trial

Heart Rate vs. Time for Subject J During 1.5 G Trial
# Measured and Normalized Heart Rate Data

## Raw Data

### Descriptive Statistics

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<tr>
<th>Statistic</th>
<th>Sample Mean</th>
<th>Sample Standard Deviation</th>
<th>Sample Size</th>
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### Correlation Analysis

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### Regression Analysis

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### Statistics Based on Normalized HR

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### D-G HR Data

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Plots of Normalized Heart Rate

The vertical lines with arrows represent the initiation or cessation of a stimulus.
APPENDIX J

Suggested Artificial Gravity Research Program

The author feels that six categories of research are needed to answer the questions posed in Table 2: 1) computer modeling, 2) studies of simulated microgravity by bed rest or water immersion, 3) short-arm centrifuge studies, 4) long-arm centrifuge studies, 5) rotating room studies, and 6) experiments in space. Presumably, these levels would be carried somewhat out in order, but certain aspects, such as adaptation research, do not require completion of research at the previous level.

The importance of computer modeling was stressed previously. The BRC study only modeled the vestibular and cardiovascular systems. Available models for these systems on Earth and in spaceflight were utilized. Spaceflight models of the vestibular and cardiovascular systems are by no means satisfactory. As with all other aspects of AG physiological research, more knowledge about how the human body responds to microgravity is required. The next steps in the computer modeling area would be to incorporate the muscular, endocrine, and skeletal systems and run simulations of intermittent 1 G stimulation. Hopefully, this level of AG research will become advanced enough so that all studies will be modeled using this system before physical trials.

After a sufficient number of simulations are run with the computer model, trials of simulated microgravity by horizontal rest can begin. The primary purposes of this level of investigation are to ascertain what amount of 1 G stimulation the human body requires and to develop an optimum plan for 1 G exposure. The optimum plan would address issues of time of day, intermittence, and types of activities. Essentially, it would answer Questions 1-4 listed in Table 2. Two methods are available for simulating microgravity’s effects on earth: horizontal bed rest and dry immersion suspension in water. Vernikos, et al. recommend 4-day -6° head-down bed rest studies as an economical model for ground-based AG research at this level (1992). However, for studies that attempt to answer Question 5, bed rest durations on the order of months may be necessary. Vernikos’s experiments (see Appendix) supply an excellent base from which to undertake investigation. The next step is try different combinations of time periods and the actions of standing, walking, jumping, and upright bicycling.

Once the optimum stimulation plan for 1 G is defined, tests should commence to see if the total exposure time can be shortened by increasing the G level. The impetus for decreasing exposure time is reduce the amount of time astronauts must spend away from microgravity research in order to maintain their stamina. Tests with hyper-G would answer Question 6 and parts of Questions 7-9 in Table 2. The simplest method of increasing the G level on Earth is with a
SAC like the AGS. The USAFSAM also operates a 1.5 m rotating disk for research purposes of this nature. John Space Center hosts their own Artificial Gravity Simulator modeled after but larger than the MIT-AGS. NASA Ames Research Center in Moffett Field, CA operates an enclosed 1.8 m-radius centrifuge that is powered by pedaling from either two subjects or an unrelated person (Greenleaf, et al. 1995). Hopefully, research at this level will arrive at a new optimum stimulation plan, shorter in duration than the previous.

To see if removing the G gradient can improve even further on the optimum stimulation plan, long-arm centrifuge (LAC) studies should be performed after SAC studies. Question 10 in Table 2 will be answered then because only by removing the G gradient can its effects be seen. Approximately 24 LAC facilities are available around the world, 4 of which are located in the U.S. The U.S. centrifuges range in radius from 5.8 to 15.85 m (Burton, et al. 1991; Meeker 1985).

The last ground-based AG investigation level should be conducted in rotating rooms. This research is only necessary for a Mars mission if engineering and cost requirements dictate that the entire spacecraft must be spun to provide AG. However, in the eventuality that a rotating G environment for permanent habitability is provided in space, on the moon, or on Mars, these studies will be fundamental in determining the best ways to live in a rotating environment. Questions 10-14 in Table 2 are the primary physiological concerns for a rotating environment in which extended movement is allowed. A criticism of past rotating room studies, and of microgravity research on humans in general, is that it is unclear whether some effects are due to the rotation environment or confinement (Sandler 1995). Simple control studies of confinement of similar duration in a stationary room would nullify these concerns. While most of the rotating rooms utilized in the 1960's and 1970's have been dismantled, Brandeis University's Graybiel Laboratory and NASA Ames Research Center both currently operate rotating rooms.

The above outlined ground studies are will take many years even if the appropriate agencies recognize their need and immediately allocate funding. However, in a view also held by another researcher (Burton 1988), to attempt AG experiments in space before they are performed on the ground would be a waste of time, resources, and money. Once the technology is established in space, NASA could begin tests with the optimum stimulation plan without countless unnecessary trials. The purposes of the space-based research should only be to verify and modify ground results and help answer Questions 15-16 in Table 2. Space is also the only environment where partial gravity stimulation at the cellular level can be performed. Experiments in partial gravity for the sole purpose of physiological study could determine the answers to the second half of Questions 7-9.

Where should AG experiments be performed in space? Several design studies have confirmed that a SAC could fit in a payload bay Spacelab module (Meeker, et al. 1996; Pancratz, et al. 1994). However, the short duration of Shuttle missions and future access to a space station
make this idea experimentally unfavorable and economically unwise. Also, rotation of an entire space station is impractical because its primary purpose is to study the effects of microgravity. The current design for the international space station incorporates a 2.5 m-radius SAC capable of 0.01-2 G for animal experiments (Sandler 1995). It is not inconceivable that someday a module could be added to the station containing a SAC for human experiments. In addition, the National Commission on Space in 1986 recommended the construction of a Variable Gravity Research Facility (VGRF) in orbit for the purpose of establishing design parameters for long-duration space missions. This would be a free-flying mini-station for the sole aim of studying AG in space. Major design studies have already been performed for a VGRF (Smith, et al. 1990; Newton 1989).

Several other concerns regarding AG research need to be addressed. The physiological parameters that should be monitored at the 6 levels are numerous. The reader is referred to Newton (1989) for a detailed listing. It is important, though, that a broad spectrum of effects across all physiological systems be observed in each experiment. To not do so will lead to repetitions of costly trials. The study presented in this paper was a prelude to a bed rest study that will monitor more than the cardiovascular system. Another concern is how many and what kinds of subjects to use. For space experiments this question is answered easily since NASA and the Russian space program have the only control over who becomes an astronaut and who flies in space. For ground-based research, the answer is not so clear. For the experiments presented here, subjects were college age for the primary reason that they were the easiest accessible at an academic institution. However, most of the astronauts are twice college age. Additionally, it is strongly suggested that half of the subjects be male and half be female. Not only will this aid assessment of differences in stimulation response due to gender, but the current astronaut pool is moving toward the general population gender percentages. Also, not all subjects should have high previous exposure levels to stressful G environments, such as pilots. A more accurate reflection of the anticipated responses of the current astronaut pool will then result.

The research strategy presented does not include several parallel studies that should be conducted to fully understand AG. Habitability and performance requirements on rotating spacecraft are also critical to development of an AG design. Furthermore, it is not clear how they interrelate with the physiological responses to AG. Also, the importance of animal experiments in AG should not go unmentioned. They should be precursors to any experiments in space and as much ground-based research as possible. Interestingly, Cardús has suggested that research related to the physiological requirements of AG can help clinical medicine on Earth. NASA's Artificial Gravity Simulator was built partially to investigate how rotation can help patients of extended bed rest, fractured bones, osteoporosis, heterotopic calcification in paralysis, certain forms of pulmonary edema, and other diseases (1993a).
Finally, an educated prediction of the requirements for a Mars mission can be made based on current knowledge. Anticipating a round-trip duration of 2-3 years, a SAC may be able to provide adequate intermittent stimulation. The apparatus would have to be long enough (> 2 m in radius) to support movements such as jumping. The best stimulation plan may be to expose the astronauts to 0.38 G on the way out to Mars and to 1 G on the way back to Earth. Not only would emergency situations such as loss of orthostatic tolerance and bone fracture be prevented, but astronauts would then be pre-adapted to their next environment. The details, of course, will be provided by the conclusions of the recommended 6 levels of AG research.