ARTIFICIAL GRAVITY RESEARCH TO ENABLE HUMAN SPACE EXPLORATION

International Academy of Astronautics

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Study on ARTIFICIAL GRAVITY RESEARCH TO ENABLE HUMAN SPACE EXPLORATION

Edited by Laurence Young, Kazuyoshi Yajima and William Paloski

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Cover Illustration: Short radius centrifuges can be motor driven or, as shown on the cover in a facility at the NASA Ames Research Center, powered by the subject (source: NASA)

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EXECUTIVE SUMMARY

The 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 Astronautical Congress (IAC) 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 15th IAA Humans in Space Conference, with 20 interested participants. The final report review was completed at the IAC congress 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 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 Study Group recognized that artificial gravity research over the past 50 years has been filled with good ideas but has made sporadic progress, at best, owing to the ebb and flow of funding associated with perceived programmatic needs for robust countermeasures against the untoward aspects of physiological deconditioning of humans during planned space flight missions.

The increased interest, world-wide, in planning missions to Mars has reinvigorated interest in artificial gravity research. The unknown, but predictable effects of 30 months exposure to hypogravity (0 G during transit and 0.38 G while on the planetary surface) are not likely to be easily countered by combinations of exercise and pharmaceuticals. So the program planners once again ask if we need to spin the vehicle during transit. The easy answer to that question is, of course, yes. However, the impact of that answer may cost the program out of existence unless there a good fundamental understanding of the artificial gravity trade space, including physiological, medical, human factors, environmental, and engineering components. While acknowledging this larger picture, the study group limited its discussions to recommending research necessary to flesh out the biomedical aspects (physiological, medical, human factors) of this trade space, leaving for the future work that needs to be done between biomedical, environmental, and engineering experts.

The Study Group report begins with brief Background and Historical Review sections, followed by a Research Program Realization section, in which the specific questions that must be addressed to realize prescriptions for continuous or intermittent artificial gravity solutions are laid out. These questions have changed little since the beginning of the space age. They focus on identifying the boundaries of the biomedical side of the artificial gravity trade space: G-level boundaries, angular velocity (and acceleration/deceleration) boundaries, duty cycle boundaries, and G-gradient boundaries. They also touch on identifying the impacts of artificial gravity on other human activities associated with the mission and on identifying any expected requirements for using supplemental counter-measures (e.g., exercise).

After reviewing potential venues, paradigms, and models (human, non-human primate, rat, and mouse) for performing the necessary research on Earth and in space, as well as some of the relevant theoretical underpinnings of artificial gravity, the report briefly reviews the experimental evidence collected to date.

The final section of the report presents the Study Group’s recommendations for future work in this area. We stress the need for cooperation across nations, laboratories, and disciplines in order to standardize and prioritize the research activities to maximize the scientific results while minimizing the programmatic expenditures. To that end, we also recommend using ground-based venues (short radius centrifuges, long-radius centrifuges, slow-rotating rooms, bed rest deconditioning, dry immersion, etc.) and animal models as much as possible, but we recognize that human flight validation will be required before any artificial gravity solution can become operational. We lament the programmatic decision deleting the animal centrifuge from the ISS, but are hopeful that it will be brought back if program managers become serious about artificial gravity for exploration missions. It could be a very important tool for getting early relevant in-flight data. Beyond that, we recommend the development of space-based short-radius centrifuges and variable-gravity research facilities to investigate some questions that cannot be answered on the ground and to validate human responses to artificial gravity prescriptions in space.

Whether used in the near-term to facilitate human missions to Mars, or put off until developing missions to destinations farther away, artificial gravity will eventually be required to protect humans exploring space. While the recommendations made by Study Group 2.2 are similar to those made by other groups in the past, they reflect technological developments and some newly available data that might have a significant bearing on the research approaches to be taken. Thus, they represent an incremental advance in the area.

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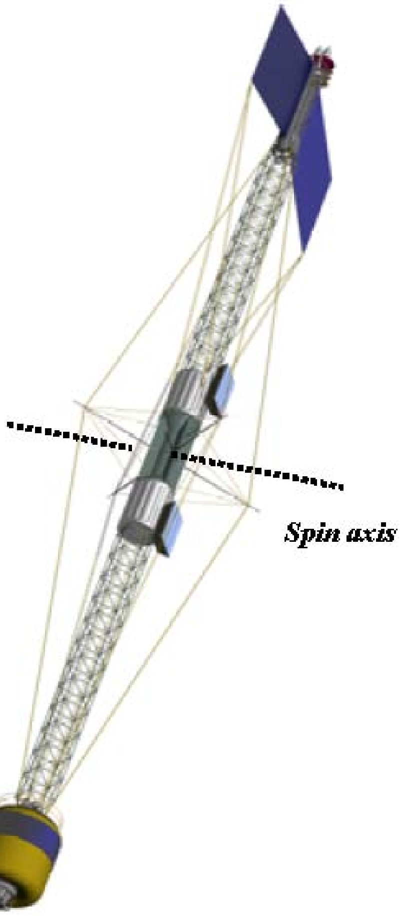


INTRODUCTION

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 to offset the untoward physiological effects of long-term microgravity exposure, has drawn increased attention to artificial gravity. The most serious threats to humans aboard long-duration space flight missions involve radiation, behavioral stresses, and physiologic deconditioning (see, for example, Buckey 1999). Artificial gravity has the potential to mitigate fully the last of these risks by preventing the adaptive responses from occurring. Unfortunately, artificial gravity research has been episodic, at best, since the beginning of space flight, and given the high costs of such research, a coordinated, international effort is warranted. Study Group 2.2 was commissioned to address these issues.

Scope

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

Approach

While multiple workshops have been held over the past 40 years to address similar issues, the starting point for this Study Group was the set of questions and recommendations reported at the most recent international artificial gravity workshop held in League City, Texas (Paloski & 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 current state of 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, and 4) to plan for a transition from ground studies of artificial gravity to flight investigations with animals and humans. 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 of the Study Group is the set of recommendations contained within this report for artificial gravity ground and flight research.

BACKGROUND

Physiologic Deconditioning During Prolonged Weightlessness

For human space voyages of several years duration, such as those envisioned for exploration of Mars, crews would be at risk of catastrophic consequences should any of the systems that provide adequate air, water, food, or thermal protection fail. Beyond that, crews will face serious health and/or safety risks resulting from radiation exposure en route as well as on some extraterrestrial surfaces, behavioral issues associated with the prolonged isolation and confinement, and severe physiologic deconditioning associated with prolonged weightlessness (Buckey 1999). The principal physiologic deconditioning risks are related to physical and functional deterioration of the musculo-skeletal systems, loss of regulation of the blood circulation, decreased aerobic capacity, and altered sensory-motor system performance. These physiologic effects of weightlessness are generally adaptive to spaceflight and present a hazard only following G-transitions upon return to Earth or landing on another planet (Young 1999). However, they may present hazards in flight in the event of a traumatic 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 remodeled: strengthened by osteoblasts using dietary calcium extracted from the blood and simultaneously destroyed by osteoclasts that return calcium to the blood for excretion. Bone maintenance requires compressive loading along the axis of the bone and some high-force impulsive loading. In the absence of these loads during spaceflight, 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 (Pavy-LeTraon et al. 2007) and during prolonged spaceflight (Cavanagh & Rice 2007). 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 (Lang et al. 2004, Sibonga et al. 2007). For a spaceflight mission lasting two 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 be-gin to weaken with disuse in a weightless environment, losing both strength and en-durance as a function of time in flight (Greenisen et al. 1999). 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 (Baldwin 1996, Adams et al. 2003).

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 (Buckey 2006, Chapter 7). 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 (Fritsch-Yelle et al. 1994, Meck et al. 2004). Neither the fluid loss, with resulting "space anemia," nor the loss of cardiovascular regulation and tone normally cause any difficulties in orbit. During entry return to 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 (Levine et al 1996).

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 (Reschke et al. 1994, Anderson et al. 1986). The balance system that keeps humans from falling depends on the detection of gravity by these sensors (Paloski et al. 1993). 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 (Parker et al. 1985). 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 (Stowe et al. 2001). 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 (NASA 1995). 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 has 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 pres-sure, or wearing a “penguin suit” to force joint extension against a resistive force) have been either marginally effective or present an inconvenience or hazard.

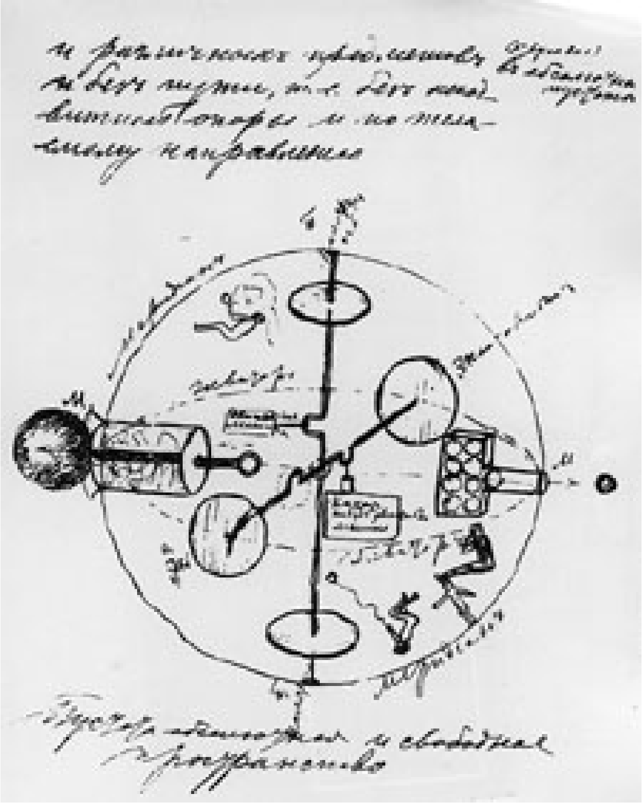
To succeed in the near-term goal of a human mission to Mars during the second quarter of this century, the human risks associated with prolonged weightlessness must be mitigated well beyond our current capabilities. Indeed, during nearly 45 years of human spaceflight experience, including numerous long-duration 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 three-year period.

Although improvements in exercise protocols, changes in diet, or pharmaceutical treatments of individual systems may be of value, they are unlikely to 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

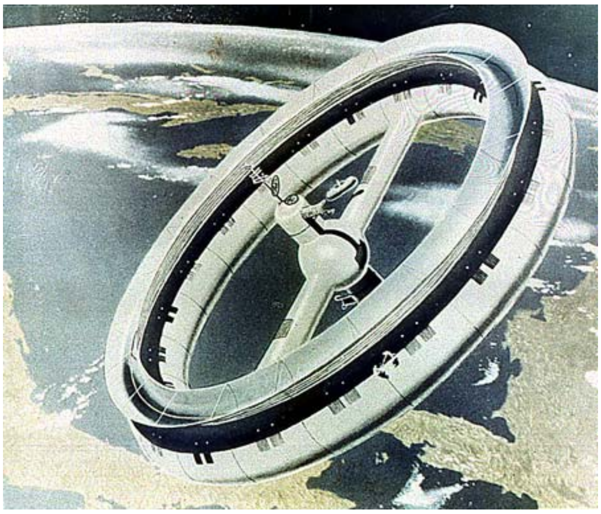
The notion of creating a substitute for gravity through centrifugation was introduced early in the conception of human space travel. Tsiolkovsky (1911), the influential Russian space visionary, discussed the idea at the beginning of the last century.



One of Tsiolkovsky's early (1883) concepts of a space vehicle, with artificial gravity produced by running along the perimeter.

Tsiolkovsky's concepts were picked up 50 years later by Korolev (1957), 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 (1928) a full 30 years before the first satellite was launched. When von Braun described his vision of space exploration (von Braun 1953), he included a large rotating torus to deal with weightlessness.

The popularization of artificial gravity, how-ever, is attributable largely 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 (Kubrick 1968).



An example of von Braun's torus design.

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 (Gurovsky et al. 1980).

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 in-conclusive and nearly led to disaster when the thruster nozzle stuck on Gemini 8, sending the pair of space vehicles into an uncontrollable spin (Williams & Adams 1967).

Planning the Gemini-Agena tether system.

The 2.5-meter radius centrifuge originally planned for the International Space Station (ISS) would have afforded the research community a great opportunity to examine the adequacy of various levels of artificial gravity in protecting small animals during spaceflight. The Study Group feels that it is very unfortunate that this centrifuge, which was the heart of the gravitational biology flight program, has been eliminated from the ISS program. Not only is this kind of device essential for basic research into the role of gravity in biological processes, but it could also have formed a basis for investigating the physiologic effects of artificial gravity in space, which is a required component of developing effective human artificial gravity prescriptions.

Continuous vs. Intermittent

The surest artificial gravity solution is clearly one that would produce a gravito-inertial environment similar to that on Earth. This could theoretically require a long-radius (~500 to 1000 m) rotating vehicle, similar perhaps to the von Braun rotating torus. However, the cost and size of such a vehicle would be excessive, but its implementation is likely unnecessary. Instead, medium-radius (~10–100 meters) rotating vehicles and/or short-radius (~2–10 meters) centrifuges seem more feasible. [Note that a clear consensus definition of short, medium, and long-radius centrifuges has not yet been achieved]

The best approach to generating artificial gravity in space can only be determined after weighing a complex set of trade-offs among vehicle design/engineering costs, mission constraints, countermeasure performance requirements, and vehicle environmental impacts. For example, an optimal artificial gravity countermeasure might spin the crew compartment continuously throughout the mission. The rotation rate would be sufficient to replicate terrestrial stresses on the bone, muscle, cardiovascular, and sensory-motor systems (approximately 1 G), the angular velocity low enough to have minimal impacts on vestibular system responses, sensory-motor coordination, and human factors (< 4 rpm), and the radius sufficient to minimize the G-gradient effects on cardiovascular loading and materials handling.

The benefits of this solution would include:

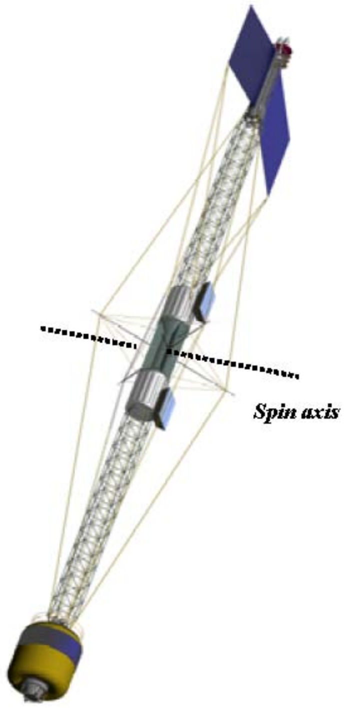
- reduced and/or eliminated physiologic adaptation in-transit,
- improved human factors in-transit (spatial orientation, WCS, galley, etc.),
- improved medical equipment/operations (countermeasures, surgery, CPR, etc.), and
- improved habitable environment (particulates, liquids, etc.).

These benefits would need to be weighed against the risks/uncertainties, which would likely include:

- engineering challenges (requirements, design: truss, fluid loops, propulsion, etc.),
- human factors issues during spin-up/down, and
- physiologic adaptations during spin-up/down.

So, while a feasible design has been put forward for a vehicle that will achieve the physiologic design goals (Joosten 2007), 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 exposures. The stresses required on the bone, muscle, cardiovascular, and sensory-motor systems would likely be substantially higher than terrestrial stresses (perhaps in the range of 2–3 G). The angular velocities would likely be high enough to affect vestibular system responses, sensory-motor coordination, and human factors (perhaps in the range of 20–30 rpm), and the radii would likely be short enough to create substantial G-gradients (perhaps in the range of 50% to 100%). While not expected to be as efficient as continuous rotation, intermittent rotation may prove effective, and the engineering costs and design risks might be lower. Note also that the physiologic responses to continuous Mars gravity 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 gravity, 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.



Joosten rotating truss design.

RESEARCH PROGRAM REALIZATION

Participants at the 1999 Workshop drafted a set of critical questions to be answered by a broad artificial gravity research program (Paloski & Young 1999). 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 (i.e., 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 (i.e., exercise, ambulation, material handling, extra and intra-vehicular 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 (i.e., 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 in-dependent 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 affect wound healing, immune responses, or pharmacologic responses?
   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 effective, 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 Moon or Mars?
   c. What are the physiologic boundaries of the trade space within which crew health and performance are acceptable (i.e., 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 (i.e., 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 (i.e., 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 affects 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 INVESTIGATIONAL TOOLS

The difficulty and expense of spaceflight experiments or feasibility demonstrations mandate the appropriate use of ground facilities to design and test artificial gravity concepts. However, contamination by the terrestrial gravity vector limits the application and interpretation of results from ground-based studies. Thus, any prescriptions developed on the ground must be validated in space before becoming operational.

Studies Using Human Subjects

Human subjects must be used for artificial gravity development and testing; however, for reasons given below, they should be supplemented where appropriate by animal experiments. Human studies are essential because of the unique aspects of their upright biped stance, 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.

<u>Deconditioning Models</u>: 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 body tilted 6˚ head-down (Pavy-LeTraon et al. 2007). Another possible deconditioning model is dry immersion (Kozlovskaya et al. 1982), which might be better at simulating sensory-motor (off-loading) effects of space flight. Analog patient populations and human single-leg suspension may have limited utility for certain studies (Widrick et al. 2002).

<u>Ground Facilities</u>: Short-radius centrifuges, particularly those in close proximity to physiological deconditioning (e.g., bed rest) facilities and those equipped for combining exercise capabilities with the artificial gravity loading, will likely be the most productive venues for investigating physiological limitations and working out intermittent artificial gravity prescriptions. Longer radius centrifuges and slow rotating rooms will be important for working out the human factors issues associated with long-term living in a rotating environment.

<u>Flight Facilities</u>: Human centrifuges small enough to fit within extant or planned vehicles (e.g., ISS) or capable of operating on the lunar surface would also prove to be very valuable for validating intermittent artificial gravity prescriptions. A more complex system, perhaps similar to the Variable Gravity Research Facilities that have been previously proposed (Webb & Parker 1987, Sorensen 2006) will be required to fully understand some of the vestibular and human factors issues as well as

to validate continuous artificial gravity prescriptions in space.

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 for animals than for 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 based on 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 The rhesus monkey provides a biomedical model with close phylogenetic ties to humans. Rhesus monkeys have served as subjects in spaceflight experiments, most notably the Cosmos/Bion series of Russian Bioflights (Kozlovskaya et al. 1989, Roy et al 2000). 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 function, musculo-skeletal system, cardiovascular system, fluid balance, sleep, circadian timing, metabolism, neurovestibular, neurosensory, and psychomotor responses.

Other primate models used in spaceflight experiments have included squirrel monkeys, capuchins, chimpanzees, cynomologous monkeys, and pig-tailed macaques (Fuller et al. 1996, Hoban-Higgins 2005). 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, the rhesus monkey is the most widely accepted biomedical non-human primate model for the human. Second, 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 allows simultaneous measurement of multiple physiologic and behavioral factors.

Rats as Models Rats also offer a number of advantages as a model system for artificial gravity countermeasure development. Because of their 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 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 ad-vantages 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 (Borisova et al. 2004, Nikawa et al. 2004). Rats flown on the Russian Bion biosatellite also have provided the only in-flight evidence for the efficacy of 1 G centrifugation in preventing many of the degenerative changes seen in a weightless environment (Gurovsky et al. 1980). 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 spaceflight could easily begin with rodent studies, since habitats and a flight centrifuge have already been developed for use with rats and mice on the ISS. Management need only raise the priority of this work and schedule the centrifuge for installation aboard ISS to begin.

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; thus the acceleration vector in both normal gravity and during centrifugation is from dorsal (back) to ventral (front) rather than from head to foot. Consequently, fluid shifts and muscle loading necessarily differ from bipeds. Weight is also distributed among four limbs rather than being principally borne on two 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.

<u>Mice as Models</u> 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; thus mice may be more suitable for some developmental studies. More so than rats, genetically defined strains of mice are seeing increased use in biomedical research with the benefit of reduced variability in studies because differences between subjects would be very small. 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 gravity 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 countermeasure should the ISS modules housing the animal centrifuge be 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 in-flight centrifuge, would provide important opportunities for gravitational biology scientists 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 1 G, 0 G testing on a limited number of species, and hyper-G testing on some species. Almost nothing is known about the effectiveness of lower G levels (between 0 G and 1 G) and behavior at the cell, organ, or whole-animal level. The existence of partial gravity for extended periods, as was envisioned for the ISS flight centrifuge for example, provides a vital research tool for gravitational biology. It would add immeasurably to the value of an artificial gravity flight program.

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, Einstein's equivalence principle states that 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 effects of artificial gravity on an extended body differ from that of true gravity, the effects on any given mass are equivalent. Thus artificial gravity is simply the imposition of acceleration on a body to recover the forces that are eliminated by the free fall of orbital flight.

In principal, artificial gravity could be pro-vided 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 (Thompson 1965, Faget & Olling 1967, Stone et al. 1968, Stone 1970).

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 (Gurovsky et al. 1980). 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 (bi-cycling) 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, Yang et al. 2007a,b).

Space Cycle

The maximum angular velocity of an artificial gravity device is limited by the Coriolis forces encountered when walking and/or moving objects, and by the motion sickness and disorientation experienced with certain kinds of head movements (e.g., Stone 1970). 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 a tangent 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.

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 (e.g., Stone 1970). 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 at about 1 m/s, 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 semi-circular 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 persistent constant angular velocity motion and, instead, they indicate that one is stationary if a turn persists for more than 10–20 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 otolith organs in the labyrinth. This conflict, before adaptation, produces both motion sickness and spatial disorientation (Guedry 1965).

When subjects in artificial gravity move their heads about an axis that is not parallel to the spin axis, two types of unexpected angular accelerations occur. First, during the head movements "cross-coupled angular velocities" occur, equal to the product of the spin rate and the head angular velocity. This produces a transient acceleration about a third orthogonal axis. Second, when the head is turned, the spin angular velocity may be 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 6–10 rpm, providing that they be built up slowly in steps of 1–2 rpm with a period of 12–24 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 two-meter tall astronaut, the radius would be at least four meters for a 50% maximum gradient.

EXPERIMENTAL EVIDENCE

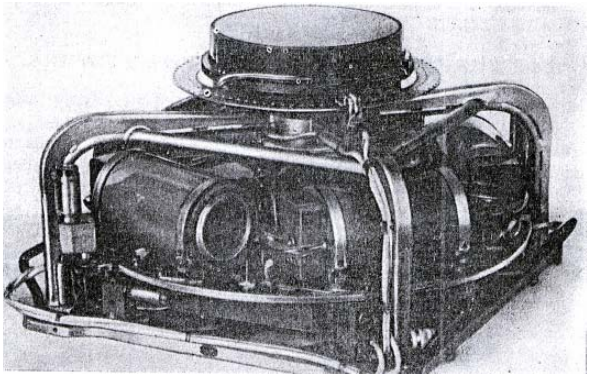
Space Experiments

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 in-flight results were anecdotal.

Flight Animal Experiments

The Soviet space research community expressed an early and intense interest in artificial gravity. In 1961, they 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-level 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 (Shipov et al. 1981).

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 (Gurovsky et al. 1980). 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 developed for the ISS was designed to provide a range of artificial gravity levels, above and below 1 G, to a large variety of fish, plants, and small animals.



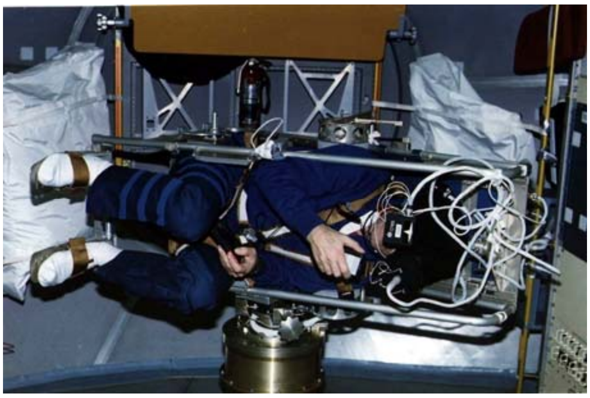
Rat centrifuge flown on Cosmos 936.

Human Space Experience with Artificial Gravity

No formal human artificial gravity experiments were performed in space during the first 50 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 (Johnston & Dietlein 1977) and later on the long-duration Salyut and Mir flights (Grigoriev et al. 2001, 2002). However, it was believed that in-flight exercise, augmented by resistance training and fluid loading, would solve the problems. As time passed, 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 (Williams & Adams 1967). 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 First International Microgravity Laboratory (IML-1) Spacelab 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.



IML-1 Rotating Chair

Similarly, in the Neurolab Spacelab mission, four 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, 2002).

Ground Centrifuge Experiments

Despite the absence of flight-test opportunities, several laboratories worldwide have continued ground-based studies of the efficacy and acceptability of human horizontal centrifugation. Of course, all of these investigations are hampered by the presence of the steady gravitational pull of the Earth. Gravity adds to the centrifugal force vectorially and produces a net specific gravito-inertial force directed between vertical and horizontal.

The earliest of the extensive tests of sustained rotation were conducted in Pensacola, beginning in 1958 (Guedry et al. 1964). The “slow rotating room” having a horizontal floor permitted subjects to adapt to rotation during several days (Kennedy & Graybiel 1962, Reason & Graybiel 1970, Graybiel et al. 1960, Graybiel 1975). 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 increases in the speed of the room were 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 after-effect and an erroneous motion sensation during head movements. They were maladapted to rotation in the opposite direction.

Beginning in the 1960s another 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 one or two subjects for up to a week. It was followed by the roomier 10-meter radius "Orbita" centrifuge, capable of rotating 2–3 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. 1980, 1981). In 4–5 hours, subjects also complained of listlessness, sleepiness, and headache–similar to the Sopite syndrome identified by Graybiel (1976). Three periods of vestibular adaptation were distinguished for these long-duration exposures. The first 1–2 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 7–10 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 (1993, 1994) in Udine, Italy, found that subjects who were pedaling on a bicycle-powered short-radius centrifuge were able to make head movements without acute motion sickness while rotating at 19–21 rpm. Young and colleagues (2001) 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. 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 G. In the Udine centrifuge, it was aligned with the subject's head-to-foot axis; whereas in the more pro-vocative 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, 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. 1979) demonstrated that subjects who were deconditioned by two weeks of water immersion could increase their post-immersion tolerance to +3 G_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 & 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_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.

More recently, a pilot study was completed for an international multi-disciplinary artificial gravity project (Germany, Russia, US). This project focused on optimizing intermittent artificial gravity prescriptions for protecting multiple physiologic systems (bone, muscle, cardiovascular, and sensory-motor). The pilot study tested subjects undergoing 21 days of bed rest with daily one-hour centrifuge episodes (2.5 G at feet, 1.0 G at heart) on a Short-Radius Centrifuge Facility in Galveston, Texas (Warren et al. 2007). The results were promising, but only partially successful for the bone muscle and cardiovascular systems (Young & Paloski 2007).

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 six 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 space-craft 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 a habitat module 225 meters from the center of mass, with a counterweight 400 meters beyond. The two would be connected by a tether and reel-out device. The total weight for this system would be about 21,000 Kg plus 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.

Others (e.g., Clark 1991, Borowski et al. 1999, 2000,) have considered other vehicle designs for Mars missions and concluded that they would be feasible. Most recently, Joosten (2007) 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. This is 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 might have been overstated.

An alternative to the continuous artificial gravity approach would be to use a short-radius centrifuge intermittently. In this case, the exposure might be as high as 2–3 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, work on adaptation shows 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 G-gradient from head to toe. Many of the ground studies of intermittent short-radius centrifugation have been conducted with rotators of radii ranging from 1.8–2.0 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 (preferably sponsored by IAA) to provide a forum for exchanging plans, results, data, interpretations, and replication of unexpected results. The forum would also be used to standardize subject recruitment, study conditions, stimulus protocols, and dependent measures. 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. These include the on-going short-radius centrifuge studies in Japan (Iwasaki et al. 1998, Iwase 2005, Iwasaki et al. 2005, Akima et al. 2005) and at the NASA Ames Research Center (Chou et al. 1997, Greenleaf et al. 1998, Evans et al. 2004), the “space cycle” studies at UC Irvine (Caiozzo et al 2004, Yang et al. 2007a,b), and the studies being planned by ESA. In the future, these studies should be coordinated and, to the maximum extent possible, use standardized test conditions and dependent measures to make the overall contribution more relevant to countermeasure development and validation. The cooperative international model that led to the successful pilot study in Galveston might serve as a model for future cooperation in this regard.

<u>Deconditioning</u> 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, etc.) and dependent measures.

- <u>Intermittent Artificial Gravity Studies</u> We recommend support of intermittent artificial gravity studies striving to use subjects deconditioned by bed rest or dry immersion. These studies should focus on protecting multiple physiologic systems (bone, muscle, cardiovascular, and sensory-motor), as optimal solutions for one system may be at odds with optimal solutions for another.

- 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 projects.

We recommend the solicitation and support of jointly-developed protocols that take advantage of centrifuges in the U.S. (including the University of California at Irvine, NASA Ames Research Center, Brandeis University, MIT, NAMRL at Pensacola, and the USAF), Russia, Germany Japan, China, the Netherlands, and ESA.

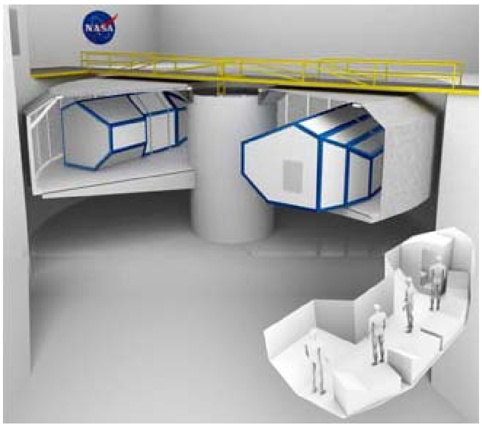
Among the specific R&D topics that we recommend for investigation are:

- 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 below and above 1 G.)
- 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.)
- 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.
- 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 bio-mechanical consequences of Coriolis effects on limb and head movements during exercise and take steps to avoid repetitive stress injuries.
- Determine limitations on angular accelerations of the centrifuge for normal opera-ions to minimize vestibular disturbances while permitting adequate emergency braking.
- 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.
- Determine independent specification of inertial and mechanical loading to allow separate optimization of artificial gravity level for cardio-vascular and musculoskeletal systems.
- Study circadian effects as they influence the relationship between time of day and artificial gravity effectiveness, including the evaluation of artificial gravity while sleeping.
- Determine gravity gradient as it affects the benefit of artificial gravity to cardiovascular training.

<u>Continuous Artificial Gravity Studies</u> 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.

- 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.
- 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.



NASA ARC Live-Aboard Centrifuge

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 un-certain. 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.

E. Variable-Gravity Research Facility

This far-term venue could provide invaluable data to calibrate/validate ground-based studies of continuous artificial gravity in humans in space. They could also provide the only accessible continuous partial-G environment for humans, which would allow evaluation of the amount of deconditioning expected during long-term exposure to the Martian gravity.

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