

A REVIEW OF CURRENT CONCEPTS
OF THE
EFFECTS OF WEIGHTLESSNESS AND ROTATIONAL ENVIRONMENT ON HUMANS

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INTRODUCTION

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INTRODUCTION

The information contained in this brochure is a compilation of current material on weightlessness which is intended for use by NASA planners and engineers. It is not a detailed medical treatise, but rather a survey of current thinking by the most knowledgeable investigators in the field, expressly designed to be of practical use in the planning of future space flight programs in the most efficient way possible. The survey is preceded by a general discussion, written in the light of current opinion, which is hopefully intended to edify and clarify rather than confuse.

For the purpose of this investigation, the subject is subdivided into two categories: (1) weightlessness and (2) response to rotational environment. The second category is discussed separately in an attempt to anticipate problems arising from the possible provision of gravity artificially by rotating the Apollo vehicle. It is also separated in an effort to eliminate the prevailing confusion concerning the overlapping role of the vestibular apparatus in both areas. Since this is written primarily from the standpoint of the necessity for actual manned space flight experience before Apollo, greater emphasis is placed on weightlessness, the real crux of the discussion.

Since the weightless state cannot be achieved for more than forty-five seconds under terrestrial conditions, the problems confronting the astronaut exposed to prolonged Zero G can be neither ascertained nor evaluated with certainty except by space flight itself.

It is well known that human experience with space flight is severely limited. Up to the present time, it has included a total of six flights, four American and two Russian, only one of which extended beyond three orbits. This was the well-known flight of Gherman Titov for seventeen orbits. Despite the presentations of Titov and Russian scientists at the recent COSPAR meeting in Washington D. C., the type of detailed medical information we would like to have concerning this flight has not been reliably available. Furthermore, it represents only one flight providing only an indication of possible problems rather than statistically significant data. The study of weightlessness, therefore, presents a uniquely difficult field of research in that it is an area wherein not only the solutions, but the problems themselves require definition, demanding answers prior to the exposure of humans to a stress situation which cannot be satisfactorily duplicated by any means other than exposure to that stress situation itself.

Yet, by evaluating experiments with airplane flights flown on Keplerian trajectories, water immersion studies, bed rest studies, elevator drops, centrifuge studies, slow rotation room experiments, the human space flight data we have, the results of animal flights, and general knowledge of physiology and psychology, it is possible to render reasonably informed guesses concerning the medical effects of prolonged human exposure to Zero G.

The importance of landing a man on the moon in minimal time has imposed the need for planning future missions with the strictest attention to timing. The question of man's ability to safely withstand prolonged weightlessness is one of three major unanswered questions concerning Apollo which requires actual space flight and, therefore, vitally important to this closely timed planning. The other two questions are the feasibility and technique of orbital rendezvous, and the effect of heavy cosmic primary radiations. The fact that the weightless state has the potential of causing serious ill-effects, and the fact that we can factually know little of these effects without actually exposing man to this stress has, along with the other two major considerations, led to the development of the Gemini program as a precursor to Apollo.

In order to evaluate Gemini more critically in its present concept, and to reevaluate the decision that artificial gravity will not be required for Apollo so that every attempt will have been made to avoid last minute decisions and attendant costly delays, this survey was accomplished. These prognostications, it must be understood, cannot be taken for factual information but only for what they are; i.e., predictions, reasoned by the major researchers in the field on the basis of the incomplete information presently available, but, nevertheless, the best predictions possible at this time.

At the conclusion, a statement is made emphasizing the importance of evaluating combined stresses. To ignore this would be tantamount to sighting the gun and forgetting the war, for as badly as we need information on weightlessness alone, we need information on weightlessness in sequence and combined with the other stresses of space flight even more.

SECTION I-A

WEIGHTLESSNESS - GENERAL DISCUSSION

SECTION I-A WEIGHTLESSNESS - GENERAL DISCUSSION

An examination of the field up to the present time reveals that the following ill effects have been anticipated, some more seriously than others, in humans exposed to prolonged weightlessness.

- Space sickness
 - Anorexia (loss of appetite)
 - Nausea
 - Emesis (vomiting)
 - Disorientation
 - Vertigo
 - Sleepiness
- Decreased tolerance to G stress following prolonged weightlessness
- Dehydration (sustained excessive urination - diuretic effect)
- Decreased heat tolerance
- Fatigue
- Restlessness
- Sleeplessness
- Euphoria
- Hallucinations
- Psychological adjustment failures
- Gastrointestinal disturbances
 - Bloating
 - Difficulty eating
 - Decreased peristalsis
- Urinary bladder retention
- Muscular incoordination
- Proprioceptive loss
- Weakness
- Muscle atrophy
- Demineralization of bone
- Decreased metabolic activity

decreased autonomic
nervous system reflexes

decreased neuromuscular reflexes

Laboratory

- Increased cholesterol
- Increased protein-bound iodine
- Decreased eosinophiles

These predictions have been made on a basis of Zero G devices, Zero G simulators, and the general fund of medical, psychological, and physiological knowledge.

Zero G devices are those actually providing the weightless state. These are free-fall apparatuses (elevator shaft, drop tower, vertical-linear accelerator), aircraft flights on Keplerian trajectories (C-131B, T-33A, F-94C, KC-135, TF-100F, F-104A, X-15), and space flight (animal and human). None of these except space flight itself can produce the weightless state for more than a few seconds at a time. Definitive data on prolonged weightlessness must, therefore, await prolonged space flight.

Zero G simulators include water immersion, tilt table, prolonged bed rest, frictionless platforms, the orbital air bearing simulator, the MASTIF trainer, and similar frictionless space flight training devices. Of the simulators, water immersion, tilt table, and prolonged bed confinement studies have supplied the vast majority of weightlessness data. It must be realized, however, that water immersion provides a sub-gravity state to the body in a non-uniform manner because of the variations in density and position of the various parts of the body. It should also be understood that it does not render the vestibular apparatus weightless. Furthermore, it imposes such artifacts as negative pressure breathing, a water medium instead of air in contact with the skin, sensory deprivation, isolation, inactivity, and confinement. This has caused a few misconceptions which, it is hoped, will be clarified in the discussion that follows.

In order to explain each of the above untoward effects in terms of how they came to be anticipated, and their relative importance in the minds of those most familiar with the subject of weightlessness, each will be taken up separately.

Space sickness is a combination of symptoms similar to any form of motion sickness caused by unaccustomed stimuli to the vestibular apparatus. This combination of manifestations is of importance primarily to the exposure of the astronauts to a rotational environment and it is, therefore, discussed in greater detail in Section II-A. However, the Russian experiences with Titov's flight and with their animal flights have led us to the conclusion that space sickness may be a syndrome induced by weightlessness itself. If so, it is strongly suspected that it is due to the absence of the normal stimulus of gravity to the otolith apparatus of the internal ear (deafferentation of the otolith). This is in contradistinction to semicircular canal sickness which is due to the bizarre stimulations imparted to the semicircular canals by the slow rotation room, riding a ship in a rough sea, engaging in complicated aircraft flight maneuvers, etc. Whether or not otolith sickness truly exists is not definitely known at the present time. This is the subject of intense investigation by the U. S. Naval School of Aviation Medicine under the direction of Captain Ashton Graybiel.

It is very pertinent in this regard that very recent Russian disclosures have indicated that Titov's capsule was rolling to the right at a variable rate up to 6 rpm throughout the flight. This casts an entirely new light on the subject since it indicates that his symptoms could very well have been and in all probability were due to rotation of the capsule rather than to weightlessness, itself. Whether this was true of the Russian animal flights as well is not known at this time,

but chances are that it was, on the basis of simple reasoning. That is, if their manned flight was troubled with uncontrolled roll, one would strongly suspect that their animal flights, which are completely reliant upon automatic control systems, would be similarly troubled and very probably to a greater extent.

First, then, the Russian experience of "space sickness" may be an effect of rotation rather than prolonged weightlessness.

Secondly, of the manifestations mentioned, the most dangerous to man and mission is probably vomiting. This is because of the danger of aspiration of the free-floating vomitus (either due to inability to clear it adequately from the throat or to inhalation of the material during sleep) and because of the possibility of the development of pernicious (continuing) vomiting. The latter could result from the continued presence of the stimulus that caused it, or from the persistence of the odor or the sight of the vomitus within the suit or cabin. Pernicious vomiting, although unlikely in highly selected astronauts, is well known to cause severe dehydration, electrolyte imbalance, and malnutrition, which frequently result in marked weakness and incapacity, and in extreme instances even death.

Of the other symptoms mentioned under "space sickness", anorexia is not of itself incapacitating and should not cause a significant reduction of performance. Nausea can adversely affect performance, but it can be remedied with medications if it should show a tendency to persist, although this is not anticipated. Vertigo, a sensation of spinning within

the environment (subjective), or of the environment spinning around the individual (objective) is much more likely to occur as a result of a rotational environment than of the weightless state. However, some degree of vertigo and, more particularly, disorientation and the illusions with which it may be associated, are suspected manifestations of otolith sickness; i.e., space sickness due to weightlessness. But despite the speculations of Gauer and Haber at the end of World War II, disorientation is not strongly anticipated in the absence of a rotational environment, provided visual and tactile stimuli are not abolished.

Sleepiness, sometimes rather striking, has been observed in experiments with the slow rotating room, and it is also thought at the present time to be the result of rotation rather than weightlessness. Furthermore, those subjects who have fallen asleep were readily aroused by touch, if voice alone proved inadequate.

The most dangerous single symptom of space sickness, then, is anticipated to be vomiting.

Thirdly, it has been reported that a high percentage (20 to 30 percent) of subjects exposed to Keplerian flights in aircraft have developed vomiting. In order to evaluate this properly it must be understood that these subjects were not necessarily highly selected individuals such as the astronauts, that freedom of motion including rotation was permitted, and that these flights consisted of repeated runs during which the subject was exposed to successive periods of up to 40 seconds of

weightlessness both preceded and followed by stresses of distinctly greater than one G. The application of the figure of 20 to 30 percent probability of vomiting to astronauts in space flight is, therefore, untenable. Current thinking places the probability much lower as will be seen in Section I-B.

Lastly, judging from all the evidence at hand, including the Russian human and animal space flight reports, it is the unanimous opinion of the investigators in the field that adaptation to the space sickness syndrome will develop with three to four hours after onset, provided these symptoms occur at all without rotation.

Decreased tolerance to G forces following prolonged weightlessness is a major consideration in evaluating the effects of this stress. Anyone who has had the experience of dizziness, brownout, blackout, or fainting on first exposing himself to one G after a prolonged period of bed rest (in which the cardiovascular system is working against virtually Zero G) can with very little effort reason that decreased G tolerance following weightlessness is a likely possibility. Similar reasoning by professionals in the various fields of biology and medicine led to a great many searching experiments which have contributed a large amount of information indicating (1) that this may be anticipated, (2) the mechanisms by which it occurs, and (3) the means of prevention.

These have consisted of carefully controlled bed rest studies, physiological experiments in the laboratory, water immersion studies, tilt table studies, centrifuge experiments, dynamic testing of various types, and combinations of these.

Essentially, there appear to be two major mechanisms involved, although the relative importance of each has not been exactly determined. Each has its own proponents but there is no doubt in anyone's mind that they both play an important role.

The first is a de-adaptation of the reflex mechanisms which control the circulation on the arterial side to maintain blood pressure. Essentially, these reflex mechanisms can be divided into two groups acting oppositely, the vascular status representing a balance between them. They consist of the sympathetic reflex system which acts to increase the heart rate and constrict the small arteries to cause a rise in blood pressure, and the parasympathetic reflex system which does the exact reverse. Considering man in the weightless state, the lack of necessity for the cardiovascular system to circulate blood against the force of gravity reduces the need for sympathetic activity. If this condition is prolonged, it is expected that the sympathetic system de-adapts or grows sluggish so that when it must react rapidly with the sudden imposition of forces of one G or more (possibly up to eleven G in the Apollo mission) it is inadequate to do so. Blood pressure is, therefore, not maintained against the G stress and blackout or some form of circulatory collapse occurs. Although the sympathetic system will gradually recover its original quick adapting ability, the time it takes for recovery depends upon the duration of weightlessness (or bed rest). The degradation and recovery of this ability have not yet been worked out as a function of time.

The second mechanism by which reentry G tolerance is expected to be decreased is somewhat more complex. The beginning of the chain of events is a redistribution of blood which occurs because of the absence of gravity, or negative pressure breathing (inhaling against a resistant valve or against external pressure, such as water in water immersion), or both. In either of these situations, there is less blood in the periphery of the body than in the trunk, specifically the thorax. The increased blood volume in the vessels of the thorax causes their distention. With the distention (stretch) of the portion of the pulmonary veins lying within the pericardial sac, and of the right auricle, a reflex mechanism is triggered which results in an increase in the amount of urine put out by the kidneys (diuretic effect).

This is mediated through the vagus nerve to the brain which causes a decrease in the amount of circulating pituitary anti-diuretic hormone and an increased output of aldosterone by the adrenals. The aldosterone causes the retention of sodium and water in the tissues, i.e., outside the blood stream.

The result, then, is a reduction of blood volume which in turn reduces the ability of the cardiovascular system to maintain an adequate blood pressure on exposure to G or multiples of G. Even this may involve more than the simple principle of inadequate fluid to maintain pressure, although this is probably the primary cause. There is additional evidence that the blood vessels themselves have less ability to constrict, due to the fact that the fluid and the electrolyte changes caused by the increased output of aldosterone affect the actual tissue of the blood vessel walls.

Whether the arterial reflexes or the blood volume changes prove to be the more important, there is no question that both mechanisms come into play. While neither is expected to impart permanent changes, the lessening of consciousness during exposure to reentry G and during possible seat ejection can pose a serious threat to the mission and the man.

Knowing the physiological mechanisms, one can then understand the preventive measures under consideration. By virtue of the application of pressure cuffs to the upper arms and thighs, Graveline has been able to maintain tolerance to tilt table maneuvers after prolonged water immersion. Without the cuffs, tilt table tolerance (ability to maintain blood pressure under quick changes of up to one G stress) is clearly decreased after as little as six hours of water immersion. The cuffs are similar to ordinary blood pressure cuffs but are inflated to only 60 mm of mercury, enough to stop venous return from the extremities, but not to interfere with the arterial circulation to them. Throughout water immersion, they were alternately inflated for one minute, then deflated for one minute, continuously. The rationale is the prevention of the redistribution of blood volume (which initiates the series of reactions resulting in diuresis and blood volume reduction) by the intermittent trapping of blood in the extremities. The experimental success of this method must be further substantiated, but it constitutes a definite in-road to the solution of this problem and also provides additional evidence to prove the mechanism.

The provision of intermittent positive pressure to the inhaled oxygen or oxygen mixture also stops the diuretic chain reaction at its source by increasing intrathoracic pressure, preventing the blood volume increase within the vessels of the chest and also counteracting what tendency there is toward negative pressure breathing due to resistant valves in the oxygen supply system. Positive pressure breathing has the additional advantage of serving to prevent the collapse of portions of the lung (atelectasis) due to G stress.

The Valsalva (straining) maneuver, the attempted forcible expulsion of air against a closed glottis also causes an increased intrathoracic pressure, but in addition it calls forth sympathetic responses which "exercise" the parasympathetic-sympathetic balance system.

The Flack test, blowing into a balloon as long and as hard as possible, is essentially the same as the Valsalva maneuver physiologically.

Muscular exercise, chiefly to stimulate the arterial side of the circulation, but also preventing, to some extent, the redistribution of blood during weightlessness is considered by many to be an important preventive measure. It also serves to prevent the development of muscle atrophy and bone demineralization which have been anticipated as effects of prolonged weightlessness.

Although very significant work has been done on these preventive measures, much more needs to be done to confirm and evaluate them. Work is also needed to determine a simple and reliable method by which decrements in reentry or emergency G load tolerance can be quantitatively predicted at any point in flight.

It is important to note that several researchers distinguished a marked difference between diminished tolerance to transverse as opposed to vertical G. They expect no decrease in transverse G resistance, but a marked one to vertical G. This is based on the lack of G tolerance reduction in studies with water immersion followed by centrifuge tests, as opposed to the marked G tolerance reduction shown in water immersion-tilt table studies. While it is undoubtedly true that transverse G can be tolerated relatively well, it is not nearly as true that the mission G stress can be completely programmed to the transverse position while still providing for emergency maneuvers such as pulse reentry and seat ejection. This is a problem area which is very much in need of study as will be seen in Section B.

Dehydration due to a sustaining of the diuretic effect discussed is another possible effect of weightlessness. Sustained diuresis, along with consequent dehydration, does occur in skin divers and in water immersion studies. Whether or not a similar sustained process is associated with prolonged weightlessness is not known at the present time.

However, dehydration is not of itself considered to be a serious threat to the mission for two reasons. One, the same preventive measures directed toward maintaining G tolerance also act to prevent sustained diuresis. And, secondly, dehydration is readily remedied by a compensatory fluid intake.

Decreased heat tolerance is a combined effect of dehydration, electrolyte changes, blood volume changes, changes in peripheral vascular reflexes, and perhaps psychological manifestations. The question arose chiefly as a result of work with water immersion, and from well known physiological principles concerning the relationships of dehydration and electrolyte imbalance to decreased heat tolerance.

Dehydration, blood volume changes, and sympathetic-parasympathetic balance have all been discussed. Sodium loss, the electrolyte change of greatest importance in heat tolerance, is not anticipated if suit temperature control is adequately maintained. But if it should occur, it is readily compensable by means of salt tablets. Therefore, with regard to sodium loss, the picture is no different than it is on earth. The one possible exception is the trapping of sodium in the tissues by an increase in aldosterone. Here again, it is expected that this chain of events will be prevented by methods directed toward maintaining G tolerance.

Psychological influences are important to any body regulating mechanism, but the tendency toward unreasonable fear is best ruled out by crew selection methods. Fear of weightlessness per se is not very likely. Whether or not a normal fear response will significantly alter thermo-regulation is open to question, but it becomes largely academic considering that the astronauts will have adequate suit temperature controls.

In summary, the evidence for decreased heat tolerance as an effect of weightlessness is not clear cut. Suit temperature control is provided for, sodium loss due to the possibility of defective suit temperature control is readily compensable, and lastly, preventive measures for G tolerance reduction should also prevent decreased heat tolerance due to weightlessness.

Fatigue is anticipated largely as a result of water immersion studies. Whether this can properly be extrapolated to the weightless state is doubtful. Furthermore, it is a highly subjective effect composed of many elements, most of which are discussed elsewhere in this paper. Although it is a very real mission concern, fatigue is not generally anticipated to be a prominent effect of weightlessness itself.

Restlessness probably has more to do with confinement than weightlessness. The provision of adequate mission tasks should compensate very well provided adequate crew medical selection methods have been utilized.

Sleeplessness has been reported as a finding in water immersion work. Graveline reported that in seven days of immersion he required significantly less sleep than normal. At the same time, Graybiel reported that some of his subjects slept excessively. In any case, the sleepy ones were readily aroused and the sleepless ones simply felt that they required no more sleep. Hence, if a variation in sleep requirement proves to be an effect of weightlessness, it is felt that it will probably not pose a serious threat to the mission, particularly with two or three astronauts in the same capsule.

Euphoria, hallucinations, and psychological adjustment failures are considered to be problems resulting from confinement and lack of sensory stimulation rather than weightlessness. Adequate crew selection methods are important to eliminate those with latent tendencies and excessive fear reactions. It is anticipated that the Apollo mission will provide adequate visual, auditory, and tactile stimuli to preclude these possibilities. However, time and space reference mechanisms in orientation, and the effects of diurnal changes require basic work since disturbances of these mechanisms or bizarre stresses on them may be important to the problem of hallucinations.

Gastrointestinal disturbances have been postulated by a few, but the view has not enjoyed serious acceptance to date. Evidence is lacking.

Urinary bladder retention has been studied in a small group of subjects on C-131 flights. After voiding while weightless the subjects again voided after an immediate landing. Some were able to void more than the amount considered normal for the intervening period, a finding suggesting abnormal retention of urine by the bladder. This was only a pilot study and does need further investigation. However, no practical problem concerning this question has arisen within human or animal space flight experience so far. In fact, the urinary output during the Aurora 7 flight was over two liters.

Decreased neuro-muscular reflexes, postulated by Gauer and Haber after World War II, and by others later is now regarded as being of little real importance to the weightless state so long as sensory stimuli (visual, auditory, and tactile) are not purposely blocked out, and so long as

muscular exercise is provided. Further, it is anticipated that any incoordination which might be brought about by changes from Zero G to G will be quickly adapted to, and that this can be enhanced by training.

Weakness and muscle atrophy are suggested by water immersion experiments and experiences with patients at prolonged bed rest. This effect is a result of muscle disuse or relative disuse due to the markedly lessened muscular effort required to move or maintain posture in the absence of gravity. It has been a striking finding in water immersion studies. Where muscle disuse has been very prolonged (chiefly a clinical observation), it has resulted in decalcification and softening of the bone, whose integrity is normally maintained by the pull of the muscles attached to them.

Fortunately, it is known that very little muscular exercise is required to maintain muscle and bone integrity. One maximum contraction per week is adequate to maintain a high muscular potential or even slightly increase it. A well planned program of daily muscular exercises, then, either utilizing an exerciser such as some form of stationary bicycle, or isometric contractions should eliminate the problem of muscle and bone integrity. It is probably also advisable, in this connection, to include joint mobility exercises to prevent any diminution in the range of joint motion due to inactivity, as well.

Decreased metabolic activity has been anticipated on the basis of several BMR (Basal Metabolic Rate) studies using bed rest and tilt table methods. This possibility has received little serious attention, however, because it is well recognized that less energy will be needed to move about in a weightless state since there is no gravity to move against. The metabolic rate, being a measure of energy output by the body, would then quite properly fall to a lower level. There is no good evidence for a greater reduction in metabolic rate under Zero G than would be anticipated at similar levels of activity on earth.

The laboratory findings of increased cholesterol, increased protein-bound iodine (an indication of elevated metabolic rate), and decreased eosinophile count are derived from water immersion studies. Neither their significance nor their reproducibility are yet worked out.

In summary, the greatest and most important biomedical unknowns in prolonged weightlessness are space sickness with special emphasis on the probability of emesis, and subsequent decreased G tolerance. With respect to the former, it is entirely possible that it does not even occur in the weightless state itself, but only in the presence of constant rotational forces or transitional rotational or linear forces. With respect to the latter, qualitative and quantitative predictability and prevention need further exploration.

This is not to state that other possible effects are to be ignored by any means. But, on the basis of present knowledge they are either less important, less likely, easily correctable, or probably not a function of weightlessness per se.

Finally, it is extremely important to emphasize the need for work on combined and successive stresses. Whereas, isolated symptoms and signs of weightlessness may or may not particularly call for a graduated series of space missions, it is the unanimous opinion of those working in the field that the study of combined and serial stresses of space flight strongly requires such a program, even though the planned interval between them may be relatively short.

SECTION I-B

RESULTS OF SURVEY ON WEIGHTLESSNESS

SECTION I-B RESULTS OF SURVEY ON WEIGHTLESSNESS

The following opinions are tabulated for brevity and rapid perception. The capital letters indicate the research scientist whose opinion is presented. Combinations of two or three letters represent two or three investigators with whom these questions were discussed as a group.

1. Opinions on Emesis:

a. Percent probability of occurrence without special preventive measures or therapy:

A 2-6%
GHN 10%
J 8-10%
S less than 3%

Range: 2 to 10% probability

b. Percent probability of occurrence with known preventive measures or therapy:

A 1-3%
GHN 1%
J 1%
S less than 1%

Range: less than 1 to 3% probability

c. Percent probability of causing Apollo mission failure without preventive measures or therapy:

A 0.3-1.5%
GHN 4%
J 1%
S 0.3%

Range: 0.3 to 4% probability

d. Percent probability of causing Apollo mission failure with preventive measures or therapy:

A 0.1-0.5%
GHN 0.9% (less than 1%)
J 0%
S less than 0.03%

Range: 0 to 0.9% probability

- 2-
- e. Types of preventive measures or therapy:
 - Vacuum aspirator in suit to remove emesis
 - Emesis receptacle in suit (solids trap)
 - Drugs - Antivertigo
 - Antinauseants
 - Anti-emetics
 - Deoderants in suit
 - Method of cleaning cabin
 - Pre-conditioning of astronauts
 - f. Necessities for further study:
 - Pre-adaptation techniques
 - More work on drugs
 - Investigation of optimal dietary regimen to prevent emesis
 - More work on selection (being done)
 - Otolith studies (being done)
 - Validation studies (space flights)
 - g. Percent probability of necessitating change in capsule design (artificial G):
 - A less than 0.1%
 - GHN negligible
 - J 0%
 - S negligible

Range: 0 to 0.1% probability

- h. Percent probability of causing other engineering changes:
 - A 0%
 - GHN 0% } Assuming aspirator and solids trap are provided for
 - J 0%
 - S 0%

Range: 0% probability

- i. Importance of Gemini to Apollo:
 - A--Gemini highly desirable even if only 8 months before Apollo:
 - To identify emesis as a problem
 - To provide confidence in Apollo
 - To provide information on serial and combined effects
 - GHN--Gemini only moderately important to Apollo re emesis alone if interval only 8 months since we should have 18 orbit Mercury and possibly 18 orbit or even 7 day orbit Apollo by then. Time factor very important.
 - J--Progressive human flights essential even if interval only 8 months. Reasons are the same as A and independently conceived.
 - S--Gemini highly important to Apollo if lead time one year or more, but not if less than one year. Reasons: To identify problems and critique methods.

- j. Two flights of 14 days adequate?
All said yes.

2. Opinions on Decreased G Tolerance

- a. Percent probability of occurrence without special preventive measures or therapy:

GJ 75%
E 100%
JM 0% transverse
100% other
M 100%
S 75%

Range: 75 to 100% (0% if G direction transverse-2 observers of 7)

- b. Percent probability of occurrence with known preventive measures or therapy:

GJ 25%
E 0-25%
JM 0% transverse
100% to some extent in other body directions.
M 0-50%
S 50%

Range: 0 to 100% Needs study and agreement on specific preventive measures used and specific end points.

- c. Percent probability of causing Apollo mission failure without preventive measures or therapy:

GJ 75%
E unable to state
JM 0% transverse
100% other
M 100%
S 50%

Range: 50 to 100% (0% if G direction transverse--2 of 6)

- d. Percent probability of causing Apollo mission failure with preventive measures or therapy:

GJ 25%
E unable to state
JM 0% transverse
100% other

M 0-45%
S 5%

Range: 0 to 45% This is clearly an area requiring more work, specifically a graduated program of manned space flights. Also more work with water immersion, tilt table, and centrifuge, and work on prevention mandatory.

e. Types of preventive measures or therapy:

Graveline cuffs.
Valsalva
Flack
Positive pressure breathing
Bicycle exerciser with ergometer
Other muscle exercises
Anti G suit
Transverse G position (program for)
Diet to keep blood volume up:
 Adequate fluid intake.
 Possibly increased sodium intake
Drugs - possibly pitressin (to increase blood pressure)
Pre-conditioning

f. Necessities for further study:

Progressive space flights
Water immersion work } for validation, time base studies,
Bed rest studies } and prevention
Blood volume studies on animals in space flight
Work with sympathectomized animals in space flight
Work on predictability of extent of G tolerance loss in flight
Possibly work on correlating tank with flight experience of
 man and animals and correlating with each other

g. Percent probability of necessitating change in capsule design (artificial G):

GJ 0-2% (so long as flight plan keeps G loads low)
E 1%
JM 0-1%
M 0-5%
S less than 3%

Range: 0 to 5% (0 to 3% probably more significant)

h. Percent probability of causing other engineering changes:

GJ 0% - except possibly added lateral impact attenuation
E 0-2% - bicycle exerciser with ergometer and generator

JM 0% - other than pressure breathing device and slight changes in couch orientation (can be added any time)

M 0-2% - oscillating couch

S 0-1% - automatic emergency protection systems (water foam immersion in 0.3-0.5 seconds)

Range: 0 to 2% probability

i. Importance of Gemini to Apollo:

GJ - Progressive human flights essential even with only 8 month interval.

E - Gemini is essential regardless of short interval. The more human experience the better.

JM - Gemini very important despite 8 month interval. Needed for definition of problems, validation of protective measures, and developing confidence. This cannot be adequately done with animals.

M - Feels Gemini lead time too short and much can be accomplished with animal flights.

S - Lead time of less than 1 year not adequate to make Gemini worth while. Can rely on 18 orbit Mercury and early Apollo flights themselves for adequate information.

j. Two Gemini 14 day flights adequate?

All said yes.

3. Notes on Dehydration Due to Diuresis:

On this question, it was agreed that dehydration is so easily prevented by maintaining an adequate fluid intake that simply by observing this precaution the chance of dehydration occurring is 0% and consequently the probability of mission failure on this account is 0% in the light of present knowledge. Gemini is not important for this particular segment.

However, it is still unknown whether the diuretic effect will persist in O G and this is important from the standpoint of maintaining G tolerance.

Adequate provision must be made for greater water storage and urine disposal than might normally be required.

Accurate fluid intake and output measurements against time are strongly urged for all future space flights.

SECTION II-A

RESPONSE TO ROTATIONAL ENVIRONMENT - GENERAL DISCUSSION

SECTION II-A RESPONSE TO ROTATIONAL ENVIRONMENT - GENERAL DISCUSSION

The possibility that the undesirable effects of the weightless state can lead to the programming of space vehicle rotation around its booster or some other object to provide artificial gravity has prompted investigations into the effects of a rotational environment upon man. Such studies are of additional importance upon consideration of the possibility of capsule rotation which might be imposed by faulty attitude control systems, such as was apparently the case in Titov's flight. The chief concern is centered upon the possibility of diminished performance or incapacity due to motion sickness which might result from this unusual stimulation of the vestibular system.

In order to understand this problem more thoroughly, some insight into the anatomy and physiology of the vestibular system is necessary.

The attached diagram illustrates the structures of the internal ear. The entire apparatus is divisible into two areas. The cochlea and acoustic branch of the auditory nerve are concerned with the function of hearing. The sacculus, utricle, and the semicircular canals together with the vestibular branch of the auditory nerve comprise the vestibular system, the special sense organ for the perception of motion and equilibrium, and the area with which this paper is concerned.

The sacculus and utricle contain the otolith organs which sense gravity and linear and translational acceleration. The three semicircular canals, one in each perpendicular plane, sense rotational (angular) accelerations, but not linear accelerations.

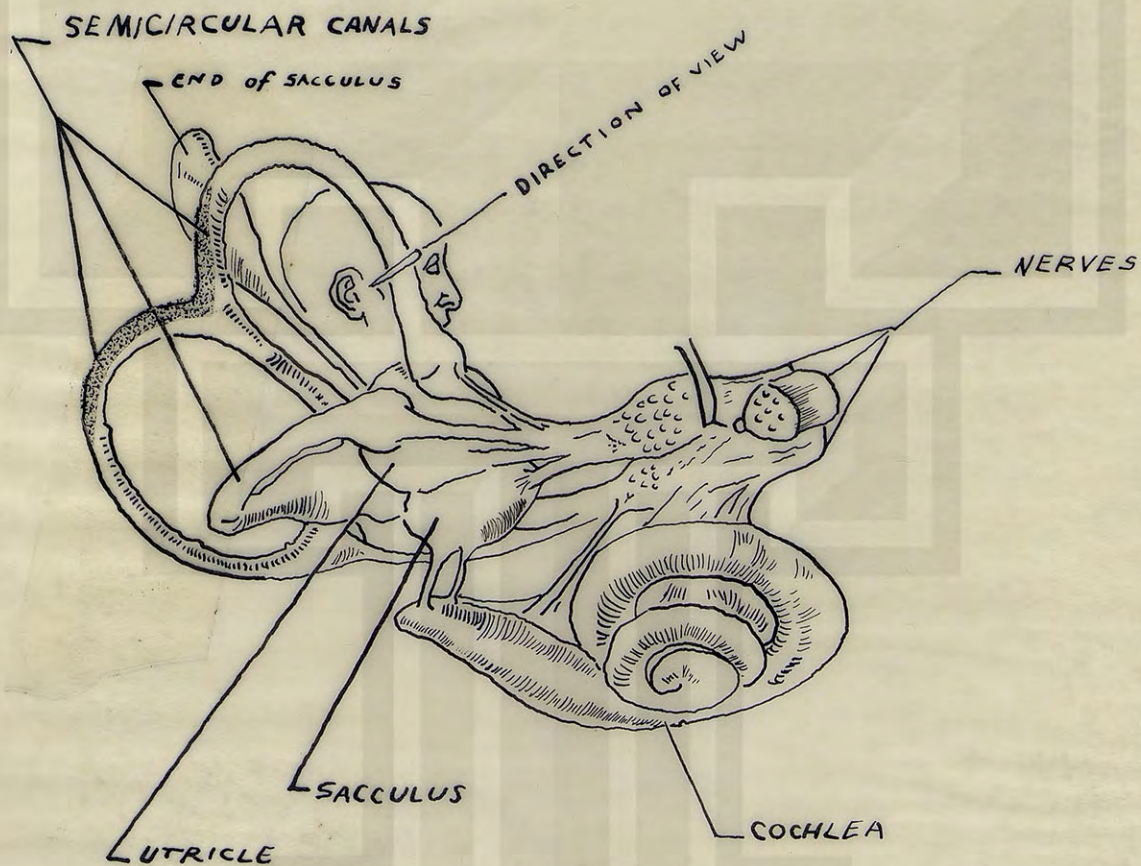


FIGURE 1
ORGANS of the
INNER EAR

(adapted from FULTON, J.F., A TEXTBOOK of PHYSIOLOGY,
p. 225, 17th ED., W.B. SAUNDERS CO., PHILIA., 1955)

If one were to dissect the vestibular system, he would find the three semicircular canals to resemble clear plastic tubes lying in a boney labyrinth. The tubes are filled with a clear fluid called endolymph, and each communicates through a small opening with the utricle. Each canal swells into a bulge near the utricle which is called the ampulla. Within the ampullae lie the sense organs (angular accelerometers in function) of the semicircular canals. These consist of a gelatinous membrane called the cupula which lies across the internal diameter of the ampulla. It is attached at one end by means of hair-like fibers to the crista, the flattened organ fixed to the wall of the ampulla which contains a portion of the nerve endings of the vestibular nerve. Movement of the endolymph fluid imparted by an angular acceleration about an axis perpendicular to the plane of a particular canal causes a deflection of the cupula which is sensed by the nerve endings within the crista. This information is then transmitted to the brain.

The otolith organs, or maculae, are situated on the floor of the utricle and saccule. They are composed of an area of thickened epithelium (cell lining) consisting of neuro-epithelial and supporting cells. Projecting from the surface of the neuro-epithelial cells are tufts of microscopic hairs. Lying across the top of these hairs is a gelatinous membrane containing numerous stoney particles called otoliths. Movement of the otoliths transmits stimuli to the hairs of the neuro-epithelial cells which are vestibular nerve endings. These, then, transmit impulses to the brain. Otolith movement is generated by orientation of the head in different positions relative to the direction

of gravity. From this it can be readily seen that the otolith apparatus is responsible for the "righting reflex," the remarkable ability of the cat, for example, to right itself when dropped to the floor from any body attitude.

It is generally recognized that persons subjected to unusual forces at sea or in the air may experience symptoms originating in the vestibular organs, for which the term "vestibular sickness" is applied. However, this term implies that both vestibular organs, the canals and the otoliths, are involved. Much work has been and is now being directed toward distinguishing the differences between the two and determining their relative roles in bringing about particular responses to particular unaccustomed motions.

Essentially, it can be stated that, if weightlessness itself causes "space sickness," it is anticipated to be an otolith response since (1) there is no input from the semicircular canals without rotation and (2) the lack of semicircular canal stimulation is a normal, everyday experience causing no symptoms. By far the strongest evidence for the existence of space sickness due to weightlessness is the report of Titov's flight. Since it has very recently come to light that Titov was very probably rotating in space and at a rate which usually does cause symptoms of motion sickness, the entire concept of "space sickness" is now open to serious question. Since prolonged weightlessness cannot be simulated, further space flight experience will be required to answer the question of the existence of "space sickness" and other

questions, such as the possibility of greater susceptibility to motion sickness while weightless.

Investigations of human and animal responses to sustained rotation have been most effectively conducted in the slow rotating room at the Naval School of Aviation Medicine, Pensacola, Florida. This consists of a 15-foot closed octagonal room, mounted centrally on a human centrifuge, and capable of constant rotation at a rate of from one to twenty revolutions per minute. Experiments with this facility have demonstrated that there are no ill effects so long as the subject is stationary and the angular velocity of the room is constant, since there is then no angular acceleration. However, if the subject then moves his head out of the plane of rotation of the room, sudden marked symptoms result. This, in physiological terms, is the Coriolis effect which is the major problem of the rotating environment.

The term, Coriolis acceleration, is used to describe the resultant acceleration imparted to the head when it is subjected to an acceleration whose axis is at right angles to the plane of its rotating environment. That is, when a body moves passively in one direction in a rotating environment and a new force is imposed which alters that direction, a third (Coriolis) force develops. The Coriolis effect in the physiological sense is used to denote the symptoms and signs resulting from Coriolis acceleration.

First order symptoms and signs are a decrease in mental alertness, visual illusions (oculogyric), nystagmus (rapid to and fro motions of the eyes), nausea, pallor, sweating, and difficulty in walking. Those of the second order are malaise, fatigue, sleepiness, headache, vomiting, collapse, over-breathing, reduction in urinary output, and lowering of

the threshold of response to symptoms such as sweating, dizziness on moving the head, and stomach awareness.

The Coriolis effect is thought by the majority of investigators to arise from stimulation of the semicircular canals. Evidence for this arises from the fact that squirrel monkeys, ordinarily extremely susceptible to the Coriolis effect, display lowered susceptibility when one or two pairs of canals are surgically blocked, and do not manifest symptoms at all after all canals are blocked with the otolith remaining intact. Further evidence is provided by the fact that tests of semicircular canal function permit predictable grading of susceptibility to Coriolis response, but tests of otolith function do not.

The mechanism by which the semicircular canals produce the Coriolis effect is not yet completely understood. It is generally held, however, that Coriolis accelerations induce a rotary circulation of endolymph in an inappropriate pair of canals because of this bizarre combination of forces. Simply stated, whereas tilting the head when in a stationary environment causes the stimulation of the pair of canals situated in the right-left plane (the plane of the lenses of a pair of glasses), the same maneuver in a rotating environment causes the stimulation of the pair of canals in the front-back plane (the plane of the bows or ear pieces of a pair of glasses) as well. This disagrees with visual and other sensory modalities, thereby resulting in a conflict of information which defies interpretation by the brain, producing the Coriolis response.

Findings obtained from a great many experiments with the rotating room, which are pertinent to the purpose of this discussion, can now be

summarized. In these experiments human subjects moved about freely in the room, remaining inside for variable periods of time up to two weeks at constant speeds of rotation ranging from one to twenty revolutions per minute. Animals were unrestrained in cages large enough to permit freedom of movement.

Most subjects experience a decreased alertness and sleepiness to a greater or lesser degree. Gibbons rotated at 10 rpm, promptly fell asleep and were kept awake with great difficulty by tapping on the cage. Some human subjects fall asleep for hours when allowed to do so, a few while conversing. This symptom is generally more severe in those who display a greater tendency toward nausea. All experimental subjects were arousable (none were comatose), but some required tactile in addition to voice stimulation.

All normal subjects (with intact vestibular systems) note the oculogyral illusion. This is the apparent movement of an object when the head is tilted to the side and is particularly noticeable when a dimly lighted object is viewed in the dark. As an example, a subject sitting at the periphery of the room facing in the direction of rotation who tilts his head toward the wall sees the target move upward. It appears to move downward again when the head is righted.

Nausea appears to be the most distressing effect to the largest number of subjects. Symptoms range from stomach awareness to severe nausea and vomiting, but a few subjects are not so affected. In some particularly susceptible individuals a summating effect is noted in which a series of small head movements finally results in severe nausea and vomiting.

An increase in anti-diuretic hormone from the pituitary gland regularly causes a decreased output of urine in motion sickness.

Pallor and a fall in body temperature due to vasoconstriction (narrowing of blood vessels) are two of the most sensitive indicators of the stress of a rotating environment. A few (three) highly susceptible individuals have collapsed in the rotating room due to severe vasomotor depression (dilation of blood vessels). One other showed non-specific and transitory ECG changes.

The higher the rate of rotation, the more intense are the symptoms.

Of great importance is the fact that adaptation to the rotational environment developed in all subjects exposed to prolonged rotation. It developed more slowly in those displaying more severe symptoms. In general, it was complete within two days, sometimes requiring only minutes. However, following cessation of rotation after adaptation, Coriolis effects again appeared until readaptation to the normal environment took place.

The phenomenon of habituation, a lowering of susceptibility to symptoms upon repeated exposure, also occurs as it does in figure skaters who learn to tolerate high rates of spin. Pre-training can therefore be expected to considerably increase tolerance to rotation, and more definitive data on this important facet is being amassed.

Finally, it should be stated that there are other integrative functions of the central nervous system that can be disturbed causing similar symptoms to canal sickness. Anxiety, fear, confusion of visual stimuli, and muscle and position sense (proprioceptive) stimuli can act

in this manner. In fact, the anticipation of an abnormal balance of stimuli in weightlessness led Gauer and Haber in the late 1940's to predict that space sickness would occur in the weightless state.

Fortunately, this has not proved out so far, and it is generally not anticipated that it will if adequate sensory stimuli are not removed. But, there is no doubt that further space flight experience is needed.

It remains nevertheless true that, insofar as the question of human response to a rotational environment is concerned, semicircular canal sickness plays a major role; and the information gained from experiments with the slow rotating room is of very direct significance.

SECTION II-B

RESULTS OF SURVEY ON RESPONSE TO ROTATIONAL ENVIRONMENT

SECTION II-B - RESULTS OF SURVEY ON HUMAN RESPONSE TO ROTATIONAL ENVIRONMENT

Because of the accord of opinion in this field, findings are presented as a simple list of pertinent facts.

1. The development of symptoms of semicircular canal sickness is dependent upon, (1) the rate of rotation of the environment, and (2) individual susceptibility (which can be predicted by known tests of canal function).

2. It is known that a rate of rotation of 5.4 rpm around a radius of 100 feet will produce a one G environment.

3. Shortening of the radius proportionately lessens the resultant G. Lengthening of the radius proportionally increases G.

4. Increasing or decreasing rpm increases or decreases G by the square of the proportional alteration of rpm.

5. Canal sickness increases as rpm is increased.

6. Ranges of 2 to 5 rpm are now being explored for their tolerability.

7. A rate of 2 rpm or less causes no ill effects and requires no protective measures.

8. At 3 rpm symptoms are in general extremely slight being detectable only if looked for.

9. On the basis of present information, it is expected that 5 rpm will be tolerated without ill effects if precautions are observed. These include adequate crew selection and pre-training, and availability of drugs for possible use. This expectation is enhanced by the phenomenon of adaptability which should occur in all cases.

10. The phenomena of adaptability and habituation provide the rationale for the possible use of a slow build up of rpm, perhaps, to even a higher level than 5 rpm if future needs should dictate.

11. The amount of G needed to prevent untoward symptoms and signs of weightlessness effectively is not known and cannot be estimated from present experience. There is probably no argument that it will not be more than one G, but space flight experience is clearly a necessity for this kind of prognostication.

CONCLUSIONS



CONCLUSIONS

In summary, the following represents the consensus of authoritative opinion on weightlessness and rotation.

Of all the symptoms and signs which have at one time or another been ascribed to weightlessness per se, only two are thought to be important, considering the probability of their occurrence, their threat to the welfare of the astronaut, and the success of the mission. These symptoms are decreased tolerance to reentry G and vomiting. A third effect, diuresis, which is strongly anticipated is an important mechanism in the loss of G tolerance, and can also result in dehydration. Its importance to reduction of G tolerance is already considered. In its latter effect, dehydration, it is not regarded prominently since dehydration is so readily prevented and corrected by an adequate fluid intake.

The phenomenon of "space sickness," of which emesis is a part, may very well not even exist, as is suggested by disclosures made even more recently than the gathering of the data included in this paper. On the other hand, there is no assurance in either direction. Then too, emesis can also occur as a result of roll, pitch, or yaw, or as a result of transitional forces changing the G load on the man. All told, reference to Section I-B reveals that emesis is given a low probability of occurrence, of causing mission failure, or of resulting in the need for artificial gravity; and no probability of causing engineering changes in the capsule interior. Further evaluation of these figures indicates that presently available methods are considered effective

enough to markedly reduce the probability of its occurrence and of mission failure resulting from it. Nevertheless, because of the potential danger of emesis in the weightless state, the development of a solids trap and of a vacuum aspirator are currently underway at the Manned Spacecraft Center.

A review of opinions in Section I-B concerning the reduction of G tolerance indicates general agreement on the very high probability of its occurrence and of its resulting in mission failure without the use of special preventive measures. It should be noted that there was uniform agreement that tolerance to G forces in the transverse direction is much greater than to those in the vertical or lateral directions; but, only two considered this to be a 100 per cent difference and were confident enough in the programming of a transverse G load into the mission to state that mission success or failure is completely dependent upon the direction of G. The wide disparity of opinion concerning the effectiveness of known preventive measures indicates the need for a great deal of work in this area. At the same time, the estimated probability of the need for artificial gravity on this account was uniformly low, largely because of the wealth of physiological data on the mechanisms involved and the promising appearance of proposed methods of prevention. These have yet to be validated. It was generally agreed that there is little probability that this question will result in significant engineering changes within the capsule.

The determination of the duration of the diuretic effect in weightlessness is entirely dependent upon prolonged space flight. The

importance of this determination to the question of reentry G tolerance has been discussed. It is generally agreed, however, that this can be determined by either animal or manned space flight.

Of significance in studies of human response to rotational environment is that it is anticipated that selected men will be able to tolerate constant rotations of up to 5 rpm if adequately pre-trained and equipped with medications for use if needed. It is already known that up to 3 rpm is well tolerated in selected individuals. The importance of the phenomena of adaptation and habituation in this regard is discussed.

Opinions regarding the usefulness of information concerning weightlessness obtained from Gemini to the Apollo program differed almost entirely on the basis of the time interval between their corresponding missions. It should be noted that the comments made were not solely confined to the ill effect under discussion. Almost all were in agreement that, if the time interval is one year or more, Gemini is a valid and important program. Out of seven individuals or groups, two indicated that Gemini is valuable if it provides any time advantage, three drew the line at 10 months, one drew the line at one year, and one indicated that the 18-orbit Mercury and the early Apollo missions would suffice. All agreed that two 14-day Gemini missions would be sufficient, but two added that more would be desirable if Apollo is delayed.

Finally, it must be strongly emphasized that the effects of the serial and combined stresses of space flight on man constitute an

unknown area of even greater importance than any single constituent factor. It is very important to realize that several of the ill effects considered to be of lesser importance in weightlessness alone may prove to be of major consequence in the total stress of space flight. Since manned space flight provides the only means by which these effects can be known in any practical way, manned space flight itself is the most positive and probably the shortest stepping stone from mission to mission. It is therefore concluded that the Gemini program is valid and valuable to Apollo if it provides any practical lead time at all.

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