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PHYSIO-PATHOLOGIC IMPLICATIONS OF CHRONIC WEIGHTLESSNESS

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The effects of chronic weightlessness on the human body are the most difficult to evaluate of all the medical problems which man will encounter in space flight. Much research has been conducted on the effects of weightlessness, but all experiments to date have to do with acute effects, and it is not safe to extrapolate to chronic effects. Now, the prospect of weightlessness for long periods of time is approaching reality, and with this reality a host of new medical and physiological problems are presented to the biomedical research community.

In terrestrial medical research, simulation of stress factors is not difficult in comparison to the simulation of the lack of gravity. The chronic null-gravity environment at present can be produced only by placing a satellite in an earth orbit, and not by any substitute method available to us on earth. The cost and risk, however, of placing biological specimens or human subjects into orbit are too great for routine research. Therefore, acceptable substitute approximations must be employed on earth to analyze theoretically the potential effects of chronic weightlessness. Thus we will be better prepared to design effective experiments to be conducted in orbit in the true weightless environment, thereby obtaining more useful data for the money invested.

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There are two situations producible here on earth which should provide physiological data of value in anticipating the effects of long-term weightlessness. These situations are:

1. Prolonged inactive bed rest; and,

2. Prolonged inactive suspension of the body in water.

Inactivity in all three situations -- bed rest, water suspension, and weightlessness, is specified in order to establish a baseline, a common factor, so that it will be easier to understand what must be done to prevent such effects.

At this point a brief review of what has been and is being done seems in order.

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 parabola 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 and by the Russians, 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 re-entry vehicle on entering denser atmosphere thus creating a "g" force which increased with descent until terminal velocity is reached during re-entry. More recently, animals have been put into earth orbit and recovered by both Russia and the United States.

These 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~~ labyrinthectomized 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. A few subjects were exhilarated by weightlessness and a few didn't like the sensation at all. The largest percentage of subjects was in between these extremes. These positive effects were undoubtedly both psychological and physiological.

In his record breaking altitude flight to 126,000 ft in the X-2, in 1956? Captain Ivan Kincheloe was weightless for about two minutes. He stated that, subjectively, he wasn't even aware of this fact. Data analysis after the flight indicated that he was weightless.

It was found, too, that man can learn very quickly to adapt to weightlesness 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 C-131 transport and the converted jet tanker KC-135 , periods of about 20 sec and 33 sec , respectively, can be obtained. Larger cabins enable the human subjects to move about more. In these aircraft many problems have been and are now under investigation. These include methods of fixation for walking (suction cups on shoes, magnetic shoes, Velcro cloth soles and walking surface.)

Propelling the body alone 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 state, and to determine the methods of fixation of the entire body so that the worker will not rotate instead of the bold, 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, time estimate, perception of a "g fraction" stimulus, reflex behavior, cardiovascular and respiratory responses, suit mobility and design, electroencephalographic and galvanic skin response effects, retinal deformation, and many others.

These aircraft are large enough to permit simultaneous investigation of many problems, including heat transfer, boiling of liquids, and testing of various kinds of equipment for operational efficiency in weightlessness, and many others. The list is now too long ~~as~~ to even mention in one short paper.

MANNED FLIGHTS OF UNITED STATES AND RUSSIA

The flights of Shepard, Grissom, Gagarin, and Titov, have indicated that man will have little or no difficulty in tolerating short periods of weightlessness. Neither Shepard nor Grissom had any apparent ill effects of weightlessness for periods of several minutes, nor did Gagarin have any after more than an hour. The flight of Titov, however, which provided a weightless period of approximately twenty-four hours, began to reveal some significant effects.

Titov, after about three hours in orbit, suffered nausea, which was aggravated on sharply turning his head. When Titov slept, and following sleep, the nausea was less, but still persisted until the retro-rockets were fired to disorbit the vehicle. This is a significant point - that without the accustomed gravitational force acting upon sensory receptors some adverse reaction may occur. If this is true, will individual differences in tolerance to the agravic state enable some subjects to adapt to the environment? Titov became nauseated in approximately 3 hours. Will Glenn follow this same schedule? If so, is there a time threshold for the onset of this reaction? If not, was Titov merely a susceptible individual, and will he prove to be an exception to the rule? And is there another time threshold, at which the average astronaut will adapt and overcome nausea? Only a statistically valid number of subjects in weightlessness for at least several hours or days will answer these questions.

Titov's nausea may have several contributing factors. The most likely explanation is vestibular, but could include gastro, intestinal, or visual disturbances, and the lack of the normal exteroceptive stimuli from the somatic parts of the body.

Titov's appetite was less than normal also. Meals were eaten on schedule, but apparently with less relish than on earth.

Loss of tolerance to g-force after weightlessness has been a debated question. It is still unanswered, since the Russians have stated that Titov's flight was too short, and that he felt <u>better</u> upon the return of a g-force beginning with the disorbiting maneuver.

CHRONIC WEIGHTLESSNESS

I have stated that man will have little or no difficulty in tolerating short-term weightlessness. This implies there may be significant differences in man's reactions to short and long-term weightlessness. This is quite true! First, at what point in time is the cross-over point between short and long? This question, too, has not yet been answered. This cross-over point may well 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 in the lung or at the tissue 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 shift in blood pressure or blood volume in various parts of the body? And, how will gastro-intestinal physiology be altered? There are literally dozens of questions concerning the implications of weightlessness. How can we get some pertinent information regarding significant changes in normal physiological functions of the body in chronic weightlessness.

The two hypodynamic environments already mentioned, i.e., bed rest and water suspension, can, if analyzed with weightlessness in mind, provide pertinent information which will be of use in predicting weightless effects, and in planning the experiments to be conducted in satellites. Let's analyze each and see how these low cost, low risk situations can be helpful in solving space flight problems.

<u>Bed Rest</u>. Living organisms are peculiarly adaptive systems. If a new stress is applied to a living thing it makes internal adjustments to enable itself to live with that stress. If a stress is removed, adaptations are also made to its absence. In one case tissue may be added to the system, and in another case, tissue may be removed. The key to this analysis is the fact that in normal function, "what the body needs it retains, and what it no longer needs it discards." And its needs are dictated by the sum of the stresses placed upon the total organism.

Prolonged, inactive bed rest has several similarities to prolonged inactive weightlessness when examined in the light of the basic principle stated above. Some of these are:

1. Muscles are not being used. In bed rest a negative nitrogen balance occurs in only 5 - 6 days. Also negative balances occur with respect to sulfur, sodium and potassium.
2. Bones demineralize, calcium and phosphorous are excreted in greater quantities. There is a tendency to formation of renal calculi, because of increased excretion of Ca & P, and a relative urinary stasis.

3. Gastro-intestinal activity decreases. Secretory activity and peristalsis is less. Fatty diets produce enterogastrone which delays emptying of the stomach (unable to relax and empty.) Constipation ensues, and occasionally food retention occurs, with nausea and vomiting in some cases.

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.

5. Metabolism is generally decreased over the entire body. Oxygen consumption is 7-8 % less, basal metabolism is reduced by 1-4.3 calories/square meter/hour. Nitrogen balance is usually 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. Muscle 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 a standing position, by palpitation, tachycardia, vertigo, dyspnea, and reduced tolerance to muscular effort. No significant changes are revealed in arterial pressures, blood velocity, ECG. However, total heart size is less and is 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, even in "normal" subjects. On arising after prolonged rest, hemorrhage sometimes occurs in the feet and ankles, due to increased capillary fragility.

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 and routine 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 beginning in the second week of confinement; average loss about 11 grams, may exceed normal excretion for three-four weeks after mobilization.

Other factors are urinary stasis, difficulty in voiding, with 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 by subjects with uncomfortably full bladders, in an F-94 jet aircraft. 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 prevent voiding during the 3-g pullouts of the parabolic flight path. 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 previously 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 brough about by the tonicity and stretch-resistance of the detrusor muscle.

to determine the importance of gravity in voiding, 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, resistance and abdominal pressure were 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 primarily 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 0-g, we are told simply that he had no difficulty.

Thus we see that we can often better 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 a weightless environment, long term studies can be carried out, and then we ~~will~~ shall know better how to use gravity in the treatment of terrestrial illnesses. For example, in cardiac conditions, the weightless treatment could be worse than bed rest. Patients with myocardial infarcts and with myocardial failure both seem to respond better, after the acute phase of the illness is past, with prescribed physical activity within the patient's tolerance.

Water Immersion. 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 and muscles, and 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, hypostatic congestion, and other effects of pressure and restricted circulation are not expected to be problems in weightlessness, or in water immersion.

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 itself. 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 physiopathological consequences which occur in bed rest and water suspension. Early astronauts will be young, vigorous individuals and will be normally dissatisfied with inactivity. Therefore it will be relatively easy for them to follow a prescribed exercise program, particularly when motivated by the prospect of incapacitating reactions on returning to earth, if they should default!

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 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 while 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 special 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 would appear that many of the evil effects of 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 presently used in design practice for life support systems. Further studies using the water immersion environment are needed to determine the kind, duration and intensity of exercises in this 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, shoulder, and back 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 exercises, which would require very few pieces of physical condition apparatus. 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. The vestibular system and muscle tissue might be affected earliest, bones next, gastro-intestinal tract next, and so on. Thus, the exercise program should 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. This requires an extensive, time-consuming, research program in order to define the requirements for such conditioning programs.

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, fewer pieces of heavy construction equipment will be required because the man can move so much more himself in materials weight and mass, and at the same time get some of the required exercise for preventive maintenance.

SUMMARY

An attempt has been made to evaluate the validity of data obtained from two hypodynamic environments available to researchers at an earth site, at low cost and risk. These are:

1. prolonged inactive bed rest; and,

2. prolonged inactive water immersion.

Neither environment simulates accurately the weightless state to be encountered in space, but, if experiments and projects are properly designed, much useful information, which will better prepare man for chronic weightlessness, can be obtained.

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