2014 International Workshop on Research and Operational Considerations for Artificial Gravity Countermeasures

Ames Research Center, February 19 – 20, 2014

Chairs: William H. Paloski, Ph.D., and John B. Charles, Ph.D.

Editorial Board: Peter Norsk, M.D.; Maneesh Arya, Ph.D.; LaRona Smith, RN, MSN; Konita Cromwell, Ph.D.; Justin Kugler MS, CAPM; Charlene Gilbert and David Baumann.

July 2014
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### Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AG</td>
<td>Artificial Gravity</td>
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<tr>
<td>AGREE</td>
<td>Artificial Gravity Research with Ergometric Exercise</td>
</tr>
<tr>
<td>ARED</td>
<td>Advanced Resistive Exercise Device</td>
</tr>
<tr>
<td>BNP</td>
<td>Bimodal Nuclear Thermal Propulsion</td>
</tr>
<tr>
<td>BNTR</td>
<td>Bimodal Nuclear Thermal Rocket</td>
</tr>
<tr>
<td>CNES</td>
<td>Centre National d'Etudes Spatiales (French National Center for Space Studies)</td>
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<tr>
<td>CNRS</td>
<td>Centre National de la Recherche Scientifique (French National Center for Scientific Research)</td>
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<tr>
<td>DLR</td>
<td>Deutsches Zentrum fur Luft- und Raumfahrt (German Aerospace Center)</td>
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<tr>
<td>DRM</td>
<td>Design Reference Mission</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>G</td>
<td>The ratio of an applied acceleration to the gravitational constant (g)</td>
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<tr>
<td>IAA</td>
<td>International Academy of Astronautics</td>
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<tr>
<td>IAGWG</td>
<td>International Artificial Gravity Working Group</td>
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<tr>
<td>IBMP</td>
<td>Institute of Biomedical Problems (Russian Federation State Research Center Institute of Biomedical Problems)</td>
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<tr>
<td>ICMWG</td>
<td>International Countermeasures Working Group</td>
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<tr>
<td>IMAG</td>
<td>International Multidisciplinary Artificial Gravity</td>
</tr>
<tr>
<td>IML</td>
<td>International Microgravity Laboratory</td>
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<tr>
<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
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<tr>
<td>LBNP</td>
<td>Lower Body Negative Pressure</td>
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<tr>
<td>MEDES</td>
<td>Médecine et de Physiologie Spatiales (French Institute for Space Medicine and Physiology)</td>
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<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<td>NAMRL</td>
<td>Naval Medical Research Laboratory</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NCPS</td>
<td>Nuclear Cryogenic Propulsion Stage</td>
</tr>
<tr>
<td>NEA</td>
<td>Near Earth Asteroid</td>
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<tr>
<td>NIH</td>
<td>National Institutes of Health</td>
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<tr>
<td>NTP</td>
<td>Nuclear Thermal Propulsion</td>
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<tr>
<td>NTR</td>
<td>Nuclear Thermal Rocket</td>
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<tr>
<td>RHMK-I</td>
<td>Rodent Habitat Mark I</td>
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<tr>
<td>SAFE</td>
<td>Subsurface Active Filtration of Exhaust</td>
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<tr>
<td>SAHC</td>
<td>Short-Arm Human Centrifuge</td>
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<tr>
<td>UC</td>
<td>University of California</td>
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<tr>
<td>UTMB</td>
<td>University of Texas Medical Branch</td>
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<tr>
<td>VIIP</td>
<td>Visual Impairment Intracranial Pressure</td>
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Executive Summary

Artificial gravity (AG) has the unique feature—in contrast to the traditional countermeasures—of protecting all physiological systems in all individuals against the effects of weightlessness, because throughout evolution all creatures on the surface of the Earth have adapted to the same 1-G level. Because it has become of concern that astronauts might experience increased intracranial pressures in space as a result of the weightlessness-induced fluid shifts, the use of AG could provide the best solution for human health protection during long-duration deep space missions. If so, the most-likely future AG scenarios in space will probably constitute 1) intermittent intravehicular, 2) intermittent part-of-vehicle, or 3) continuous whole-vehicle centrifugation. Technical feasibility studies have indicated that continuous, whole-vehicle centrifugation is possible during a transit to Mars, but physiological requirements such as G-level and rotation rate have not yet been defined. This information is needed before AG-configuration concepts can be determined. Results of previous ground studies have shown some protective effects of intermittent short-radius centrifugation on muscle, bone, the central nervous system, heart, and circulation. More research, however, is needed to better understand the relationship between physiological responses and G-levels between zero and one. AG rodent research on the International Space Station (ISS) can be a starting point in 2015 with NASA and Japan Aerospace Exploration Agency (JAXA) rodent habitats. Several ground-based short-radius human centrifuges are available worldwide for ground-based intermittent AG research, whereas only a few long-radius centrifuges exist for long-duration exposures (United States and Russia). Thus, for definition of the physiological requirements to the engineering community, NASA should initiate an AG research program encompassing animal investigations on the ISS and short- and long-radius centrifugations in humans on the ground to 1) identify the specific gaps associated with possible AG profiles, 2) perform trade-off feasibility analyses between potential AG profiles and non-AG solutions, and 3) initiate international collaboration for the most efficient and strategic use of available resources.
Introduction

In the executive summary of the “Proceedings & Recommendations” of the AG Workshop 15 years ago in 1999 in League City, Texas,\(^1\) we stated that “More than 30 years of sporadic activity in AG research has not elucidated the fundamental operating parameters for an AG countermeasure. For this reason, we do not advise NASA to discontinue support of countermeasures under development. Instead, we recommend that NASA appropriate the resources—primarily deploying and funding a peer-review research program—necessary to initiate AG parametric studies on the ground and in flight. Such rudimentary studies would serve as a basis for exploring an AG countermeasure and must precede prescriptions for the application of AG during long-duration space flight.” Finally, we concluded (1) “our final recommendation is that NASA establishes a standing AG working group. The group would meet annually for the purpose of continuing and advancing our progress.”

The only difference from then to today is that 15 more years have elapsed. The above statements are as valid today as they were back then, except the opening statement could be “More than 45 years of sporadic activity in AG research has not …” Because NASA’s vision for space exploration includes some nine design reference missions to send humans into deep space for long-duration (years) periods, the selection of the final health protecting countermeasure suites should include considerations for AG. The unique feature of AG is that it protects not just one but all of the physiological systems against low gravitational loads (hypo-G). For the time being, protective countermeasures are being developed to target specific physiological systems, which may be protective for one system, but with less or no protection for other systems. In addition, gender differences and individual differences exist in the response to various countermeasure interventions, which further complicates development of efficient countermeasure suites. AG has none of these drawbacks, because all humans have throughout evolution adapted to the same 1-G level.

One possible reason why NASA has not seriously implemented AG as a health-protecting countermeasure during spaceflight is that the development of AG in spacefaring vehicles is perceived as being too expensive and complicated, from an engineering standpoint. Multiple studies,\(^2,4\) however, have shown that this argument may not be valid. Also, in the intervening years of research, NASA has gained insight into the efficiencies of our currently used countermeasures—in particular from utilization and research on the previous Mir space station and now on the ISS—so that a trade-off of these against implementing AG can be implemented on a more mature basis. This was the reason for reconvening this AG Workshop at Ames Research Center on February 19-20, 2014.

Almost 100 scientists from the United States and abroad (Appendix 1) participated in an update of the state of the art of what we know about AG today. In particular, emphasis was placed on integrating engineering aspects with physiological health requirements (Appendix 2). It is pivotal to have this collaboration between engineering and physiological research established as early as possible in the evaluation and trade-off processes. Furthermore, it was a goal of the Workshop to include presentations from NASA’s international partners to exploit available worldwide resources, thereby lowering costs and gaining the best knowledge (Appendix 3).

The main conclusion from the Workshop is that AG during long-duration space missions are feasible from an engineering perspective, and that three types of scenarios should be considered: 1) centrifugation inside a space vehicle; 2) spinning part of a vehicle; or 3) spinning the whole vehicle. Research should be initiated as soon as possible to establish the life science AG requirements such as G-levels, durations, and
centrifuge size, and in regard to whole-vehicle spinning the minimum G-level (threshold). In addition, the extent to which current countermeasures need to be combined with AG must be determined.

As in the AG Workshop in 1999, it was in 2014 concluded to establish an international working group. This working group will either be a separate group (International Artificial Gravity Working Group [IAGWG]) or part of the existing International Countermeasures Working Group (ICMWG). This will be one of the first steps in the new international AG-research collaboration.

As Dr. Larry Young stated in 1999: “Artificial gravity is an idea whose time has come around…and around…and around…”

NASA, Johnson Space Center, April 2014

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NASA/JSC

John B. Charles, Ph.D.
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1.0 Historical Workshop Background

1.1 The 1999 Artificial Gravity Workshop

In 1999, the AG Workshop was held on January 14th in League City, Texas. The purpose of the workshop was to provide recommendations to NASA Headquarters regarding the pursuit of AG as a multi-system countermeasure. Recommendations were based on 1) American and Russian countermeasure programs, 2) previous AG studies and results, 3) engineering possibilities for and constraints upon AG, 4) existing ground based facilities appropriate for AG research, and 5) physiological requirements for AG. From this workshop, recommendations indicated that NASA should appropriate the resources necessary to initiate AG parametric studies on the ground and in-flight. Such studies would serve as the basis for exploring an AG countermeasure, and should precede prescriptions for the application of AG during long-duration spaceflights. Four fundamental goals were listed:

1. Implement a rigorous, coordinated, and peer-reviewed research and development project to investigate rotational AG. The desired outcome should be a multi-system countermeasure against the detrimental health and performance effects of long-duration, exploration-class space flight.

2. Determine the optimal design characteristics for an AG countermeasure facility that will best promote human health and performance. Advocate multidisciplinary investigator teams.

3. Support the upgrade of existing ground and flight research sites and facilities as needed to perform fundamental research and development activities.

4. Promote the participation of and communication among all concerned, including experts from the bone, muscle, cardiovascular, and neurovestibular fields, human factors, international space agencies, mission and vehicle design, crew representation and training, and rehabilitation.

The time line for implementation of these goals was divided into immediate (0 – 6 months), near-term (6 – 24 months), long-term (2 – 7 years), and sustaining. The specific recommendations were:

Immediate implementation (0 – 6 months):

- Establish a cross-disciplinary, international working/advisory group on AG.  
- Provide scientific guidance and support to the two existing human-rated, in-flight centrifuges. Concurrently, initiate a process to develop, and peer-review pilot studies. These flight studies would characterize physiological effects of g transitions encountered during intermittent rotation.  
- Implement a peer-review process for parametric research and development activities. Prescriptions for both intermittent and continuous AG should maintain bone, muscle, cardiovascular, and neuromotor function required during exploration-class missions.

Near-term implementation (6 – 24 months):

- Fund ground-based research activities through competitive solicitations.  
- Establish a joint NASA/National Institutes of Health (NIH) research initiative to investigate the use of centrifuge devices in treating clinical populations (e.g., osteoporotic patients).  
- Evaluate the degree to which critical AG questions can be addressed using the ISS animal centrifuge.
- Begin flying AG pilot studies on the Space Shuttle using the human-powered centrifuge or possibly the Neurolab centrifuge.
- Provide AG recommendations and requirements to Mars vehicle designers.

Long-term implementation (2 – 7 years):
- Solicit, develop, and perform ISS animal and human AG experiments.
- Answer critical questions necessary to make a go/no-go decision for a 2014 Mars mission.
- Fund AG countermeasure development activities as warranted by research findings.

Sustaining implementation:
- Fund, upgrade, and support key ground-based facilities and establish a peer-reviewed research program that balances basic and applied AG research, and attracts promising young scientists.

1.2 International Academy of Astronautics Study Report, 2005: Artificial Gravity Research to Enable Human Space Exploration

In 2004, the International Academy of Astronautics (IAA) set up a Study Group (2.2) on the subject of AG. This group developed a position for the IAA on research steps needed to realize an effective AG countermeasure. The starting point for the Study Group was the set of questions and recommendations reported by the 1999 AG Workshop.

The Study Group recognized that AG research over the past 50 years was filled with good ideas. However, only sporadic progress was made due to funding associated with programmatic needs. The unknown, but predictable effects of 30 months exposure to hypo-gravity during a Mars mission (0 G during transit and 0.38 G while on the planetary surface) were not likely to be easily countered by combinations of exercise and pharmaceuticals. So, the program planners once again asked if spinning the vehicle during transit to Mars was needed. Although the easy answer is yes, the impact of that answer may be extremely costly unless there is a good understanding of the AG trade space. The AG trade space includes 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 of this trade space. Thus, future work was left to be done among biomedical, environmental, and engineering experts.

The Study Group report focused on identifying the boundaries of the biomedical side of the AG trade space such as, G-level, angular velocity, duty cycle, and G-gradient. The report also discussed identifying impacts of AG on other human activities associated with the mission, and requirements for using supplemental countermeasures, such as exercise. Further, the report reviewed theoretical underpinnings of AG and current experimental evidence. Potential venues, paradigms, and models (human, non-human primate, rat, and mouse) for performing research on Earth and in space were also explored.

The final section of the report presented the Study Group’s recommendations for future work. It stressed a need for cooperation across nations, laboratories, and disciplines to standardize and prioritize research activities that maximize results while minimizing expenditures. To that end, recommendations were made to use ground-based venues and animal models as much as possible, recognizing that flight validation was required before any AG solution became operational. It was strongly recommended to
bring animal research back to the ISS as this could be a very important tool for getting early, relevant in-flight data. Beyond that, it was recommended to develop 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 AG prescriptions in space.

1.3 Summary of Historical Workshop Background

A number of years have elapsed since the 1999 AG Workshop and the 2005 IAA Study Group report. During this time, NASA never implemented the original recommendations of the 1999 AG Workshop. Furthermore, emerging health concerns such as the Visual Impairment Intracranial Pressure (VIIP) syndrome are not easily alleviated by currently available countermeasures. Based on these issues and others, the NASA Human Research Program wishes to reconsider use of AG during long-duration missions into deep space. Knowledge gained by revisiting the notion of AG research helps to make a more mature and sound trade-off between currently available countermeasures and AG to insure the optimal health and performance of astronauts in space.
2.0 2014 International Workshop on Research and Operational Considerations for Artificial Gravity Countermeasures Proceedings

2.1 Introduction and Background (Bill Paloski)

2.1.1 Purpose
As space agencies plan the next generation of human space exploration missions to destinations beyond the Earth-Moon system, it is incumbent on mission designers to review the technologies and habitats necessary to maintain optimal health, safety, and performance of the crewmembers designated to carry out those missions. This 2-day workshop brought together knowledgeable space physiologists, crew surgeons, astronauts, vehicle designers, and mission planners to review, evaluate, and discuss the need for incorporating AG technologies into the vehicle design.

With the end of the ISS era only a few years away, and the international human spaceflight community turning its attention toward new exploration objectives far beyond low Earth orbit, it behooves us once again to consider what role, if any, AG should play in these missions. Commitments by spacecraft designers to spin a vehicle, part of a vehicle, an exercise device within a vehicle, or even just a crewmember will only come following acceptance of a well-argued requirement from the life sciences community. Questions that will need answers are: 1) What evidence do we have to support such a requirement; 2) What design parameters would we levy upon the engineers; and 3) What prescriptions would we recommend to the crewmembers? Unfortunately, at this point it is difficult to answer any of these key questions. But, we have a 0-G platform (ISS) and multiple ground-based venues with which to develop the answers.

So, how should we prioritize the research? ISS studies might focus on a proposed rodent centrifuge facility that would allow us to establish the long-term effects of hypo-gravity exposure or possibly an AG Research with Ergometric Exercise (AGREE)-like human short-radius centrifuge that would allow us to test specific AG exercise prescriptions. Ground-based facilities would allow us to examine various short-radius exposure paradigms in subjects de-conditioned by bed rest, medium- and (proposed) long-radius live-aboard paradigms to investigate long-term effects of rotation on behavior and performance, and small animal centrifuges to investigate the mechanisms of the physiological adaptive responses.

The purpose of this workshop was therefore to bring together the international AG community to review the current status of AG facilities and research plans, discuss and debate the need for and challenges to implementing AG countermeasures in human exploration missions beyond the Earth-Moon system, and to create an international working group to help focus plans for using available facilities to answer the key questions in time to influence the decisions for the next generation of space exploration missions.
2.1.2 Expected workshop outcome

Two deliverables are expected from this workshop: 1) A consensus report (White Paper), and 2) initiation of an International AG Working Group (IAGWG). The White Paper should focus on:

1. The current levels of interest among the operations, engineering, and research communities regarding the relative need for and challenges to incorporating AG countermeasures in human exploration missions beyond low Earth orbit.

2. The current and planned international AG resources and research projects relevant to informing the feasibility and priority of incorporating AG into the design of human exploration missions beyond low Earth orbit.

3. Recommendations for future activities.

The tasks of the IAGWG should be to:

1. Coordinate integrated approaches to planning and review of future life science research projects necessary to test, verify, validate, or set requirements for operational AG countermeasures, and

2. Advise various space agency research, engineering, and operational programs on current knowledge and recommendations for practical implementation of AG countermeasures.

2.1.3 Operational and research considerations

The main question for NASA and the international partners is how we can ensure the health of human explorers during space missions beyond low Earth orbit. According to NASA’s flexible path, the next steps in human spaceflight include flyby and orbital missions to the Moon, Mars, and near Earth asteroids (NEAs), lunar and Martian landings, and combinations of these scenarios. The first crewed deep space mission is expected no earlier than 2022 and the decision criteria will include whether we can protect the health and performance of astronauts. Therefore, AG should be considered in defining the suite of countermeasures to be used. Therefore, research to determine this has a time frame of less than 8 years.

The primary hazards leading to health and performance risks are: 1) decreased gravity (G-forces) including G-transitions; 2) isolation and confinement with altered light-dark cycles; 3) a hostile and closed environment; 4) radiation; and finally 5) distance to Earth. The severity of all of these factors increases with mission duration and distance; therefore, since distance is immutable, the best solution would be to decrease the mission duration through the use of new propulsion capabilities that would increase transit speed considerably. Until such capabilities become available, it will be necessary to reduce the deleterious effects of extended exposure to the weightlessness, radiation, isolation, and confinement of ballistic spaceflight between the planets.
The physiological systems affected by each of these spaceflight environmental hazards are summarized in figure 1. As can be seen, weightlessness and hypo-gravity are associated with most of the physiological systems such as the cardiovascular system (orthostatic intolerance), muscle atrophy, sensorimotor performance, bone demineralization, immune deficiencies, back pains, renal stone formation, etc. Lately, special focus of concern is changes in vision acuity in astronauts onboard the ISS, which is hypothesized to be caused by weightlessness-induced fluid shifts to the upper body leading to intracranial hypertension. Even though vision disturbances have been reported earlier on the shorter shuttle flights, it is of more concern now because if the hypothesis is confirmed, changes in vision acuity could be an impediment for future long-duration deep space missions. Thus, an effective countermeasure against these effects will be required, and since it concerns reestablishing G-induced hydrostatic gradients, AG might be the most efficient.

Even though centrifugation forces have been known to induce AG in animals and humans for more than 100 years (Tsikolkovsky 1857-1935), relatively little is still known about the physiological effects and in particular the effects of longer duration centrifugations. Animals and humans have adapted to some 4 billion years of 1 G on the surface of the Earth by developing anti-gravity systems (musculoskeletal, sensorimotor, cardiovascular, and bone). Actually, we know more about the effects of weightlessness in space than about the effects of centrifugation just beyond a few hours duration. Furthermore, we also know more about high-G centrifugations. This leaves us with lack of knowledge of the effects of G-variations between 0 and 1. The dose-response curve between physiological variables and 0 G to 1
G is virtually unknown (figure 2). Thus, we do not know, for example, whether a Martian surface G-force of 0.38 is at all protective, and what G-threshold is needed for maintaining bodily functions during long-duration weightlessness. To define the physiologically protective G-threshold of AG is one of the most important requirements for the engineers when developing AG in space.

**Physiological Responses to Hypogravity?**

![Figure 2. The dose response curve of physiology versus G-force between 0 and 1 is unknown in humans (adapted from Paloski).](image)

Based on NASA’s flexible path for future crewed deep space missions, design requirements for AG will be sought circa 2022. Regarding the physiological requirements for AG, the following scenarios are considered as indicated in figure 3: 1) centrifugation inside the space vehicle (intermittent, autonomous and/or human powered; radius less than 2.5 m); 2) centrifugation of part of the vehicle (chronic or intermittent; radius between 3 m and 15 m); and 3) spinning the whole vehicle (chronic; radius between 15 m and 56 m or greater). Thus, from a countermeasure perspective, there are two types of centrifugations: 1) intermittent (inside or part of vehicle); and 2) continuous (whole vehicle). To validate AG as an effective countermeasure, the following research questions should be addressed:

Intermittent (short-arm) centrifugation:

1) How much AG is needed to maintain physiological function and performance?
   - How is effective maintenance of physiological function and performance defined?
   - What are the physiological thresholds for effective gravitational force?
   - What minimum or optimum G-force should be used during transit?

2) What additional countermeasures would be required to supplement AG?

3) Would AG be required on a Martian surface?
Continuous (long arm) centrifugation:

1) What range of centrifugal forces should be used in a rotating transit vehicle to maintain acceptable crew health and performance?
   - What are the physiological limits for effective gravitational force during continuous AG regarding protection from bone, muscle, cardiovascular, and sensory-motor deconditioning?
   - What are the human factors limits for effective gravitational force during continuous AG regarding exercise, ambulation, material handling, extravehicular activity/intravehicular activity, etcetera?
   - What are the human factors limits for angular velocity during continuous AG regarding disorientation and mal-coordination caused by cross-coupling and Coriolis forces?

2) What crew health and performance consequences are expected during and following spin-up and spin-down of a rotating transit vehicle?
   - What are the severities and time courses of the physiological consequences associated with onset and offset of prolonged rotational AG?
   - What operational restrictions should be placed on crewmembers during these phases?

3) What additional countermeasures would be required to supplement continuous AG during transit?

Figure 3. Future human AG in space will encounter either 1) spinning inside the vehicle (left, AGREE-concept for ISS), 2) spinning part of the vehicle (middle, Nautilus X-concept), or 3) spinning the whole vehicle (right, Fire Baton concept). For cost benefit estimations of each of the scenarios, the physiological requirements must be determined in close collaboration with engineering teams (adapted from Paloski & Joosten).
2.1.4 **Physics and side effects of artificial gravity**

There are limitations to using AG as a way of simulating gravitational effects. The AG level (G) during centrifugation is determined by the radius (r) of rotation, and the angular velocity (ω) so that \( G = r \omega^2 \). Thus, in a short-arm centrifuge, the G will vary with the distance from the center of rotation so that it is not constant throughout the body, as is the case in a gravitational environment or during linear accelerations. Therefore, the longer the radius, the more uniform the G-level will be throughout the body. Another limitation of AG centrifugation is induction of the Coriolis force (-2mωv; m = mass of the moving object and v = velocity), which displaces a moving limb to the side and can augment cross-coupling effects and induce motion sickness. The longer the radius (or the shorter the body) the less are these limitations. Cross-coupling effects seem, however, to disappear in space, judging from in-flight rotating chair investigations.

These considerations will be part of the final decision whether to conduct short- or long-arm centrifugations in space and whether whole or only part of the space vehicle should be spun. Thus, the following limitations of AG in humans should be determined:

1. Intermittent, short-radius AG: What are the acceptable and/or optimal ranges for radius and angular velocity of a rotating space vehicle or centrifuge?
   - What are the untoward physiological consequences of rotational AG?
   - What are the physiological limits for angular velocity, G-gradient, etc.?
   - What duty cycle is optimal for intermittent applications?

2. Continuous, long-radius AG: What range of angular velocities should be used in a rotating transit vehicle to avoid unacceptable crew health and performance consequences?
   - What are the physiological limits for angular velocity during continuous AG regarding disorientation and motion sickness caused by cross-coupling and Coriolis forces?

2.2 **Engineering Concepts, Designs, and Structural Constraints (Kent Joosten, Stanley Borowski & John Zipay)**

Providing an AG environment by crew centrifugation aboard deep space human exploration vehicles, long a staple technique of science fiction, has received surprisingly limited engineering assessment. This is most likely due to a number of factors:

1. The lack of definitive design requirements, especially acceptable AG levels and rotation rates;
2. the perception of high vehicle mass and performance penalties (not so with nuclear thermal propulsion (NTP));
3. the incompatibility of resulting vehicle configurations with space propulsion options (i.e., aerocapture, which is only being considered for cargo capture at Mars, crewed missions will use propulsive capture and the bimodal NTP (BNTP) system—long and linear—is naturally compatible with AG operation);
4. the perception of complications associated with de-spun components such as antennae and photovoltaic arrays; and
5. the expectation of effective crew microgravity countermeasures.
These perceptions and concerns may have been overstated, or may be acceptable alternatives to countermeasures of limited efficacy.

A study was undertaken in 2002 as an initial step to try to understand the implications of, and potential solutions for, incorporating AG in the design of human deep space exploration vehicles. Of prime interest were the mass penalties incurred by incorporating AG, along with any mission performance degradation. The characteristics were the following: 18-24 months of round trip with 3 months stay on Mars. Continuous AG was anticipated at a G-level of one, which in this case, would mean a spin of the habitat at a radius of ≥ 56 m at ≤ 4 rpm. Nuclear electric propulsion was envisaged because it would make a good match to the vehicle design (constant low thrust) and be compatible with other technical matters of a rotating vehicle.

The crew habitat with a diameter of 8.3 m and three levels would in one scenario (“Fire Baton”-configuration, figure 4) would be rotated at one end with a G-variation inside the habitat of less than 0.1 G, thus minimizing the heterogeneity of distribution of G $Z$-forces throughout the upright body as well as the Coriolis force and the cross-coupling effects. It was concluded that this scenario was feasible and provided trade-off advantages in that it would 1) reduce the Mars transit time, 2) not require excessive propellants, 3) be of significant advantage for system test and certification (no long-duration 0-G tests required) with no massive de-spun joints, etcetera, and 4) constitute a good convergence between power system mass and habitat as counterweight.

Thus, the study in 2002 on whole vehicle AG in space proved to be technically feasible and technically advantageous in many respects. NASA studies conducted several years earlier using BNTR propulsion showed that this propulsion technology and vehicle configuration were naturally compatible with AG demands.
operation and could readily support AG environments ranging from 0.38-G to 1-G using rotation rates of approximately 4 to 6 rpm.

### 2.2.1 Design reference missions

NASA utilizes a set of Design Reference Missions (DRMs) to help focus space exploration capability development activities across the agency. These DRMs are intended to demonstrate capability needs and represent a set of various potential implementations. The “Mission Class” context is used to establish temporal priorities and a limited set of DRMs is used to capture mission capabilities. The DRMs represent “snapshots” in time of current thinking, and do not represent all potential future missions. They are generic in nature with stated assumptions for some supporting capabilities and elements, but these do not represent firm requirements.

NASA is currently evaluating nine different DRMs:

1) EM-1, uncrewed lunar flyby,
2) EM-2, lunar orbit crewed mission,
3) EM-X, exploration mission X, crewed mission,
4) trans-lunar missions,
5) crewed mission to a redirected asteroid,
6) crewed mission to a NEA,
7) crewed mission to lunar surface,
8) crewed mission to Martian moons (8a, crewed Mars orbital mission), and
9) crewed Mars surface mission (9a, crewed Mars surface mission of minimal duration).

Of these missions, EM-1, -2, and –X are under development and DRM 5, 8, and 9 are primary, whereas the DRM 3 and 6 are secondary and DRM-7 is considered under international lead.

### 2.2.2 Artificial gravity and NASA’s design reference missions

The DRMs, where whole-vehicle or part-of-the-vehicle AG should be considered, are DRM-8 and DRM-9 because of the long durations to Mars. For the other DRMs, spinning inside the vehicle could be an option.

### 2.2.3 Vehicle structural considerations for human exploration missions

The spacecraft required for a long-duration, crewed, deep space exploration mission will most likely be assembled in space from multiple elements launched on separate launch vehicles. It will have to accommodate visiting vehicles ferrying crew and cargo, it could have solar arrays, radiators, antennae, or other appendages, and it will have to withstand a wide variety of loads including those induced by crew exercise. It may also include some form of AG as an adaptive countermeasure against prolonged exposure to microgravity.

Other than AG, all of the aspects of the previous paragraph apply to the construction and utilization of the ISS, so the current generation of space engineers has direct experience with an engineering project of this magnitude.
If AG is considered as an adaptive countermeasure, trade studies must be performed to determine whether a local portion of the spacecraft or the entire vehicle needs to rotate as well as the G-level required and the exposure duration to be an effective countermeasure. These trade studies will develop a significant array of configurations based on the G-level and portion of the spacecraft required to generate AG. The effects of vehicle vibration induced by centrifugation will be an important part of these trade studies. Although this problem is solvable, it must be considered during the design phase of the vehicle. Configurations developed from these trade studies will have a wide range of complexity and structural mass.

Next steps will be to perform vehicle conceptual design studies for a range of G-levels, durations and portions of a crewed spacecraft requiring AG to understand the ranges of overall vehicle size, mass, complexity, power, and launch vehicle requirements as a function of the artificial G-level.

### 2.2.4 Conventional and bimodal nuclear thermal rocket artificial gravity Mars transfer vehicle concepts

A number of AG spacecraft concepts have been proposed with a variety of habitat module orientations. Human factor issues associated with each have been identified along with mitigation strategies. High thrust nuclear thermal rocket (NTR) and bimodal NTR (BNTR) space transfer vehicles can readily be adapted for AG operation (4). Both conventional NTR vehicle concepts (using photovoltaic arrays for spacecraft auxiliary power), and the BNTR configuration (which uses the engines to generate the spacecraft’s electrical power during the coast phase) are attractive options and are currently under study (figure 5). The NTR’s high specific impulse of approximately 900 seconds (~100% higher than liquid oxygen/liquid hydrogen chemical rockets) is particularly attractive for AG missions because it can more readily accommodate the heavier payload mass and increased Reaction Control System propellant loading required for multiple spin-up/spin-down cycles. Also very important is the fact that NTP can enable shorter transit times (~3 – 6 months) to and from Mars. These shorter transit times can help reduce the crew’s exposure to galactic cosmic radiation and solar flares.

![Figure 5. The conventional NTR AG Mars Transfer Vehicle has Twin Habitat Modules and utilizes Photovoltaic Arrays for Auxiliary Power (left). The BNTR spacecraft configuration (right)—long and linear—is naturally compatible with AG operations. By rotating the BNTR vehicle about its center-of-mass and perpendicular to its flight at approximately 4 to 6 rpm, AG environments ranging from 0.38-G to 1-G can be provided to the crew (adapted from Borowski).](image-url)
Finally, it should also be noted that NTP is not new, but is a proven technology successfully demonstrated in 20 rocket/reactor ground tests conducted at the Nevada Test Site during the Rover/Nuclear Engine for Rocket Vehicle Application programs. Today, this technology is receiving increased attention. NASA restarted an NTP technology development and demonstration effort through the Nuclear Cryogenic Propulsion Stage (NCPS) project in fiscal year (FY)’12. The initial 3-year Phase I effort (FY’12 – 14) will be followed by a Phase II effort in FY’15 –17 involving fuel element irradiation testing and non-nuclear, subscale validation testing of the Subsurface Active Filtration of Exhaust (SAFE) ground test option at the Nevada Test Site. Ground testing a NTR engine could occur in the early 2020s, in time to support long-duration crewed missions to NEAs, Mars, and its moons in the 2028 – 2033 time frame.

2.3 Human Health, Safety and Performance Requirements (Jeff Davis)

Protection of astronauts’ health and performance in space is based on a risk mitigation strategy, whereby standards define the acceptable range of a certain health variable and the mitigation strategy is based on maintaining the variable within the standards at a certain accepted risk level. Policy, operations, and research are integrated through a human health risk framework involving NASA’s Chief Health and Medical Officer, who develops the medical policy for health and performance standards, bioethics, and risk mitigation implemented via the Health and Medical Authority at Johnson Space Center. This authority connects the operating and research arms as well as technology and protocol development into a risk mitigation strategy, which is implemented into any relevant DRM, currently the ISS. In this picture of risk mitigation, it is the research arm—the Human Research program—that will explore the benefits for health risk mitigation of AG on a peer-reviewed research basis.

The hazards described for the hostile environment of spaceflight that increase the risk to health include altered gravity, radiation, isolation, confinement, closed environment, and distance from Earth. In particular, the additive and/or synergistic effects are of concern during deep space missions. In this connection, 30 risks have been identified by the program, and in addition two are considered concerns or watch items (see figure 1). NASA’s Human Systems Risk Board decides whether a certain risk level is acceptable for a certain DRM, based on estimation of its likelihood and consequence. Thus, a risk is considered red, which usually means unacceptable for a given DRM, when the likelihood of occurrence is 1.0% or higher and the consequence high, which again means irreversible and with major impact to quality of life, strong disability, or death. A risk is considered yellow, meaning acceptable, when the consequence is low with high (>1.0%) probability, medium with any probability of occurrence or high with a low probability (<0.1%). Finally, a risk is considered green (acceptable for a given DRM), when the consequence is low or very low (reversible with no effect on quality of life) and the likelihood either less than 1.0% or high with a very low consequence (no effect on quality of life and minimal or no treatment).

It is thus the purpose of a countermeasure—for example, AG—to reduce the health risk level for astronauts during the different DRMs with emphasis on moving a risk away from the red category.
2.4 Current Countermeasures: Benefits, Consequences, and Uncertainties (Lori Ploutz-Snyder)

Exercise is currently the dominating countermeasure utilized during spaceflight to maintain primarily muscle and cardiovascular fitness, as well as bone mineral density (strength). However, it probably also benefits other physiological systems such as the sensorimotor system. It has been shown that introduction of systematic resistive exercise on the ISS improves muscle and bone strength, and that the success depends on the intensity and load applied. The most efficient exercise prescription, however, has yet to be finally determined. But the so-called Sprint protocol is currently being tested, where a combination of aerobic and resistive exercise prescription is tested using a cycle, treadmill, and the Advanced Resistive Exercise Device (ARED) that can apply up to 600-pound loads. Preliminary results show that using ARED improves muscle strength and bone mineral density and strength.

Exercise prescriptions will be required during long-duration, deep space missions; however, the question is whether adding AG will make it possible to reduce in-flight mass, power, and time, and make exercise more efficient. This has been studied to a limited extent (only 30 papers have been published exploring exercise combined with AG). There are promising results on muscle and orthostatic tolerance with 21 days of bed rest using AG combined with shallow squat and heel raise exercises. Treadmill exercise coupled with Lower Body Negative Pressure (LBNP) has also been shown effective as a cardiovascular countermeasure during 56 days of bed rest (Women's International Space Simulation for Exploration 2005 studies).

The current evidence for using exercise as a countermeasure during long-duration space missions in low Earth orbit indicates that astronauts can probably travel to Mars and back with exercise alone as a countermeasure for maintaining muscle and bone strength, and muscle performance as well as aerobic capacity using a Sprint-like protocol. However, it is likely that adding AG will make the exercise programs more efficient and reduce in-flight resources including crew time. AG could prove to be a determining factor for mission success should the exercise equipment fail during the mission.

2.5 The Astronaut Perspective (Mike Barratt)

The main drivers cited in the literature for AG research are 1) life science and physiological understanding, 2) prevention of physical deconditioning, 3) human factors, and 4) habitability, and these were considered by members of the astronaut office. Gravity is one of the basic elements shaping human development along with atmospheric pressure and composition. Understanding the role of gravity for fundamental physiological processes is required for understanding spaceflight physiology and adaptation and thus for development of the most efficient countermeasures. In this context, the gravitational dose-response curve should be defined and for this purpose AG is pivotal. In particular, the dose-response curve between 0 and 1G is required and this can only be investigated by AG in space.

Regarding physical deconditioning, AG will target most physiological systems; but, even so, exercise will be combined with AG. Just as astronauts are required to exercise as part of their non-flight career, AG alone will not suffice to maintain a desired level of crewmember fitness during flight. An important driver for introducing AG may be as a countermeasure for the VIIP syndrome (which might also be called the Microgravity Cerebral Syndrome pending a complete mechanistic understanding). The hypothesis is that the weightlessness-induced fluid shift is the precipitating factor inducing impairment in cerebrospinal fluid re-sorption and central nervous system venous drainage. It is possible that interventions like venous
limb occlusion and lower body negative pressure could play a preventive role, and these are being investigated. However, chronic AG might be the most efficient countermeasure. For the time being, we do not fully understand all ramifications of the VIIP syndrome and whether it has long-term effects on brain function. However, the VIIP syndrome is currently of the highest concern for long-duration missions. The possible role of AG in VIIP prevention should be investigated.

AG employed as a countermeasure during a weightless coast phase will probably not play a significant role in protecting crews during entry, but may be of benefit for the immediate post-flight adaptation to a gravitational load on a planetary surface in regard to orthostatic intolerance and sensorimotor performance.

From an astronaut perspective, short-arm centrifuges for intermittent AG exposures during flight may not be preferred over continuous spinning of the entire craft, because astronauts generally prefer less complexity in machines on which they depend. From a habitability standpoint, spacecraft are inherently small; the limited volume becomes more usable in weightlessness, an aspect that might be sacrificed for a spacecraft or module that was spun for AG. Human factors represent a nearly even trade. Some tasks are easier and some more difficult in weightlessness, and the crew office does not see human factors as a driver for AG. From a behavioral health and performance perspective, benefits will depend on the method of providing AG. There is evidence to suggest that intermittent AG has a negative effect on cognitive performance; this bears further understanding.

In conclusion, even though it is doubtful for the moment that AG is critical for any DRM currently being considered, the role of AG should be considered for:

1) Determining the physiological G-response curve and the G-thresholds for maintaining proper physiological functions to enable full understanding of the trades for mission planning.
2) Possibly mitigating the VIIP syndrome and immediate post-landing decrease in performance (orthostatic intolerance and sensorimotor disabilities).

Human factors, habitability, and behavior and performance are not major drivers for AG. The ultimate countermeasure is in fact speed, flying faster and minimizing the weightless cruise time to mitigate the physiologic deficits along with the radiation acquired dose associated with deep space travel.

2.6 International Research Plans and Facilities (Oliver Angerer, Timo Frett, Gilles Clement, Masaki Shirakawa, Satoshi Iwase, Oleg Orlov, Jack van Loon)

2.6.1 European Space Agency

The European Space Agency (ESA) received a new mandate in 2001 to prepare for human exploration beyond low Earth orbit. This led to the following ground-based facilities involving AG:

- Two short short-arm human centrifuges (Médecine et de Physiologie Spatiales (MEDES) French Institute for Space Medicine and Physiology; and Deutsches Zentrum fur Luft- und Raumfahrt (DLR), German Aerospace Center)
- The third ESA bed rest roadmap 2012 with campaigns lasting up to 60 days studying effects of nutrition and intermittent AG.
Six studies between 2008 and 2013 were initiated using a short-arm human centrifuge but without bed rest primarily focusing on the cardiovascular and sensorimotor system.

A centrifuge at Envihab in Germany will be used during the next ESA sponsored bed rest studies.

In addition, a European contribution was the publication of a book edited by Drs. G. Clement and A. Bukley on AG in 2007.  

### 2.6.2 Deutsches Zentrum fur Luft- und Raumfahrt

The Institute of Aerospace Medicine of DLR has a long experience with centrifugation. DLR has done research under AG conditions for more than 60 years, beginning with a long arm centrifuge built in the 1950s. A large number of studies in the field of fundamental research or applied science have been performed successfully. In 2008, the new ESA short-arm human centrifuge (SAHC) enhanced DLR capacities.

In July 2013, the German Aerospace Center (DLR) in Cologne, Germany, commissions its new medical research facility Envihab. One central element of the facility is a new type of short radius centrifuge called Envifuge. Equipped with the capacity to instantaneously and independently move the four nacelles along the acceleration axis, the centrifuge allows the possibility to perform up to four complex trials simultaneously. The shift of subjects above heart-level on a short-arm centrifuge allows unique studies about, for example, the cardiovascular regulation in surroundings with a high gradient of AG. The maximal acceleration is 6 G at the outer perimeter and each nacelle provides enough space for up to 150 kg payload, additionally 2 x 100 kg equipment can be mounted on the main arm. Standard features of the centrifuge include a six-camera motion capturing system and two tri-axial force plates to study the kinematics of physical exercise (e.g., squatting, jumping, or vibration training) under increased gravity.

Future projects involving Envifuge will allow to perform complex physical exercises under AG for a proper bone and muscle loading including the control of motion sickness as well as ultrasound examinations under AG (e.g., from the heart).

### 2.6.3 Centre National d'Etudes Spatiales

There are two short-arm human centrifuges in France at MEDES in Toulouse for space research and Centre National de la Recherche Scientifique (CNRS) in Marseille for clinical research. In addition, there are animal (rodent) centrifuges at the Institut National de la Santé et de la Recherche Médicale (French National Institute for Health and Research) in Marseille and Saint-Etienne, where in particular the sensorimotor system and the skeletal systems are being studied. Studies exposing mice to 21 days of centrifugation ranging from 2 G to 4 G have shown immune system alteration, increase in stress responses, slower vestibule-spinal reflexes, and alteration of spatial memory as the gravity level increased.

L. Vico and V. Gnyubkin have investigated the skeleton of 7-week mice exposed to 2 G and 3 G for 21 days. At 2 G, they found a 5% increase in bone formation and a 3% decrease in bone re-sorption. These effects were opposite during exposure at 3 G; i.e., a 5% decrease in bone formation and a 5% increase in bone re-sorption. These results confirm the need for establishing the curve of dose versus response for various gravity levels as this relationship is not linear.
Results of very recent studies (not yet published) on human subjects in the ESA SAHC at MEDES have shown that during 5 days of bed rest, 5 x 6 min of centrifugation per day with 1 Gz at the center of body mass interrupted by 3-min intervals protects better against orthostatic intolerance and is better tolerated by the subjects than 30-min continuous SAHC treatment per day.

European researchers are currently conducting fundamental studies on the SAHC investigating the interaction between postural and cardiovascular control centers, as well as the effect of the gravity gradient on the subjective perception of tilt in humans. The SAHC is also being used in multi-centric clinical studies, in particular in ambulatory subjects. Other potential applications of the SAHC are training for car racing drivers and rehabilitation for vestibular patients.

2.6.4 Japan Aerospace Exploration Agency and the Artificial Gravity Research with Ergometric Exercise project

The AG Research with Ergometric Exercise (AGREE) project was selected as a result of an International Life Science Research Announcement in 2009 and proposed the first in-flight testing on the ISS of the effectiveness and acceptability of short radius AG as a countermeasure to human deconditioning on orbit. It was planned to be constructed by ESA and placed at the end of the ISS Permanent Multipurpose-Module; however, NASA cancelled the project because analysis showed that the ISS platform would have been structurally compromised by the AGREE loads. The ground-based research supporting the in-flight AG validation was extensive, and included research at ground centrifuges under the direction of the members of the investigator team in Nagoya/Nagakute, Houston/Galveston, Boston, Antwerp, Cologne, and Toulouse. ESA had planned to produce the facility and JAXA would carry the facility to the ISS via H-II transfer vehicle.

In connection with physiological testing of the AGREE concept that constituted a short-radius centrifuge combined with ergometric exercise with Dr. Iwase as the principal investigator, it was concluded that using a ground-based centrifuge with same characteristics as the AGREE-centrifuge as an intermittent AG countermeasure during bed rest was effective to improve orthostatic tolerance, prevent arterial stiffness, counteract myatrophy, and improve bone metabolism. The everyday protocol of gravity-exercise step-up method was effective for prevention of space deconditioning, whereas using the protocol every other day showed to be insufficient.

JAXA has just started development of an ISSKibo mouse habitat system including centrifugation facilities (figure 6) for AG of 1 G with a radius of 15 cm (77 rpm). The mice are planned to be accommodated in the habitat from 1 to 6 months, and there will be provisions for euthanasia by carbon dioxide in-flight, but the mice can also be retrieved alive by SpaceX. The habitat is expected to be launched in September 2015 and a first 12-mice experiment to be conducted on-board in March/April 2016. Six mice will be exposed to 0 G and six to 1-G centrifugation. The main focus is to investigate bone and muscle preservation by AG.
2.6.5 **Russian artificial gravity history, facilities, and research plans**

AG is an old idea that started already in the beginning of the 19th century, where Konstantin E. Tsiolkovsky, considered one of the founders of rocketry, in 1903 wrote about using rotation to create AG in space and in 1911 stated that “The Earth is the cradle of the mind, but we cannot live forever in a cradle.” Centrifugation in space has never been realized and only in people’s minds in the 2001: A Space Odyssey movie by Stanley Kubrick. In Russia, ground-based long-term rotation of humans were conducted in a slow rotating room named SRR-1 in 1963 (Lebedinskiy, Grigoriev, and Gorizontov) and physiological experiments were done and in 1967-72, studies were done by the Orbit program (Galle, Kitaev-Smyk, Korsakov). From 1979-86 the Test bench Jupiter-1 was conducted in a centrifuge with a radius of 7.25 m, and this was followed by Jupiter-2 in 1989-92 at the Institute of Biomedical Problems (IBMP). A whole series of experiments with centrifugation of humans for up to 1 month was done in Russia with international collaboration. The conclusion was that it is possible for humans to exist in a rotating environment during constant angle speed. It was, however, also noted that during these long-term rotating conditions, the subjects became motion sick, which resembled motion sickness in space.

In space, the efficacy of AG to counteract the negative effects of weightlessness in muscle and bone systems was shown in experiments with rats on board biosatellite COSMOS-936 flights (Gurovsky et al., 1980) and in simulation experiments on the ground in non-human primates (Korolkov et al., 2004).

A series of short-arm human centrifugations were conducted at IBMP from 1973 to 1979 with a radius of 1.7 m, between 1 to 2 G; it was shown that intermittent AG was protective for what was described as “gravitation stability” in combination with exercise and water-salt supplements. In summary, short-radius
centrifugation would be an efficient countermeasure against the effects of weightlessness on the multiple systems including in particular orthostatic intolerance.

Future plans include evaluation of the efficiency of short-radius centrifugation as a countermeasure against deconditioning of weightlessness. The work is divided up into three stages: 1) short-radius centrifugation as countermeasure against effects of simulated weightlessness in combination with traditional countermeasures; 2) implementation of AG protocols to be tested in space; and 3) implementation of short-radius centrifugation during deep space explorations.

The primary expected outcome of stage 1 are a) determination of the optimal modes of +Gz-exposure, b) determination of the negative effects, c) development of specific AG protocols in combination with traditional countermeasures, d) establishment of an integrated system for processing and analysis of medical and technical information during short-radius centrifugation by telemedicine and development of recommendations for an in-flight short-radius centrifugation model, and e) determination of clinical effects of cumulative repeated +Gz-centrifugation bouts.

From a Russian perspective, it is a good idea to establish an international working group (e.g., IAGWG), but it would be beneficial to have it as part of the existing International Countermeasure Working Group (ICMWG). This would make more sense than to have it independently, since AG as a countermeasure should not be separated from work concerning other countermeasures. An IAGWG would be a natural extension of the previous International Multidisciplinary AG (IMAG) work.

2.6.6 A case for long-duration centrifugation on Earth

Why would we need a large human-rated centrifuge? Understanding the impact of temperature on human physiology, one explores body responses to both at high and low temperature environments. Exploring gravity should not be any different. Understanding the impact of gravity on humans, we need to expose humans to low gravity (using ISS) and high gravity (using centrifuges).

To date, no studies have reported effects of long-duration (weeks-months) exposure of humans to more than 1 G. We have gained valuable knowledge on how the human body adapts to microgravity, and, as such, on basic human physiology and psychology from previous space flight programs such as Apollo, Salyut, Mir, and ISS. Knowledge on effects of high-G environments is mainly driven by military/fighter pilot operations and training to levels as high as 9 G for very short times. There are few reports of humans exposed to G levels slightly greater than 1 for periods of hours or, at most, a few days. The latter studies were mainly related to vestibular investigations, but little or no information has been reported on other organs or functions. However, numerous long-duration hyper-gravity studies have been performed on animals. Chickens, mice, rats, dogs, rabbits, turtles, snails, and many more species have been exposed to continuous hyper-gravity for weeks, months, or even over a year. These studies provided important information on adaptation to higher accelerations. The obvious targets were the vestibular and musculoskeletal systems, but the immune and cardiovascular systems also show clear plasticity to hyper-gravity environments.

The last decade has seen increasing interest in the application of chronic acceleration in the study of neuromuscular, metabolism, general animal behavior, and cognitive function. Hyper-gravity increases bone and specific muscle masses. Otoconia size changes and, in nearly all these long-duration studies, hyper-gravity reduces fat mass in animals. Such an observation provides an important clue to exploring sustained hyper-gravity in humans in light of current societal issues like obesity and aging.
An initiative has been started in Europe with a large multidisciplinary group of scientists and engineers geared toward the possibility of developing and implementing a very large radius human centrifuge (AGP/H3, figure 7\textsuperscript{10,11}). This system could be used for physiological, psychological, and operational studies (e.g., for the application of large in-flight rotating platforms for long-duration missions), but may also be applied as a test bed for Life Support Systems, for example, or as a Coriolis platform. We should also explore future operational parameters such as partial pressure and hypoxic environments. The AGP/H3 should be such that a group of 6-12 persons are exposed to a mild but constant hyper-gravity environment for weeks or months. Current estimates foresee a centrifuge with a diameter of 150 to 200 m.
2.6.7 **International facilities for human centrifuge research**

A list of international centrifuge facilities is depicted in Table 1.

<table>
<thead>
<tr>
<th>Short/Long</th>
<th>Location</th>
<th>Radius</th>
<th>Max G</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-Radius (ESA)</td>
<td>DLR, Germany</td>
<td>2.8 m</td>
<td>+4.5 G</td>
<td>Angerer, Frett</td>
</tr>
<tr>
<td>Short-Radius (ESA)</td>
<td>MEDES, France</td>
<td>2.8 m</td>
<td>+4.5 G</td>
<td>Angerer, Clement (5)</td>
</tr>
<tr>
<td>Short-Radius (Envifuge)</td>
<td>DLR, Germany</td>
<td>3.8 m</td>
<td>+6 G</td>
<td>Angerer, Frett</td>
</tr>
<tr>
<td>Short-Radius</td>
<td>CNRS, Marseille</td>
<td>2.0 m</td>
<td>+3 Gz</td>
<td>Vercher</td>
</tr>
<tr>
<td>Short-Radius</td>
<td>Aichi Med. Univ., Japan</td>
<td>2.0 m</td>
<td>+5.7 G</td>
<td>Iwase</td>
</tr>
<tr>
<td>Short-Radius</td>
<td>IBMP, Russia</td>
<td>2.5 m</td>
<td>+7.21 G</td>
<td>Orlov</td>
</tr>
<tr>
<td><strong>Long-Radius</strong></td>
<td>Karolinska Inst., Sweden</td>
<td>7.2 m</td>
<td>+9 Gz</td>
<td>(10)</td>
</tr>
<tr>
<td><strong>Long-Radius</strong></td>
<td>IBMP, Russia</td>
<td>7.25 m</td>
<td>+30 Gz</td>
<td>Kotovskaia</td>
</tr>
</tbody>
</table>

*The list is not exhaustive, and some of the centrifuges may have to be refurbished for specific purposes. **There is also a centrifuge with a radius of 18 m at the Cosmonaut Training Center in Russia.

2.7 **NASA Artificial Gravity History, Background, Research, and Facilities**

(Larry Young, John B. Charles, Gilles Clement, Bill Paloski, Mike Stenger)

2.7.1 **History and background**

We are all familiar with Stanley Kubrick’s 1968 movie *2001: A Space Odyssey* in which a big rotating wheel in space was shown, while an aircraft looking space transportation system was docking into the structure at the center accompanied by the music of Richard Strauss’ “Thus spake Zarathustra.” AG, however, has been in people’s minds since 1883, where Konstantin Tsiolkovsky, in his manuscript “Free Space,” described centrifugation as a means of creating AG in space. The manuscript was not published until 1956. In 1928, the Austrian writer, Hermann Noordung, proposed an entire AG space station that had wheel-shaped structure, a power station attached to the central hub and an astronomical observation station. There have been suggestions of rotating space colonies and in the real world. In the 1960s, Lockheed suggested several space station concepts including AG. NASA suggested a self-inflating rotating hexagon in 1962, and later, in 1969, a concept with rotating spent Apollo program stages.
On the ground, AG experiments in humans have primarily been done in short-radius centrifuges with the test subject being totally passive or performing exercise simultaneously. An example is a short-radius human-powered centrifuge at University of California (UC) Irvine under the name Space Cycle, where two subjects could be centrifuged and could counterbalance each other and perform squats or other types of exercise to power the centrifuge and obtain from 1 to 5 G without any external power supply. At NASA’s Ames Research Center, two centrifuges are in use in human research: 1) a short-radius with rotation of supine humans with both external power and powered by human exercise, and 2) a long-radius (20 ft) with a rotating cabin, where the test subject(s) can be seated and strapped in. A third and even longer-radius (50 ft) centrifuge exists at Ames, where a small room is rotated. It is not being operated for the time being but could be set up for longer lasting AG in humans. Finally, several long-arm centrifuges are in constant operation within the Navy and Air force for training fighter pilots at e. g. Brooks AFB in San Antonio, Texas.

Bacteria, cells, fish turtles, and rats have been centrifuged in space in the Russian COSMOS missions and in Skylab, Salyut, Mir, and Spacelab on the Space Shuttle. Even though the US space program has long planned to install human AG facilities such as a small human centrifuge on the Apollo-Lunar Exploration Module and recently an intravehicular 2.5-m-radius centrifuge on ISS (AGREE, cancelled as indicated previously for technical reasons) in space, only a very few studies have in fact been conducted in space on AG in humans. On the Gemini-11 mission in 1966, the first and, until now, only attempt of an AG space station was made by rotating the spacecraft connected to an Agena rocket casing using a tether and obtaining 0.15 rpm, inducing only 0.0005 G for 4 h in the astronauts (Charles Conrad and Richard F. Gordon). The only other attempts to induce AG in space in astronauts were on Spacelab-1 in 1985 using an ESA-developed linear sled for vestibular experiments obtaining G-levels from 0.2 to 1 but for a very short period (seconds) and with rotating chairs on the International Microgravity Laboratory (IML)-1 in 1992 and with an off axis rotator on the Neurolab mission on STS-90 in 1998, obtaining in both cases G-levels up to 1 for investigating the vestibular system.

2.7.2 **Long-radius, long-duration centrifugation: The Pensacola studies**

Few studies have been done in the US using long-duration AG for days and weeks. The most famous studies began in 1958 at the Naval Medical Research Laboratory in Pensacola, in a slowly rotating room with complete living facilities in which the subjects lived for up to 3 weeks. The limitation was that the floor of the room stayed horizontal so that the G-vector was not aligned to the Z-axis of the body. The main purpose was to observe whether the subjects could sustain the rotations from 1 to 10 rpm with a radius of 5 m without becoming motion sick. It was also investigated how the postural system adapted to centrifugation with variations of the rpm from 3 to 10 and how posture adapted to stopping the rotations.

As indicated in figure 8, the test subjects would experience sensorimotor disturbances during and after the G-transitions lasting for a few days and then adapt. The rate of rotation would be a determining factor as to how fast the adaptation would occur; from these studies it was concluded that humans can adapt to a rotation rate of 3 rpm and that a 14-day period of rotation at this velocity causes no significant changes in general condition or performance. However, when the velocity was increased to 10 rpm for 12 days, no adaptation occurred, which implied that a 10-rpm rotation rate is close to the upper threshold of endurance. However, when the velocities were increased incrementally by 1 rpm every 2 days during 16 days of rotation, adaptation was possible. In addition, periodic stops lasting for some 10-15 min had to be made for logistic purposes. The on-board experimenters adapted to these G-transitions, as well. This is
termed “dual-adaptation,” indicating that it is possible to simultaneously adapt to rotating and non-rotating environments. This ability was retained in the exposed individuals for several days.

The Pensacola studies are unique, and are comprised some 30 individuals. Later studies have expanded on the experience from that time and demonstrated that complete adaptation to rotation rates as high as 10 rpm can be achieved within minutes if repeated voluntary movements are made. Such movements were avoided in the early Pensacola studies.

The slow rotating room experiments need to be expanded upon and include systems other than the sensorimotor in developing the requirements for future whole-vehicle rotation during long-duration spaceflight. The 52-ft centrifuge at Ames Research Center could be used for this purpose (Appendix 4).

![Adapting to a Slow-Rotating Room](image)

**Figure 8.** Sensorimotor effects of exposure to a rotating environment (10 rpm) in four test subjects for 12 days (adapted from Graybiel et al.13).

2.7.3 Recent NASA artificial gravity research (Bill Paloski & Mike Stenger)

Short-radius centrifugation work in humans was conducted at NASA Ames Research Center in 1998-99 and again in 2003-04 concerning effects on the cardiovascular system. A comprehensive study was done in 2006-07 at University of Texas Medical Branch (UTMB) as part of the International Multidisciplinary AG collaboration to investigate effects of intermittent AG by short-radius centrifugation during 21 days of simulated weightlessness by head-down bed rest on several physiological systems (bone, muscle, cardiovascular, central nervous, immune, and metabolic) as well as psychological and clinical assessments. Head-down bed rest was done at -6 degrees and AG for 1 hour daily with 1 G at the heart and 2.5 at the feet. The results on the different physiological systems are depicted in figure 9, showing that bone density, muscle mass and strength, orthostatic tolerance, aerobic capacity, sympathetic nervous responses, and proprioceptive reflexes were improved by AG compared to bed rest subjects, who had not undergone AG. Some systems, however, were not protected by AG in that the immune systems did not respond to either bed rest or AG and there were no effects on cognitive performance. Even though AG
protected against bone mineral density loss, bone homeostasis was still changed by bed rest and AG, which could indicate insufficient loading effects of the daily 1-hour AG procedure.

Conclusions based on the outcome of the study include the following:

1. The AG prescription was well-tolerated by all subjects over the 21-day deconditioning period; however, women were excluded, and much longer deconditioning periods must be tested.

2. The AG prescription tested was effective in ameliorating many of the adverse changes associated with 6˚ head-down bed rest.

3. The project should continue, focusing on: Increasing n, testing women, increasing the study duration, adjusting the prescription parameters (g-level, ω, r, duration/duty cycle) for optimal effectiveness and/or efficiency, and adding exercise capability.

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<td>Bone</td>
<td>↔ bone mineral density</td>
<td>as expected not supported</td>
<td>short duration insufficient loading?</td>
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<tr>
<td></td>
<td>↑ bone homeostasis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscle</td>
<td>↑ strength</td>
<td>supported</td>
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<td></td>
<td>↑ fiber-type homeostasis</td>
<td>supported</td>
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<tr>
<td></td>
<td>↓ muscle atrophy</td>
<td>supported</td>
<td></td>
</tr>
<tr>
<td>Cardio</td>
<td>↑ orthostatic tolerance</td>
<td>supported</td>
<td></td>
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<td></td>
<td>↑ sympathetic response</td>
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<td></td>
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<td>Neuro</td>
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<td>↔ SVV</td>
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<td>no Δ either group</td>
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<tr>
<td>Psych</td>
<td>↔ cognitive performance</td>
<td>supported?</td>
<td>↓ trend, but low n</td>
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Figure 9. Results of the UTMB study on effects of short-radius AG during 21 days of head-down bed rest in male subjects. CDP = Computerized Dynamic Posturography; OCR = Ocular Counterrolling; SVV = Subjective Visual Vertical (adapted from Paloski).
2.7.4 **US facilities for human centrifuge research**

A list of centrifuges in the US for human AG research is depicted in Table 2.

<table>
<thead>
<tr>
<th>Short/Long</th>
<th>Location</th>
<th>Radius (m)</th>
<th>Max G</th>
<th>Ref.</th>
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<tr>
<td>Short-Radius</td>
<td>Mt. Sinai School Med., NY</td>
<td>1.0</td>
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<td>Short-Radius</td>
<td>Brandeis Univ., Waltham, MA</td>
<td>1.2</td>
<td>±3.0 G_{y}</td>
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<td>Short-Radius (AG Sleeper)</td>
<td>MIT, Cambridge, MA</td>
<td>2.5</td>
<td>+3.0 G_{x}</td>
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<td>Short-Radius (Human Powered)</td>
<td>NASA-Ames, CA</td>
<td>2.0</td>
<td>+5.0 G_{x}</td>
<td>5</td>
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<tr>
<td>Short-Radius (Space Cycle)</td>
<td>UC, Davis, CA</td>
<td>2.0</td>
<td>+3.0 G_{x}</td>
<td>5</td>
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<tr>
<td>Long-Radius (Slow Rotation Room)</td>
<td>Brandeis Univ., Waltham, MA</td>
<td>6.7</td>
<td>±4.0 G_{x,y,z}</td>
<td>5</td>
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<tr>
<td>Long-Radius (Slow Rotation Room)</td>
<td>NAMRL, Pensacola, FL</td>
<td>7.0</td>
<td>±3.0 G_{x,y,z}</td>
<td>5</td>
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<tr>
<td>Long-Radius (Slow Rotation Room)</td>
<td>NASA-Ames, CA</td>
<td>7.9</td>
<td>+2.0 G_{x}</td>
<td>Appendix 4</td>
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*The list is not exhaustive and some of the centrifuges probably have to be refurbished.

2.8 **NASA Animal Centrifuge Capabilities and Research (Jeff Smith, Chuck Fuller, Frances Donovan, Jack van Loon, Kirt Costello, Richard Boyle & Justin Kugler)**

2.8.1 **Science plans and applications for rodent research aboard the International Space Station**

NASA is nearing completion of the first-generation habitat for performing rodent research aboard the ISS. This new facility, the Rodent Habitat Mark I (RHMk-I) will allow for fundamental and applied biomedical research on the ISS using rodent models. Early flights (2014-2015) will be for female mice only and will allow for mission durations of 30-60 days. Later flights will have increasing durations of up to 180 days and will also include the capability to support both male and female mice, as well as rats. RHMk-I is based on the NASA Animal Enclosure Module, which successfully flew rats and mice on 27 separate Space Shuttle missions, ranging in duration from 5 to 17 days. RHMk-I builds on this Shuttle legacy with an inflight animal video system and improved lighting and access to animals to increase
mission duration up to 30 days. Longer-duration flight experiments are possible with an improved waste filter system and by transferring animals into fresh habitats every 30 days.

The National Research Council’s 2011 Decadal Survey Report, “Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era,” identified the highest priority research topics to be addressed in space life and physical sciences over the next 10 years. Animal and rodent research is specifically called out in six of the highest priority recommendations (AH3, AH4, AH12, AH15, AH16, CC8); and rodent research is also expected to make a significant contribution to eight additional highest priority recommendations (AH2, AH5, AH7, AH9, AH14, CC2, CC9, CC10). In the coming decade, ISS will provide the research platform for rodent research to address these recommendations, which span NASA’s Human Research Program objectives and NASA’s Space Biology science objectives. Rodent research on the ISS will also be critical for the ISS National Lab, providing a key biomedical research component for commercial utilization of space and for gaining novel insights and new knowledge supported by other government agencies as well.

Critical applications, using the rodent model, for fundamental and applied research in space include the following:

- Rodents are the only mammalian model that can be used to study long-term physiological effects without any interference from the obligatory countermeasures normally required for humans; this cannot be done with humans.
- Many procedures are possible with rodents that cannot be performed in humans; e.g., dissections, injection of infectious agents and/or biomarkers. This makes it possible to utilize all available analytical tools to uncover the mechanisms of spaceflight adaptation on mammalian systems including spaceflight homeostasis, countermeasure efficacy, and post-flight re-adaptation. As a corollary to this, rodent studies can allow many physiological systems to be studied together to ascertain integrated physiological responses due to spaceflight.
- Rodents (particularly mice) offer a vast array of genetically modified strains and special breeds that can target specific molecular and genetic pathways affected by spaceflight. Fourth, rodents are the most complex mammalian model that can be supported in space for multiple generations, offering incredible insight and new understanding into reproductive health, developmental biology, maturation, and aging beyond the Earth over multiple lifetimes.
- Rodents offer a very well-established and widely used Earth-based biomedical research model that can be used in unique ways, not only to help solve the problems facing long-term human health in space, but also to address human health issues and diseases on Earth where inactivity, disuse, and degeneration mimic the human health conditions seen in space.

NASA plans for rodent research aboard the ISS with the RHMk-I include the development, test, and validation of the hardware and procedures on a 30-day mission (to be launched on SpaceX-4 in 2014) followed by successively more complex and longer-duration science missions that include fundamental research, applied human research for NASA, as well as research by commercial partners, other government organizations, and collaborations with international partners.

2.8.2 Animal artificial gravity research and benefits for human health protection (panel discussion)

The main conclusions from the panel discussion regarding AG animal research in space were as follows:

- Use of animals both on ground and in space should play an important role in facilitating the development of a human AG countermeasure and be part of a translational science-based approach.
• Even though mice seem to readily adapt to centrifugation in space, the suggested rodent to be used should be the rat primarily because of its larger size.

• AG in space can be also be beneficial for more fundamental animal research for understanding; e.g., vestibular system adaptation to variations in Gs. A case was made for using AG on ISS in rodents. Despite the permanence of 1G in evolution, the animal immediately senses exposure to a novel, non-1G environment and adaptive mechanisms are initiated. In the short term, compensation is likely confined to the peripheral sensory receptors or the brain—or both. For longer exposures, structural modifications of the end-organ may also result. How these functional and structural changes within the otolith organs affect performance and neurovestibular perception, particularly following transitions between gravity states, are yet to be determined, but clearly pose severe challenges to long-term missions. AG tools used either intermittently or on a prolonged basis on the ISS are essential and can directly address these challenges.

• There is an urgency to define whether additional facilities are required on the ISS for centrifugation or AG: Most EXPRESS rack storage is full in 2015 with additional accommodations not becoming available until 2018. SpaceX flights will remain full and rodent research will be on most future flights.

• Collaboration between international partners and research programs is highly desired, because the partners do have in-flight animal facilities (e.g., the JAXA Mouse Habitat Unit).

2.9 Space Agency Plans for International Space Station Animal Research

From the previous presentations at the workshop (Shirakawa and Smith), it is clear that NASA and JAXA plan for in-flight ISS rodent research starting with the launch of the NASA rodent habitat in 2014. This research will investigate female mice for 30 to 60 days—with future possibilities for extensions up to 180 days—and will also investigate rats. JAXA will launch a mice habitat in 2015, and will conduct the first investigation of 12 mice for 30 days, with six of the mice being subjected to AG centrifugation of 1 G. The immediate animal research plans for the ISS are depicted in Table 3.

Table 3. Immediate Future Plans for Animal Research on the ISS with or without Centrifugation

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Animal</th>
<th>AG</th>
<th>Launch</th>
<th>Experiment duration</th>
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<tr>
<td>NASA RH Mk-I</td>
<td>Mice,</td>
<td>No</td>
<td>2014</td>
<td>30-60 days, then up to 180</td>
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<td></td>
<td>rats</td>
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<tr>
<td>JAXA Mouse</td>
<td>Mice</td>
<td>Yes, (1 G, r = 15 cm)</td>
<td>2015</td>
<td>30 days, then up to 180</td>
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RH Mk-I, Rodent Habitat Mark I.
2.10 Summary of Proceedings

The workshop revealed a broad interest among engineers, researchers, managers, and international partners to pursue AG in a coordinated trans-disciplinary and international collaboration as an alternative physiological health protective countermeasure against weightlessness for long-duration, crewed, deep space missions. During a transit to Mars, for example, the choice has to be made between continuous or intermittent AG. For continuous AG, the whole vehicle probably has to be spun. For intermittent AG, either an intravehicular centrifuge should be developed or part of the vehicle has to be spun, perhaps maybe continuously. AG will hopefully give us another solution set for mission trades along with a deeper understanding of the gravitational physiological dose-response curve. The latter is fundamental to a complete understanding of the human in spaceflight and to determine whether the G-level on Mars is sufficient for protection of human health and performance, or whether AG is still a requirement on the planetary surface and, if so, for which physiological systems.
3.0 Conclusions, Next Steps, and an International Artificial Gravity Working Group

3.1 Conclusions

- Since the last AG Workshop in 1999, much research has been pursued in regard to exploring the feasibility of AG for long-duration missions (IMAG, Bed Rest Artificial Gravity, AGREE, and animal centrifuge studies), but much more has to be done, and it needs better coordination on a global scale.
- Before the 2022 time frame, the human medical and physiological requirements for AG should be defined based on a peer-reviewed research program.
- Short-radius centrifuges are available and already in use for human AG research abroad and in the United States. A few long-radius, rotating room centrifuges (e.g., NASA Ames Research Center and IBMP and Cosmonaut Training Center, Russia) exist and might be refurbished for future long-duration AG research.
- Animal research facilities on the ISS are being established from 2014 (NASA) and forward, and JAXA plans for a mouse habitat to be launched in 2015, including a centrifuge for 1-G AG rodent research from 2016 in the ISS Kibo-module.
- Three main AG scenarios are the most eminent (figure 3): 1) Intermittent AG inside the space vehicle with or without human-powered inputs; 2) continuous AG by spinning part of the vehicle; and 3) continuous AG by spinning the whole vehicle.
- From an engineering aspect, feasibility studies have shown that AG in-flight in humans is possible, whether it concerns any of the three scenarios above, but the physiological requirements should be available in the initial engineering planning phase to perform a programmatic cost-benefit analysis.
- From an engineering perspective, a number of different vehicle configurations (figures 4 & 5) were considered for whole-vehicle spinning on a transit into deep space. One such configuration is the Fire Baton-concept utilizing an anticipated 1-G continuous AG level by spinning the whole vehicle with a radius of rotation of 56 m. Also, the NTR and BNTR options can be adapted for AG operations and are attractive, because nuclear thermal propulsion can enable shorter transit times to and from Mars, thereby reducing exposures to galactic cosmic radiation and solar flares.

3.2 Next Steps

- The physiological requirements to engineering should be defined and constitute answers to the following questions: 1) Should intermittent or continuous AG be used; 2) If intermittent AG is used, what are the G-levels, durations, and radius of rotation needed; 3) If continuous AG is used, what are the minimum G-levels and radius of rotation needed?
- An AG peer-reviewed research project should be established according to the management aspects in figure 10. On an international basis, ground-based AG facilities worldwide should be exploited in a coordinated fashion.
The main physiological drivers for AG during long-duration space missions should be defined (such as the VIIP syndrome) and the physiological G-dose response curve established to define thresholds.

The physical side effects of spinning such as Coriolis forces, cross coupling effects, and motion sickness should be determined in close cooperation with engineers for deciding optimal spinning radius and G-level.

The critical research path based on international solicitations should be established with several parallel tracks toward 2022 involving 1) cell culture centrifugation research (ground based and on ISS), 2) animal centrifugation research (ground based and on ISS), 3) human ground-based bed rest and short-radius centrifugation research, 4) human ground-based long-radius centrifugation and long-duration (days) research.

Consideration should be given to whether an intravehicular human centrifuge should be installed on the ISS and/or an additional centrifuge module attached to the ISS.

3.3 An International Artificial Gravity Working Group?

It was agreed during the workshop to establish an IAGWG, but it was argued that since there already is an ICMWG, the IAGWG should be part of, or a sub-committee to, this. It was, however, not finally decided whether this should be the case, and it is therefore under consideration. Thus, the next step is to decide among the international partners whether: 1) An independent IAGWG should be established; or 2) AG should be part of the existing ICMWG; or finally, 3) a subcommittee on AG should be established under the ICMWG.
4.0 References


## Appendix 1: List of Participants

### Speakers

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Appendix 2: Workshop Agenda

2014 International Workshop on Research and Operational Considerations for AG Countermeasures
NASA Ames Research Center, Moffett Field, CA
February 19-20, 2014

Chairs
John Charles & Bill Paloski

Organizing committee
Peter Norsk, Maneesh Arya, LaRona Smith, Ronita L. Cromwell, and Albert C. Maese.

Workshop location
Building 152, Business Park, Ames Research Center, Moffett Field, CA.

Purpose
As space agencies plan the next generation of human space exploration missions to destinations beyond the Earth-Moon system, it is incumbent on mission designers to review the technologies and habitats necessary to maintain optimal health, safety, and performance of the crewmembers designated to carry out those missions. This two-day workshop will bring together knowledgeable space physiologists, crew surgeons, astronauts, vehicle designers, and mission planners to review, evaluate, and discuss the need for incorporating AG technologies into the vehicle design.

With the end of the ISS era only a few years away, and the international human spaceflight community turning its attention toward new exploration objectives far beyond low Earth orbit, it behooves us once again to consider what role, if any, AG should play in these missions. Commitments by spacecraft designers to spin a vehicle, part of a vehicle, an exercise device within a vehicle, or even just a crewmember will only come following acceptance of a well-argued requirement from the life sciences community: What evidence do we have to support such a requirement? What design parameters would we levy upon the engineers? What prescriptions would we recommend to the crewmembers? Unfortunately, at this point it is difficult to answer any of these key questions. But, we have a 0-G platform (ISS) and multiple ground based venues with which to develop the answers.

So, how should we prioritize the research to be done? ISS studies might focus on a proposed rodent centrifuge facility that would allow us to establish the long-term effects of hypo-gravity exposure or possibly an AGREE-like human short-radius centrifuge that would allow us to test specific AG exercise prescriptions. Ground based facilities would allow us to examine various short-radius exposure paradigms in subjects deconditioned by bed rest, medium- and (proposed) long-radius live-aboard paradigms to investigate long-term effects of rotation on behavior and performance, and small animal centrifuges to investigate the mechanisms of the physiological adaptive responses.
The purpose of this workshop is to bring together the international AG community to review the current status of AG facilities and research plans, discuss and debate the need for and challenges to implementing AG countermeasures in human exploration missions beyond the Earth-Moon system, and to create an international working group to help focus plans for using available facilities to answer the key questions in time to influence the decisions for the next generation of space exploration missions.

Objectives

The objectives are to develop a White Paper and establish an International AG Working Group (IAGWG):

- **White paper content:** 1) Summary of current interest among the operations, engineering, and research communities regarding the relative need for and challenges to incorporating AG countermeasures in human exploration missions beyond the Earth-Moon system; recommendations for future activities, 2) Summary of current and planned international AG resources and research projects relevant to informing the feasibility and priority of incorporating AG into the design of human exploration missions beyond the Earth-Moon system; and 3) recommendations for establishing an IAGWG: membership, sponsorship, objectives, etc.

- **IAGWG:** Integrated planning to advise various space agency research programs on current and future life science research directions necessary to test, verify, validate, or set requirements for operational AG countermeasures.

Format

An invited subject-matter expert will provide an overview of each topic and pose discussion questions. Immediately following this 30-minute introductory lecture, the Chairs will moderate a discussion among the participants. Brief coffee or lunch breaks will be held between topic discussions. For the final session, the Chairs will summarize the main points from the first day’s discussions and facilitate follow-on discussions leading to consensus agreement of the next steps (if any) in exploring AG approaches.

Schedule

1st day, Wednesday February 19, 2014:

0800–0815:
Safety Briefing and Welcome
*ARC Center Management*

0815–0845:
Introduction and background for workshop
*Bill Paloski*

0845–0930:
Current concepts and design constraints for human space exploration missions
*Invited Speaker: Kent Joosten*
0930-1000:
Vehicle Structural Constraints for human space exploration missions
*Invited Speaker: John Zipay*

1000-1030:
Coffee Break

1030–1115:
Human health, safety, and performance requirements for human space exploration missions
*Invited Speaker: Jeff Davis*

1115–1200:
Benefits, consequences, and uncertainties of conventional (exercise) countermeasure approaches
*Invited Speaker: Lori Ploutz-Snyder*

1200-1300:
Lunch Presentation on history of AG
*Invited Speaker: Laurence Young*

1300–1430:
Benefits and consequences of employing AG approaches: Human Health & Performance
*Invited Speaker: Bill Paloski*

1430–1600:
Benefits, consequences, and uncertainties of employing AG approaches: Engineering
*Invited Speaker: Kent Joosten*
Conventional and Bimodal Nuclear Thermal Rocket AG Mars Transfer Vehicle Concepts
*Invited Speaker: Stanley Borowski*

1600-1630:
Coffee Break

1630–1730:
Astronaut Perspective
*Invited Speaker: Mike Barratt*

1730-1800:
Summary and conclusion of 1st day
*Invited Speaker: John B. Charles*

1830-1930:
Social Hour at Golf Course
2nd day, Thursday February 20, 2014:

0800–0830:
ESA-AG Facilities & Research Plans
Invited speaker: Oliver Angerer

0830–0900:
DLR-AG Facilities & Research Plans
Invited speaker: Timo Frett

0900–0930:
CNES-AG Facilities & Research Plans
Invited speaker: Gilles Clement

0930-1000:
Coffee Break

1000–1030:
JAXA-AG Facilities & Research Plans
Invited speaker: Masaki Shirakawa
Artificial Gravity with Exercise – Remarks on Research
Invited speaker: Satoshi Iwase (Aichi Medical University)

1030–1100:
Russian AG Facilities & Research Plans
Invited speaker: Oleg Orlov

1100-1130:
Plans for Earthbound, Long-term Centrifugation of Humans
Invited Speaker: Jack van Loon

1130-1230:
Lunch

1230–1500:
ISS Rodent Centrifuge Capabilities and Research Plans
Panel Members: Chuck Fuller, Richard Boyle, Jack van Loon, Jeff Smith, Kirt Costello, and Justin Kugler

1500-1530:
Coffee Break

1530-1600:
ISS Rodent Centrifuge Capabilities and Research Plans (continued)
1600-1630
Summary, conclusion and next steps (if any)
Moderator: Bill Paloski

1630-1800
Tour of ARC-AG facilities

Products
The following outcomes will be delivered to the participants within 60 days following the Workshop:

1. A set of PowerPoint charts from each invited lecturer.
3. Establishment of an IAGWG.
Appendix 3: Presentations


Appendix 4: The Ames Research Center 52-ft Centrifuge

52-Ft.

52-FOOT CENTRIFUGE
Operational Characteristics:

- Chronic exposure (weeks to months)
- Humans, rodents, small primates, and plants.
- Human free roaming habitat within a cab
- The 52-Foot Diameter Centrifuge can support chronic human, animal, and plant studies under gravity forces up to 2 G. The centrifuge accommodates two rooms that can be configured as an animal habitat and a human habitat. Each habitat is 190 sq ft in size. The two habitats can be connected by a passageway to enable human operators to move from one habitat to the other while the centrifuge is in operation. The animal habitat accommodates an animal holding room and a surgical station. A central area in the habitat can be configured “as-needed” for specific research requirements.

The human habitat accommodates up to four individual sleep chambers positioned along the rear wall of the habitat. Each sleep chamber is a small room (6 ft x 4 ft) and accommodates a person standing or sitting as well as sleeping. Each chamber can be configured to contain a folding bed, a fold-down table, a storage area for personal belongings, a video monitor, and a lap-top computer.

The restroom/shower is located at one end of the habitat with room for a toilet, a sink, a shower, and a storage cabinet for toiletries.

The central area can be configured as a group area. With a table opened to full length (3 ft), four people are able to use the area for dining, conversation, or recreation. A video monitor can be located above the table on the wall. The area also accommodates a refrigerator and a microwave oven.

At the opposite end of the habitat from the restroom/shower is an area available for conducting experiments.

Each habitat may be equipped with an access panel to a radial passageway which connects the habitat to the central hub of the centrifuge. A motorized delivery system can be used to transport materials (e.g., food, clothing, data tapes, animal cages) into and from the centrifuge without interruption of rotation.

Video monitoring of subjects is available. An intercommunication system between operators within the habitat and experiment support personnel outside can be provided. During experiments, human subjects have access to experiment support personnel through an intercom system. While studies are in progress, P.I. staff, engineers, and facility support personnel monitor subjects from an experiment operation control center (EOCC) adjacent to the centrifuge. Experiment data can be downloaded through slip rings in real-time or off-line. Medical monitors are available on call, 24 hrs./day.

Performance limits and specifications:

- Radius - 13.4-22.2 ft, fixed
- Payload - 5000 lbs
- Max G - 2.5 G
- Max RPM - 22.4 RPM
- Drive - 75 HP DC Motor
- Cabs - 25' L x 8' W x 8' H

P.O.C.: Tianna L. Shaw, 650-494-4496, NASA Ames
http://lifesci.arc.nasa.gov/CGBR/
As space agencies plan the next generation of human space exploration missions to destinations beyond the Earth-Moon system, it is incumbent on mission designers to review the technologies and habitats necessary to maintain optimal health, safety, and performance of crewmembers on those missions. The 2014 International Workshop on Research and Operational Considerations for Artificial Gravity (AG) Countermeasures brought together almost 100 scientists from the United States and abroad who participated in an update of the state of the art of what we know about AG today. Emphasis was placed on integrating engineering aspects with physiological health requirements. Furthermore, it was a goal of the workshop to include presentations from NASA’s international partners to exploit available worldwide resources, thereby lowering costs and gaining the best knowledge. The main conclusion from the workshop is that AG during long-duration space missions is feasible from an engineering perspective, and that three types of scenarios should be considered: centrifugation inside a space vehicle; spinning part of a vehicle; or spinning the whole vehicle. Research should be initiated as soon as possible to establish the life science AG requirements. In addition, the extent to which current countermeasures need to be combined with AG must be determined.