ARTIFICIAL GRAVITY AS A TOOL IN BIOLOGY & MEDICINE

Study Group 2.2
International Academy of Astronautics
IAA STUDY GROUP 2.2: ARTIFICIAL GRAVITY AS A TOOL IN BIOLOGY & MEDICINE

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# Table of Contents

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Summary</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td>Motivation</td>
<td>2</td>
</tr>
<tr>
<td>Scope</td>
<td>2</td>
</tr>
<tr>
<td>Approach</td>
<td>2</td>
</tr>
<tr>
<td>Goals</td>
<td>2</td>
</tr>
<tr>
<td>Product</td>
<td>2</td>
</tr>
<tr>
<td>Background</td>
<td>2</td>
</tr>
<tr>
<td>Physiologic Deconditioning During Prolonged Weightlessness</td>
<td>2</td>
</tr>
<tr>
<td>Why Artificial Gravity?</td>
<td>4</td>
</tr>
<tr>
<td>History of Artificial Gravity</td>
<td>4</td>
</tr>
<tr>
<td>Continuous versus Intermittent</td>
<td>5</td>
</tr>
<tr>
<td>Research Program Realization</td>
<td>6</td>
</tr>
<tr>
<td>Continuous Artificial Gravity Questions</td>
<td>7</td>
</tr>
<tr>
<td>Intermittent Artificial Gravity Questions</td>
<td>7</td>
</tr>
<tr>
<td>Potential Tools for Investigation</td>
<td>8</td>
</tr>
<tr>
<td>Studies Using Human Subjects</td>
<td>8</td>
</tr>
<tr>
<td>Studies Using Animal Models</td>
<td>8</td>
</tr>
<tr>
<td>Non-Human Primates as Models for Human Artificial Gravity Exposure</td>
<td>9</td>
</tr>
<tr>
<td>Rats as Models for Human Artificial Gravity Exposure</td>
<td>9</td>
</tr>
<tr>
<td>Mice as Models for Human Artificial Gravity Exposure</td>
<td>11</td>
</tr>
<tr>
<td>Gravitational Biology as Beneficiary</td>
<td>11</td>
</tr>
<tr>
<td>Current Knowledge</td>
<td>11</td>
</tr>
<tr>
<td>Theoretical Considerations</td>
<td>11</td>
</tr>
<tr>
<td>Experimental Evidence</td>
<td>14</td>
</tr>
<tr>
<td>Space Experiments</td>
<td>14</td>
</tr>
<tr>
<td>Flight Animal Experiments</td>
<td>14</td>
</tr>
<tr>
<td>Human Space Experience with Artificial Gravity</td>
<td>14</td>
</tr>
<tr>
<td>Ground Centrifuge Experiments</td>
<td>15</td>
</tr>
<tr>
<td>Artificial Gravity Design Options</td>
<td>17</td>
</tr>
<tr>
<td>Recommendations</td>
<td>19</td>
</tr>
<tr>
<td>International Cooperation/Coordination</td>
<td>19</td>
</tr>
<tr>
<td>Ground-Based Studies</td>
<td>19</td>
</tr>
<tr>
<td>Flight Validation and Operations</td>
<td>23</td>
</tr>
<tr>
<td>Key Artificial Gravity References</td>
<td>24</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

International Academy of Astronautics Study Group 2.2 on the subject of artificial gravity was commissioned to develop a position of the Academy on the research steps necessary to realize an effective artificial gravity countermeasure. The first meeting of the Study Group was held during the International Astronautics Federation (IAF) meeting in Vancouver, Canada on October 5, 2004, with 16 interested participants, and the second meeting was held in Graz, Austria on May 24, 2005 during the Humans in Space Conference, with 20 interested participants. The final report review was completed at the IAF meeting held in Fukuoka, Japan on October 18, 2005.

The scope of the Study Group 2.2 activities and report covers the key questions that need to be answered to make artificial gravity a practical countermeasure, the facilities and flight opportunities required to answer these questions, and a progression of activities to accomplish the research project. Experimental models considered include human and animal experiments on Earth and in space using short-radius intermittent centrifugation and/or long-radius continuous rotation. The starting point for the study was the set of questions and recommendations reported by the 1999 Artificial Gravity Workshop held in League City, Texas, USA. Current programs and plans for artificial gravity research within the member agencies and organizations also were considered.

The goals of this study were to recommend research models, venues, and approaches aimed at reducing the uncertainty in the questions of how to produce artificial gravity (spin rate, intermittent versus continuous, G gradient, etc.), determine the likely effectiveness and acceptability of artificial gravity as a countermeasure, and to consider the design implications for a space mission using artificial gravity. If the recommended program of artificial gravity facility development and accompanying research is carried out, we will be able to inform managers and mission designers as to the specific artificial gravity requirements and their costs and benefits for any given mission scenario.
INTRODUCTION

Motivation

The recent U.S. announcement of a Vision for Space Exploration involving long-duration flights to Mars, coupled with the current absence of effective countermeasures, has drawn increased attention to artificial gravity. The most serious threats to long-duration flight involve radiation, behavioral stresses, and physiologic deconditioning. Artificial gravity has the potential to fully mitigate the last of these risks by preventing the adaptive responses from occurring, but is not likely to have significant impact on any of the other threats.

Scope

The scope of the Study Group activities and report covered the key questions that need to be answered to make artificial gravity a practical countermeasure, the facilities and flight opportunities required to answer key questions, and a timeline or schedule to accomplish the research project. Human and animal experiments, on Earth and in space, were considered for both short-radius intermittent centrifugation and long-radius continuous rotation paradigms.

Approach

The starting point for the study was the set of questions and recommendations reported at the international 1999 Artificial Gravity Workshop held in League City, Texas (Paloiski & Young 1999). Current programs and plans for artificial gravity research also were reviewed.

Goals

The goals of this Study Group were: 1) to assess the state of current knowledge concerning the requirements and effectiveness of artificial gravity, 2) to plan appropriate human ground-based studies to identify the usable parameter space for artificial gravity and to develop a preliminary prescription for artificial gravity countermeasures in space, 3) to plan synergistic animal studies where appropriate, 4) to plan for a transition from ground studies of artificial gravity to flight investigations with animals and humans, and 5) to make early recommendations about the relative merits of intermittent versus continuous rotation approaches. The Study Group anticipates that the suggested program of research will lead to determination of desired parameters for centrifuge design (radius and angular velocity) and for applying an artificial gravity countermeasure (G level, G gradient, angular velocity, frequency, duration, and synergistic countermeasures).

Product

The final product is the set of recommendations contained within this report for artificial gravity ground and flight research. These recommendations will be transmitted to the Academy via a written report and a special session to be presented at a future IAF meeting.

BACKGROUND

Physiologic Deconditioning During Prolonged Weightlessness

For human space voyages of several years’ duration, such as those envisioned for exploration of Mars, crews are at risk of catastrophic consequences should the systems that provide adequate air, water, food, and thermal control fail. Beyond that, crews will face serious health and/or safety risks resulting from radiation exposure en route and on some extraterrestrial surfaces, behavioral issues associated with the prolonged isolation and confinement, and severe physiologic deconditioning associated with prolonged weightlessness. The principal physiologic deconditioning risks are related to physical and functional deterioration of the skeleton and muscles, loss of regulation of the blood circulation, decreased aerobic capacity, and altered sensory-motor performance. These physiologic effects
of weightlessness are generally adaptive to spaceflight and present a hazard only upon return to Earth or landing on another planet (Young 1999). However, they may present hazards in flight in the event of a bone fracture, alterations in the heart’s rhythm, development of renal stones, or sensory-motor performance failure during piloting, EVA, or remote guidance tasks.

Bones are living tissue, constantly being strengthened by dietary calcium extracted from the blood and destroyed by returning calcium to the blood for excretion. Bone maintenance requires a compressive load along the axis of the bone and some high-force impulsive loading. In the absence of these loads, which are normally provided by gravity and walking, the major bones that support body weight begin to deteriorate and a net loss of body calcium occurs, independent of the amount taken in with food or supplements. The long bones in the legs and the vertebrae in the spine lose size and strength during prolonged bed rest. Similarly, they lose strength during prolonged spaceflight. Calcium is lost at a rate of about 1.0% to 1.5% per month, and the losses are reflected in the density and size of weight-bearing bones. For a spaceflight of 2 years, a 40% decrease in bone size might occur (unless the process reaches a plateau), thus increasing the risk of fracture and possibly severely hampering the bone’s ability to mend.

Muscles involved in weight bearing also begin to weaken with disuse in a weightless environment, losing both strength and endurance as a function of time in flight. The major muscle groups in the legs and back that normally support weight loss mass are also “reprogrammed,” so that fibers previously devoted to slow, steady tension are used for brief bursts instead.

Cardiovascular deconditioning begins with the shifting of fluid from the legs and lower trunk to the head and chest immediately upon insertion into orbit. This produces the first symptoms of fullness of the head and associated discomfort on orbit and initiates an early loss of body fluid, including blood plasma. The relative excess of red blood cells is countered by stopping their production in the bone marrow and additionally by destroying young red blood cells. The cardiovascular regulating system that acts to maintain adequate blood pressure when we stand up is no longer needed in space and shows signs of deterioration. Neither the fluid loss, with resulting “space anemia,” nor the loss of cardiovascular regulation and tone normally cause any difficulties in orbit. During reentry and back on Earth, however, the renewed exposure to gravity can cause weakness and fainting. In addition, cardiovascular fitness is compromised during flight, resulting in a diminished maximum oxygen consumption capability during exercise.

Sensory-motor deconditioning begins in a weightless environment with the loss of gravitational stimulation of the inner ear (otolith), skin, and body sense (proprioceptor) receptors. The balance system that keeps humans from falling depends on the detection of gravity by these sensors. Because the only stimulus to the organs in a weightless environment is linear acceleration, considerable reinterpretation of vestibular signals may take place, and new sensory-motor strategies must be developed. A consequence of this process is the common occurrence of space sickness early in flight, and postural disturbances and vertigo after return.

Immune system function also may be compromised by spaceflight, reducing the ability to fight infection. The degree to which weightlessness plays a role in this is currently unknown.

Human-factor problems also arise in a weightless environment, including the constant need for handholds or footholds for stabilization and the possibility of disorientation within a spacecraft. Waste management, fluid handling, food preparation, and hygiene are but a few of the human factors issues present in weightless operations. However, these problems are often balanced by
the ease of moving heavy objects, the use of three-dimensional space, and the sheer pleasure of floating in a weightless environment.

**Why Artificial Gravity?**

Space biomedical researchers have been working for many years to develop “countermeasures” to reduce or eliminate the deconditioning associated with prolonged weightlessness. Intensive and sustained aerobic exercise on a treadmill, bicycle, or rowing machine coupled with intensive resistive exercise has been used on U.S. and Russian spacecraft to minimize these problems. The procedures were uncomfortable and excessively time-consuming for many astronauts, and their effectiveness for maintaining bone, muscle, and aerobic fitness have not been demonstrated, owing, at least in part to the low reliability of the devices flown to date. Furthermore, they have had inconsistent effects on postflight orthostatic hypotension or sensory-motor adaptive changes. With the exception of fluid loading before reentry, other kinds of countermeasures (e.g., diet, lower body negative pressure, or wearing a “penguin suit” to force joint extension against a resistive force) have been either marginally effective or present an inconvenience or hazard.

To succeed in the near-term goal of a human mission to Mars during the second quarter of this century, the human risks associated with prolonged weightlessness must be mitigated well beyond our current capabilities. Indeed, during nearly 45 years of human spaceflight experience, including numerous long-duration missions, research has not produced any single countermeasure or combination of countermeasures that is completely effective. Current operational countermeasures have not been rigorously validated, and have not fully protected any long-duration (>3 month) crews in low-Earth orbit. Thus, it seems unlikely that they will adequately protect crews journeying to Mars and back over a 3-year period.

Although improvements in exercise protocols, changes in diet, or pharmaceutical treatments of individual systems may be of value, they are unlikely to adequately eliminate the full range of physiologic deconditioning. Therefore, a complete research and development program aimed at substituting for the missing gravitational cues and loading in space is warranted.

The urgency for exploration-class countermeasures is compounded by the limited availability of flight resources for performing the validation of a large number of system-specific countermeasure approaches. Furthermore, recent evidence of rapid degradation of pharmaceuticals flown aboard long-duration missions, putatively because of radiation effects, raises concerns regarding the viability of some promising countermeasure development research. Although the rotation of a Mars-bound spacecraft will not be a panacea for all the human risks of spaceflight (artificial gravity cannot solve the critical problems associated with radiation exposure, isolation, confinement, and environmental homeostasis), artificial gravity does offer significant promise as an effective, efficient multi-system countermeasure against the physiologic deconditioning associated with prolonged weightlessness. Virtually all of the identified risks associated with bone loss, cardiovascular deconditioning, muscle weakening, neurovestibular disturbances, space anemia, and immune compromise might be alleviated by the appropriate application of artificial gravity.

**History of Artificial Gravity**

The notion of creating a substitute for gravity through centrifugation was introduced early in the conception of human space travel. Tsiolkovsky, the influential Russian space visionary, discussed the idea in 1911, and his concepts were picked up 50 years later by Korolev, who designed a flexible tether system for the Voskhod manned missions (Harford 1973), which was never built. A detailed engineering proposal for
an artificial gravity station was introduced by Noodung in 1928, a full 30 years before the first satellite was launched. When von Braun described his vision of space exploration in 1953, he included a large rotating torus to deal with weightlessness (von Braun 1953).

The popularization of artificial gravity, however, is attributable to the science fiction community. The large rotating torus in Kubrick’s “2001: A Space Odyssey” presented an idealized version of life in space, free of health problems and the negative effects usually associated with transiting from the rotating to the stationary parts of the station.

By 1965, preliminary tests on a short-radius centrifuge first showed that subjects who were deconditioned by bed rest could be protected against cardiovascular deconditioning by periodic centrifugation (White et al. 1965). Experience with artificial gravity in space has been quite limited. Rats were centrifuged continuously at 1 G for several days and showed no deconditioning. Human experiments, however, have not been conducted to date. Early attempts to test artificial gravity by tethering a Gemini spacecraft to an Agena rocket were inconclusive and nearly led to disaster when the thruster nozzle stuck on Gemini 8, sending the pair of space vehicles into an uncontrollable spin.

The planned 2.5-meter radius centrifuge on the International Space Station (ISS) would afford the opportunity to examine the adequacy of various levels of artificial gravity in protecting rodents during spaceflight. The study group feels that it would be very unfortunate if this centrifuge, which is the heart of the gravitational biology flight program, were to be eliminated from the ISS program. Not only is it essential for basic research, but it forms the basis for understanding the physiologic effects of short-radius artificial gravity in a manner needed for effective human artificial gravity prescription.

Continuous versus Intermittent

The surest artificial gravity solution is clearly one that produces a gravito-inertial environment close to that on Earth. This would require a long-radius (~500 to 1000 meters) rotating vehicle, similar perhaps to the von Braun rotating torus. However, the cost and size of such a vehicle would likely be excessive and the implementation of 1 G with little G gradient may be
unnecessary. Instead, medium-radius (~10 to 100 meters) and short-radius (~2 to 10 meters) vehicles/centrifuges seem more feasible. [Note that a clear consensus definition of short, medium, and long-radius centrifuges has not yet been achieved. Apart from radius, the definition might include G gradient (>0.1 G/m = short, 0.1-0.01 G/m = medium, and <0.01 G/m = long) or subject mobility (short = subject immobile (strapped in or otherwise constrained), long = subject completely free to move about, medium = either).]

The best technique for implementing artificial gravity in space can only be determined after weighing a complex set of trade-offs among vehicle design/engineering costs, mission constraints, countermeasure efficacy and reliability requirements, and vehicle environmental impacts. For example, from a physiologic countermeasure perspective, a good solution might be to provide artificial gravity continuously throughout the mission by spinning the crew compartment at a G amplitude sufficient to replicate terrestrial stresses on the bone, muscle, cardiovascular, and sensory-motor systems (approximately 1 G), an angular velocity low enough to have minimal impacts on vestibular system responses, sensory-motor coordination, and human factors (< 4 rpm), and a radius sufficient to minimize the G gradient effects on cardiovascular loading (currently unknown). However, the benefits of this solution, which include reduced or eliminated physiologic adaptation in-transit (bone, muscle, cardio, neuro ...), improved human factors in-transit (spatial orientation, WCS, galley ...), improved medical equipment/operations (countermeasures, surgery, CPR, ...) , and improved habitable environment (particulates, liquids, ...), would need to be weighed against the risks/uncertainties, which include engineering challenges (requirements, design: truss, fluid loops, propulsion ...), human factors issues during spin-up/down, and physiologic adaptation during spin-up/down (neuro, cardio, ...). So, while a feasible design has been put forward for a vehicle that will achieve the physiologic design goals (Joosten 2002), the full set of trade-offs cannot be evaluated until after further physiologic research and vehicle design concept evaluations have been completed.

Should the risks/uncertainties outweigh the benefits for feasible continuous artificial gravity solutions in space, an alternative approach would be to provide intermittent artificial gravity (likely combined with exercise) by spinning crewmembers periodically aboard a centrifuge within the habitable environment. From a physiologic countermeasure perspective, this solution would likely provide periodic artificial gravity at a G amplitude substantially higher than terrestrial stresses on the bone, muscle, cardiovascular, and sensory-motor systems (perhaps in the range of 2 to 3 G), an angular velocity high enough to effect vestibular system responses, sensory-motor coordination, and human factors (perhaps in the range of 20 to 30 rpm), and radii short enough to create substantial G gradients (perhaps in the range of 50% to 100%). While not expected to be as efficient a solution from a physiologic standpoint, it may prove effective, and the engineering costs and design risks might be lower.

Note that the physiologic responses to continuous Mars G exposure are unknown. Indeed, the physiologic responses to continuous exposure to anything other than 1 G are unknown. If it turns out that substantial physiologic adaptation/deconditioning occurs at Mars G, then artificial gravity may be required to protect crews during long stays on the surface of Mars. The only feasible implementation on a planetary surface would be intermittent artificial gravity.

RESEARCH PROGRAM REALIZATION

Participants at the 1999 League City Workshop drafted a set of critical questions to be answered by a broad artificial gravity research program. This list has been updated as follows in light
of recent research and the likely uses of artificial gravity for a Mars mission:

**Continuous Artificial Gravity Questions**

1. What level of continuous artificial gravity exposure is required to maintain acceptable crew health and performance during transit to Mars?
   a. What is the “trade space” of continuous artificial gravity (radius, angular velocity) that leads to effective protection of crews against bone, muscle, cardiovascular, and sensory-motor deconditioning?
   b. What are the physiologic boundaries of the trade space within which crew health and performance are acceptable (re: disorientation, motion sickness and malcoordination caused by cross-coupling and/or Coriolis forces)?
   c. What are the human factors performance limits on the trade space for continuous artificial gravity to avoid unacceptable constraints on crew performance (re: exercise, ambulation, material handling, extra and in-travehicular activities, etc.)?
   d. What are the severities and time courses of the physiologic consequences associated with onset (spin-up) and offset (spin-down) of continuous artificial gravity on a rotating transit vehicle (re: sensory-motor adaptation, orthostatic hypotension, fluid shifts, etc.)?
   e. What operational restrictions should be placed on crewmembers during these spin-up and spin-down phases?
2. What is the impact of continuous artificial gravity on human responses to other spaceflight environmental factors or independent countermeasures?
   a. Is the physiologic response to radiation exposure changed by continuous artificial gravity?
   b. Is the physiologic response to altered light/dark cycles changed by continuous artificial gravity?
   c. Is the behavioral response to spaceflight changed by continuous artificial gravity?
   d. Does continuous artificial gravity have other secondary effects on wound healing, immune response, or pharmacologic response?
   e. Are other countermeasures independent of or synergistic with continuous artificial gravity exposure?

3. What additional countermeasures are required to supplement continuous artificial gravity exposure to form an integrated countermeasure prescription during a flight to Mars?

4. How would human factors issues be affected by continuous artificial gravity designs?

5. What are the impacts of the trade space on vehicle or mission design?

**Intermittent Artificial Gravity Questions**

1. What level of intermittent artificial gravity exposure is required to maintain acceptable crew health and performance during transit to Mars or surface operations upon Moon or Mars?
   a. What is the “trade space” of intermittent artificial gravity (radius, angular velocity, G level, G gradient, duty cycle) that leads to effective protection of crews against bone, muscle, cardiovascular, and sensory-motor deconditioning?
   b. Would intermittent artificial gravity exposure be required on the lunar or Martian surface?
   c. What are the physiologic boundaries of the trade space within which crew health and performance are acceptable (re: G load, G gradient, disorientation and motion sickness caused by cross-coupling, etc.)?
   d. What are the human performance factors limits on the trade space for intermittent artificial gravity to avoid unacceptable
constraints on crew performance (re: disorientation and malcoordination caused by cross-coupling and/or Coriolis forces)? How does the transition onto and off the centrifuge influence the astronaut’s performance and sense of well-being?

e. What are the severities and time courses of the physiologic consequences associated with onset and offset of intermittent artificial gravity (re: sensory-motor adaptation, orthostatic hypotension, fluid shifts, etc.)?

f. What operational restrictions should be placed on crewmembers during the onset and offset phases?

2. What is the impact of intermittent artificial gravity on physiologic responses to other spaceflight environmental factors or independent countermeasures?

a. Is the physiologic response to radiation exposure changed by intermittent artificial gravity?

b. Is the physiologic response to altered light/dark cycles changed by intermittent artificial gravity?

c. Does intermittent artificial gravity have secondary effects on wound healing, immune responses, or pharmacologic responses?

d. Are other countermeasures independent of or synergistic with intermittent artificial gravity exposure?

3. What additional countermeasures are required to supplement intermittent artificial gravity exposure to form an integrated countermeasure prescription during transit or surface operations?

4. What are the impacts of the trade space on vehicle or mission design?

**Potential Tools for Investigation**

The difficulty and expense of spaceflight experiments or feasibility demonstrations mandate the appropriate use of ground facilities to design and test artificial gravity concepts.

**Studies Using Human Subjects**

Human subjects must be used for artificial gravity development and testing, supplemented where appropriate by animal experiments. Human studies are essential to consider the unique aspects of the upright biped, especially with respect to cardiovascular implications of gravity gradient. Furthermore, human factors issues, essential to the success of artificial gravity in flight, can only be worked out with human subjects.

Deconditioning Models: Analog environments to simulate the effects of weightlessness on long-duration physiologic deconditioning have been studied for many years. The most adequate human model appears to be bed rest, with head tilted down by 6 degrees. Another possible alternative is dry immersion. Analog patient populations and human 1-leg suspension may have limited utility for certain studies.

Ground Facilities: Short and medium-radius centrifuges, as well as slow rotating rooms all have their roles.

Flight Facilities: Short-radius centrifuges small enough to fit into a Shuttle mid-deck or in the ISS are feasible. Later flight accommodations could consider the crew exchange vehicle, or a lunar habitat centrifuge.

**Studies Using Animal Models**

Animal studies would provide a useful adjunct to the human studies for the following principal reasons. First, animal tests will reduce the total numbers of human subjects needed, and thereby make schedule and cost targets achievable. Both cost per subject and schedule-associated costs are far lower using animals compared to humans. Animal tests cannot fully replace human tests; however, animal tests can achieve a total reduction in numbers of human subjects needed by replacing or eliminating select human tests. Furthermore, the large sample size possible
using animals to test artificial gravity regimens yields results with less scatter (lower error), and thus improves the basis for drawing definitive conclusions regarding success or failure of the test conditions. Modeling on the basis of a well-defined set of animal responses allows extrapolation from a limited data set derived from human subjects. Finally, tests with animals can include invasive telemetry, hazardous procedures, and post-mortem tissue analysis to define artificial gravity prescriptions.

**Non-Human Primates as Models for Human Artificial Gravity Exposure**

The rhesus monkey provides a biomedical model with close phylogenetic ties to humans. Rhesus monkeys have served as subjects in spaceflight experiments, most notably in the Cosmos/Bion series of Russian Bioflights. They have been used in the study of the responses of numerous physiologic systems to alterations in the gravitational environment. Rhesus monkeys have been the subjects of studies on the effects of exposure to a weightless environment on thermoregulation, immune responses, musculoskeletal system, cardiovascular system, fluid balance, sleep, circadian timing, metabolism, and neurovestibular/neurosensory and psychomotor responses.

Other primate models used in spaceflight experiments have included squirrel monkeys, capuchins, chimpanzees, cynomolgous monkeys, and pig-tailed macaques. While many of these flights were of short duration, a pig-tailed macaque was studied for 8 days on the Biosatellite III mission and 2 rhesus monkeys were studied on Bion flights that ranged in duration for 5 to 14 days.

In ground-based studies, rhesus have served as subjects in experiments using the weightless models head-down tilt (bed rest) and dry immersion as well as experiments in artificial gravity produced via centrifugation, both chronic and intermittent. The systems examined in many of these studies have paralleled those examined during spaceflight.

The rhesus monkey confers many advantages as a model system in the field of artificial gravity. First and foremost, the rhesus monkey is the most widely accepted biomedical non-human primate model for the human. Secondly, the rhesus has a bipedal upright posture, and thus experiences the ambient force environment along the same body axes as the human. Third, the reproductive cycling of the female rhesus is menstrual, similar to humans, and in contrast with virtually all other biomedical models. Fourth, the cognitive abilities of the rhesus monkey allow the use of psychomotor testing to discern the effects of artificial gravity on neurovestibular physiology, performance and behavior. Finally, the larger size of the rhesus also allows for collection of larger tissue samples and provides the ability for simultaneous measurement of multiple physiologic and behavioral factors.

**Rats as Models for Human Artificial Gravity Exposure**

Rats also offer a number of advantages as a model system for artificial gravity countermeasure development. Because of small body size they are especially well suited to the initial exploratory studies where many permutations of G level, rotational rate, and duty cycle will be explored. With modest caging and care requirements, higher numbers of subjects can be accommodated to increase the statistical power of analyses. Rats, unlike primates, do not require special isolation or quarantine procedures. Rats readily adjust to centrifugation and since they also can be used in hind-limb immobilization and tail-suspension studies, they can also serve as models for deconditioning. Rats are the most commonly used biomedical research model, and thus a great deal is known about their normal physiology, including characteristics of well-established strains. The relative uniformity of specific strains also presents fewer of the confounding factors that are typical of human
studies, so studies are likely to be both easier to interpret and to repeat.

Previous centrifugation and suspension studies also provide a baseline against which artificial gravity protocols can be evaluated. Similarly, rats can be used in exercise studies of metered activity using running wheels or treadmills. However rats provide opportunities for more invasive or terminal procedures that would not be possible with human subjects. Rats can be used for studies involving both acute and chronic implantation, including use of catheters, electrodes and telemetry. When fully implanted, these also provide the means for completely hands-off data collection, including monitoring of blood pressure and flow, ECG and heart rate, as well as temperature and activity. Rats also can provide repeated samples of fluids such as blood or urine. Postmortem tissue sampling is easily accomplished and at considerably less expense than alternates such as non-human primates. The short generation time and rapid development of rats also lend themselves to developmental studies. Further, the time scale of some changes, for example muscle wasting in a weightless environment or hind-limb unloading is more rapid than in humans, thus shorter and multiple studies could be accomplished in the same time frame using rats.

Rats are also relatively well studied in a weightless environment, and share the advantages of other non-human spaceflight subjects in not having conflicting schedules and operational duties to confound experimental findings. Thus rats have been important in contributing to our understanding of spaceflight changes in musculoskeletal, neurovestibular, immune, developmental, cardiovascular, and metabolic physiology. Rats flown on the Russian Bion biosatellite also have provided the only inflight evidence for the efficacy of 1 G centrifugation in preventing many of the degenerative changes seen in a weightless environment. Since rats have been among the few species studied in both microgravity and hypergravity, they have provided rare evidence for the direct scaling of many physiologic changes with G level, both above and below the terrestrial level. Validation of artificial gravity countermeasures in space-flight will almost certainly begin with rodent studies, since habitats and a flight centrifuge are in development for use with rats and mice. With no human-rated centrifuge being flown in the foreseeable future, initial flight studies using artificial gravity for full 1 G replacement or conditioning to partial G (Moon, Mars) will necessarily be performed with rodents.

Rats are not without disadvantages, however. Their small body size, relative to rhesus monkeys for example, imposes limits on how much instrumentation, including telemetry, can be used in a given animal. Small body size also means that smaller blood and urine volumes are available, especially in the case of repeated sampling. Unlike rhesus, which sit for most of the time in an upright posture, rats are quadrupedal and thus the acceleration vector in both normal gravity and during centrifugation is from dorsal to ventral rather than from head to foot. Consequently, fluid shifts and muscle loading necessarily differ from bipeds. Weight is also distributed among 4 limbs rather than being principally borne on 2 limbs. Rats also differ from both rhesus and humans in being nocturnal, which reverses the relationship of certain endocrine cycles, notably that of melatonin, to that seen in diurnal species.
including rhesus and humans. In addition, rats have poorly consolidated circadian cycles, including sleep and wake. Rats, thus, are not ideal models for human sleep and circadian rhythms. Rats also are estrous in their reproductive cycle. Finally, although much is known about the physiology of rats, some responses do not match those of humans, limiting their utility for some studies.

**Mice as Models for Human Artificial Gravity Exposure**

Like rats, mice are small, easily managed and have short generation times. Being even smaller than rats makes it easy to increase sample sizes and reduces required maintenance, thus making mice more cost-efficient. Generation and maturation times are further reduced from rats and thus mice may be more suitable for some developmental studies. More so than rats, genetically defined strains are seeing increased use in biomedical research with the benefit of reduced variability in studies because of differences between subjects. Numerous genetically manipulated strains have been developed with specific properties making mice uniquely suited for detailed examination of mechanisms and pathways. These include a large number of transgenic, knock-in and knock-out strains, including several with deficient vestibular pathways for G sensing. Since many mouse and human genes are homologous, mice are well-established models for many physiologic mechanisms in humans. For example, the mouse has been especially useful in immunologic studies. Mice are good candidates for centrifuge studies and have been used successfully in the past. They have also been used in hind-limb unloading studies. Like rats, they are candidates for spaceflight and validation of artificial gravity countermeasures since ISS modules and the animal centrifuge are installed. However, mice share some of the disadvantages of rats as experimental subjects, with smaller body size further aggravating many of these. Their ability to tolerate implants and telemetry is further reduced, as is the available quantity of tissues and fluid for sampling. Like rats they are nocturnal and possess somewhat poorly consolidated circadian rhythms. Since mice have a more objectionable odor than rats, their acceptance as flight animals is also impaired. Also, since not all of their physiologic responses parallel those of humans, they may not be the best model for some studies, and this will need to be evaluated on a case-to-case basis.

**GRAVITATIONAL BIOLOGY AS BENEFICIARY**

The existence of an artificial gravity research program, including an inflight centrifuge, would provide important opportunities for gravitational biology to attack several critical problems. All of biology on Earth has both evolved and developed in 1 G. We are largely ignorant of the importance of gravity on development, and experiments have been limited to 0 G testing on a limited number of species. Almost nothing is known about the effectiveness of lower G levels, between 0 and 1, and behavior at the cellular, organ or whole animal level. The existence of partial gravity for extended periods, as envisioned for the ISS flight centrifuge for example, provides a vital research tool for gravitational biology. It would add immeasurably to the value of the artificial gravity flight program.

**CURRENT KNOWLEDGE**

**Theoretical Considerations**

Artificial gravity is not gravity at all; it is an inertial force. However, in terms of artificial gravity’s action on any mass, it is indistinguishable from gravity. Instead of gravitational pull, artificial gravity exerts a centrifugal force, proportional to the mass that is being accelerated centripetally in a rotating device. Although the effect of artificial gravity on an extended body differs from that of true gravity, the effects on any given mass are equivalent. Thus artificial gravity is simply the imposition of acceleration
Artificial Gravity as a Tool in Biology & Medicine

on a body to recover the forces that are eliminated by the free fall of orbital flight.

In principle, artificial gravity could be provided by various means. A continuously thrusting rocket that accelerated a spacecraft halfway to Mars would generate artificial gravity equal to the acceleration level. Intermittent impulsive artificial gravity would be imposed on an astronaut who jumps back and forth between two opposing trampolines or even between two stationary walls in a spacecraft. However, the term artificial gravity is generally reserved for a rotating spacecraft or a centrifuge within the spacecraft. Every stationary object within the centrifuge is forced away from the axis of the rotation with a force proportional to its distance from the center of rotation and the square of the angular velocity of the device.

The envelope of operation for artificial gravity is limited by several factors, as pointed out by von Braun and adapted by others. The “comfort zone” for artificial gravity is bounded by many factors.

The minimum gravitational level, normally measured at the rim of a centrifuge, is the key parameter in the design space. The limited animal tests in orbit confirm that continuous rotation to yield 1 G at the feet of a small rodent is sufficient to maintain normal growth. However, it remains to be determined whether a lesser G level will suffice. Based on centrifuge studies of long duration, Russian scientists suggest that the minimum level of effective artificial gravity is about 0.3 G and recommend a level of 0.5 G to increase a feeling of well-being and normal performance (Shipov et al. 1981).

The maximum gravitational acceleration level also is a factor if short-radius intermittent artificial gravity is used. Levels up to 2 G at the feet are probably useful, especially if combined with exercise. Passive, 100% G gradient levels as high as 3 to 4 G at the feet are tolerable for more than 90 minutes in most subjects (Piemme et al. 1966). Active (bicycling) exercise on the Space Cycle is well tolerated from a hemodynamic perspective at G levels up to 3 G at the feet (Caiozzo et al. 2004).

The maximum angular velocity of the artificial gravity device is limited by the Coriolis forces encountered when walking or when moving objects, and by the motion sickness and disorientation experienced with certain kinds of head movements. Coriolis accelerations are real inertial accelerations that occur when moving within a rotating framework. Any movement in a straight line with respect to the rotating frame, except for one parallel to the axis of rotation, is in fact a curved motion in inertial space. The curve reflects acceleration sideways and entails a sideways inertial reaction force.

People trying to walk radially outward on a spinning carousel will feel a surprising force pushing them sideways, parallel to the circumference. As seen by an observer stationed outside the carousel, the walker’s path is really curved in the direction of the carousel’s spin. The sideward inertial acceleration requires a sideward force (Coriolis), according to Newton’s second law, and the subjects need to apply that unexpected force to avoid walking a path that is curved relative to the carousel. They also must apply an unexpected postural reaction to avoid falling over.
Additionally, anyone trying to walk along the rim of the artificial gravity spinning vehicle in the direction of the spin is subject to an unexpected radial inertial acceleration inward, which entails a downward Coriolis force, making the space walker feel heavier. If the astronaut were to turn around and walk along the rim in the direction opposite to the spin, the Coriolis force would be upward and the apparent weight of the astronaut would be reduced. From considerations of human factors, the Coriolis accelerations should be kept to less than some fraction of the artificial gravity level. Stone (1970) suggests that this be no higher than 1/4. The minimum rim velocity is limited only by the need to maintain enough friction for locomotion when walking against the direction of spin. For walking, Vmax is about 1 m/s, and it has been assumed that the estimated minimum rim velocity is 6 m/s.

The most disturbing aspect of artificial gravity rotation is probably the cross-coupled angular accelerations detected by the semicircular canals in the vestibular systems of the inner ear. The organs function to detect angular velocity of the head relative to inertial space for most normal head movements. However, because of their mechanical structure, they fail to register long-lasting constant velocity motion and, instead, indicate that one is stationary in a turn that lasts more than 10 to 20 seconds. In artificial gravity, these vestibular signals are apparently inconsistent with what one sees in the spacecraft and also with the linear acceleration registered by the otolithic organs in the labyrinth. This conflict, before adaptation, produces both motion sickness and spatial disorientation.

When subjects in artificial gravity move their heads about an axis that is not parallel to the spin axis, 2 unexpected angular accelerations occur. First, during the head movement a “cross-coupled angular acceleration” occurs, equal to the product of the spin rate and the head angular velocity that produces transient acceleration about a third orthogonal axis. Second, when the head is turned, the spin angular velocity is moved from one head plane to another, producing a sensation of deceleration about the first axis and acceleration about the second one. A sensation of rotation with components around both axes usually occurs for up to 10 seconds, as the semicircular canals return to their neutral position. The directions of both the Coriolis force and the cross-coupled angular accelerations depends on the direction the subject is facing in the rotating spacecraft, as well as the direction of head movement, thereby complicating the process of general adaptation to the unusual environment.

All of the unexpected sensations are proportional to the artificial gravity spin rate. Although further adaptive schedules might increase the tolerable rate, the maximum spin rate for continuous rotation has been estimated at 6 rpm, with possible elevation to 10 rpm. Almost all subjects can adapt quickly to work in a 2 rpm rotating environment. It is believed that most could tolerate increased rotational rates to 6 to 10 rpm, providing that they are built up slowly in steps of 1 to 2 rpm with a period of 12 to 24 hours at each increment (NASA 1970).

The gravity gradient refers to the change in artificial gravity level with radius and can affect both physiologic function and the ease of handling materials in space. Since the “G
level” is proportional to the radius, the gravitational gradient from head to foot is simply the ratio of height to radius: gradient = h/R. For continuous rotation at smaller radii, comparable to the astronaut’s height, the gravitational gradient may become more of a problem. For a 2-meter astronaut, the radius would be at least 4 meters for a 50% maximum gradient.

**EXPERIMENTAL EVIDENCE**

**Space Experiments**

Despite the long-standing interest in artificial gravity, experimental evidence from space is very limited. Only two space missions early in the space program were devoted to animal studies, and all of the human inflight results were anecdotal.

**Flight Animal Experiments**

The Soviet space research community expressed an early and intense interest in artificial gravity and, in 1961, began testing rats and mice in the 25-second weightless periods of parabolic flight. Animal locomotion appeared normal during these brief periods if they were housed in a centrifuge producing at least 0.3 G, thus suggesting this as a minimum G requirement (Yuganov 1964). The first animals to be centrifuged in space were on the Cosmos 782 mission in 1975, when fish and turtles centrifuged at 1 G were found indistinguishable from their ground controls. Furthermore, turtles centrifuged at levels as low as 0.3 G showed none of the muscle wasting typical of weightless. A much more extensive investigation was carried out on rats centrifuged during the 20-day mission of Cosmos 936 in 1977. These animals, housed in a small-radius (32 cm), high-speed (53.5 rpm) 1 G centrifuge, showed deficits in equilibrium and postural control postflight, consistent with the observed reduction in vestibular sensitivity. Faring less well than their ground controls, they also failed to counter fully the usual effects of weightlessness on loss of muscle and bone, circumstances that may have been the result of the small cage size and the high G gradient. The large animal centrifuge planned for the ISS is designed to provide a range of artificial gravity levels, above and below 1 G, to a large variety of fish, plants, and small animals.

**Human Space Experience with Artificial Gravity**

No formal human artificial gravity experiments were performed in space during the first 40 years of the space age. During the earliest years of human spaceflight, the major physiologic disturbances involved “space adaptation syndrome” and were of concern only for the first few days in orbit. The debilitating effects of weightlessness on the bone, muscle, and cardiovascular system were demonstrated on the Skylab missions in the early 1970s and later on the long-duration Salyut and Mir flights. However, it was believed that inflight exercise, augmented by resistance training and fluid loading, would solve the problem. As time passed, the opportunities for human centrifuges or rotating spacecraft in orbit disappeared. During a 1966 Gemini mission, an orbiting Agena rocket casing was tethered to the spacecraft, and the two were put into a slow spin. No data were taken. On Gemini 8, when Gemini was docked to the Agena, a planned slow rotation got out of control because of a stuck thruster, and the crew was saved only by the skillful use of an orbital maneuvering engine. No further spacecraft artificial gravity tests have been conducted. Since then, the only opportunities for investigation have come from uncontrolled, anecdotal reports.
During the Skylab missions, the crew took advantage of the large open compartment to run around the curved circumference. They produced a self-generated artificial gravity by running. The crew reported no difficulty with either locomotion or motion sickness.

Although no specific artificial gravity human experiments have been performed, some centrifugation for other purposes has produced a measure of centripetal acceleration. During the Spacelab International Microgravity Laboratory (IML-1) mission, subjects were spun on a rotator in which the head was 0.5 meters off center, experiencing an acceleration of \(-0.22\, G_z\) and the feet were on the other side of the axis, experiencing an acceleration of \(+0.36\, G_z\) (Benson et al. 1997). No unusual inversion phenomena were reported. Similarly, in the Neurolab Spacelab mission, 4 subjects received periodic rotation in a similar situation without reorientation. In that case, however, those subjects seemed to have achieved some measure of resistance to postflight orthostatic instability and did not show the usual decrease in vestibular sensitivity to tilt (Moore et al. 2000).

The earliest of the extensive tests of sustained rotation were conducted in Pensacola (Guedry et al. 1964), beginning in 1958. The “slow rotating room” having a horizontal floor permitted subjects to adapt to rotation during several days (Kennedy & Graybiel 1964, Reason & Graybiel 1970). Initially, most subjects developed motion sickness symptoms when they made head movements at room rotational rates in excess of 3 rpm and, through that experience, learned to restrict them. Incremental increase in the speed of the room was employed. After several days, most subjects were able to make head movements without symptoms at rotational rates up to 6 rpm. Only some of the subjects could go further to move comfortably at 10 rpm. When the rotation was stopped, subjects felt an aftereffect and an erroneous motion sensation during head movements. They were maladapted to rotation in the opposite direction.

Beginning in the 1960s a major ground research program on artificial gravity was conducted at the Institute for Biomedical Problems in Moscow (IBMP). Their earliest tests in the MVK-1 small rotating chamber at speeds up to 6.6 rpm allowed rotating 1 or 2 subjects for up to a week. It was followed by the roomier 10-meter radius “Orbita” centrifuge, capable of rotating 2 to 3 people for several weeks at speeds up to 12 rpm. The longest tests were for 25 days at 6 rpm. The initial exposures produced the expected disturbance of equilibrium and coordination. Within an hour, the usual pattern of motion sickness symptoms occurred, including vomiting in some cases (Kotovskaya et al. 1981). In 4 to 5 hours, subjects also complained of listlessness, sleepiness, and headache—similar to the Sopite syndrome identified by Graybiel. Three periods of vestibular adaptation were distinguished for these long-duration exposures. The first 1 to 2 days were characterized by severe motion sickness. This
was followed by a week during which the nausea and related acute symptoms disappeared, but listlessness and headache remained. Finally, after the first 7 to 10 days, subjects showed immunity to motion sickness, even when additional vestibular stimulation was imposed. The generalizability of this adaptation has not been determined. The Soviet centrifuge tests indicated an absence of any motion sickness symptoms at 1 rpm, moderate symptoms at 1.8 rpm, and marked symptoms at 3.5 rpm. Head movements brought on discomfort in all cases.

More recent investigations have assessed the ability of subjects to avoid motion sickness during head movements while rotating at the high speeds associated with short-radius centrifugation. Antonutto and colleagues in Udine, Italy, found that subjects who were pedaling on a bicycle-powered short centrifuge were able to make head movements without acute motion sickness while rotating at 19 to 21 rpm. Young, Hecht, and colleagues used the 2-meter radius centrifuge at the Massachusetts Institute of Technology (MIT) to show that most subjects could adapt both their eye movements rotating at 23 rpm (Young et al. 2001). Both the Udine and the MIT studies were conducted at speeds sufficient to produce 1 G of horizontal centripetal acceleration or a net gravito-inertial acceleration of 1.4 Gs. In the Udine centrifuge, it was aligned with the subject’s head-to-foot axis; whereas in the more provocative MIT studies, the subject remained horizontal.

The Coriolis forces associated with limb movements, head movements, and walking in a rotating environment are initially both surprising and disturbing. However, in almost all cases, appropriate new motor control strategies are developed, so that subjects can adapt to the new environment and no longer are even aware of the unusual forces. Extensive experiments in the Brandeis University rotating room demonstrate the remarkable ability to adapt to unusual environments (Lackner & DiZio 2000). A measure of dual adaptation apparently exists, so that subjects can switch from the rotating to the non-rotating environment with minimal relearning.

The adequacy of artificial gravity in stimulating the cardiovascular system has been investigated in ground studies. In most studies, the debilitating effects of weightlessness are simulated by sustained bed rest, often at 6-degree of head-down tilt and occasionally by partial submersion in water to approximate the fluid shift better than occurs in space. In a pioneering study in 1966, White and his colleagues at Douglas (White et al. 1965) showed that intermittent exposure to 1 G or 4 G on a 1.8 m radius centrifuge was effective at alleviating the usual decrease in tolerance to standing (orthostatic intolerance). Exercise produced little additional benefit. The principal cardiovascular reactions of interest for centrifugation are the venous tone, especially in the legs, and the baroreflex regulation of blood pressure. For a short-radius centrifuge small enough to accommodate a subject only in a squatting position, the centrifugation does little to encourage venous return by stimulating the muscles. The IBMP ground centrifuge tests (Shulzhenko et al.
Artificial Gravity as a Tool in Biology & Medicine

1979) demonstrated that subjects who were deconditioned by 2 weeks of water immersion could increase their post-immersion tolerance to +3 G\text{z} by intermittent acceleration on a 7-meter radius centrifuge. For some time, it was debated whether the intermittent centrifugation conditioned only the passive motor tone or whether the body’s active baroreflex to counter the effects of gravity on blood pressure was also affected. Burton and Meeker (1992), using a 1.5-meter radius centrifuge intermittently, showed that the baroreceptors are adequately stimulated during artificial gravity. Their slow compensation for the hydrostatic pressure drop during rotation permits the G tolerance to gradual onset acceleration to exceed that to rapid onset acceleration. Beyond even the benefit of intermittent acceleration on cardiovascular responses is the effect on blood volume. Normally, weightlessness or head-down bed rest produces a fluid shift toward the head that in turn leads to fluid loss, including plasma, and a resulting increase in hematocrit. However, Yajima and his colleagues from Nihon University School of Medicine in Tokyo (Yajima et al. 2000) showed that 1 hour per day of 2 G\text{z} exposures of their subjects, using a 1.8-meter radius centrifuge, was sufficient to prevent hematocrit from increasing during a 4-day bed-rest period. In other studies, they confirmed the effectiveness of intermittent centrifugation on maintaining baroreflex and parasympathetic activity (Iwasaki et al. 1998). To prevent motion sickness, the Nihon investigators stabilized the head during these centrifuge runs.

The interaction between the cardiovascular fitness enhancement of regular exercise and the tolerance built up during centrifugation has also been studied. Katayama et al. (2004) showed that cardiovascular fitness could be protected by intermittent artificial gravity exposure in individuals exposed to 20 degrees of head-down bed rest.

Artificial Gravity Design Options

The choice of artificial design depends on a basic decision whether the crew is to be transported with continuous artificial gravity, requiring a large-radius device, or exposed to intermittent artificial gravity, in which case a small rotator can be employed. The classical large spinning space station, as epitomized by the von Braun torus, was the basis for early designs in the Apollo era (Loret 1963). At one time, a large toroid 150 feet in diameter and constructed of 6 rigid modules joined by an inflatable material, was envisioned. The large mass and excess volume of a torus or hexagon forced consideration of alternate ways of generating centrifugal forces at large radii. The two that emerged are the rigid truss, or boom, and the tether concept. A rigid truss design typically would have the crew quarters and operations module at one end and a large counterweight at the other end. The counterweight might be an expended fuel tank or an active element such as a nuclear power source. In most cases a counter-rotating hub is present at the center of rotation to provide both a no spinning docking port and to allow for a 0 G workspace for experiments. A variation on the rigid truss is the extendable or telescoped boom concept, in which the radius of the artificial gravity systems could be varied more easily than with a fixed truss and slider. However, both of these designs imply considerably more mass and power requirements than a tether system. A variable length tether that could be unreeled in orbit and used to connect a spacecraft to a counterweight has emerged as the most acceptable design for a large artificial gravity system. As envisioned for a Mars mission (Schultz et al. 1989), it would consist of an 80,000 kg habitat module 225 meters from the center of mass, with a 44,000 kg counterweight 400 meters beyond. The 2 would be connected by a tether, weighing 2400 kg, reeled out by a deployer weighing 1700 kg. All told, the additional weight for accommodating a tethered artificial gravity system for a human Mars mission
would be about 21,000 kg plus about 1400 kg of propellant.

One of the obvious concerns about a tethered artificial gravity system is vulnerability to tether breakage. For the Mars mission design, a tether in the form of a band 0.5 cm × 46 cm × 750 m would provide a dynamic load safety factor of 7, offering a working strength of 630,000 N. That concern has otherwise been addressed by using webbing or braided cable to maintain tether integrity, even in the event of a meteoroid collision. (The probability of tether impact with a micrometeoroid of mass greater than 0.1 gm was calculated as 0.001 for a mission of 420 days.) A second concern about a tethered system is dynamic stability, especially during unreeling and during spin up and spin down. The interaction with orbital maneuvers is complex, whether the spin axis is inertially fixed or tracking the Sun to facilitate the use of solar panels.

More recently, Joosten (2004) developed a truss-based vehicle design capable of meeting archetype Mars mission requirements while providing acceptable artificial gravity parameters (continuous 1 G at 4 rpm and a 50-meter radius). The vehicle mass associated with the mission is consistent with previous design solutions, and steering strategies were identified consistent with mission requirements without excessive propellant expenditure. The vehicle mass penalties associated with artificial gravity were minimal (a few percentages). He noted that providing an artificial gravity environment by crew centrifugation aboard deep-space human exploration vehicles has received surprisingly limited engineering assessment, most likely because of: the lack of definitive design requirements, especially acceptable artificial gravity levels and rotation rates, the perception of high vehicle mass and performance penalties, the incompatibility of resulting vehicle configurations with space propulsion options (i.e., aerocapture), the perception of complications associated with de-spun components such as antennae and photovoltaic arrays, and the expectation of effective crew weightless countermeasures. Joosten concluded that these perceptions and concerns may have been overstated.

An alternative to the continuous artificial gravity approach would be to use a short-arm centrifuge intermittently. In this case, the exposure would not be limited to less than 1 G, but might be as high as 2 to 3 G to deliver adequate acceleration in exposures of perhaps 1 hour daily or several times per week. Of course, such a short-radius device would have to spin much faster than the 6 rpm limit envisioned for a large continuous system, and it would produce significant Coriolis forces and motion sickness stimuli if the head is moved, at least until adaptation occurs. However, recent work on adaptation shows the likelihood of successful adaptation by most subjects to head movements even at high centrifuge angular velocities (Young et al. 2001). The short-radius centrifuge becomes particularly attractive when the dimensions shrink to the point that intermittent centrifugation could be carried out within the confines of a spacecraft.

A 2-meter radius artificial gravity device would permit subjects to stand upright and even walk
within the device’s limited confines. Of course, the head would be close to the center of rotation resulting in a significant gravity gradient from head to toe. Many of the ground studies of intermittent short-radius centrifugation have been conducted with rotators of radii ranging from 1.8 to 2.0 meters. As the radius shrinks even further to less than 1.5 meters, the taller subjects can no longer stand erect but must assume a squatting or crouching posture. For many such designs, the subject might also provide the motive power to turn the device and perform valuable exercise by pedaling the centrifuge into rotation. While power saving may be trivial, or not even used, the importance of active exercise while exposed to intermittent centrifugation might be protection against syncope as the body is exposed to the unaccustomed footward forces that tend to pool blood in the lower extremities.

**RECOMMENDATIONS**

**International Cooperation/Coordination**

We recommend that substantial international effort be focused on cooperative/coordinated studies designed to answer the critical questions posed above in the Research Realization section. Both human and animal models have their place in the exploration of the proper application of artificial gravity with the goal of a practical and effective flight countermeasure. At a minimum we recommend regular focused workshops for exchange of results/plans to permit data exchange, replication of unexpected results, and standardization of stimulus and measurement protocols. Furthermore, we recommend general coordination among sponsoring agencies to encourage synergy among the programs. Finally, we suggest consideration of a general international structure for the management of the various activities.

**Ground-Based Studies**

We believe that the most efficient means of developing an effective flight artificial gravity countermeasure is by appropriate and timely use of ground facilities. The likelihood of a successful flight validation will be significantly elevated when the ground studies are thoroughly conducted.

A. **Human Ground Studies**. Several current studies are underway that contribute to the growing understanding of artificial gravity, in conjunction with exercise. In particular, the ongoing short-radius centrifuge (SRC) cardiovascular studies in Nagoya, at NASA Ames Research Center, the NSBRI sponsored artificial gravity studies, the newly initiated NASA-DLR-IMBP artificial gravity program, and the planned ESA studies, can be coordinated to make the overall contribution more relevant to countermeasure development and validation.
1. **Deconditioning.** Where appropriate, we recommend use of head-down tilt bed rest or dry immersion to simulate human physiologic deconditioning associated with spaceflight. Furthermore, we recommend international coordination of bed-rest standard conditions (subject recruitment/selection, dietary control, activity monitoring …) and dependent measures.

2. **Intermittent Artificial Gravity Studies.** An international project (Germany, Russia, US) for ground-based testing of intermittent artificial gravity in subjects deconditioned by bed rest is already underway. This project is focused on optimizing intermittent artificial gravity prescriptions for protection of multiple physiologic systems (bone, muscle, cardiovascular, and sensory-motor). We recommend continued support of this project, and expanded coordination with international partners including JAXA and ESA. We also recommend support of focused, system-specific studies, particularly in the short time-constant sensory-motor/neuro-vestibular and cardiovascular systems to supplement the integrated system project.

   a. Phase 1, currently being conducted under NASA JSC leadership with widespread university and government participation, has begun with the testing subjects undergoing 21 days of bed rest with a controlled exposure to daily intermittent centrifugation on the Short-Radius Centrifuge Facility at the University of Texas Medical Branch in Galveston, Texas. We recommend early presentation of the preliminary results within 1 year of the start of testing, and convening of the next meeting of an international artificial gravity steering committee to consider the detailed improvements in artificial gravity protocols for improved effectiveness and minimum interference with astronaut activity.

   b. Phase 2 is planned to include 2 more SRCs, to be installed in Russia (IBMP) and in Germany (DLR) for the purpose of expanding the test population and taking advantage of the unique capabilities for bed rest and subject evaluation at those facilities. Common test protocols will enable the comparison of results and the rapid accumulation of sufficient numbers of subjects to draw statistically meaningful conclusions about the effectiveness of certain artificial gravity parameters. We recommend continued international support of the program, and installation of the centrifuges in Russia and Germany during 2006. We also support the complementary bed-rest centrifuge studies to be performed in Nagoya in the summer of 2006.

   c. In addition to the use of standardized bed-rest protocols, Phase 2 will enable the inclusion of different dependent measures of artificial gravity effectiveness and acceptability. We recommend the solicitation and support of jointly-developed SRC protocols to take
Among the specific R&D topics that we recommend for investigation are:

1) Determine the best parameter space of radius, angular velocity and G level from the point of view of effectiveness, acceptability, and practicality. (Include G levels both below and above 1 G.)

2) Study placement of the head at different distances from the SRC axis of rotation to investigate the effectiveness of intermittent otolith stimulation on long-term vestibular and cardiovascular effects. (Control of head position rather than foot position will allow study of the influence of gravity gradient on the artificial gravity effectiveness.)

3) Consider subject position issues, including orientation relative to the radius and spin axis (e.g., supine versus lying on the side or seated); investigate other postures than supine, and study the pros and cons of head restraints to reduce motion sickness.

4) Develop exercise devices and protocols for their use on the SRC, both to enhance the countermeasure effectiveness and to permit deconditioned subjects to tolerate the centrifugation. Consider the importance of the venous blood pump in returning blood to the heart during high G gradient centrifugation. Investigate active versus passive centrifugation. Study the biomechanical consequences of Coriolis effects on limb and head movements during exercise and take steps to avoid repetitive stress injuries.

5) Determine limitations on angular accelerations of the centrifuge for normal operations to minimize vestibular disturbances while permitting adequate emergency braking.

6) Study visual surround during rotation (external, bed fixed, head fixed, goggles, or darkness) as it effects motion sickness and the compatibility with work and recreation.

7) Determine independent specification of inertial and mechanical loading to allow separate optimization of artificial gravity level for cardiovascular and musculoskeletal systems.

8) Study circadian effects as they influence the relationship between time of day and artificial gravity effectiveness,
including the evaluation of artificial gravity while sleeping.

9) Determine gravity gradient as it affects the benefit of artificial gravity to cardiovascular training.

3. Continuous Artificial Gravity Studies. We recommend studies of the sensory-motor and human factors effects of extended exposure to artificial gravity provided in medium-radius centrifuges and slow-rotating platforms to determine how freely moving humans adapt to and perform in rotating artificial gravity environments. These environments will serve as analogs to the conditions encountered in a revolving Mars transit vehicle. These studies should focus on adaptation and transient changes in performance, as well as long-term changes in locomotion, material handling, gross and fine motor control, postural balance, and work-rest cycles. Analysis of human habitability issues such as food preparation and eating, donning and doffing garments, housekeeping, personal hygiene, sleeping conditions, off-duty activities, lifting and stowage capabilities, accommodations and affordances and human interaction with displays and controls should also be examined and evaluated under continuous rotating artificial gravity conditions. The results of these studies will inform vehicle designers of critical issues before a decision is made to spin a Mars transit vehicle, and before the design of the vehicle is fixed.

a. Live-Aboard Studies. We recommend that the primary focus of this research area be to create ground-based rotating habitats, within which crews of normal subjects could freely move about while living and working for extended periods of time (days to weeks). The key issues to be studied will be related primarily to rotational velocity, rather than G level.

b. Transient Studies. We recommend that some limited information be obtained, particularly in sensory-motor adaptation, from experiments allowing free movement during transient exposures (minutes to hours) to rotating environments. These studies should be designed to supplement the live-aboard studies.

B. Animal Ground Studies. We recommend that wherever feasible, the human ground-based studies discussed above be supplemented or informed by supporting studies using animal models. Animal studies must be planned and coordinated closely with the human studies, ensuring integration to meet the common objectives. Once candidate prescriptions for artificial gravity have been identified, additional high-risk physiologic systems should be tested in animals, since they cannot be tested in humans. Tests with animals can additionally include invasive telemetry, hazardous procedures, and post-mortem tissue analysis to define artificial gravity prescriptions. Animal tests also can entail provocative testing of physiologic systems yielding results that could not be obtained using human subjects. To minimize the number of human subjects and/or the range of independent parameter variations, some animal
studies should precede the human studies. Also, to examine the detailed mechanisms of unexpected results in the human studies, animal studies may need to follow some human studies. The animal models of choice should include both rodents and non-human primates as appropriate. Conditioning of the animals can be altered in controlled ways using techniques such as hind-limb suspension. As with the human studies, international standards should be established for care, handling, feeding, and monitoring (dependent measures) animal experiments.

**Flight Validation and Operations**

The artificial gravity approaches and prescriptions must be validated and tested in space. Owing to contamination by the terrestrial gravitational field, the applicability of ground-based results will be somewhat uncertain. Thus, the likelihood of successful flight operations will be significantly improved by flight validation. We recommend that agencies seriously consider the following sequence of potential venues for flight validation and testing studies:

A. **Flight Animal Centrifuges on the ISS and/or Free Flyers.** These near-term venues could provide invaluable data to calibrate/validate animal studies of intermittent and/or continuous artificial gravity in deconditioning animals. They could also provide the only accessible continuous partial-G environment, which would allow early evaluation of the amount of deconditioning expected during long-term exposure to the Martian gravity.

B. **Human Short-Radius Centrifuges on the ISS.** This relatively near-term venue could provide an important test bed to calibrate/validate ground-based findings of human responses to intermittent artificial gravity.

C. **Artificial Gravity Capability of Crew Transit Vehicles.** While not likely required for short-duration lunar transits, artificial gravity capability may be essential for Mars transit vehicles and their precursors.

D. **Artificial Gravity Devices and Protocols for Lunar or Martian Surface Operations.** A habitat centrifuge will be essential for testing protocols and operations necessary to protect crews during long stays on the lunar or Martian surface.
KEY ARTIFICIAL GRAVITY REFERENCES


