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Research recommendations of the ESA Topical Team on Artificial Gravity

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Abstract

Many experts believe that artificial gravity will be required for an interplanetary mission. However, despite its attractiveness as an efficient, multi-system countermeasure and its potential for simplifying operational activities, much still needs to be learned regarding the human response to rotating environments before artificial gravity can be successfully implemented. The European Space Agency (ESA) Topical Team on Artificial Gravity recommended a comprehensive program to determine the gravity threshold required to reverse or prevent the detrimental effects of microgravity and to evaluate the effects of centrifugation on various physiological functions. Part of the required research can be accomplished using animal models on a dedicated centrifuge in low Earth orbit. Studies of human responses to centrifugation could be performed during ambulatory, short- and long-duration bed rest, and in-flight studies. Artificial-gravity scenarios should not be a priori discarded in Moon and Mars mission designs. One major step is to determine the relationship between the artificial gravity dose level, duration, and frequency and the physiological responses of the major body functions affected by spaceflight. Once its regime characteristics are defined and a dose–response curve is established, artificial gravity should serve as the standard against which all other countermeasure candidates are evaluated, first on Earth and then in space.

Keywords: Human spaceflight; Countermeasure; Microgravity-induced physiological effects; Weightlessness

1. Introduction

Several aspects associated with how we sense and use the force of Earth's gravity are apparently involved in maintaining normal health and fitness. These include the pull of gravity in the + Gz (head-to-foot) direction, exertion against gravity forces during normal activity, the element of "change" provided by postural and other movement and orientation, and directional cues about our spatial orientation relative to the gravitational vertical. Without regular exposure to these + Gz forces, as during spaceflight [1] or bed rest [2], important cardiovascular, musculo-skeletal and neural, primarily vestibular-mediated functions, are compromised. Gravity, or the lack thereof, is directly or indirectly the root of the spaceflight physiological deconditioning problem. Whether replacing gravity will fully restore Earth-like health in space remains in the realm of conjecture until the question is attacked in a concerted and systematic manner.

In the view of many [3–7], artificial gravity will be required for an interplanetary mission. Artificial gravity

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can be generated by linear accelerating or rotating transit vehicles, or by using short-radius human centrifuge devices within the transit vehicle or inside the surface habitat. However, despite its attractiveness as an efficient, multi-system countermeasure and its potential for simplifying operational activities, much still needs to be learned regarding the human response to rotating environments before artificial gravity can be successfully implemented.

It is presumed that a daily bout or two of artificial gravity along the Gz axis would replace the gravitational force that constantly surrounds us and therefore affects all body systems [8]. A few continuous hypergravity exposure studies in humans in rotating rooms have been performed, but were of limited duration with a focus on addressing tolerance limits and the appearance of unpleasant side effects [9]. With the exception of the attempts to use centrifuges in the 19th century to treat mental disorders [10], most research on the use of artificial gravity in humans as a countermeasure to space deconditioning has been concentrated on the cardiovascular system. Animal research, on the other hand, has provided more information on the effects of hypergravity exposure on other physiological systems, but has predominantly focused on nearly continuous hypergravity exposure, with the apparatus stopped daily for only an hour or two for cleaning [11].

A Topical Team on Artificial Gravity was formed as a result of a proposal submitted to an International Space Life Sciences Research Announcement at the European Space Agency (ESA) in November 2004. The group consisted of world-renowned experts in the fields of space physiology and medicine. After an extensive review of past and present studies, a gap analysis was performed, the results of which led to the identification of the next steps in artificial gravity research, both short- and long-term, required to assess whether continuous or intermittent artificial gravity prescriptions (mostly centrifugation) can limit deconditioning of sensory-motor, cardiovascular, and musculo-skeletal systems, and validate the operational aspects of using artificial gravity as an effective countermeasure for long-duration space travel. The basic recommendations of this ESA Topical Team are presented below. The full report of the Topical Team appears in the book referenced in [7].

2. Potential tools for investigations on artificial gravity

Research on the effects of centrifugation is required to prioritize and determine the optimal range of parameters on the physiological responses and well-being of the crew. These include the radius of rotation, rotation rate, gravity level, gravity gradient, as well as frequency and duration of artificial gravity exposure. However, once the optimal combination of centrifugation parameters is found, the resulting artificial gravity prescription will have operational consequences on both the vehicle and mission designs. For example, centrifugation exposure executed in several shorter bouts instead of one longer period is likely to improve both the efficiency and the tolerance of the centrifugation by the crew. But, in turn, such a prescription will impose a burden on crew time and the mission operational constraints. Therefore, both fundamental physiological, medical, and well-being issues as well as operational issues must be addressed.

The key research questions that must be addressed before artificial gravity can be prescribed to humans en route to Mars or for any long-duration space mission include: How much artificial gravity, i.e., at what duration and level, is needed to prevent this deconditioning? Is $1g$ required or is a fraction of this level sufficient? If intermittent artificial gravity is enough, how many centrifugation exposures and at what g level per day are required? More importantly, from a medical standpoint, what is the tolerance of the human body to repeated centrifugation? [12].

Although a definite answer to these questions will only come from validation studies performed in space, some important preliminary screening and evaluation studies can be carried out via ground-based studies on Earth. In fact, the difficulty and expense of spaceflight experiments or feasibility demonstrations mandate the appropriate use of ground facilities to design and test artificial gravity concepts.

Analog environments to simulate the effects of weightlessness on long-duration physiological deconditioning have been studied for many years [13]. The most widely used human model is continuous bed rest, with the head tilted down by 6°. Bed rest is known to result in muscle atrophy, bone loss, redistribution of body fluids and body mass, and decreases in plasma volume and red blood cells [2]. After bed rest, subjects manifest orthostatic intolerance similar to that typically demonstrated by returning astronauts. Although the physiological consequences of bed rest are in most respects quite similar to those of weightlessness, there are a few notable differences. For example, while diuresis is common during the early days of bed rest, it has not been clearly demonstrated in space [14]. Furthermore, bed rest does not produce the full range of vestibular disorders characteristic of space travel. It is likely that postural disturbances seen after bed rest