Refer: RFI Focus Area – Design Principles, Objectives, and Guidelines
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The Effect on the Crew and Design Implementations of Artificial Gravity Transportation Systems

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Summary

Many of the human responses to space flight are related to loss of the loading and stimulation provided by gravity on the surface of Earth. In fact, 24 of the 50 biomedical risks identified in the Bioastronautics Critical Path Roadmap result in part from absence of gravity during transit and/or reduced gravity during surface operations in planned exploration class missions.

The artificial gravity (AG) generated by a rotating vehicle could provide simultaneous, passive mitigation of these risks, and thereby reduce the uncertainties, complexities, and development times of alternate countermeasures currently under development. It is a concern that lunar or Martian gravity levels will not provide sufficient loading and stimulation to protect humans from risks similar to those expected for transport. Thus, some level of gravity replacement therapy may be required during surface operations phases of exploration class missions, most likely in the form of intermittent, short-radius centrifugation, perhaps supplemented by exercise and/or pharmacological countermeasures. An intermittent, short-radius solution may also be required during transit phases should engineering cost, schedule, or technical considerations preclude vehicle rotation. Critical questions regarding the optimal application of AG as a multisystem biomedical countermeasure for exploration class missions still remain unanswered. Answers to these questions and implementation of developed AG requirements are necessary to reduce overall research and development costs, up mass, power, and crew time requirements across the exploration program.

In addition, to the human physiology questions to be answered, providing an AG environment by crew centrifugation aboard deep-space human exploration vehicles has received surprisingly limited engineering assessment. This is most likely due to a number of factors: the lack of definitive design requirements, especially acceptable artificial gravity levels and rotation rates, the perception of high vehicle mass and performance penalties, the incompatibility of resulting vehicle configurations with space propulsion options (aerocapture), the perception of complications associated with de-spun components such as antennae and photovoltaic arrays, and the expectation of effective crew microgravity countermeasures. These perception and concerns may have been overstated, or may be acceptable alternatives to countermeasures of limited efficacy. Design studies are proposed to investigate these implications.

Specific products necessary to resolve open questions include:

1. Evaluation of conceptual spacecraft design, utilizing a mission parameter range that will allow systems trades such as propulsion, power, habitation, etc. and establish the impact of an artificial gravity configuration. The results of this study should retain a certain level of

mission-independence, allowing the results to be applied to a range of destinations, mission classes, and AG requirements.

2. The evidence base necessary to advise engineering designers on optimal radii, angular velocities, angular accelerations, centrifugal force, etc. to be used in designing rotating vehicles to provide continuous AG during crew transit phases of exploration class missions.
3. The evidence base necessary to devise optimal prescriptions for application of short-radius, intermittent AG, with and without augmentation by exercise or other countermeasures, to be used in designing human centrifuges for use within non-rotating transit vehicles or surface habitats during exploration class missions.
4. The biomedical database necessary to fully characterize short and long-term, multisystem responses to G-transitions expected during exploration class missions (0 G to 1 G, 1 G to 0 G, 0 G to 3/8 G, 3/8 G to 0 G, etc.)
5. The biomedical database necessary to fully characterize the multisystem physiological consequences of long-term exposure to hypogravity environments expected during exploration class missions (1/6 G, 3/8 G, and possibly other G-levels).

Issue or Problem Statement

Goals from The Vision for Space Exploration:

- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration
- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020
- Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations

During 30 years of human space flight experience, including numerous long-duration missions, biomedical research has not produced any single countermeasure or combination of countermeasures that is completely effective at protecting human crews from the effects of microgravity. Since current countermeasures do not fully protect crews in low-Earth orbit, they will certainly be insufficient for crews journeying to Mars and back over a 3-year period or for long duration stays on the Moon. While rotating a Mars-bound spacecraft will not mitigate the critical problems of radiation exposure, isolation, confinement, and environmental homeostasis, the gravity equivalent centrifugal force it provides offers significant promise as a multidisciplinary countermeasure to nearly half of the biomedical risks identified for exploration class missions. The critical and possibly fatal problems of bone loss, cardiovascular deconditioning, muscle weakening, neurovestibular disturbance, space anemia, and immune compromise may be alleviated by the appropriate application of AG. Unfortunately, data required to answer basic questions of how much g is needed, how often it should be applied, what is the minimum acceptable radius, and what is the maximum rotation rate do not yet exist.

If AG is successfully implemented; many other aspects of countermeasures development research will be obviated. Most of the physiological risks associated with exploration class missions will be mitigated using AG provided by rotating the transit vehicle and or intermittent centrifugation on the lunar or Martian surface. To successfully implement AG within exploration class vehicles, studies should be undertaken in parallel with the human research as an initial step in understanding the implications of and potential solutions to incorporating artificial gravity in the design of human deep-space exploration vehicles. Of prime interest will be the mass penalties incurred by incorporating AG, along with any mission performance degradation.

Background

NASA's biomedical research programs have resulted in hundreds of articles related to the efficacy of AG being published in the peer-reviewed literature. Unfortunately, most have been limited to uncoordinated individual investigator initiated grants, usually focused on single physiological systems. The International Multidisciplinary Artificial Gravity (IMAG) project has recently been initiated develop a database of biomedical response data to characterize the multisystem physiological characteristics of an intermittent, short-duration AG countermeasure, as well as some of the multisystem consequences of long-term exposure to hypogravity environments. Numerous ground based venues and models for AG research exist and are available to support AG research, but an overall examination of AG has not yet been begun.

It should be noted that AG is not a simple countermeasure for either the human body or to implement within a vehicle. A number of potential issues must be investigated. For example, transition from 1 gravito-inertial force (GIF) environment to another causes adaptive responses in the bone, muscle, cardiovascular, and neurovestibular systems. Detrimental physiologic changes associated with transitions between space flight and Earth include orthostatic intolerance and balance control disturbances may also occur on transition from AG to 0 G or 3/8 G. Also, rotational environments introduce peculiar physical characteristics that may lead to negative physiological consequences. One such peculiarity occurs with movements made out of the plane of rotation of the vehicle or centrifuge and results in "cross-coupling" and Coriolis forces, which have both biomechanical (human factors) and vestibular effects. The resulting vestibular sensations experienced by astronauts in a rotating spacecraft would differ from those experienced by subjects working erect in a rotating room on Earth. When subjects make out-of-plane head movements, they experience nauseogenic cross-coupled vestibular stimulation. Similarly, Coriolis forces deflect the subjects' limbs in a consistent and predictable direction that is dependent upon the direction of room rotation and head movement. In order to validate the continuous short/medium radius AG approach as a countermeasure, we must first determine how fully humans can adapt to the complex vestibular sensations induced by living perpendicular to the angular velocity vector of their habitat. Finally, another characteristic of rotational environments is that the AG force amplitude varies directly with the radial distance from the center of rotation. For some orientations or motions of a crewmember within the AG field, this might elicit adverse physiological consequences. The central nervous system (CNS) can adapt to sensory rearrangements in which the relationship between motor commands and sensory inflow remains consistent. Consequently, rotating room subjects who experience 1 g at low rotation rates eventually adapt to the predictable Coriolis stimuli and are no longer sick.

The parameters of gravity-level (a_{AG}) and rotation rate (ω) are crucial to the feasibility of AG spacecraft designs, since they determine the required rotational radius: $a_{AG} = \omega^2 r$. The interaction of the rotating segments of the spacecraft with the propulsion techniques employed is also of primary concern. "High thrust" systems (for example, chemical or nuclear thermal propulsion) may require de-rotation prior to performing any propulsive maneuvering. This may be unfavorable from a crew and systems performance standpoint, and may increase the consumables mass (spin-down, spin-up propellant). "Low thrust" systems (electric propulsion) involve long-duration thrust arcs and vehicle steering while under spin. This may lead to complex de-spun spacecraft segments with fluid and power connections through rotating interfaces.

Previous design studies (Refs. 1, 2) treated artificial gravity as a design requirement that was often dependent upon other parameters, specifically, propulsion technologies. Often times, an AG option was "tacked on" to propulsion choices made *a priori*, with questionable compatibility. In this study, AG should be considered the driving requirement, with other system choices made (within "technology horizon" constraints) to be most compatible.

Options

There are essentially 2 solutions for implementing AG and 2 primary approaches available for determining the thresholds and prescriptions necessary to implement AG during space-based operations.

Options for AG implementation solutions include:

1. Long radius continuous vehicle rotation – This option will require a vehicle to be developed that implements the specifications of g level, rotation rate, and radius. This option requires that these specifications be determined prior to vehicle concept development and design. This option will also require new concepts for space operations to be developed.
2. Short radius intermittent centrifugation of crews that can be either motor driven/powered or human powered – This option will require the development of human centrifuges that can be utilized on a vehicle or during surface operations. Research will be required on the ground and on ISS to determine the specific functional requirements of this centrifuge. A design solution will be required to integrate the centrifuge design with that of the vehicle and surface habitats.

To specify whether one or both of the above implementations is required to sustain a human being flying to and working on Mars and to answer the basic design questions (how much "G" is needed, how often it should be applied, what are the minimum acceptable radius? and the maximum rotation rate?), there are 2 primary research approaches that can be taken by the Agency.

Options for **research approaches** include:

1. Continue providing funding for individual investigator initiated or specific study grants to study single systems and answer individual hypothesis. – This is the approach taken to date for AG research and while it has produced a broad literature base of information, no specific countermeasure has been identified. This approach will require a significant investment of funds into research projects and will also require oversight of the research to provide for answers to each and every question.
2. Implement a broader based coordinated and directed effort to provide a timely set of multisystem answers to the basic questions of AG implementation. – This option would provide a multi-pronged approach to developing optimal prescriptions for implementing AG aboard exploration class missions. Most of the research will be performed in ground-based venues. Experimental models that make use of both animal and human subjects will be employed. Opportunities for conducting animal and human research in space will follow the initial ground-based studies to further direct the evolution of an AG countermeasure. Research will first elucidate basic AG parameters (how much g is needed, how often it should be applied, what are the minimum acceptable radius and the maximum rotation rate) and later progress to investigate AG countermeasure approaches. In addition, studies will carefully examine the potential pitfalls to an AG countermeasure and research will be directed to understand what biomedical countermeasures might be required during lunar or Martian surface operations. As a corner stone of this approach all research will be initiated as part of an overall research plan aimed at meeting the schedules and requirements of the exploration program.

Recommendations

Broad, directed Artificial Gravity Human and Vehicle Research Projects using existing and to be developed hardware and facilities should be implemented to:

1. Evaluate a conceptual spacecraft design, using a mission parameter range that will allow systems trades such as propulsion, power, habitation, etc. and establish the impact of an artificial gravity configuration. The results of this study should retain a certain level of mission-independence, allowing the results to be applied to a range of destinations, mission classes, and AG requirements.
2. Develop the evidence base necessary to advise engineering designers on optimal radii, angular velocities, angular accelerations, etc. to be used in vehicles providing continuous AG for long-duration exploration class missions
3. Develop the evidence base necessary to devise optimal prescriptions for application of short-radius intermittent AG, with and without augmentation by exercise or other countermeasures, to be used in designing human centrifuges for use within non-rotating transit vehicles or surface habitats during exploration class missions
4. Develop the biomedical database necessary to fully characterize short- and long-term, multisystem responses to g-transitions expected during exploration class missions (0 G to 1 G, 1 G to 0 G, 0 G to 3/8 G, 3/8 G to 0 G, etc.)

5. Develop the biomedical database necessary to fully characterize the multisystem physiological consequences of long-term exposure to hypogravity environments expected during exploration class missions (1/6 G, 3/8 G, and possibly other G-levels).

Conclusions

A solution to provide an artificial-g environment onboard long-duration human spacecraft will fundamentally change our thinking about crew health care in space. Establishing this requirement upon vehicle design studies may result in innovative and "practical" concepts.

References

[1] Boeing Defense & Space Group, Advanced Civil Space Systems, *Space Transfer Concept and Analysis for Exploration Missions, Final Report Phase One*, Contract NAS8-37857 to NASA Marshall Space Flight Center, Huntsville, Alabama, March, 1991.

[2] McDonnell Douglas Space Systems Company – Houston Division, *Integrated Mars Mission Analysis*, January 1992.

Appendix 1 Addressed CPR risks

Risk No.	Discipline	Risk Title	Risk Description *(Brief)*
1	Bone	Accelerated Bone Loss and Fracture Risk	Failure to recover bone lost during mission coupled with age-related bone loss can lead to osteoporotic fractures at a younger age. Important for long duration missions for crew health and for designing rehabilitation strategies.
2	Bone	Impaired Fracture Healing	Bone fractures incurred during and immediately after long duration space flight can be expected to require a prolonged period for healing, and the bone may be incompletely restored, owing to the changes in bone metabolism associated with space flight.
3	Bone	Injury to Joints and Intervertebral Structures	Fascia, tendon and ligament overuse or traumatic injury, joint dysfunction upon return to normal/partial gravity. Hypogravity changes to intervertebral discs may increase risk of rupture, with attendant back pain, possible neurological complications.
4	Bone	Renal Stone Formation	Urine calcium concentration is increased due to increased bone resorption during hypogravity and to decreased urine volume during periods of dehydration.
5	Cardio	Occurrence of Serious Cardiovascular Dysrhythmias	Cardiac dysrhythmias pose a potentially lethal risk during long-duration space flight. Cardiac dysrhythmias may also cause hypotension and syncope. Cause is unknown.
6	Cardio	Diminished Cardiac and Vascular Function	Short-duration space flight has been associated with a decrease in cardiac mass. Long-duration space flight may result in greater decrease in cardiac mass and additional alterations that may diminish cardiac function, aggravate underlying cardiovascular disease (e.g., arterial atherosclerosis) leading to myocardial infarction, stroke or heart rhythm disturbances that could be irreversible.
8	IIH	Immunodeficiency / Infection	It is possible that space flight may suppress immune function, a newly designated form of secondary immunodeficiency disease. Secondary immunodeficiency causes an unusual number of infections, with greater severity and duration. Secondary immunodeficiency leads to reactivation of latent virus infections with organisms that lay dormant until immune resistance is lowered and virus replication begins.
9	IIH	Virus-Induced Lymphomas and Leukemia's	This risk occurs in humans who are immunosuppressed and develop latent virus reactivation. Since the astronauts all carry many latent viruses in their bodies because of universal exposure, it is possible that if their immune resistance is lowered to a critical level, they may be subject to B-cell lymphomas and T-cell leukemias.
10	IIH	Anemia, Blood Replacement & Marrow Failure	There is loss of plasma and red blood cells due to exposure to microgravity and a here is a decrease of RBCM of 15% in the first week in space (2 units of blood). This can lead to problems with spaceflight anemia, or hemorrhage.

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Risk No.	**Discipline**	**Risk Title**	**Risk Description *(Brief)***
11	IIH	Altered Host-Microbial Interactions	The balance between human host and microbes found on Earth may be altered in space because of responses associated with microgravity, stress, radiation, or other space flight factors
12	IIH	Allergies and Autoimmune Diseases	Genetic inheritance and environmental insults are the two factors that trigger development of allergic and autoimmune diseases. Failure of immunologic tolerance due to malfunction of regulatory immune mechanisms leads to immune-mediated diseases in life. Space flight conditions have been shown to upset immune regulation and produce immunologic disease in experimental systems.
13	Muscle	Skeletal Muscle Atrophy Resulting in Reduced Strength and Endurance	Given that deficits in sensory-motor regulation of muscle-force generation capacity and movement skill occur in space flight, this deficiency could result in an inability or reduced ability/fidelity in performing mission-directed physical activities (especially when the system becomes loaded), as well as cause a proneness for muscle/connective tissue (muscle fiber; fiber-tendon; tendon-bone interfaces) damage and soreness, further exacerbating intrinsic muscle performance capacity.
14	Muscle	Increased Susceptibility to Muscle Damage	Given that muscle fiber atrophy and corresponding contractile protein phenotype shifts occur in response to space flight, this deficiency could result in an inability or reduced ability/fidelity in performing mission-directed physical activities, as well as cause a proneness for muscle/connective tissue damage and soreness further exacerbating one's performance.
15	Neuro	Vertigo, Spatial Disorientation and Perceptual Illusions	When astronauts transition between gravitational environments, head movements and/or vehicle maneuvering can cause spatial disorientation, perceptual illusions and/or vertigo. Should any of these occur in flight deck crewmembers during critical entry or landing phases it could lead to loss of vehicle. In-flight spatial disorientation can cause operational difficulties during docking and remote manipulation of payloads that can (and has) caused dangerous collisions, while in-flight frame-of-reference illusions, direction vertigo, or navigation problems could cause reaching errors, spatial memory failures, difficulty locating emergency egress routes and/or fear of falling during EVA (height vertigo). While rotational artificial gravity (AG) has great potential as a bone, muscle, cardiovascular and vestibular countermeasure, head movements out of the plane of rotation will produce illusory spinning sensations about an axis orthogonal to the head motion, which may lead to spatial disorientation.

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Risk No.	Discipline	Risk Title	Risk Description *(Brief)*
16	Neuro	Impaired Movement Coordination Following G-transitions	When astronauts adapt to 0-G transition to an Earth, Moon, or Martian gravitational environment, balance, locomotion and eye-head coordination are transiently disrupted. Some symptoms may be masked by sensory substitution, only to emerge unexpectedly in response to changing sensory affordance contexts. Muscle atrophy and orthostatic hypotension may also contribute to post-flight balance and locomotion impairment. Some long-duration crewmembers have been unable to egress the spacecraft unassisted in 1-G, so affected crew are at an increased risk of emergency at or soon after landing. There are large individual differences, but recovery of normal abilities requires several days to weeks. Recovery time increases as the 0-G exposure time increases. Lower extremity coordination is often the slowest to return. Post-flight rehabilitation currently employs only traditional methods and may not be optimal. Sensory-motor changes on long-duration flights increases the potential risk of post-landing falls and bone fractures and delays safe return to normal daily activities (running, driving and flying).

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Refer: RFI Focus Area – Crosscutting Design Drivers and Architecture Elements
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Risk No.	Discipline	Risk Title	Risk Description *(Brief)*
17	Neuro	Motion Sickness	Motion sickness symptoms frequently occur in crewmembers during and after G-transitions. Symptoms include nausea, stomach awareness, gastrointestinal stasis, anorexia, dehydration and less overt but operationally significant symptoms such as "space stupids," irritability, profound fatigue ("sopite" syndrome) and changes in sleep-wake cycle. Motion sickness symptoms decrease crew work capacity, vigilance and motivation, impair short-term memory and increase the likelihood of cognitive error. Although only 10-20% of Shuttle crews vomit, 75% experience symptoms for the first 2-4 days in 0-G and many experience similar symptoms for hours to days after landing. Several crewmembers have remained symptomatic during flight for up to two weeks. Current anti-motion sickness drugs are only partially effective. Though they appear to reduce symptoms and delay onset, they have significant side effects that prevent regular prophylactic use. While rotational AG has great potential as a bone, muscle, cardiovascular and vestibular countermeasure, head movements out of the plane of rotation may lead to motion sickness. How provocative the AG stimulus is at levels between 0 and 1-G and how rapidly and completely humans can adapt is largely unknown and cannot be fully determined in ground laboratories. If motion sickness drives an EVA crewmember to vomit in the extant extravehicular mobility unit (EMU), a complete shutdown of the primary and secondary oxygen supplies could occur, leaving only a few minutes of residual oxygen in the suit, creating a serious emergency. Vomit on the faceplate could also block vision. Even if the crewmember survives, vomit is biologically active, so the EMU cannot be reused and must be returned to the ground for refurbishment..
18	Nutrition	Inadequate Nutritional Requirements	Without scientifically supported nutritional requirements, a food system cannot be developed to support astronaut health. Nutritional requirements for space include fluids, macronutrients, micronutrients and compounds or elements that may be essential and may include compounds that may be required to optimize health status such as lipids, energy distribution (e.g., % calories from carbohydrate), fiber, and non-nutritive factors such as various phytochemicals, etc. Requirements must take into account any changes in the sensory system that might influence taste and smell influence intake, and the role of countermeasure-induced alterations on nutrient requirements.

Table 0-1 Crosscutting Area: Autonomous Medical Care

Risk No.	Discipline	Risk Title	Risk Description *(Brief)*
20	Clinical	Major Illness & Trauma	Major Illness & Trauma (Diagnosis, Management, CPR, BCLS, ACLS, BTLS, ATLS, DCS, Toxic Exposure-Detection and Management, Surgical Management, Medical Waste Management). There is a risk of major illness that increases with length of mission. There is always a risk of trauma, which can vary according to activities (e.g. construction, vehicle driving, etc.) Lack of capability to treat these major illnesses and injuries poses a threat to life and mission.
21	Clinical	Pharmacology of Space Medicine Delivery	Pharmacology of Space Medication Delivery (Space flight Physiology Effects – Pharmacodynamics/Pharmocokinetics, Drug Stowage/Utilization/Replenishment, Drug Use Optimization). If issues relating to pharmaceutical stowage, generation, effectiveness, and administration methods are not solved then we may be unable to treat some medical conditions during flight, resulting in a threat to both life and mission.
23	Clinical	Return to Gravity/Rehabilitation	Return to Gravity/Rehabilitation. Possibility of deconditioning during space flight to another gravitational body entails the need for rehabilitation once a crewmember returns to gravity. Otherwise the crewmember may not be able to function as needed.

Table 0-2 Crosscutting Area: Behavioral Health and Performance (BH&P)

Risk No.	Discipline	Risk Title	Risk Description *(Brief)*
27	BH&P	Human Performance Failure Due to Poor Psychosocial Adaptation	Human performance failure due to problems associated with adapting to the space environment; poor interpersonal relationships and/or group dynamics; inadequate team cohesiveness; and poor pre-mission preparation.
29	BH&P	Mismatch Between Crew Cognitive Capabilities and Task Demands	Human performance failure due to inadequate accommodation of human cognitive limitations and capabilities. If human cognitive performance capabilities are surpassed due to inadequate design of tools, interfaces, tasks or information support systems, mission failure or decreased effectiveness or efficiency may result. Identifying, locating, processing or evaluating information to make decisions and perform critical tasks in short time-frames in nominal and emergency situations, with limited crew size, relying on strictly local resources is extremely subject to human error.

Table 0-3 Crosscutting Area: Radiation Health

Risk No.	**Discipline**	**Risk Title**	**Risk Description *(Brief)***

Table 0-4 Crosscutting Area: Advanced Human Support Technology (AHST)

Risk No.	**Discipline**	**Risk Title**	**Risk Description *(Brief)***
43	ALS	Maintain Acceptable Atmosphere	Inability to control atmosphere concentration CO_2, O_2 and trace contaminants in habitable areas (excessive airborne chemical pollutants e.g., formaldehyde, ethylene glycol, Freon from leaks, fires, etc.) including microbial contaminants (microbial degradation of biological wastes).
44	ALS	Maintain Thermal Balance in Habitable Areas	Inability to acquire, transport and reject waste heat from life support systems reliably and efficiently with minimum power, mass and volume. Capability is crucial to enabling extended human exploration of space.