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Space Station Centrifuge: A Requirement for Life Science Research

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NASA

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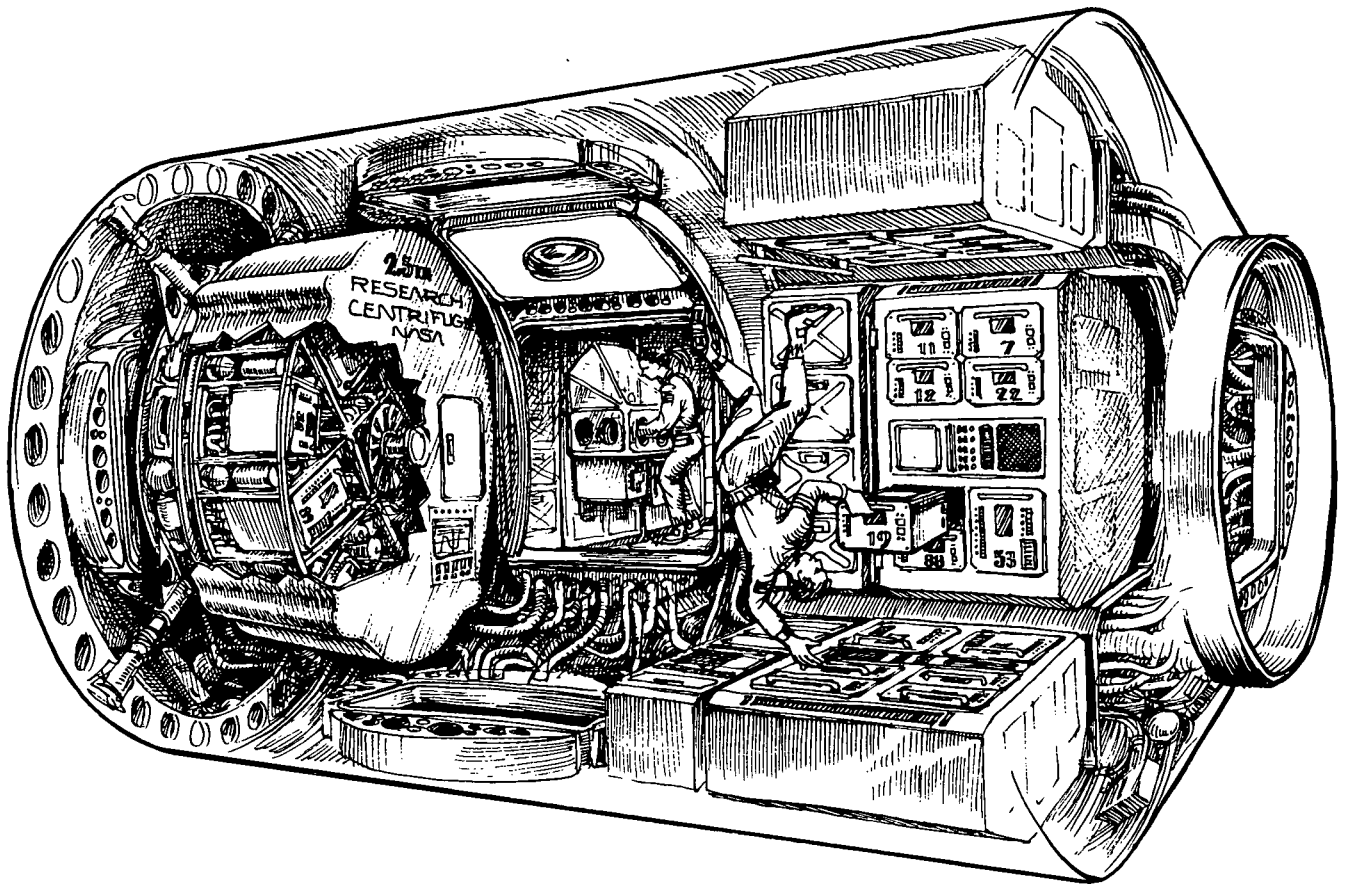## NASA
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Artist's concept of the 2.5 m diameter centrifuge and μ-g specimen holding units in a node of the Space Station Freedom. Through the open hatch, one can see the glovebox in the U.S. Laboratory.

Preface

In the intervening time since this conference was held at the University of California, Davis and the publication of this conference report, the Life Sciences Division of NASA's Office of Space Science and Applications (OSSA) has committed to the development of the largest possible diameter research centrifuge to be flown on the International Space Station Freedom. The Biological Flight Research Projects Office at Ames Research Center, Moffett Field, California, is responsible for developing the centrifuge facility, which consists of a suite of hardware including the centrifuge, a zero-gravity holding facility for specimens, a glovebox for performing experiment protocols, and a specimen chamber service unit for providing clean specimen chambers via replacement or cleaning.

Initially the largest centrifuge that could be accommodated in the U.S. Science Laboratory module was approximately 1.8 m in diameter. However, with the removal of the centrifuge from the U.S. Lab to a node or to another module, it was feasible to increase the diameter of the centrifuge to 2.5 m and that size has been base-lined by OSSA for the Space Station Program.

Following the recommendations of the conference report, a Centrifuge Facility Science Working Group (SWG) was formally established in 1988, which was composed of both animal and plant physiologists interested in promoting gravitational biology. That group specified the science requirements for the centrifuge facility that were then translated into engineering requirements for a conceptual design study. Two contractors, Lockheed Missiles & Space Company, Inc., Sunnyvale, California, and McDonnell Douglas Space Systems Company, Huntington Beach, California, were selected for a 17-month conceptual design study, which was completed in February 1991. The SWG has participated in major reviews of the study and will continue to be active during the design, development, and fabrication of the Centrifuge Facility.

Introduction

As planning for Space Station Freedom progresses, NASA Life Sciences Division is addressing the requirements necessary to conduct Life Sciences research programs aboard the space station. A key facility for such a research program, which has been identified frequently by other panels as a requirement, is a centrifuge (table 1). Recently, for example, a group of surrogate users established a large series of potential studies, comprising 171 experiments, for Space Station Life Sciences research (Johnson, Arno, and Mains, 1989). More than half of these potential studies required a centrifuge. To identify and rationalize the need for such a research device, a panel of scientists (table 2) was assembled at the University of California, Davis, in January 1986. The panel consisted of experienced investigators representing a wide range of the biological sciences. A majority of the investigators had centrifuge experience and a third of the investigators had orbital experience. The charge was: "Does NASA need a centrifuge aboard Space Station Freedom? If so, why?"

This group deliberated the need and scientific rationale for such a facility (preliminary considerations for design criteria and implementation recommendations). The group was not a user working group, so planning was not appropriate. Rather, this conference was held to consider only the beginning of an evolutionary process—to determine the need for a space station centrifuge; to identify and recommend resolution of the remaining unknown factors; and to recommend that NASA establish a program to ensure the continuing development of gravitational biology.

Requirement for a Centrifuge on Space Station

A space station centrifuge is an absolute requirement for life science research: as a research tool for understanding how gravity and the lack thereof affects basic biological processes; to provide a 1-g control environment; and to assess the efficacy of artificial gravity as a countermeasure for deleterious biological effects of spaceflight.

Data from spaceflight and ground-based experiments have clearly demonstrated the importance of Earth gravity to normal hematologic, cardiovascular, musculoskeletal, and vestibular function in man and animals and to normal orientation and growth responses in plants. All of these systems and functions are profoundly affected by exposure to microgravity. Understanding the mechanisms of these effects and the development of rational and effective countermeasures to astronaut deconditioning in space requires the investigation of these gravity-dependent systems and functions under conditions of long-term weightlessness/microgravity.

To fully generalize the nature of the interaction of biological systems and gravity, it is necessary to make repeated observations at several field strengths between 0 and 1 G. A space station centrifuge provides the only method for such studies of these gravity-dependent phenomena between microgravity and Earth gravity. The centrifuge must be capable of accommodating humans, experimental animals, and plants—intermittently and/or continuously.

Table 1. Previous centrifuge recommendations

Year	Group	Reference
1970	Space Sciences Board, NRC	Space Sciences Board, 1970
1971	Space Sciences Board, NRC	Space Sciences Board, 1971
1974	Space Sciences Board, NRC	Space Sciences Board, 1974
1975	Space Sciences Board, NRC	Space Sciences Board, 1975
1976	Space Sciences Board, NRC	Space Sciences Board, 1976
1978	Life Sciences Advisory Committee	Life Sciences Advisory Committee, 1978
1979	Space Sciences Board, NRC	Space Sciences Board, 1979
1983	Fabricant Report	Fabricant, 1983
1983	AIBS Centrifuge Symposium	Spaceflight Centrifuge Workshop, 1983
1984	Developmental Biology Workshop	Souza and Halstead, 1984
1984	ICES Conference: Space Station Centrifuge	Halstead, et al., 1984
1986	Paine Report: Pioneering the Space Frontier	Paine, 1986

Table 2. Conference participants

Coordinators:

Arthur H. Smith, Chairman	University of California, Davis
Charles A. Fuller	University of California, Davis
Charles M. Winget	NASA Ames Research Center
Catherine C. Johnson	NASA Ames Research Center

Review Committee:

Robert S. Bandurski*	Michigan State University
Emerson L. Besch	University of Florida
Allan H. Brown*	University of Pennsylvania
Russell R. Burton	USAF/SAM, Brooks Air Force Base, TX
Dave Chapman	University of Pennsylvania
James A. Cheney	University of California, Davis
Brian R. Duling	University of Virginia
Leon E. Farhi	SUNY at Buffalo
W. Francis Ganong*	University of California, San Francisco
Frederick W. Hanson	University of California, Davis
J. Richard Keefe	Case Western Reserve University
Jiro Oyama	NASA Ames Research Center
Hermann Rahn	SUNY at Buffalo
R. C. Simmonds*	USUHS, Bethesda
Douglas G. Stuart	University of Arizona
David Tomko	Univ. of Pittsburgh/NASA-ARC
C. Herbert Ward	Rice University
Lawrence Young	MIT

Others in Attendance:

Roger Arno	NASA Ames Research Center
Millie Hughes-Fulford	Payload Specialist
Beth Inadami	NASA Ames Research Center
Jenny Kishiyama	NASA Ames Research Center
Adrian Mandel	NASA Ames Research Center
Dean M. Murakami	University of California, Davis
Robert Phillips	Payload Specialist
Delbert Philpott	NASA Ames Research Center
Nancy Searby	Lockheed Missle & Space Corp., Sunnyvale, California
Joseph Sharp	NASA Ames Research Center
Ken Souza	NASA Ames Research Center
Lynn Wiley	University of California, Davis
John Zicker	NASA Ames Research Center

*Participated in preparation and review of this report.

Gravitational Biology

Gravitational biology has had a delayed development, because of the constancy of Earth gravity. However, with the recent renewal of research with centrifuges, and more recent research with Earth-orbital vehicles, progress is being made in understanding the biological effects of gravity and gravity-like fields upon plants, animals, and microorganisms.

Gravitational biology is concerned with the functional and structural alterations that occur in biological systems exposed to altered gravitational fields. These have been observed in studies using a variety of experimental approaches, some ground-based and some in Earth orbit. A more detailed description and documentation of these studies is provided in appendix A.

Some of the gravitationally induced changes in plants, humans, and animals can be explained as a direct result of the altered gravitational load. However, in some other cases a causal relationship to the altered load is not apparent, nor in some cases can these responses be explained by conventional understanding. Since such gravitational effects must result ultimately from the altered load, it is most likely that some gravitationally sensitive organ, organelle or tissue transduces the physical stimulus, thereby producing agents or secondary stimuli that cause the observed biological response. This implies that organisms have gravity sensors, perhaps many of them, that are not currently identified and that Earth gravity exerts, as yet, undetected biological influences. Consequently a full understanding of gravitational biology will be as important to humans on Earth as it is to humans in other gravitational environments—in space, on the Moon, on Mars, etc. Developing such understanding will require a broadly based and vigorously pursued gravitational biology research program involving a variety of species and using a significant number of gravitational field strengths, including weightlessness/microgravity.

Requirement for a 1-G Centrifuge

An onboard centrifuge developing a 1-G field is essential to the analysis of the nature of the Space Station Freedom environment, and to the study of the immediate effects of a controlled change in field strength.

The principal physical change in the environment of orbiting vehicles is the removal of the effects of Earth gravity—weightlessness—and understanding this phenomenon is essential for the continuing development of gravitational biology. The environment of the space station also has other factors that may modify biological function, such as solar and cosmic radiation, forces and

materials produced in the space station (noise, vibration, environmental contaminants, etc.), and illumination schedule. These secondary factors may produce separate biological effects, or modify the effects of weightlessness. An interaction of the effects of ionizing radiation and gravitational fields has been demonstrated in rats (Casey et al., 1967; Edwards, 1963), and in plants and microorganisms in orbiting satellites (Saunders, 1971).

In short-term orbital experiments these extraneous factors may not significantly affect results; however, in the protracted exposure anticipated with the space station, their cumulated effects may seriously interfere with the research. It is essential that any influence of extraneous factors upon biological experiments in the space station be identified so they can be separated out and not be confused with the effect of weightlessness. For this, provision must be made for a suitable control as a part of space station experiments, which can only be fulfilled by an onboard centrifuge operating at 1 G. If the only biologically significant factor in the space station environment is weightlessness, the responses of onboard 1-G controls should be the same as those exhibited by equivalent ground-based controls. The use of onboard 1-G controls on the space station should be continued until all variables in the space station environment are identified and determined not to have interfering biological effects.

The space station centrifuge facility will also be used for specimen holding so that the transition to weightlessness and return to 1 G can be made in a controlled manner, thereby permitting careful and repeated observations of the immediate responses to a 1-G change in the ambient acceleration field. For this, biological material will be maintained at 1 G from launch and provision made for its ready transfer to the space station environment. Similarly, it must be arranged for materials maintained under conditions of weightlessness to be readily transferred to the 1-G centrifuge. Animals and plants could also be preadapted to other fields, for example, Lunar–0.16 G, or Martian–0.35 G.

Other potential uses of a space station centrifuge include (1) investigation and provision of countermeasures for gravitational de-adaptation of astronauts, and (2) studies of labyrinthine function in weightlessness. Potentially, periodic exposure to a 1-G field could prevent or limit the severity of the decompensations seen in circulatory, skeletal, and muscular systems that occur during continued weightlessness. Some information is available on human use of a centrifuge in space; this is reviewed in appendix B.

Requirement for a Large-Diameter Variable-Gravity Centrifuge

To understand the interaction of gravity and biological systems, the effects of fields other than 0 and 1 G must be investigated. Of particular importance is the determination of threshold of quantitative effects for various biological processes.

For large animal species it is essential that a large-diameter centrifuge be available on the space station, for reasons that will be discussed later. This emphasis on a large-diameter apparatus does not preclude, nor minimize the importance of smaller diameter centrifuges that will be useful for small animals, cell, tissue, and some invertebrate and plant experiments (appendix D). However, small-diameter centrifuges can be developed and provided as part of a space station experiment, whereas a large-diameter centrifuge must be available as part of the space station. Consequently, the discussion of this section will emphasize only the large-diameter centrifuge.

To determine gravitational effects satisfactorily, it is essential that a space station centrifuge be capable of providing multiple fields between 0 and 1 G. Observations in weightlessness establishes the mass-determined biological function that is retained in weightlessness. The difference between observations made at Earth gravity and in weightlessness will establish the weight-determined biological function, which develops under a 1-G gravitational load. However, such information will be based on only two points of observation, and as such it cannot be generalized—*and if space biology is to have scientific merit it must be amenable to generalization.* Observations in at least three, and preferably more gravitational fields will be necessary for developing any generalization, such as determining the kinetics of gravitational responses.

Multi-field strength capability of a space station centrifuge also is essential in determining threshold fields for gravitational responses (appendix A). It can be demonstrated that for some biological processes an acceleration field greater than minimum strength is required to elicit a gravitational response. Understanding such thresholds and kinetics is essential to the development of a coherent science of gravitational biology. Understanding thresholds for adaptive responses will also provide information of biomedical concern. The "permanent presence of man" in space may be jeopardized by human inability to adapt to chronic weightlessness. Artificial inertial fields (artificial gravity) in future spacecraft or stations may provide the required countermeasure for our successful habitation of space. Understanding the threshold-G for various physiological processes will be an essential

contribution in establishing the appropriate fractional-G for such countermeasures.

Using threshold fields may also be necessary in some biological experiments to yield meaningful results. Some systems may require at least a very low intensity field (threshold about 0.03 G) to provide an essential internal orientation or organization—and at lesser fields the system may become nonviable.

For example, in the normal incubation of chicken eggs, the buoyancy of the yolk and its density gradient orient the developing embryo close to the shell. This minimizes the diffusion distance for oxygen (which diffuses through pores in the shell), making available an adequate supply to the developing embryo. If this arrangement is frustrated by incubating chicken eggs "pointed end-up," so that viscous albumen prevents the yolk from approaching the shell, then an inadequate oxygen supply will cause a 90-95% mortality of embryos (Cain and Abbott, 1971). This effect of inverted incubation applies only to the early embryo. The allantoic membrane, which is developed by 10 days incubation, spreads over the inside of the shell, acting as a "lung" for the embryo. So inversion of chicken eggs after 10 days incubation would not inhibit embryonic development. Weightlessness, eliminating both the yolk's buoyancy and orienting effect of the density gradient, will have an effect on the early embryo that is similar to incubation of chicken eggs in an inverted position.

Examination of the density gradient of chicken egg yolks have indicated that they can be suitably oriented with a very small gravitational field, about 0.03 G (Sluka, Smith and Besch, 1966). Consequently early embryogenesis can be done in orbit by providing an 0.03 G field, a suitable use of the space station centrifuge. This does not mean that the early embryo has a requirement for a minimum acceleration field—it is merely for oxygen. In smaller egg (Coturnix) diffusion distances for oxygen are no longer critical, and they can be successfully incubated in space (Boda et al., 1991).

Plants also may have minimal field requirements for normal orientation and growth; a lesser field will adversely affect their production capacity. Identifying such thresholds will be important in developing a suitable artificial gravity for protracted space travel, with the use of plants in a Controlled Ecological Life Support System (CELSS).

It also will be advantageous for the space station centrifuge to have capacity greater than 1 G, perhaps 2 to 3 G. These greater fields will be useful in provocative testing—determining the gravitational responses of biological materials after periods of weightlessness. Where the 1-G centrifuge is used for specimen holding

(discussed in previous section), a greater than 1-G capacity will permit a reproduction of the launch G-profile as part of the controlled introduction into weightlessness.

Centrifuge Characteristics

Centrifuge geometry determines the rotation rate to establish a particular G-field, and also the magnitude of head-to-foot G-gradients. It is essential that ground-based research begin as soon as possible to evaluate the biological effects of these centrifuge characteristics, and the effects of continuous fields versus interruption of centrifugation.

In addition to providing an inertial field, centrifuges have other characteristics that may, if not controlled, confuse the gravitational effects. The physical relationships of a centrifuge are

$$a = r\omega^2; \text{ or } G = r\omega^2/g$$

where:

a   is the acceleration (inertial) field,

r   is the radius of rotation,

ω is the rotation rate (radians/time),

G   is the field characteristic (the weight-to-mass ratio), and,

g   is the Earth's gravitational constant.

The reciprocal relationship between radius and rotation rate allows the same field to be developed at infinite combinations of radius and rotation rate. Whether rotation rate has an effect, separate from field strength, upon gravitational experiments has never been adequately determined. In practice, the possibility of such interference has been recognized, but avoided by providing a large radius (usually 2-3 m) which minimizes any separate effect of rotation. However, in the space station, centrifuge radius may be limited and any separate rotatory influence must be identified by ground-based experiments. It is important that any interaction between rotation rate and G-field be thoroughly explored. Such information may provide suitable correction factors or may indicate the maximum fields (for a given radius) that do not develop interference from rotatory effects. A more detailed discussion of rotatory effects is provided in appendix C.

The ratio of specimen stature ("height") to the radius of rotation also is important because of potential interference from "head-to-foot" G-gradients in experimental subjects.

This potential complication also has been recognized by investigators using centrifuges, and similarly avoided by providing a large radius of rotation. In a space station there will be dimensional limits placed upon centrifuge size, potentially introducing artifacts in biological experiments. Consequently, it is imperative that ground-based research be initiated to identify the biological effects of head-to-foot G-gradients influence of rotation rate (as distinct from G field). For this it will be necessary to use several species of organisms with a significant size range. Such information may indicate the maximum G-gradient that will not interfere with experimentation or provide suitable correction factors. The latter may limit the numbers of species (on the basis of stature) amenable to centrifugation on the space station. A more detailed discussion of G-gradients in centrifuges is provided in appendix C.

Animal maintenance on a space station centrifuge can be performed by either periodically stopping the centrifuge or by rotating the crew to match the angular velocity of the centrifuge. The latter approach would provide the animals and plants with a constant field. Further, there would be no tangential stimulation as a result of starting and stopping the centrifuge, although tangential fields could be eliminated by adding a second degree of freedom to the centrifuge cage. Finally, such a facility, appropriately designed, would also provide critical information on the various human responses to rotatory and/or acceleration forces.

Ground-based studies (Burton and Smith, 1972) indicate that there is a time-intensity summation for gravitational effects, so that brief interruptions do not greatly affect the results of a biological experiment. Experiments that involve a daily 15-min interruption in centrifugation (about 1% of a day) will yield results similar to those from experiments in which the centrifugation is continuous, but at 99% of the field strength. The variability in biological response (in general ±20%) to ground-based acceleration is such that this difference could not be detected. However, this relationship may not apply in a space station where the suspension of centrifugation will involve weightlessness, potentially producing a disorientation that may induce separate and significant biological effects.

For studies with plants, space station centrifuge characteristics are somewhat different than those appropriate for animal studies, and these are discussed in appendix D.

Conclusions and Recommendations

The achievements of space and ground-based gravitational research indicate the importance of the continued development of these research activities, particularly for protracted periods in Space Station Freedom.

It is essential that the Space Station Freedom be provided with a centrifuge designed to support biological research. The availability of such a centrifuge is critical for identifying any nongravitational factors in the space station. For example, if similar results are obtained with orbital 1 G specimens and static ground controls, one can be assured that the changes observed in the space flight (0 G) specimens are due to the loss of gravity. The centrifuge is also necessary for exploring the biological effects of 0 G and of fields intermediate between 0 and 1 G..

The space station centrifuge also will be used in developing countermeasures for the prevention of deconditioning of astronauts in weightlessness and in developing suitable artificial gravity for very long-term residence in space, including those factors relating to the Controlled Ecological Life Support System.

The principal discussions have dealt with problems related to centrifuge size (radius of rotation). Further research will be necessary to resolve these considerations, however, they should not delay the development of the centrifuge. The centrifuge should be as large as structural plans for the space station permit, and should be capable of carrying loads up to human size in fields up to 2 or 3 G.

To implement these conclusions, the following recommendations are made to develop information important to the advancement of NASA Life Sciences in gravitational biology and in artificial gravity:

1.   To provide centrifuge design criteria, initiate ground-based studies to identify and evaluate the biological effects of rotation rates and G-gradient.

2.   To identify any specimen incompatibilities with the proposed centrifuge, these studies should use a variety of species, with suitable ranges of body stature and size, and examine a variety of biological parameters (circulatory, neurological, hematological, metabolic, etc.).

3.   Provide for the ground-based centrifuge research necessary for the continued development of the science of gravitational biology.

4.   Establish a program in artificial gravity, implementing and coordinating the use of both flight and ground-based centrifuge facilities.

5.   Develop the largest possible diameter centrifuge for space station use, to be available at the earliest possible date.

6.   The centrifuge should be capable of producing gravitational forces from 0.01 G to 2 or 3 G.

7.   Assess the feasibility of maintaining test specimens or subjects on the centrifuge for long periods, that is, automatic feeding and waste change out, and/or of spinning the crew up to match the angular velocity of the centrifuge for necessary servicing.

8.   Test subject compatibility with the centrifuge should include a range of species including mammals (humans to small rodents), plants, developmental animal models, and other animal models (viz. invertebrates) of basic biological interest.

9.   Ensure that animal caging for the centrifuge is similar, if not identical, to space station specimen habitats so that "caging artifacts" do not interfere with the results.

10.   Establish a Centrifuge Advisory Committee to ensure that user needs are met as these research programs develop and as the criteria for a space station centrifuge are designed and specified.

Appendix A: Gravitational Biology

Gravitational biology deals with the biological effects of gravity and gravity-like fields. These fields interact with restrained objects (both physical and biological) that have mass, thereby, producing a load (called weight) that tends to deform them, and which determines the work required for movement in the field. If exposed objects are not restrained, they merely move under the influence of the field, and no load develops. Gravitational fields are evaluated by the weight-to-mass ratio they produce, and this is commonly designated as "G." Alteration of the weight-to-mass ratio from the natural, terrestrial 1 G is the physical basis for gravitational biology (Smith, 1983).

Research in gravitational biology depends upon either changing the effect of Earth gravity or simulating a change in Earth gravity by combining it with inertial fields (produced by motion). The effect of gravity can be changed by immersion (buoyancy), recumbency (which unloads postural muscle and bone and greatly reduces intravascular hydrostatic pressures) or counter-weighting (which removes postural loads). However, in all such procedures, the effect of gravity is not completely removed, and at least parts of the organism continue to be gravitationally stimulated. However, by combining gravity with an inertial field it is possible to produce weightlessness (as in an Earth-orbital satellite) or produce net fields greater than 1 G (as with a ground-based centrifuge). With a centrifuge in an Earth-orbital satellite, it is possible to produce fields between 0 and 1 G. The effects of combining gravity and inertial forces are symmetrical, and all parts of exposed systems are affected equally (Kelly et al., 1960; Kelly and Smith, 1974).

Chronic Acceleration of Animals

Chronic acceleration describes exposure of organisms to an altered acceleration field for a sufficient period to permit a physiological adaptation. This condition simulates a change in the field of gravity. Chronically accelerated animals exhibit a variety of physiological modifications, not all of which can be explained in terms of the increased gravitational load.

When animals are exposed, over sufficiently long periods, to altered acceleration fields, they will exhibit the sequence of biological stress and physiological adaptation that also is exhibited by organisms exposed to other extreme environmental conditions (hypoxia, thermal extremes, etc.). The physiological changes observed in high G-adapted organisms indicate the adaptational responses to a simulated increase in Earth gravity. A similar stress and adaptation sequence has not been observed in plants (Brown, Dahl, and Chapman, 1975).

Many of the adaptive responses to chronic acceleration can be directly related to the increased load (the increased weight-to-mass ratio). The metabolic requirements for maintenance of posture and locomotion are increased by the gravitational load and this results in an increased energy turnover which has been observed in several species (Katovich and Smith, 1978; Pace and Smith, 1981, 1983; Smith, 1978; Smith and Burton, 1971; Smith et al., 1974). Characteristics of the load-bearing system (bone and muscle) also increase in response to the gravitational load. There is a selective increase in antigravity (extensor) muscles (Burton, et al., 1967), and they exhibit a greater contractile strength (Matthews, 1953) and resistance to fatigue (Canonica, 1966). Although the geometry of bones does not increase, there is an increased bone mineral mass (Pace et al., 1985) and an increased breaking strength (Wunder et al., 1979). There also is an enhanced functional activity of the vasomotor apparatus, presumably in response to the increased intravascular hydrostatic pressures (Duling, 1967). The myogenic resistance of the circulatory system and the responses of the baroreflexes are greatly increased. There also is an increased plasma volume which appears to result from the gravitational displacement of blood and the action of the Henry-Gauer reflex (Burton and Smith, 1969).

Other physiological changes are observed in animals that have adapted to chronic acceleration in which the relationship to the gravitational load is not apparent. Such adaptive changes have been rationalized as resulting from the stimulation of some gravitationally sensitive tissue or organ which transduces the stimulus and secondarily produces the observed adaptive response. This concept implies that animals have gravity receptors that are not yet identified.

One such adaptive response which cannot be related to the gravitational load is a decrease in growth rate and in mature body size, which is proportional to species body size and field strength (Oyama and Platt, 1965, 1967; Pitts, 1977; Pitts, Bull, and Oyama, 1975; Smith and Burton, 1967). This growth repression appears to be a regulated phenomenon since an additional loss of body substance, by a superimposed fast, is readily regained upon realimentation (Smith and Burton, 1967). This indicates that the acceleration-induced repression of growth does not result from an inability to acquire feed or from any metabolic insufficiency.

Most of this reduction in body size results from a decreased body fat content (Keil, 1969; Miller and Wise, 1975; Oyama and Daligcon, 1967; Oyama and Zeitman, 1967; Smith et al., 1975), with only a minor reduction in lean body mass. This loss of body fat, which is proportional to body size as well as field strength, has been observed in all studies of mammals and birds with the exception of monkeys (Pace et al., 1978; Smith et al., 1974). Studies of liver enzymes of chronically centrifuged rats and chickens have indicated a decreased activity for those involved in fat synthesis (Daligcon and Oyama, 1975; Evans et al., 1969; Feller and Neville, 1965; Feller et al., 1965; Neville and Feller, 1969; Oyama and Daligcon, 1967). Otherwise the mediation and regulatory mechanism of the gravitational de-fatting is not known. However, this phenomenon has not been reported in studies using mass-loading of animals.

Another phenomenon observed in some centrifuging animals is an increase in plasma proteins, which is proportional to field strength (Burton and Smith, 1969). The biological advantage of such an arrangement is obvious in maintaining plasma-tissue water exchanges (as proposed by the Starling Hypothesis). However, conventional understanding cannot explain the relationship between this phenomenon and the gravitational field. There also is an increase in body red-cell mass in some chronically accelerated animals (Burton and Smith, 1969) which is hyperbolic, becoming maximal between 1.5 and 2.0 G. This is not the limit of red-cell mass which is capable of a much greater production under a hypoxic stimulus. This gravitational phenomenon also cannot be explained by conventional understanding.

Scale Effects

Scale effects are structural and functional differences among animals that result from differences in body size. Scale effects are very important in gravitational biology.

Gravitational load, the weight-to-mass ratio, is the product of mass and field strength, so in a given field, load will increase with increasing size. This relationship was recognized by Galileo in 1638 (Galilei, 1638) and later named the "Principle of Similitude" (Thompson, 1916). One expression of this principle is the selective increase in skeletal mass in terrestrial animals of increasing size:

$$\text{Skeletal mass}_{(kg)} = 0.093 \text{ Body mass}^{1.024}$$

There also is a scale effect for acceleration-tolerance, the maximum tolerated field strength inversely related to body mass (Smith, 1975) shown in table 3.

Table 3. Scaling of chronic acceleration tolerance

Species	Body mass (kg)	Tolerance (G)
Mice	0.03	7 G
Rats	0.20	5 G
Rabbits	2.00	3 G

A corollary of this relationship is that below some limit in body size (probably 20-30 gms body mass) there will be no significant physiological response to a 1-G change in the ambient acceleration field—and no change should be observed when such small animals are placed in weightlessness. The concept of a minimal gravitationally susceptible body size in terrestrial animals is quite old, and it has been reviewed elsewhere (Smith, 1974).

However, in different kinds of systems, particularly those with large density gradients, very small structures can respond to less than a 1-G change in field strength. The animal prototype of such structures is the vertebrate utricle which responds to fields as low as 0.0034 G (Howard and Empleton, 1966; Roberts, 1967; Wagman and Dong, 1975). A more sensitive geo-orienting apparatus, the statocyte, is also found in plants (Iverson, 1982; Moore and Evans, 1986; Osborne, 1984; Sach and Leopold, 1982), in which the sedimentation of dense particles, statoliths, appears to initiate the geotropic response (Audus, 1979; Bandurski, Schulze, and Momonoki, 1984; Pickard, 1985). The mediation of the process is not understood, although morphological changes have been observed in weightless cortical cell mitochondria (Slocum and Galston, 1982).

It also has been demonstrated that less differentiated cells respond to a 1-G change in the gravitational field (Cogoli, 1985; Cogoli and Bechler, 1986). This was first recognized by decreased activity of lymphocytes in both astronauts and cosmonauts following spaceflight (Kimsey, 1977). Studies with lymphocytes *in vitro* indicated a direct effect of the ambient acceleration field on both proliferation rate and immunological properties of lymphocytes (Cogoli et al., 1980). This is not a general effect, and is not found in other cells, such as chick embryo fibroblasts and Galliera sarcoma cells (Tschopp et al., 1981). Other more organized but small structures, such as the early chick embryo, are sensitive to a 1-G change in the gravitational field (Smith and Abbott, 1981). Embryos and aquatic organisms generally exist in a buoyant environment so that even marked changes in ambient field strength produce little or no change in the net load and gravitational effects result from an interaction between the field and density gradients within the organism (Smith et al., 1984).

Relationship Between Hyper- and Hypo-gravitational Fields

An important concept in gravitational biology is the relationship between the effects of fields greater and less than Earth gravity. For some processes there appears to be a "continuity of effect" between hyper- and hypogravitational fields.

Where chronic acceleration treatments are repeated at several field intensities, the degree of induced change is related to field strength. These can be rationalized by a regression of the degree of response upon field strength. Such an analysis will yield an equation with two coefficients: one that is a proportionality coefficient, relating the two parameters, and another that is an intercept value—a mathematical prediction of the effects of weightlessness. Implicit in such a procedure is the concept that the effects of gravitational fields are continuous, so that the changes produced by hypo- and hypergravitational fields are related. There is some support for this concept.

All observations obtained by various methods in gravitational biology indicate that the independent variable is the acceleration field strength, which, of course, is a continuous function. Consequently, the biological responses, which are dependent variables, also should be continuous, except where there are qualitative changes in the field effect. For example, some threshold field may be required for a particular biological response. Above that threshold, the character of the response will be proportional in some way to field strength. However, in lesser fields any changes in that process would not have the same relationship to changes in field intensity, and the kinetics established in the gravitationally effective range would no longer apply. Also, some gravitationally sensitive processes may have maximal limits and become nonresponsive in greater fields.

At present there is not sufficient equivalent information for a reasonable test of the validity of a continuity-of-effect concept; although for some phenomena it does appear to apply. The gravitational effects on lymphocytes appear to be a continuous function across hyper- and hypogravitational fields (Tschopp et al., 1981). Body bone mineral content, at least in some species is arithmetically proportional to the ambient gravitational field, a +1 G change in its strength producing a +16% change in bone mineral (Pace et al., 1985). Changes in body fat content exhibit a similar gravitational continuity, being increased in rats by a period of weightlessness (Pitts et al., 1983; Ushakov et al., 1980). A comparison of plasma volumes in animals that are chronically accelerated or exposed to orbital weightlessness likewise indicates a

continuity of the gravitational effect above and below Earth gravity (Burton and Smith, 1972). Red-cell mass increases in chronically accelerated animals (Burton and Smith, 1969), and in astronauts exposed to 60 days of weightlessness, red-cell masses decrease about 12% (Kimsey et al., 1976), so body red-cell mass also appears to have a similar continuity of gravitational effect.

Biological Effects of Earth Gravity

Gravitational biology research indicates that Earth gravity exerts significant, but generally unrecognized control of biological processes. It is important that the mechanisms of these gravitational effects be examined.

The concept of a continuity of hypo- and hypergravitational effects indicates that Earth gravity exerts significant, but generally unrecognized effects upon biological systems. If there were high and low gravity regions as there are regions of high and low altitude, or if there were high and low gravity days as there are high and low temperature days, the effects of Earth gravity would be well understood. But Earth gravity is constant and we lack any way to modulate it, so the biological effects of Earth gravity have remained largely unknown. However, it is important to fully identify and understand the effects of Earth gravity, even though we will still lack the ability to moderate or control Earth gravity.

The direct utility of gravitational physiology information to purely terrestrial situations is generally overlooked. Such information will provide a better understanding of phenomena where gravity is a factor, as well as assist in resolving problems in which gravity is a factor. Since much of the research to identify these gravity-controlled processes has not been performed, a detailed discussion is not possible at this time. However, sufficient research has been done to indicate that gravity-controlled processes do exist.

There is evidence indicating that gravitational fields control body red-cell mass (Burton and Smith, 1969; Kimsey et al., 1976), separately from mechanisms based upon oxygen availability. Understanding the mechanisms of this gravitational influence on red-cell mass could enlarge the current understanding of erythropoiesis and regulation of body red-cell mass. Such information might be applicable to the treatment of currently resistant blood dyscrasias (viz., polycythemia vera), which, hypothetically may result from malfunction of the gravitational-control mechanism.

Similar considerations also apply to the influence of Earth gravity upon plants and the use of such information in resolving problems in terrestrial agriculture as well as in

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life-support systems for long-duration manned space journeys.

Gravitational Physiology of Plants

The gravitational physiology of plants comprises a large body of literature representing about a half century of biophysical and biochemical studies in Earth-based laboratories. This has defined salient aspects of the various basic, gravity-related processes whereby plants perceive and make use of gravitational information acquired from their environment. Research areas are fairly well identified: gravimorphogenesis, gravitropism, hyponasty, reaction wood formation, biosensor morphologies, circumnutation, G-force influences on circadian and other rhythms, and the gravity relationships of various other tropic and nastic responses along with extensive biochemical studies on physiological mechanisms of growth alterations by plant hormones and other growth regulators. All these and more are partially understood and most are ripe for further investigations involving experimental manipulation of imposed G forces both above and below Earth gravity.

Therefore, plant gravitational physiology is a broad and diverse research field of great potential importance to better understand how plants grow and use gravitational information. Such understanding will have not only scientific but also practical importance; to better understand how plants grow is sure to be useful in many ways we cannot yet predict in detail. We believe this will be true for agriculture on Earth and probably for the food supply and energy economy of manned space journeys of very long duration.

A major improvement in plant research methodology is the ability to manipulate the environmental G force (with space laboratories and centrifuges) over its biologically compatible range. This was begun with a few pioneering experiments on unmanned space vehicles and the Space Shuttle and should be continued into the era of a space station.

For planning purposes it should be recognized that most plant experimentation in hypogravity (from microgravity to 1 G) does not and probably will not require many weeks or months of time for plants to grow. Probably well over 80% of all plant gravitational biological studies in the last 30 years have characteristically used tests lasting from 1-10 days. For such tests the advantage of the space station will be the opportunity to replicate tests as many times as statistically desirable in the same mission extending perhaps over weeks or months. This will be a significant advantage especially for reducing the cost of a series of experiments.

In other cases growing plants in orbit for several months will make it possible to explore effects on several developmental stages of plant ontogeny, to assess the impact of microgravity on crop yields, and to identify scientifically interesting effects of altered gravity that may be revealed only at a specific stage of development.

Initially the most pressing kinds of plant experiments that can only be performed in space will continue to focus on relatively small plant specimens: seedlings, tissue cultures, excised plant organs, and fungi. These are the materials of choice for tests, on the ground or in space, that can be accomplished in less than 10 days. Therefore the production of a non-zero, hypogravity environment or a 1-G environment in space must be done with onboard centrifuges, which may be of relatively small dimensions albeit of sophisticated design.

For some objectives of "space agriculture" (in context of NASA's Controlled Ecological Life Support System (CELSS) Program) long-duration tests (at least several months) will be needed. It seems unlikely that all of these can be done only in microgravity; for some tests centrifugation will be required, if only to provide a 1-G comparison.

Appendix B: Human Use of Space Station Centrifuge

Human acceleration research on Earth routinely uses centrifuges with radii of 20 to 50 ft, with and without gimbaled gondola (Meeker, 1985). These long arms are useful in minimizing the coriolis phenomenon and the head-to-foot G-gradient. Since centrifuge size will be limited in a space station, two questions arise regarding human use of short-radius centrifuges: (1) can humans tolerate large g-gradients, and (2) what types of research and/or 0-G deconditioning prevention treatments can be conducted? Some human research has been conducted (Piemme et al., 1966; Piemme, McCally, and Hyde, 1966; Shropshire et al., 1969) on a short-arm centrifuge with a radius of 145 cm (4.76 ft). In these cardiovascular studies the subjects were supine with hips and knees bent, and lower legs elevated (fig. 1(a)). The head was at the axis of rotation, which produced a 100% $+G_z$ gradient.

The effects of fields of 1-7 G, at 1-G increments, were studied, with an arbitrary exposure limit of 120 min at each G level. Visual symptoms (blackout), persistent tachycardia (excess of 170 bpm), nausea, and voluntary stopping were the criteria used to determine human $+G_z$ tolerances. Fatigue never caused a subject to stop the exposure, although on longer radii centrifuges subject fatigue is a common tolerance criterion (Burton, 1986; Meeker, 1985). No differences were found for onset rates of 0.05 G and 0.1 G per sec. The highest $+G_z$ level used, $+7$ G_z resultant vector at the feet, was tolerated for a mean time of 2 min and 41 sec in 7 men.

Comparisons of human tolerance blackout data from long- and short-arm centrifuges, appear to indicate that humans have a mean G tolerance of approximately 2 G greater on the shorter radius centrifuge. Nausea and coriolis symptoms were not problems if the head was kept in a fixed position. Nystagmus was not apparent in any subject after any treatment, and more sensitive vestibular function tests were not conducted (Piemme et al., 1966). Heart rates rapidly reached a maximum level and remained there or slowed as the $+G_z$ exposure continued on the short-arm centrifuge. This is different from the cardiac response on long-arm centrifuges in which heart rate increases gradually to a maximum rate of approximately 170 bpm, which coincides with subject fatigue. So, fatigue is not a problem in the high-gradient centrifuges.

Differences in responses to $+G_z$ exposure between short- and long-arm centrifuges are a function of the hydrostatic pressures:

$$PH = hdg$$

where:

PH   is hydrostatic pressure at head level (mm Hg)

h   is column height (mm)

d   is fluid density (1/13.6)

g   is G level

In short-arm centrifuges (100% G-gradient), the top of the head remains at $+1$ Gx (0 G_z) regardless of the rotational rate of the centrifuge, and the G component on hydrostatic pressure increases radically. At $+5$ G_z the eye-heart PH on a long-arm centrifuge is 120 mm Hg (level of immediate
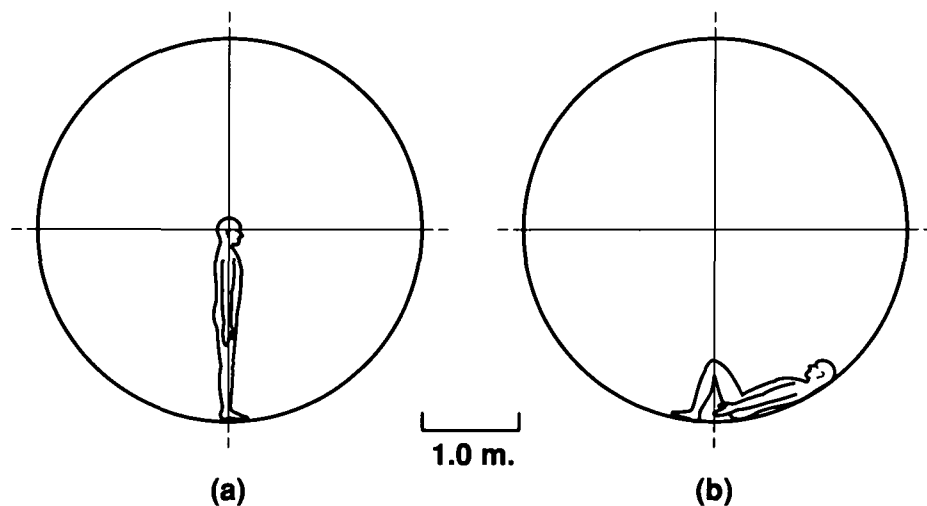

1.0 m.

(a)   (b)

Figure 1. Orientation of human subjects on a short-arm space station centrifuge. (a) Subjects oriented for cardiovascular fluid-balance and g-tolerance studies, (b) subjects oriented for neuro-vestibular studies.

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blackout), but in a short-arm centrifuge it remains at approximately 20 mm Hg—the same as at Earth gravity in an erect man.

Short-arm centrifuges may be useful as a method to counteract some adverse effects of weightlessness. Piemme, McCally, and Hyde (1966), demonstrated that fluid volume could be controlled with this centrifuge by activating the Henry-Gauer reflex. Shropshire et al. (1969), observed increases in plasma lactate (an index of fatigue) in baboons on a short-arm centrifuge, indicating that gravitational fatigue studies could be carried out (Burton, 1986; Miller et al., 1959). The effectiveness of such a centrifuge on preventing the adverse effects of weightlessness on the skeletal circulatory and muscular systems was not examined. However, since these systems would be loaded, even with a short-arm centrifuge, the prophylactic use of such devices to limit weightless-deconditioning seems promising.

Other information is available regarding exposure times to increased G-fields and the cumulated adaptive response of animals to repeated exposures (Burton and Smith, 1972). These studies used chickens as subjects, which are bipeds with vascular characteristics similar to those of humans. Groups were exposed daily to 2 G for periods of 10 min, 1 hr, 4 hr, 8 hr, 12 hr, and 16 hr. This treatment was continued for 5 months, after which the birds were chronically accelerated at 2 G. The degree of physiological stress was monitored, both in the intermittent and chronic treatments, by measurement of lymphocyte frequency (Burton et al., 1967). These studies indicated that the adaptive response to the intermittent G-treatment was directly proportional to the duration of the daily treatment. So there is some evidence that periodic exposures of weightless humans to a 1-G field may improve their response to Earth return. However, the influence of the intermittent g-exposure upon weightless-deconditioning would have to be determined separately.

A short-armed centrifuge could also be used with human subjects to examine how vestibular reflexes adapt during short periods of fractional-G, and to test how humans would respond to short fractional-G periods which might serve a countermeasure function. For vestibular stimulation in human subjects, the subject would most likely be configured as shown in figure 1(b). With the centrifugal force vector directed from front to back across the subject and his head, the effect of the centrifuge's G-gradient could be minimized, while allowing precise measurement of vestibular reflexes under different G-levels provided by the centrifuge.

A variety of gravity-sensitive vestibular and neural functions could be measured in humans with such a device during adaptation to short periods of fractional-G. Among them are eye and head movements, postural muscle responses, visual and proprioceptive perceptual effects, and motion-sickness susceptibility. Ground-based studies using such a device for vestibular stimulation and nervous system testing do not now exist. It is imperative to begin a ground-based research program on human neurovestibular responses to centrifugation as soon as possible to gather background data.

Appendix C: Centrifuge Design Criteria

Centrifuges have two characteristics (rotation rate and radius of rotation) that may have effects independent of those produced by the G-field. It is essential that the biological effects of rotation and G-gradient be examined. Although this information may not apply to the design of the space station centrifuge, it may be useful in selecting species as subjects for space station research.

Centrifuge geometry produces several irregularities in acceleration fields, all of which are inversely related to the size of the radius of rotation (Kelly and Smith, 1974). These have been recognized and commented upon by all biologists using centrifuge techniques but, for a variety of reasons, these potentially adverse aspects of centrifugation have not been critically examined. So far, complications from these irregularities in field strength have been resolved by avoidance—by arranging a large radius of rotation that minimizes field irregularities. However, where rotational radii must be limited, as in a space station, these factors may interfere with research objectives and they must be considered either during design of such centrifuges or as a factor in their experimental usage.

Rotation Rate

Potential critical points for a space station centrifuge are shown graphically in figure 2 (Hill and Schnitzer, 1962). At present, these concepts are either inferred or intuitive, and it is essential that research to identify and evaluate them begin as soon as possible.

All vertebrates possess organs that respond to rotatory stimuli, which sometimes produce eye and head movements (nystagmus) and, in some cases, disorientation and motion sickness. Repeated rotatory stimulation (for humans, >60°/sec) leads to an habituation, recognized as a progressive reduction in the rotatory response. Rotation of animals in a large-diameter centrifuge does not appear to produce the same habituation response, which has been interpreted as a result of the "one-degree-of-freedom" attachment of cages in which only one field is perceived. Observation of animals on a centrifuge operating at a steady state does not indicate any unusual posture or mobility or any (head) nystagmus (Briney and Wunder, 1960; Kelly and Smith, 1974; Wunder et al., 1966), although if the centrifuge is stopped rapidly post-rotatory nystagmus is observed. These post-rotatory phenomena result from tangential decelerations developed by rapidly decreasing angular rate, and they can be prevented by adding a second degree of freedom (tangential to the rotation) to the centrifuge carriage. The process of habituation also has not been observed to be produced by the
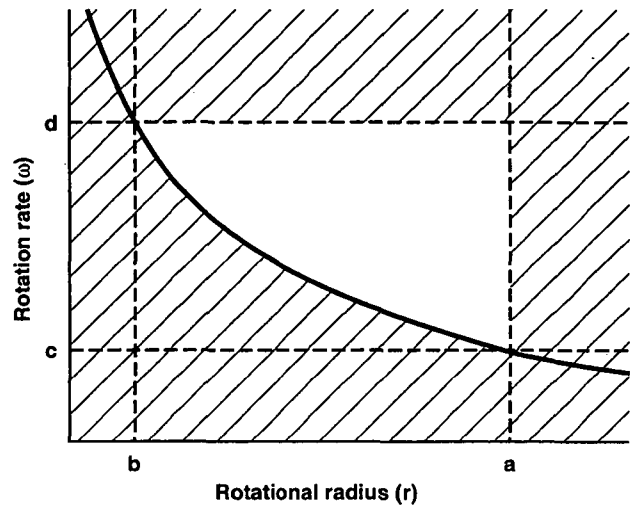

Figure 2. Schema of design criteria for a space station centrifuge, after Hill and Schnitzer (1962). a = radius limit imposed by space station configuration; b = minimum radius consistent with acceptable G-gradients; c = minimum rotation rate (radians/time) to produce a required/desired G field; and d = maximum rotation rate (radians/time) without producing adverse vestibular effects.

rotation of a large-diameter centrifuge (Winget et al., 1962). This indicates that there is a qualitative difference in response to planar rotation and rotation on a centrifuge, in which only one field is perceived.

However, in cases where the rotation radius of a centrifuge is restricted, rotatory effects cannot be ruled out and these must be investigated in a variety of species. Obviously there are thresholds for rotatory effects, since a human "static" at the Earth surface is rotating 15"/sec. The relationship between rotation rate and G-field at different radii of rotation is shown in figure 3 (Kelly and Smith, 1974).

G-Gradients

G-gradients are inherent in all gravitational fields. In humans on Earth there is a calculable head-to-food G-gradient. Therefore, the problem of G-gradients in animals on centrifuges is a quantitative, rather than qualitative one.

In terrestrial centrifuges, G-gradients are complicated by the presence of Earth gravity, which participates in determining both the magnitude and direction of the net gravitational field (Kelly and Smith, 1974). However, on a space station, gravity will not be a factor in determining

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the G-field of an operating centrifuge, so the acceleration field of a centrifuge will be perpendicular to the axis of rotation at all field strengths, and the head-to-foot gradient will apply to the animal's full stature (fig. 4).

Centrifuges have other G-gradients that arise from cage geometry. Generally cages are rectangular and are attached to radial elements of the centrifuge, so that the cage floor becomes a chord. Consequently the ends of the cage will have a larger radius of rotation (and larger G-field) than that at the center of the cage floor. For large cages at short rotational radii this gradient provides a potential source of variation of field strength. Consequently, the length of cage floors should be reduced in proportion to the decreasing centrifuge arm length, or,
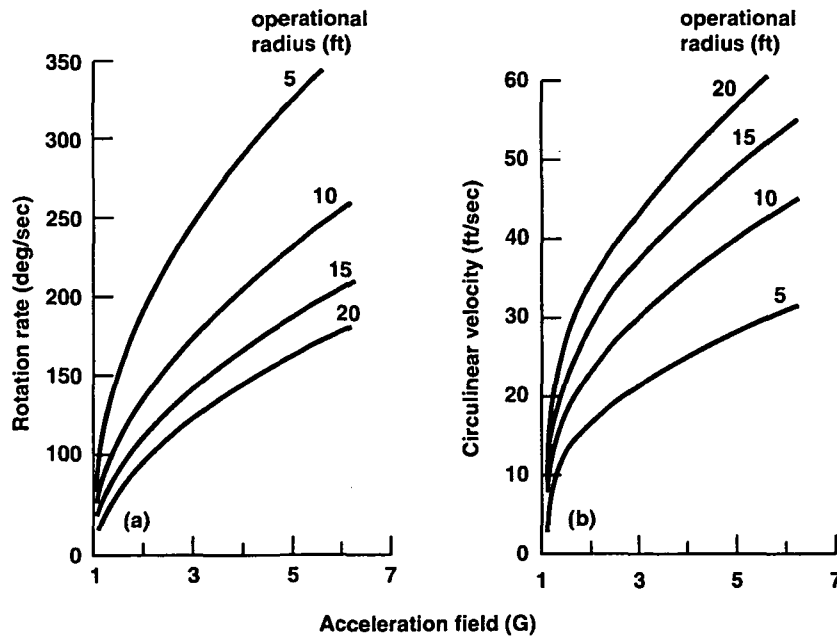
Figure 3. Centrifuge yield as related to (a) radius and rotation rate, and (b) circulinear velocity.
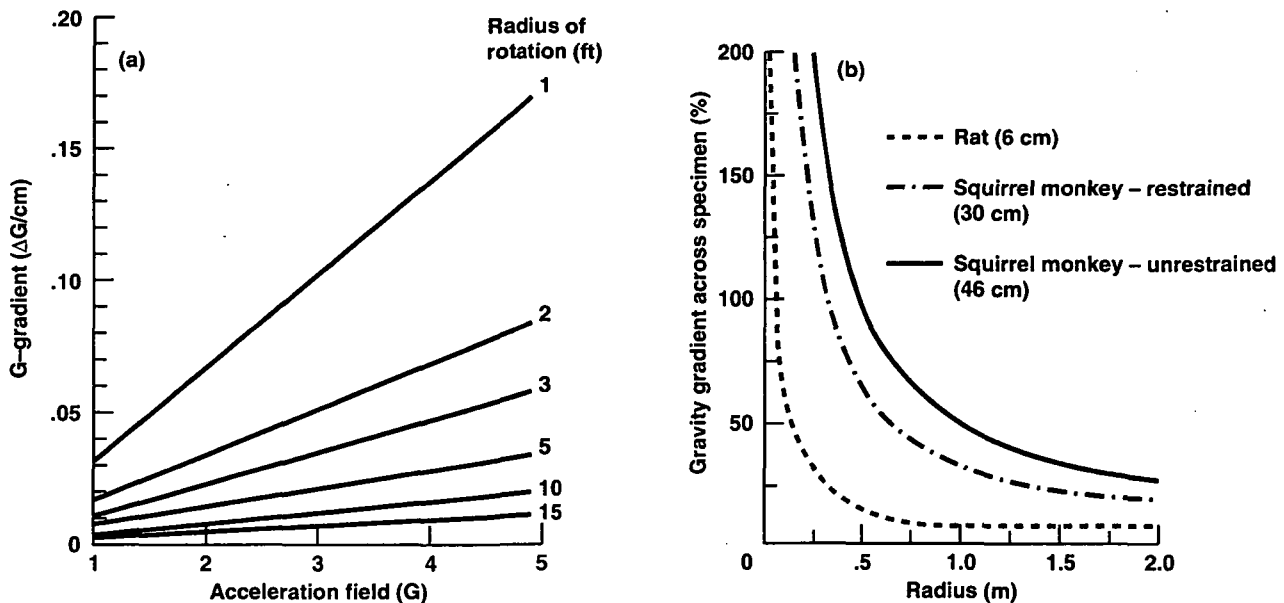
Figure 4. (a) Gravity gradient as a function of G-field and radius, and (b) percent gravity difference across specimens as a function of centrifuge radius.

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theoretically, they should be curved to match the circumference of rotation, thereby eliminating this source of G-gradient (fig. 4).

Adverse Effects of G-Gradients

Since the physiological effects of G-gradients in animals have not been investigated, adverse effects can only be considered to be potential. It is possible that parts of an animal (graviceptors) may be affected differentially because of G-gradients, and this could lead to abnormal (if not pathological) responses. However, if the G-gradient is large, there is more likely to be a problem in assigning an "effective-G" to the treatment. Such indeterminacy of field strength would be disadvantageous in rationalizing the results of multi-field experiments.

Appendix D: Centrifuge Criteria for Plants

The requirements for optimum centrifuge design will depend on future research in space because it is not possible to specify with confidence what practical problems will be encountered or, at this stage, what crop plants will emerge as the best candidates for CELSS system development. However, following are minimal essential requirements for the kind of centrifuges that plant scientists will need as soon as they have experimental access to the international Space Station Freedom.

Centrifuge Radius in the Range 20-40 cm

Rotors in the lower part of the range can be fitted into the space of a Space Shuttle middeck locker. With small (3 cm or less) test subjects the G-gradient is not a serious disadvantage and test subjects of choice will be mostly small seedlings. In some cases the G-gradient can even be an advantage since substantially different G values can be applied to specimens spread out over the radius. Also small centrifuges can be packaged in stacks to run simultaneous tests on full payloads at different gravitational levels. Both Soviet and NASA centrifuges in this size range already have been used in flight experiments and it seems reasonable to predict that such relatively small centrifuges will play an important scientific role on Space Station Freedom.

Illumination Source

In some plant studies in microgravity, the test subjects' light energy requirement for photosynthesis has been important (Cowles et al., 1984) and no doubt this will sometimes be important for centrifugation studies on the space station. Design details of the visible light source will be peculiar to any given experiment. However, the fact that relatively bright lights will be used makes it necessary to provide adequate cooling for the plant culture unit, either on or off a centrifuge.

If an illumination source for photosynthesis is not required (as with young seedlings for a few days) there may be a photographic requirement to record, by time-lapse imagery, the course of development of a tropic or nastic response, of circumnutation, or of a leaf movement circadian rhythm. An infrared (IR) system for efficient illumination and IR imagery has been developed and flown on Spacelab-1 (Brown and Chapman, 1984). Brief, intermittent, low-intensity exposure to illumination for data acquisition purposes (duty cycle, 10 sec every 5 or 10 min) no doubt also will be used on the space station and will greatly simplify the thermal control problem.

Temperature Control

For the majority of plant physiological studies on the space station it seems certain that all or nearly all tests will have (for the engineers) very tight specifications on thermal control of the test environment; ±1°C might be considered a typical specification. It has been demonstrated that the Space Shuttle (middeck environment), in four or five missions for which such data were acquired, did not maintain a stable ambient temperature. Therefore, at the present state of the art, any middeck experiment with tight thermal tolerances must provide its own thermoregulation. It may be anticipated that this practical requirement will continue into the space station era. For homeotherms the subject itself may provide adequate regulation, but for poikilotherms (including plants) effective temperature regulation of on-board flight centrifuges will be a prudent requirement.

Acquisition of Plant Growth and Behavior Data

For measurements of plant growth and physiological behavior it sometimes is necessary to stop the centrifuge and perform some manipulation (such as cytological fixation) on some test samples. In other kinds of experiments it is necessary to record (by imagery) the time course of development or movement of the test subjects. Whether data are taken in color or in black and white (including IR), camera surveillance of test subjects during centrifugation is desirable. The camera or cameras may (1) ride on the centrifuge, or (2) attach to a nonrotating mount external to the rotor. Both methods have been used and probably will continue to be used. For method (1) slip rings are required.

Can a Large Animal Centrifuge be Designed to Accommodate Small Plant Experiments as Well?

It would be possible to design a large animal centrifuge that could accommodate small plant experiments as well, but it would be an uneconomical use of spacecraft resources. Functional and logistic requirements of the two are so different that it would be injudicious to develop them as a single facility. Currently the number of different kinds of scientifically worthwhile experiments proposed for small plants and other small subjects on flight centrifuges far exceed the number and diversity of those proposed for primates and other large animals.

NASA has flown or is developing impressive and useful small payload centrifuges. More small payload centrifuges are in the design and development phases. It would be counter-productive to close out design efforts for small plant centrifuges, and thus delay their use on either the Space Shuttle or the space station, and wait for a much larger all-purpose centrifuge to be designed, built, and tested. It appears prudent to proceed independently with both large- and small-diameter centrifuges.

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13. ABSTRACT *(Maximum 200 words)*

A centrifuge with the largest diameter that can be accommodated on space station is required to conduct life science research in the microgravity environment of space. (This was one of the findings of a group of life scientists convened at the University of California, Davis, by Ames Research Center.) The centrifuge will be used as a research tool to understand how gravity affects biological processes; to provide an on-orbit 1-g control; and to assess the efficacy of using artificial gravity to counteract the deleterious biological effects of space flight. The rationale for the recommendation and examples of using ground-based centrifugation for animal and plant acceleration studies are presented. Included are four appendixes and an extensive bibliography of hypergravity studies.

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