THE BIOLOGICAL EFFECTS AND IMPLICATIONS OF WEIGHTLESSNESS

James G. Gaume, M.D.
Chief, Life Support Systems
The Martin Company
Denver, Colorado

The effects of prolonged weightlessness is the most difficult to evaluate of all the problems which man will encounter in space flight. The prospect of weightlessness for long periods of time presents a host of new medical and physiological problems with which man has never before been confronted. The greatest difficulty in attacking this problem lies in the fact that it is impossible to provide exact simulation of the weightless environment here on earth so that the effects can be determined readily and economically, and without the risk associated with putting the man into orbit.

Early research was first directed toward devising methods of achieving weightlessness for short periods on or near the earth's surface. All of you have experienced subgravity states for perhaps a second or two. This time is not sufficient to evaluate effects. These states include any sudden drop or fall associated with express elevators, rollercoaster and other amusement park rides, diving, trampolining, parachute jumping, diving in aircraft and many other similar activities. All these are more or less uncontrolled trajectories. It was desirable to achieve a controlled trajectory of longer duration.

Except for slight air drag, free falling objects are weightless for several seconds depending on the height from which they are dropped. Even a few seconds is enough to determine some effects on physical matter such as fluids and gases enclosed in a container. But the biologist is interested in the effects on living matter.

In the normal flight of commercial airliners the passengers are subject to gravity and have weight because the speed of the aircraft is only a fraction (about 1/30) of that required of a satellite in orbit. The vehicle which provides a weightless environment for more than ninety minutes is an orbital vehicle in which the earth's gravitational force is balanced or nullified by its velocity of more than 17,000 mph.

It was determined by calculation that intermittent weightlessness could be achieved by aircraft flying a roller-coaster type parabolic trajectory. The period achieved at the top of the hill was determined by the performance of the aircraft used. A T-33 jet could achieve about 33 sec., the F-94 about 44 sec. and the F-100 about 60 sec., the F-104 about 80-90 sec. Early in the program only the T-33 and F-94 jets were available as experimental vehicles for human experimentation.

Animals were sent up in experimental rockets such as the Aerobee, the Viking, the Redstone (V-2) and others, to obtain longer periods of weightlessness up to several minutes. This occurred after burnout of the rocket fuel, during the ballistic flight of the nose cone, until air drag began to slow the nose cone on entering denser atmosphere thus creating a "g" force which increased with descent until terminal velocity is reached during re-entry.

Early experiments revealed that several minutes of weightlessness had no significant effects on animals other than transient effects on heart and respiratory rate, and that normal animals were confused as to up and down, but that labrynthectomized animals were not disturbed in this regard.

On the other hand, human subjects showed a variety of responses - some were nauseated or disoriented as to direction, others were not. Some of these positive effects were undoubtedly psychological and some were physiological. A few subjects were exhilarated by weightlessness and a few didn't like the sensation at all. The largest percentage of subjects were in between.

These periods were as long as 44 seconds in the F-94. In his record breaking altitude flight to 126,000 ft. in the X-2, Captain Ivan Kincheloe was weightless for about two minutes. He stated that he wasn't even aware of the fact, subjectively. Data analysis after the flight indicated that he was weightless.

It was found, too, that man can learn very quickly to adapt to weightlessness in psychomotor activity, to use his muscles for specific tasks. He can eat and drink, and he can even void, although first attempts were unsuccessful.

In larger aircraft such as a twin-engine Convair transport and the converted jet tanker KC-135, periods of 15-20 seconds and 30-33 seconds respectively can be obtained. Larger cabins enable the human subjects to move about more. In these aircraft many problems have been and are now being investigated. These include methods of fixation for walking (suction cups on shoes, magnetic shoes, Velcro cloth soles and walking surface.)

Moving the body through weightless space must also be learned. Various means of propulsion investigated were the subject's own muscular force, the use of jet guns held in the hand to move the body, and how to maintain proper body position during motion. In both cases the thrust vector must be aligned with the center of mass of the body to avoid tumbling. Sometimes a certain amount of rotation is desired. How is this rotation controlled by these methods of propulsion?

The use of tools in zero-g has been investigated. These experiments have furnished data which will be used in the design of specialized tools for use in the weightless environment, and to determine the methods of fixation of the entire body so that the worker will not move instead of the bolt, nut, or screw. Other projects include mass discrimination, handling of bulky materials, personal gyro stabilizers, and tethering devices.

Some physiological and psychological problems under investigation include subjective rotation responses and time estimate, perception of "g fraction" stimuli, reflex behavior, cardiovascular and respiratory responses, suit mobility and design, EEG and GSR effects, retinal deformation, and many others.

These aircraft are large enough to permit simultaneous investigation of many problems, including those physical such as heat transfer, boiling of liquids, and testing of various kinds of equipment for operational efficiency in weightlessness, and many others. The list is now so long as to preclude inclusion in one short paper.

The flights of Shepard, Grissom, Gagarin and Titov indicate that man will have little or no difficulty in tolerating short term weightlessness. This implies that there may be significant differences in man's reactions to short and long-term weightlessness. This is quite true. First, where in time is the cross-over point between the short and the long? This question has not yet been answered. This cross-over point may vary with the physiological function under consideration.

For example, we know that all the astronauts mentioned were able to exchange gases in the lung or they would not have survived. Gas exchange was also adequate at the capillary level for the time periods involved. But will there be any significant effect on gas exchange at the capillary level after one week, two weeks, or two months?

Similarly, will the nitrogen or mineral balance be significantly altered after 1 day, 5 days, 10 or 100 days? Will the astronaut be afflicted with renal calculi? What would happen to total blood volume after one, three, or six months in weightlessness? Is there a significant change in blood pressure in various parts of the body? How will gastro-intestinal physiology be altered?

There are literally hundreds of questions to be asked concerning the implications of weightlessness. How can we get some information regarding significant changes in physiological functions of the body in prolonged weightlessness?

There are two environments, readily accessible, which are comparable to certain extent. Analyses of these which can be made from data available in the literature and from experiments designed specifically to simulate some of the effects of weightlessness. These two hypo-dynamic environments are 1) prolonged inactive bed rest, and, 2) prolonged inactive suspension of the body in water.

How can these hypodynamic environments tell us anything useful for space flight? Let's analyze each one.

Bed Rest

Prolonged, enforced bed rest has several similarities with prolonged inactive weightlessness.

1) The muscles are not being used. In bed rest a negative nitrogen balance occurs.

2) Bones demineralize, calcium and phosphorus are excreted in greater quantities. There is a tendency to formation of renal calculi.

3) Gastrointestinal activity decreases. Secretory activity and peristalsis is less. Fatty diets produce enterogastrone which decreases emptying time of the stomach (unable to relax and empty.) Constipation ensues, as well as nausea and vomiting in some cases, from food retention.

4) Total blood volume decreases by 500 cc in one month. Less blood is required, therefore the excess is eliminated. This sentence is the key to many physiological questions, whether related to a gravity field or a zero-g field. What the body needs it retains and what it no longer needs it discards.

5) Metabolism is generally decreased over the entire body. Oxygen consumption is 7-8% less, basal metabolism is reduced from 1-4.3 calories/square meter/hour. Nitrogen balance is often negative despite an adequate protein intake, and may not be restored until 6-8 weeks after termination of the period of rest. Liver function tests indicate impairment of liver parenchyma. Muscular creatine storage is less, indicated by lowered creatinine tolerance during immobilization. One investigator (Blotner) found reduced carbohydrate tolerance.

6) Cardiovascular effects include deterioration of cardiovascular responses to stress, evidenced on assuming upright position, by palpitation, tachycardia, vertigo, dyspnea, and reduced tolerance to muscular effort. No significant changes are revealed in arterial pressures, blood velocity, heart size and ECG. However, myocardial strength <u>must</u> be reduced. Blood volume is less by about 500 cc, and a lower peripheral venous pressure is observed. Occasionally with drop in blood pressure on standing, cardiac arrhythmias are seen, in "normal" subjects. On arising after prolonged rest, hemorrhage sometimes occurs in the feet and ankles.

7) Sleep requirement is reduced. You all have had patients who complain that they don't sleep well when they have been in the hospital for long periods. It is not merely the hospital noise which is responsible, but sleep periods are shorter, lighter and just about as effective because less sleep is required.

8) Nervous System. Loss of control function in peripheral vessels of lower extremities and other parts of body, indicate some neural disturbances as a part of total syndrome of deterioration.

9) Genito-urinary System. In bed rest, excretion of calcium is increased for the last five weeks of a 6 or 7 week confinement, average loss about 11 grams, may exceed normal excretion for three weeks after mobilization.

Other factors are urinary stasis, difficulty in voiding, and incomplete evacuation of the bladder in the recumbent position, infection, high pH (excessive calcium or alkaline ash in diet), and low citric acid in urine.

Renal function, in both the glomeruli and tubules probably behave in much the same or similar manner as capillary-cellular function in other tissues when exposed to the weightless environment. We must assume so at present because there is no related experimental evidence.

However, there is evidence that bladder function is affected, and this evidence may upset accepted theory on the initiation of the reflex mechanism of micturition.

The first attempts at voiding in the weightless state were made in an F-94 jet aircraft with uncomfortably full bladders. These attempts resulted in failure to void in the weightless portion of the flight. On the other hand subjects found that it was quite difficult to avoid voiding during the 3g pullouts of the parabolic flight trajectory. Bear in mind that these two extremes in gravity occurred in less than two minutes so that there was no appreciable change in volume and stretching of the bladder. This indicated that, since the only variable concerned was the g-factor or weight of bladder contents, that a factor heretofore not considered by theory on the mechanism of voiding, must be present. This factor is weight of bladder contents on some receptor in the floor of the bladder, either in the trigone or in a smaller portion of the trigone at the urethral opening, the most dependent portion of the bladder. If this is true then the desire to void must be caused by the head of pressure above these receptors in the floor of the vesicle. The head of pressure is determined by two factors: 1) the pressure exerted by the column of fluid over a given area containing these receptors, and 2) the increase in this pressure brought about by the tonicity and stretch-resistance of the detrusor muscle.

To determine the relative importance of these two factors a simple experiment was set up. The bladder was allowed to fill again to the uncomfortable level. The subject then stood on his head to void. The theory was that if gravity or weight of bladder contents were more important, this position would produce a negative "g" with respect to weight of bladder content stimulating the sensors presumed to be in the bladder floor. If the subject was able to void easily, then stretch was the more important. If the subjects were not able to void freely and found it difficult, then the presence of weight sensors was the important factor. The subjects found that the desire to void while doing a headstand disappeared completely. Only one of the first four subjects was able to void in the inverted position. The bladder was just as distended upside down as right side up, which indicates the presence of gravity sensors in the bladder floor.

This in no way disagrees with accepted theories on micturition except that the reflex is initiated by stimulation of receptors in the floor rather than by stretching of the vesicle wall. Nor does there appear to be any conflict concerning mechanisms in pathological physiology.

As the number of subjects used in the jet flight experiments grew, it was found that about 75% of subjects were able to void in the weightless state. Flights of Shepard, Grissom and Gagarin were too short to require voiding. With regard to Titov's flight of nearly 24 hours in O-g, we are told simply that he had no difficulty.

Thus we see that we can often understand normal function under ordinary circumstances by removal of a factor so long taken for granted that we are blind to its true role. How many other physiological functions of the body are dependent upon gravity, either wholly or in part? It is difficult to say today, but when we have manned laboratories in space in weightless environment, long term studies can be carried out, and then we will know better how to use gravity in the treatment of terrestrial illnesses.

All these effects of prolonged bed rest occur also, and more severely, in the hypodynamic state of water immersion in which the gravity factor is removed from the bones, muscles, nervous system, etc. when considering the body as a whole. These are some of the effects of bed rest and water immersion which can be compared to 0-g effects on the same functions. Other effects of bed rest, such as formation of venous thrombi, bed sores and other effects of pressure and restricted circulation are not expected to be problems in weightlessness.

In the weightless state all the effects on the functions compared can be expected to be more severe. In addition, the relative difference in the change from weightlessness to 1 g upon returning from orbit is greater than it is in changing from bed rest to the ambulatory state. Therefore, the astronaut would be expected to be more seriously affected on returning to gravity. Graveline, in his water suspension experiment, was more severely incapacitated after one week in water than he would have been after one week in bed. Few debilitating effects were observed during the actual immersion period.

Graveline also recorded an unexplained increase in leucocycte count and elevated hematocrit, and some decrement in complex performance task. The latter might be serious in a prolonged hypodynamic state for longer periods, even while still in that state.

Can man be in weightless space for more than a few days? What must be done to prevent such consequences as these?

I believe that the means can be devised to enable the astronaut to go to space and return safely, without these physiological consequences which occur in bed rest and water suspension.

PREVENTIVE MAINTENANCE OF THE BODY IN WEIGHTLESSNESS

Since these changes already mentioned occur in hypodynamic states easily provided on the surface of the earth and since these environments on earth still provide gravity acting on the body albeit less than or different from the normal, it follows that complete removal of gravity can produce these changes more rapidly and/or to a greater degree. Moreover, these changes are largely the result of insufficient muscular activity. Therefore, the answer to our question lies in the design of an exercise program to be accomplished in the weightless environment. This program must provide enough muscular work to replace that performed in moving the body about on the earth's surface working against gravity, plus enough specifically designed exercises to perform specific conditioning.

Muscle conditioning should not be difficult. Opposing muscles can be put to work against each other in either isotonic or isometric contraction. By routinely exercising all muscle sets of the body, it appears that many of the consequences listed for bed rest can be prevented. The pertinent questions are - how long must each muscle set work, and how hard must it work. This in turn reflects on the oxygen consumption which might be much higher than figures commonly used in design practice at present for life support systems. Further studies using the water immersion environment are needed to determine the kind, duration and intensity of exercises in the program, prior to putting man into orbit for a week.

For bone maintenance, exercises designed to put a weight stress on the long bones will be required. Again, how much, how long, and how often must the stress be applied? Application can take the form of grasping handles attached to a floor (or wall) and forcing the feet against that surface using arm and shoulder muscles to apply the force. At the same time, the anti-gravity muscles would be working in the opposite direction.

Artificial gravity provided or designed into the satellite might achieve the same objective. Again, how much gravity? Must it be constant or could it be intermittent? Do we need a full "g" or only a fraction? What fraction? Muscle applied "g" just described would be intermittent and probably fractional.

All or nearly all the potential effects of weightlessness which have been enumerated could theoretically be prevented by properly designed exercise. This in turn will require a larger oxygen supply, a larger carbon dioxide absorbent system, a larger odor removal system, and a more efficient dehumidifying system, for either recovery or removal, or a larger supply of stored water at the beginning of the flight. A more critical examination of all these requirements is in order.

The time in weightlessness required to upset each organic system in the body might vary considerably. Muscle tissue might be affected earliest, bones next, gastro-intestinal tract next, and so on. Thus, the exercise program could be designed specifically for each mission, depending on its length and the systems of the body most likely to be affected in that time period.

Some aspects of the subgravity or zero gravity states can benefit the astronaut. It will be easier to move about on the moon, for example, where the gravitational field is 1/6 that of the earth's gravity. More ground can be covered for the same amount of oxygen which would be consumed on earth for the same effort. And when we start building structures on the moon, less heavy construction equipment will be required because the man can move so much more in materials weight and mass and at the same time get some of the required exercise for preventive maintenance.

BIBLIOGRAPHY

Wiggers, Carl J. : Physiology in Health and Disease, Fifth Edition pp 969-973, Philadelphia, Lea & Febiger, 1949.

Karpovich, P.V. : Physiology of Muscular Activity, Fourth Edition pp 278-282, Philadelphia, W. B. Saunders & Company, 1953.

Symposium: Abuse of Bed Rest, J.A.M.A. 125, 1075, 1944.

Hein, M.M. : Preliminary Investigation of the Problem of Maintenance of Muscle and Bone Mass and Function Under Conditions of Immobilization and Zero Gravity, Internal Report, The Martin Company, Denver, Colorado, April 1960.

ARDC Zero Gravity Survey, Directorate of Advanced Systems Technology, Wright Air Development Division, Wright Patterson AFB, Ohio, 1960.

Stutman, L.J., and Olson, R. : Effects of Zero Gravity Upon the Cardiovascular System, U.S.Armed Forces Medical Journal 11 (10), 1162-1168, October 1960.

Schock, G. J. D. : A Study of Animal Reflexes During Exposure to Subgravity and Weightlessness, J. Aerospace Medicine, 32:336, 1961.

Haber, F., and Haber, H. : Possible Methods of Producing the Gravity-free State for Medical Research, Journal Av. Medicine, 27:5, 1951.

Henry, J.P., Ballinger, E.R., Maher, P.J., and Simons, D.G. : Animal Studies of the Subgravity State During Rocket Flight, Journal Av. Medicine 23:421, 1952.

Gerathowohl, S.J., Ritter, O.L., and Stallings, H.D. : Producing the Weightless State in Jet Aircraft, School of Aviation Medicine, USAF Report 57-143.

Haber, H., and Gerathowohl, S.J. : On the Physics and Psychophysics of Weightlessness. Journal Av. Med., Vol. 22:180, 1951.

Gerathowohl, S.J., Strughold, H., Stallings, H.D.: Sensomotor Performance During Weightlessness, Journal Av. Med., 28:7, 1957.

Gerathowohl, S.J.: The Labrynthine Posture Reflex (Righting Reflex) in the Cat During Weightlessness, Journal Av. Med., 28:345, 1957.

Ward, J.E., Hawkins, W.R., Stallings, H.D. : Physiologic Response to Subgravity. School of Aviation Medicine, USAF, Report No. 59-2, January 1959.

McKenzie, R.E., Hartman, B., Graveline, D.E. : An Exploratory Study of Sleep Characteristics in a Hypodynamic Environment, School of Aviation Medicine USAF Report No. 60-68, October 1960.

Hartman, B., McKenzie, R.E., Graveline, D.E., : An Exploratory Study of Changes in Proficiency in a Hypodynamic Environment. School of Aviation Medicine, USAF, Report No. 60-72, July 1960.

Graveline, D. E., Balke, B. : The Physiologic Effects of Hypodynamics Induced by Water Immersion, School of Aviation Medicine, USAF, Report No. 60-88, September 1960.