NASA-TM-111129

PSB NASA
IN-54-TM
71358
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Limitations to the Study of Man in the United States Space Program

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June 17, 1992

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(NASA-TM-111129) LIMITATIONS TO THE STUDY OF MAN IN THE UNITED STATES SPACE PROGRAM (Alabama Univ.) 17 p

N96-14289

Unclas

G3/54 0071358

ABSTRACT

Research on humans conducted during space flight is fraught both with great opportunities and great obstacles. The purpose of this paper is to review some of the limitations to United States research in space in the hope that an informed scientific community may lead to more rapid and efficient solution of these problems. Limitations arise because opportunities to study the same astronauts in well-controlled situations on repeated space flights are practically non-existent. Human research opportunities are further limited by the necessity of avoiding simultaneous mutually-interfering experiments. Environmental factors including diet and other physiological perturbations concomitant with space flight also complicates research design and interpretation. Technical limitations to research methods and opportunities further restrict the development of the knowledge base. Finally, earth analogues of space travel all suffer from inadequacies. Though all of these obstacles will eventually be overcome; creativity, diligence and persistence are required to further our knowledge of humans in space.

Keywords: Space Research, Physiology of Space Flight, Limitations of Human Research, Space Shuttle Experiments

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INTRODUCTION

Depending on one's perspective, we either know a great deal about the physiology of man in space, or we know very little. A review of Biomedical Results from Skylab, the report of the U.S.'s first and most extensive effort to study human physiology in space, (2) or the more recent Space Physiology and Medicine (7), may impress the reader initially. Flight studies plus a wealth of ground studies have established that humans can successfully live and work in space. On the other hand, a more careful consideration of the multitude of unanswered questions may impress the reader with how little we know. Because of unique problems inherent in the study of man in space, the safe and productive presence of humans in space for very long periods of time will require some very creative problem solving. The purpose of this paper is to highlight some of the key limitations in this research endeavor.

Regardless of whether you are impressed by the abundance, or the relative absence, of knowledge of the physiology of humans in space, consideration of the limitations to the study of man in space should result in a more knowledgeable judgement. Likewise, knowledge of these limitations is invaluable in planning future experiments, and in eliminating or at least reducing the impact of many of these contemporary limitations to research.

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Many scientists fail to realize that the study of man in space is fraught with a number of obstacles not encountered by researchers who exclusively work in a 1 G environment. The purpose of this paper is to describe some of the limitations of space physiological research in the hopes that some of these problems can be addressed in novel approaches by readers previously unaware of the problems.

LIMITATIONS OF RESEARCH DESIGN

Subject Pool: Our lack of knowledge of man in space has not been from lack of trying. The problems particular to studying man during spaceflight have seriously hampered progress. One of the less obvious hindrances to the scientific study of man aloft is simply the small sample size. Though the public may feel as though NASA is constantly launching someone into low earth orbit, actually the number of subjects available to be tested is quite small relative to scientific requirements, because of the tremendous variability in the nature of flights. Different crews fly for different numbers of days, with different circadian rhythms, with different diets, using different prophylactic drugs, and with different sorts of potentially interfering experiments. It could be argued that the problems of small sample size are partially offset by the small population to which the results must be inferred (i.e. there are only 90-100 astronauts at any time) (6). It must be realized that this population is quite diverse, resulting in large inter-subject variability.

Accessibility to astronauts immediately before and after a mission is extremely constrained. Astronauts go into quarantine seven days before launch and are difficult to test within 10 days of launch. On landing, accessibility is much greater but the number of researchers anxious to test, sample, question and otherwise study the astronauts results in considerable competition. Some of the post-flight tests are bound to confound others, so when a given test is scheduled may influence the quality of the data. What magnifies the accessibility problem is that many physiological measures are subject to change between the pre-launch measure and the actual launch. This problem is worse after landing in that the adaptation to 1 G starts immediately. The Soviet space program sometimes transport cosmonauts from their space capsule on stretchers which may facilitate determination of the effects of null gravity. The U.S. shuttle flights require 30 or more minutes to make the necessary checks to ensure the shuttle is safe before the crew leaves the craft. Recently, in August 1991, utilization of a crew transport vehicle was initiated whereby the crew is asked to move from the shuttle directly to semi-recumbent couches where they remain until transported to the clinic where tests are conducted. Before this, crews walked off the craft and to a transport van, sometimes after a walk around the shuttle.

Accessibility has another dimension as well. Consider that over the last five years, a researcher would likely only have the opportunity to repeatedly study the same astronaut for only about three trips into space in that astronaut's entire career. The number of repeat-flights has increased somewhat, but opportunities to study a given subject repeatedly in space have been limited. Currently only one active astronaut has had six space flights, with several who have made four. Up through the current date, only 9

U.S. astronauts have been on space flights with a duration longer than 2 weeks and all of these occurred during Skylab flights (1973-1974) (6,7).

Contrary to popular thinking, the astronauts in the U.S. have considerable latitude in selecting in which experiments they will participate, and which they will not. Each proposed in-flight experiment, which is not a direct part of that flight's specific mission, is called a Detailed Supplemental Objective (DSO). These supplemental objectives are secondary, which means that their completion is not necessary to the accomplishment of the detailed primary mission objective. Also DSOs involving humans are clearly experiments which fall under the auspices of the Human Research Policy and Procedures Committee at Johnson Space Center. Since ethical and humanitarian considerations require that all experiments be performed only on fully informed volunteers, each investigator tries by tact and friendly persuasion to non-coercively induce volunteers. The astronauts are both personally and professionally interested and inclined to participate; however, some are understandably reluctant to participate in measurements they perceive as threatening to their hard-won flight medical qualifications. For example, participation in 12-lead electrocardiographic studies during stress are avoided by some subjects (unpublished observation). Occasionally, the very nature of some experiments interfere with either primary duties or responses to other in-flight experiments. Also, these experiments often take time before, during, and after the mission, and time is at premium for astronauts who have training, other research, and many other responsibilities besides physiological experiments.

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Likewise, ethical standards of research in humans demand that safety be the foremost consideration. Even nominal risk in the earth laboratory becomes particularly dangerous in space. The inaccessibility of extensive medical services, and the public nature of the space program tends to increase the risk and the perception of risk and results in a very conservative approach to research techniques. Perhaps the fairly early occurrence of an in-flight cardiac arrythmia on Apollo 15 (1969), contributes to a very conservative attitude. Because of safety concerns, procedures which are non-invasive are favored. Likewise, crew safety makes simple tasks such as access to gas calibration bottles (pressure vessels pose safety risks in space) more difficult and precludes some typical measurement techniques such as mercury sphygmomanometry (mercury is toxic and is hard to control in 0 G).

PHYSIOLOGICAL COMPLEXITIES

The interaction of physiological systems complicates experimentation. Subjects who are participating in an exercise countermeasures training regimen would often not make good subjects for studies of lower body negative pressure or other countermeasures. Likewise, it is often impossible to accurately view any group of astronauts as true experimental controls. The altered circadian cycles incumbent in space flight operations, the use of prophylactic and palliative motion sickness drugs, the use of sleep-inducing medications, planned and contingency extra-vehicular activities, possible alterations in cabin environment, dietary changes, and the psychological stress of flight all operate such that every space traveler is subject to a host of treatments in addition to the treatment intended by a researcher. Obviously this milieu of treatments together with the inevitability of variability in response among subjects complicates the observations for control as well as experimental subjects.

Even beyond the external complexities of studying humans in an unusual environment, the immense complexity and interrelationships of physiological systems imposes research design problems. For example consider the commonly observed decrease in total body fluids. This loss in fluid volume could impact upon heart rate, stoke volume, cardiac dimensions, blood pressure, measured muscle mass, maximal cardiac output and oxygen uptake, as well as humoral concentrations and orthostatic tolerance. The lack of control over individual adaptations to microgravity exposure makes interpretation of results difficult at best.

All of this is further complicated by the variable duration of space flight missions. Even when planned for a particular duration, vagaries of weather, mission accomplishment, and failures of mission critical equipment, may alter the plan. Given that physiological adjustments to reduced gravity appear to be both time dependent and possibly somewhat cyclical, variable durations of exposure makes pooling mission data complicated and difficult to interpret.

TECHNICAL LIMITATIONS

In addition to the limitations with regard to the study population, there are numerous technical limitations inherent in studying humans in the hostile environment of space and the limited research environment of the shuttle. The Space Transportation System (Shuttle) flight deck is only 220 x 350 x 210 cm (7.3 x 11.5

x 6.9 ft). The mid-deck, located below and aft of the flight deck, is 107 x 200 x 185 cm (3.5 x 6.5 x 6.1 ft). The only positive aspect of this small experimentation space is that because of weightlessness, all the space from floor to ceiling is usable.

The limited space available has some inherent and unique restrictions. Proximity means noise can be a practical problem. Noise specifications particularly impact upon exercise hardware and experiments. Noise production restrictions are frequency dependent, but generally limited to about 50 dB (15). Given the size and weight limitations, it is currently unlikely that a human exercise treadmill can be designed to meet this noise restriction. Unless there is a breakthrough in design or materials, a waiver of this requirement may be required.

Volume and weight restrictions impact on what experimental hardware can be launched into space. In general, hardware must fit into a standard shuttle locker with inside dimensions of 25 cm high by 43 cm wide by 51 cm deep (10 x 17 x 20 inches) and encompassing 0.057 m^3 (2 ft^3) (11). Weight is obviously limited by the thrust available to accelerate the orbiter to approximately 17,500 mph required to achieve the centrifugal force necessary to balance gravity in order to maintain orbit. Equipment weight is limited to 24 Kg (54 lbs), or 32 Kg (70 lbs) total inclusive of protective shielding, trays, bungees etc. This weight must be distributed within the hardware such that the equipment's center of gravity is as far rearward within the device as possible.

An alternative hardware stowage space is occasionally available, the middeck payload floor space. This space can accommodate payloads somewhat larger and heavier than the mid-deck lockers, but total weight limits are based upon the load center of gravity location (15; R. Connell, personal communication). Equipment stowed here or elsewhere which could injure personnel or obstruct an emergency egress from the shuttle must be able to withstand up to a 20 G crash load (other items must withstand 12.5 G), so equipment designs must balance structural integrity against weight restrictions (15).

Designing equipment which is both strong and light is further complicated by materials and power-use restrictions. Materials must generally meet three requirements: they must have low flammability, must not off-gas toxins, and must not propagate particulate contaminants (12). Electrical power supplies available are limited to 28 volts DC drawing 5 amps maximum, or 115 volts AC, 400 Hz, 3 phase at up to 3 amps per phase. Hardware may occupy only one power outlet at a time and total electrical load cannot exceed 115 watts maximum for eight hours. All electrical circuit boards must be individually certified as meeting flight specifications. None of the experiment related hardware may be supplied power during orbiter ascent or descent. Electromagnetic interference is problematic and shielding may be required to avoid excessive emissions which could potentially interfere with communications essential to safe space craft operation (15).

Vibration is particularly a problem with some flight equipment because it can interfere with some delicate microgravity experiments. Another problem with electrical and electronic equipment is the absence of convective cooling in microgravity. Passive cooling in middeck lockers is limited to 60 watts, therefore fan cooling is often required and must be incorporated within other specifications. Exhaust air must be less than 49 °C (120 °F) for crew safety (15).

The rigor with which each of these specifications is observed is a function of the criticality and hardware classification of the items flown. Criticality is defined by the impact on safety of hardware failure. Most research hardware is "criticality three" because its failure would not result in loss of life, the orbiter, or the mission. Research hardware, in circumstances wherein its function is crucial to a primary mission objective, might be criticality two because its failure might possibly compromise successful completion of the mission. If it were determined in the future that lack of some human physiological countermeasure significantly compromises orbiter egress or other safety procedures, the involved hardware could be designated criticality two.

The hardware classifications are used by the Safety, Reliability and Quality Assurance Office of Johnson Space Center (JSC) to describe the balance between economic cost and non-safety hardware failure. Four classes exist ranging from "minimum risk" to "minimum single attempt cost". Waivers of specific hardware requirements are possible, although the higher the criticality and classification, the more difficult it is to obtain waivers (10).

Because equipment is normally designed for 1 G operation, we seldom consider the role of gravity in measurement. Even simple measures, such as determining body mass becomes more complex in the absence of gravity. Other measures such as wet spirometry have to be reconsidered for 0 G where there are no forces to keep the water in its proper place. As previously mentioned, the lack of gravity also rules out the use of mercury in tonometers etc. for both

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practical and safety reasons. Mass can only apply inertial resistance, being useless in providing muscle loading in 0 G.

The result of all these technical requirements is that getting equipment designed and built to meet both the practical and technical requirements of 0 G operation in space makes all flight research equipment more expensive and often more limited in application than common laboratory equipment. Likewise the time required to design, build, test, and achieve approval for flying aboard the shuttle can be extensive. For example, an exercise cycle, a relatively simple and obvious exercise modality for 0-G, did not fly in space in the interval between Skylab 4 (Feb 1974) and SLS-1 (1991). More complicated devices such as VO2 measurement equipment, is even more difficult to flight certify. Hence, this equipment has only flown in space when space and weight limitations were considerable less, such as Skylab (1974), and SLS-1 (1991). Large complex measurement equipment such as this finds few flight opportunities in the shuttle.

Safety considerations mandate that flight hardware undergo a series of reviews depending on criticality, classification and the complexity of the hardware. Although numerous reviews may be necessary for certain equipment, the initial important review occurs at the Preliminary Design Review. This is followed by the critical design review, flight acceptance and certification tests, verification test, a design certification review, and a flight readiness review. If significant design changes are required, additional critical design reviews are held as necessary. All steps are not always involved, but the time required for design, fabrication and approval of flight hardware in some cases may

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require over two years. Very simple class "D" items with low criticality can be approved for flight in a matter of weeks, but this is not always a desirable mode of operation from an engineering and safety viewpoint (10).

LIMITATIONS OF EARTH MODELS OF 0-G

Given the many limitations of flight missions, good models of low-gravity are in high demand. Unfortunately, every model is limited in its fidelity to true microgravity exposure (4, 8, 13,14). Even earth models of space flight can be cumbersome and provide less than optimal simulation. Bed rest, either level or with head-down-tilt, is probably the best known and most utilized (13) simulation of reduced gravity. In bed rest, the gravity vector still is operational, but the action is in the "X" direction, i.e. it is not distributed in the head to foot configuration of upright subjects in 1 G. The biggest drawback of bedrest is that unlike space flight in which there is considerable movement, bedrest is hypokinetic. The same can be said for seated rest which simulates the minimal leg activity of spaceflight, but is more hypokinetic than flight itself.

Among the oldest null gravity simulation is water immersion. Water immersion, with the subject upright or supine, simulates space in that the gravitational forces are partially offset by the buoyant force of the water. Like space flight, immersion is accompanied by a headward shift of body fluids, caused in immersion by the hydrostatic pressure of the water rather than by the lack of gravity, and hence is more extreme. Cardiovascular changes are somewhat different from spaceflight in that during upright immersion, cardiac output goes up by 30% or more due to increase in stroke volume without subsequent bradycardia (1). The compressive force of the water also alters lung and cardiovascular function (3), and prolonged exposure results in skin maceration and thermoregulation problems. Also, making measurements under water further complicates research. Possible effects of sensory deprivation further confounds study of human responses (14). Studies of motion in the water which is about 1000 times more viscous than air, are difficult to extrapolate to the thin atmosphere of planets or space because of the high drag in the fluid medium. Some of these disadvantages are avoided by separating subjects from direct water contact by surrounding them with compliant plastic sheeting. Similarly, this model known as dry immersion, has some of the same limitations as wet immersion. Thermoregulation problems and personal hygiene can be obstacles to long wet or dry immersion studies. Prolonged bedrest and immersion studies are expensive and it can be difficult to recruit physically active subjects to undergo prolonged studies.

A recently revived human model of reduced gravity is limb suspension. In this procedure, an arm or leg is placed in a rigid cast in such a way that minimal force is placed on the limb. This is obviously more of a hypokinetic model rather than a minimal gravity model. Too, in this model, the limb is part of a physiological system which is exposed to normal gravity and this model is usually limited to single limb.

Animal models can be treated with the same general simulations of reduced gravity as used with humans, except simulations can be more rigorously applied than for humans. For example, rats can be subjected to prolonged hind-limb suspension. But, one reason it is difficult to extrapolate some aspects of animal physiology to humans is because most experimental animals live in a horizontal posture as quadrupeds and hence experience different gravity loadings than humans in 1 G. Some research animals have unique problems in adapting to reduced gravity, as is the case for canines whose lapping method of hydration is difficult in 0 G. Primates were used in early U.S. studies of tolerance of space flight, but have not been used extensively of late. At least part of the reason for the reluctance to fly non-human primates is fear of ubiquitous monkey-borne viruses such as Herpes saimiri of the squirrel monkey (9).

The recent Space Life Sciences (SLS-1) flight exemplifies another obstacle to good life sciences research. The "Announcement of Opportunities", the request for proposed experiments for SLS1 was initiated in 1978. For various reasons, including the Challenger tragedy, the experiment was actually flown in late summer of 1991. In cases such as this, planned experiments may be preempted by advances in knowledge obtained in earth studies. Also the same thing can occur because of the long lead time needed to design equipment, test procedures, train astronauts to perform measurements, etc. In short, the study to be flown may be less than ideal by the time it is actually flown, due to the time lags involved.

SUMMARY

The conquest of space is difficult to say the least. Studying human in the unique environment of microgravity is likewise extremely challenging. The inability to exercise the same control in space as the researcher exerts in ground studies makes research and data interpretation much more difficult. The fact that the

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principal investigator is physically located some 150 to 200 miles from the orbiting laboratory is just one of the hurdles of this research. The longer null gravity exposure of inhabitants of Space Station Freedom should provide better opportunities for studying man in space, but can not solve all the problems of human research there. Inevitably, these obstacles will be overcome one by one, but each bit of knowledge gained will require the creativity, diligence and persistence of dedicated scientists who understand the limitations to the study of man in space.

Acknowledgement

Much of the information on the technical limitations was located and interpreted by Glenn Klute of the Anthropometric and Biomechanics Laboratory of Johnson Space Center. We appreciate his assistance.

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