THE BIOMEDICAL ACCEPTABILITY OF 45 TO 60 DAY SPACE FLIGHT (AN ANALYSIS)

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1 - Introduction

This paper is an evaluation of man's ability to undertake 45 to 60 day space flights. Specifically it attempts to identify the nature and significance of the biological changes to be expected in man during exposure to flights of this duration.

This analysis is based primarily upon the experience gained from the manned missions of NASA Projects Mercury, Gemini and early Apollo, and to a lesser extent from the Soviet manned flights. The longest duration of any of these flights is 14 days; therefore, the analysis has attempted to predict the crew effects of a 3 to 4 fold extension in flight duration. To do this a consideration of the information that has resulted from the increasing numbers of long term ground-based simulations of the space environment is necessary. Further the analysis has considered the vast bank of information developed by environmental physiological research. The reliance upon these sources of ground data is assumed to be valid because it appears that the responses of man to similar environmental stresses, whether produced in the laboratory or in space, are identical. The degree of response and the resultant of the interplay of multiple stresses may vary with the situation. This implies that the results of biomedical simulations must be applied with caution to the situation of interest, space flight.

This evaluation builds from the position taken by the USAF Manned Orbiting Laboratory Program at the time of its termination, including the biomedical research being accomplished in support of its 30-day mission. The opinion expressed in 1964,[1] that man could confidently and safely undertake a 30-day mission was based upon a relatively similar fund of data. The longest flight which had been accomplished at that time was 5 days in duration. The mission under study, (MOL), required a 6 fold extension of that experience. Ground simulations and research data were used to predict the impact on man of 30 days in the space environment. Subsequently longer flights up to 14 days and extensive ground studies have verified the 1964 predictions. In the current case, similar circumstances exist, the requirement to extrapolate from the existing 14-day flight experience to flights of 45 to 60 days. As was the case in the original MOL biomedical paper evaluating 30-day flights, many areas requiring study are identified by this analysis. Where it is known that there are plans to accomplish the tests, the plans are discussed. Most of the supporting studies identified are needed only to reinforce the paper's conclusion that 45-60 day flights may be undertaken with confidence, rather than being considered as absolutely required to avoid threats or limitations to such flights.

The paper was written shortly before the termination of the Manned Orbiting Laboratory program, and was intended for non-medical as well as medical readers. For this reason an attempt was made to limit the use of medical terminology and a brief glossary is provided.

II - The Space Environment

The environment to which the space crewman is exposed is extremely complex. In the preflight period there is superimposed upon his normal earth surface state of physiologic adaptation an increased workload (mission simulations, experiments reviews, travel, etc.) and an augmentation of his level of physical fitness. In the prelaunch phase he is exposed to a period of recumbency in the spacecraft under one gravity conditions and to 100% oxygen breathing to eliminate the nitrogen from his body to prevent decompression sickness. This is followed at launch by psychological inputs, acceleration, vibration and noise associated with powered flight and orbital insertion.

In orbital flight he is weightless, is relatively physically inactive most of the time because of the small free volume in which he works and probably because of the lower energy cost of performing well planned tasks in the weightless environment. He is exposed to an artificial atmosphere, and may have periods of vigorous physical exertion and of exposure to heat and cold. He consumes unusual foods and water from an unusual system. At the end of the mission during reentry, now in a space adapted state, he is subjected to acceleration and some heat loading, impact upon landing, and heat loading and complex motion while resting on the ocean surface. This array of environmental factors, imposed simultaneously and sequentially, poses a fascinating but extremely difficult biomedical problem for analysis and research.

The analysis of the effects of the space environment which is presented in the following sections identifies certain factors to be of greater importance than others. Among these are weightlessness, physical inactivity, physical exertion, heat and humidity, acceleration and impact, work-sleep schedules, nutrition and water provisions and the composition of the spacecraft atmosphere. These are felt to have a greater potential for inducing physiologic adaptive changes or for imposing acute stresses which are possibly dangerous to the space adapted crewman.

Other facets of the space flight environment have not been considered in as much detail. Vibration and noise of medically significant intensity are not likely to be imposed upon astronauts except during launch. The levels are controlled by booster and spacecraft design.

The neglect of radiation exposure in this paper is warranted by the assumption that the 60-day missions contemplated are in low earth orbit where the earth's magnetic field protection is present for a major part of each orbit and where penetration of the Van Allen belts is not required. Protective or evasive action in the event of solar flares can be accomplished. Nevertheless, the human risks from radiation involved with missions of this type and duration ultimately must be carefully studied.

Personal hygiene, waste management, and the closely related microbiologic environment in a 60-day flight should not be a significant problem from the standpoint of crew health and performance even though aesthetic aspects may not be ideally satisfied. The accuracy of this statement hinges upon the success of the systems to accomplish these functions now undergoing testing for the Apollo Applications Workshop.

This paper does not deal with contingency situations imposed by spacecraft systems failure or malfunction. The assumption is made that if such events occur, they will be managed in real time, and that mission success may or may not be compromised by them. The greatest threat to the effectiveness of men in 60-day space missions is clearly not related to his physiological adaptation to the space environment, but rather to his normal vulnerability to the effects of failure or malfunction of the environmental control and life support hardware.

Environmental Simulations

As isolated entities most of the factors contributing to the space environment can be simulated accurately in earth based research (Fig. 1). There are a few exceptions: weightlessness (discussed below); radiation, to which human beings cannot be deliberately exposed because of the production of permanent injurious effects, and non-physical (emotion producing) stresses, where equivalency of the ground models departs radically from the real case because of the synthetic vs. the real flight situation and because of the special psychointellectual structure of the astronaut.

Multienvironmental simulations pose problems of two types. The first is the impossibility from the logistic standpoint of assembling all of the factors into single research efforts, and the second is that of the interpretation of cause and effect relationships when multiple adapting inputs are imposed on the physiologic systems simultaneously. The compromise course has been (and will be) to isolate and understand the effects of a single environmental factor first, and then to mount research aimed at clarifying the important interactions among simultaneous or sequential combinations of environmental inputs affecting the function of the same body systems.

The simulation of weightlessness has been approached by the use of bed rest and water immersion. The rationale for the use of these models is in the reduction of the gravitationally produced hydrostatic pressure gradients within the body and the relative physical inactivity which results. Physical activity may be restricted more in the models than it is in actual space flight. Neither is a completely effective model. The results of the bed rest research are more cohesive and interpretable than those of water immersion mostly because of the technical difficulties, i. e., thermal effects, breathing pressure variations, etc. encountered in the latter which tend to produce artifactual physiologic responses. For this reason bed rest findings will be cited more frequently in the discussions to follow.

Space cabin simulation has been extremely effective in answering biomedical questions concerning sealed cabin atmospheres, contaminants, etc. Additionally, this model may be designed to impose a degree of physical inactivity somewhat less than that of bed rest, and therefore enable the environmental physiologist to fill in other points on the curves of adaptive responses to that factor of space flight. The physiologic data resulting is qualitatively completely consistent with the bed rest data, showing trends in the same directions but of a less severe degree.

One of the most important goals of astronaut biomedical measurement programs must be that of confirming the validity of the earth-based environmental physiologic models. This will entail, as mentioned previously, inflight and postflight measurements of sufficient scope, detail and accuracy to detect and quantify the space-induced environmental responses, and ultimately to define the time course of their occurrence inflight and their resolution back to the normal earth surface status postflight. This will serve as additional justification for our present confidence in our ability to predict the environmental input -- body system response patterns to space flight and their operational significance to 45-60 day missions, and to extend it to deal with much longer missions of the future.

III - Physiologic Effects of Space Flight

Circulatory System

As judged by telemetered and recorded data, the response of the circulation to the environmental factors imposed on the astronauts during space flight must be considered to be normal and appropriate to the stresses.[2-9] Furthermore, no evidence of change or degradation of these flight responses has been seen as mission durations of up to 14 days have been achieved.

The effects of the space environment on the circulatory function of the astronauts have been detected only by testing procedures designed to impose quantified loads to the circulatory system in the pre- and postflight periods, rather than by measurements made at rest or during flight. The loads chosen challenge the integrated regulation and performance of the entire system; heart, blood vessels and control mechanisms, rather than selected aspects of circulatory function.

Orthostatic Tolerance

In the Mercury and Gemini programs, the crewmen were subjected to the tilt-table test, and in Apollo to lower body negative pressure, both of which provide indices of orthostatic tolerance.[2-5] The integrated control response of the entire circulatory system evoked by these procedures is characterized by cardiac and vascular reactions intended to maintain adequate cerebral circulation in the face of the pooling of blood in the lower part of the body induced by the test conditions. Without exception, a degradation of this control response as measured by abnormal increases in heart rate and changes in blood pressure has been observed in the astronauts following flight, with return to the preflight patterns in 48-72 hours (Fig. 2). A few of the astronauts have fainted or approached that state in the first postflight test, a condition representing complete failure of the regulation mechanisms to compensate for the stress of the test conditions. Measurements adequate to determine the site(s) of the altered regulatory functions have not been carried out.

Reports of detailed results of tests of orthostatic tolerance in the Soviet cosmonauts are not available, but Russian scientists have alluded to the presence of similar findings.[6-9]

Several facets of the space environment can be incriminated as possibly related to the loss of orthostatic tolerance, based upon information derived from earth-based biomedical studies. Weightlessness, together with the physical inactivity resulting from confinement and the sedentary nature of most of the mission activities, may be involved, since it imposes over time a diminished requirement upon the circulation to regulate against the effects of gravitational forces and in response to muscular activity. An inadequate intake of water and solute, either absolute, or relative to losses of body fluid incurred through active sweating or by the requirement to lose body heat by evaporation of fluid from the skin during prolonged periods of space suit wear may be involved in some instances. Such body fluid losses may produce orthostatic intolerance through an effect on blood volume or on the mechanical properties of blood vessels because of electrolyte deficiency. Orthostatic intolerance is associated with fatigue, which has frequently been present in the astronauts as a result of inadequate sleep and excessive workloads.

Orthostatic intolerance regularly occurs as a result of exposure to bed rest and water immersion, to a degree comparable to that seen after space flight.[10-12] Its severity, although somewhat difficult to judge because of the inherent variability of response to the orthostatic tests, does not increase perceptibly after 14 to 18 days of continued bed rest. This is compatible with the fact that most of the circulatory adaptive response to a new set of input conditions seems to occur in the first 2 to 3 weeks and that the adaptation is complete within a 4 to 6 week period. The implication may be drawn that exposure to space flight durations of 45 to 60 days will not continue to increase orthostatic intolerance as long as the environmental milieu remains relatively constant. Improvement in environmental control and life support systems, shirt sleeve operation, better provision for sleep, improved management of work/rest schedules, and improved ability to monitor crew water intake and output and food consumption all should reduce the inputs eliciting the orthostatic intolerance.

There is preliminary evidence that exercise and other methods of conditioning may partially prevent the orthostatic effect of bed rest. It is possible that this may be true in space flight as well, although the type of conditioning device and the intensity, frequency and time duration of use required to produce the desired effects are at present unknown.

The significance to space flight of orthostatic intolerance per se is questionable. In earth orbital flight no "orthostatic" stress will occur, since the significant accelerative loads of reentry are applied in a transverse rather than in a headward orientation. It is possible that an astronaut's ability to fend for himself after landing could be effected by the orthostatic intolerance, but this is unlikely considering, (1) that any physical activity overcomes the lower body pooling of blood and stabilizes the circulation, and (2) that lying down which the astronaut can be trained to do in the event of orthostatic symptoms does the same.

In short the orthostatic tolerance tests may be considered to be strictly laboratory procedures used to detect and quantify alterations in circulatory regulation, but not representative of a realistic stress imposed in actual space flight. However, degradation of orthostatic tolerance may suggest the presence of a relative regulatory disability with respect to the compensation for circulatory loads imposed by heat, exercise, etc.

Exercise Tolerance

A highly reproducible form of exercise test has been employed pre- and postflight in some of the Gemini astronauts. (Fig. 3).[2-5] The procedure used a bicycle ergometer pedaled continuously with gradual increase of the load until exhaustion or a heart rate of 180 beats per minute is reached. In nearly all crewmen a postflight decrement of tolerance to exercise has been demonstrated by this procedure. The heart rate at a given workload has been higher indicating an increased circulatory cost to accomplish that workload. The peak oxygen consumption, the workload achieved and the total time to the end point have been less than in the preflight control studies, all of which demonstrate a loss of total capacity for physical exertion. Not enough followup data have been accrued to disclose the time required for return to the preflight status.

The Russians have used exercise in the postflight period in the physiological evaluation of the cosmonauts. The test employed was apparently a milder form of exercise, but a diminised tolerance to it, persisting for several days, has been reported.[6-9]

The "endurance" exercise test performed by the astronauts requires a high level of circulatory performance, but in addition may be limited by the status of respiratory function, blood and tissue gas transport functions, and the cellular metabolic (energy production) function, especially of muscle. The decrement in performance induced by space flight must be interpreted with these factors in mind.

Weightlessness and physical inactivity, body water and electrolyte changes as described in a later section, decline in circulating red blood cell mass (see below), and fatigue all may be of significance in explaining the exercise intolerance.

Bed rest always produces a loss of exercise performance ability, in degree similar to that observed to result from space flight.[13] The loss is manifest both in the "endurance" type of procedure, similar to that used in testing the Gemini crewmen and in the briefer maximal load procedure. Performance of the latter is felt by most exercise physiologists to be limited primarily by circulatory function. It is difficult to discern that a greater degree of intolerance to either form of exercise test results when bed rest is continued longer than 3 to 4 weeks. The reverse is also true, that the greater part of the circulatory training effect of regularly programmed exercise is apparent prior to about 4 weeks, and little if any training effect is seen after 6 weeks.[13, 14]

The loss of exercise tolerance resulting from bed rest has been nearly completely prevented by an adequate amount of exercise carried out in the supine position in bed. About 1 to 1 1/2 hours of vigorous exercise, inducing a daily expenditure of 700-900 K cal. has been the only regimen tested to date which prevented loss of exercise capacity during three weeks of bed rest.[15] Programmed exercise at a rate of 500-600 K cal. daily was completely effective in preventing exercise intolerance in a 56-day space cabin simulation.[16] The application of exercise in space flight in a form and of an intensity adequate to modify the deconditioning effects substantially has yet to be carried out. Again, improvement in environmental control and life support systems will be very valuable in minimizing the loss of fitness for physical work.

Loss of capacity for physical exertion potentially has a greater significance to space flight than does orthostatic intolerance. The ability of the astronaut to deal with contingencies (or nominal activities) requiring physical effort may be compromised. This is epitomized by extravehicular operations, wherein the crewman must accomplish his activities against the resistance to motion imposed by the pressurized suit. The task of fending for himself in the survival situation after landing may require physical exertion. There is an interdependent adaptation to heat loading which accompanies physical fitness. It is probable that thermal tolerance may be depreciated as exercise tolerance declines in space flight, a thesis which has not been directly tested in astronauts or bed rest subjects. If true, the astronaut's ability to tolerate the thermal loading possible during off-nominal ECS function, during suited operations, during reentry and while awaiting recovery may be compromised.

Hematopoietic System

No measurement of the effect of the space environment upon the blood has been made during space flight. Alterations in the cellular elements of the blood have been observed in the postflight period, most significantly in the red cells.

Red Blood Cell Changes

In most American flight crewmen and in the Russians where data is available, hemoglobin, red cell count and hematocrit values of peripheral blood have been elevated immediately postflight.[2, 4, 8] This most probably reflects hemoconcentration, a relative loss of plasma (liquid) phase of the blood as the primary response to the relative hypervolemia encountered upon entry into either the recumbent or the weightless state. (See discussion below, "Body Fluid Metabolism"). This apparent hemoconcentration has tended to disappear rapidly as body fluid volume has been restored in the first few postflight days. Therefore, it should not be interpreted as being the result of a primary change in erythropoieisis. Hemoconcentration does in itself diminish the stimulus to red cell production, and hence may be a factor in the apparent loss of red cells described below.

In the 4, 8 and 14 day Gemini flights, and in the first three Apollo flights (11, 6 and 10 days' duration) more specific measurements of the red blood cell have been accomplished.[3-5, 17] In several of the astronauts in the Gemini flights the total mass of circulating red blood cells was observed to have fallen; in some cases, to a surprisingly large degree, (Fig. 4). Evidence of increased fragility of the red cells was also observed. In all but one of the six crewmen of the first two Apollo flights no change in red cell mass occurred. In the third Apollo flight two of the three astronauts had some degree of decrease in red cell mass.

This body of data obviously is difficult to interpret. The inconsistency of these findings suggests that a measurement artifact might have occurred. On the other hand, certain differences in environmental factors are present, which conceivably could contribute to the disparity.

Breathing high partial pressures of oxygen will diminish the normal rate of red cell production and release from the bone marrow. Under certain laboratory conditions, an actual damage to mature red cells has been demonstrated to result from high oxygen levels in the blood, leading to increased fragility and rate of destruction.[18] In Gemini, several fairly long periods of high pressure (~16 PSI) oxygen breathing occurred during training; this has been minimized in Apollo. In the first two Apollo flights, the use of a two gas (oxygen and nitrogen) atmosphere during launch, together with the low leak rates on orbit has resulted in a small (~5%) residual of nitrogen throughout the flight. Diluent gases were carefully and completely purged on the pad in Gemini, and in the third Apollo flight the EVA effectively purged all nitrogen, which was followed by about 7 days of flight in pure oxygen.

The possibility that thermal loading, acceleration (reentry) or physical activity (especially after landing) may impose detectable destructive trauma to the red cells is supported by ground-based studies.[19-21] These factors may become significant if the red cell population is already damaged. However, it is difficult to find great differences between Gemini and Apollo as far as these environmental factors are concerned. The lack of physical exertion in space flight probably diminishes the stimulus to red cell production, but again Gemini and Apollo are not greatly different in this respect.

Obviously, it is impossible to establish the role of these and other factors in producing red cell changes, let alone to consider their time course based upon the inconsistent findings to date.

In bed rest studies moderate increases in hematocrit occur within the first few days, clearly established to be a result of the loss of plasma volume.[19] This primary response to adjust blood volume to the recumbent state and relative inactivity of bed rest leads to secondary responses reflected in real and relative changes in red cell volume, hematocrit, and plasma volume. The increase in hematocrit is maintained as bed rest continues, even though there is a gradual and moderate fall in total circulating red cell volume. This suggests that there is a tendency for plasma volume to increase slightly as bed rest continues. In the studies available, the loss of red cell mass seems to be compatible with a diminished stimulus to production, probably related to the decreased tissue demand for oxygen which results from the marked degree of physical inactivity. Quantitatively, the loss of red cells in a 4-6 week period of bed rest is considerably less than that which occurred in some of the Gemini astronauts. When the bed rest subjects are ambulated, plasma volume increases, hematocrit falls, and evidence of mild traumatic red cell destruction may be present. These changes are considered to be normal to the environmental circumstances. Return of the blood to the prebed rest condition is complete after about 3-4 weeks of normal activity.

In a study of the effects of 56 days exposure to a 5 PSI, oxygen-helium atmosphere[17] the losses of red blood cells and changes in hematocrit, although qualitatively similar to bed rest, were minor in degree. A moderate degree of physical inactivity was present, probably more like that to be expected in space flight than is the severe inactivity of bed rest. The results of this study are reassuring from the standpoint of inactivity effects, and also from its demonstration that a 60 day flight with an atmosphere containing helium as a diluent gas and providing an alveolar oxygen pressure equal to that in normal air at sea level will not affect the kinetics of the red cell population significantly.

The effect of moderate diminution of red cell volume on physiologic function is not apparent at rest but only when relatively intense physiological challenge is imposed. The capacity for vigorous exercise may be diminished, either because the total blood volume is decreased, or because the oxygen carrying capacity (RBC) per unit volume of blood is less. The evidence that exists indicates that acceleration tolerance (especially transverse) is not diminished by red cell changes of this degree.

Ground-based research indicates that adaptation of the cellular elements of the blood to new and constant environmental conditions is nearly complete in 4-6 weeks. This suggests that changes in physiological capacities dependent on alterations in the red blood cell mass beyond those present at the end of thirty days will be minimal. Furthermore, the RBC stimulating effect of physical exertion suggests that programmed exercise will be beneficial in modifying the decline of red cell volume. The form and amount of exercise required is not known.

It will be important that other space environmental factors which may augment red cell changes be eliminated as much as possible. Hyperoxia will not be a problem, since the decision has already been implemented to use two gas atmospheres, with a normal lung partial pressure of oxygen, in the NASA and DoD long-duration space vehicles.

Respiratory System

No evidence of alteration of respiratory function has resulted from manned space flight. Measurement of this body system in flight has been limited to breathing frequency which has been normal.[2, 4, 8] Detailed evaluation of pulmonary ventilation has been obtained preflight and postflight, and has not demonstrated any changes to have occurred. Measurements of the gas diffusion function of the lungs have not been made, but nothing has suggested the possibility of an alteration therein. Detailed studies of pulmonary ventilation and diffusion have been carried out in bed rest subjects, and no significant changes have been disclosed.[13, 15]

The only "obligatory" space environmental factor known to produce a deleterious alteration of respiratory function is the transverse acceleration experienced during launch and reentry. This results in a maldistribution of ventilation relative to blood flow through the lungs. In turn, this permits part of the blood to pass through the pulmonary circulation without being normally oxygenated, so that the arterial blood does not have the normal quantity of oxygen. The levels of acceleration imposed do not produce a severe degree of this oxygen unsaturation. Therefore, it is easily compensated by moderate increases of total blood flow, maintaining a perfectly normal psycho-physiologic functional status during the "G" exposure. The transverse "G" also may produce atelectasis (collapse of some of the air sacs in the lungs), usually at higher levels of acceleration than those normally seen in space flight. This atelectasis is potentiated by 100% oxygen breathing, since all of the gas in the alveoli (air sacs) can be rapidly absorbed by the blood if the airways are blocked by the distortion introduced by the "G" force. The presence of even small amounts of an inert diluent gas (nitrogen or helium) diminishes the tendency to production of atelectasis strikingly. In future missions the exposure of astronauts to periods requiring the breathing of 100% oxygen will be limited to the prelaunch, launch and reentry phases of flight (barring emergencies). During these periods they will be breathing gas from the closed, single gas, suit ventilation circuit. During the orbital phases long duration spacecraft will be flown with two gas cabin atmospheres and the men normally will be exposed to this "shirtsleeve" environment. Both of the effects, oxygen unsaturation and atelectasis, whether related to acceleration alone or with oxygen breathing, are transient and disappear completely immediately after the "G" load is removed.

In short, there is no known effect of the space environment on the respiratory system which should limit the ability to accomplish 45-60 day flights.

Metabolism

For the purposes of this paper, body metabolism will be considered in three segments, (1) body fluid composition and distribution, (2) bone and muscle metabolism, and (3) cellular metabolism. Little definitive information has resulted from flight data, except for that which is descriptive of the space environmental factors that may have contributed to metabolic changes. An attempt to measure relatively detailed metabolic function has only been mounted in one flight, the 14-day Gemini VII, and operational difficulties resulted in data of limited interpretability. Thus, an evaluation of metabolism and the space environment rests on postflight measurements. The ability to reconstruct the time course of metabolic changes is severely limited by this factor.

Body Fluid Metabolism

Loss of body weight has occurred in virtually all space crewmen, American and Soviet.[2-7] It has averaged 3-5% of the preflight weight in crewmen of missions greater than one day's duration, (Fig. 5), and has ranged from about 2 to as much as nearly 10%.

In those cases where serial weight determinations have been made in the early postflight period, it has been found that virtually all of the weight loss in crewmen of short flights, and a major part of that occurring in crewmen of the long flights is restored in the first few days, (Fig. 6). The rapidity of onset of the weight loss, and the speed of its restoration postflight both imply that body fluid is being lost, since metabolism of tissue could not produce weight losses of this degree in periods so brief, even in total starvation. Some tissue loss may have occurred in the long flights, expecially in certain instances where caloric intake is known to have been inadequate.[4]

Several factors may be implicated in the production of the weight losses. In all cases, it is postulated that during the early phase of exposure to weightlessness there is induced an acute renal loss of fluid through changes in the pituitary and adrenal cortical regulation of the kidney. These mechanisms become operative when peripheral blood is displaced into the central (intrathoracic) circulation and recognized by intrathoracic sensory mechanisms as hypervolemia. The smaller circulating blood volume which results should be considered to be a normal adaptation to the weightless state. Since loss of plasma water via the kidneys will tend to increase the osmotic pressure of the blood, shifts of fluid from the extracellular-extravascular space, and from the intracellular space will tend to follow, to produce appropriate osmotic and ionic balances among the body fluid compartments.

Other losses of body fluid may be superimposed upon this "obligatory" loss due to weightlessness. It is known that plasma volume and total body water fall in response to relative physical inactivity, which certainly has been present in space flight. Abnormally large evaporative water losses have occurred, both from the prolonged wear of pressure suits where cooling of the body depends heavily upon evaporation of skin water, and from frank sweating produced by increases in ambient temperature/ humidity (as in Mercury astronauts) and by vigorous physical exertion (as in some of the astronauts performing EVA). These evaporative losses should not have resulted in weight loss over time provided that replacement of water and solute in appropriate amounts was provided. However, it is known that water and food intake has been marginal or grossly inadequate in several crewmen. When this has been recognized it has correlated with greater postflight weight losses. The effects of these factors are portrayed in Fig. 5.

Loss of body weight has not often occurred in bed rest. This is explained by the fact that caloric intake has been deliberately regulated to maintain the body weight. However, careful studies have shown that bed rest subjects gain fat and lose lean, water containing tissue.[19] Negative water and sodium balances and losses of plasma volume and total body water are observed during the early phases of bed rest, followed usually be normal water and sodium balances, slight increases in plasma volume and presumably by a small decline in extravascular body fluid. These adjustments appear to be relatively stable after 3 to 5 weeks of bed rest, although further studies to confirm the foregoing are highly desirable.

Adequate exercise has not been imposed in the bed rest research where body fluid metabolism has been measured in detail. This should be studied. One report suggests that the application of lower body negative pressure (LBNP) during bed rest may induce a positive water balance and a return of plasma volume toward normal.[12] Since LBNP produces pooling of blood and an increase in tissue fluid in the lower body, the effects are to some degree opposite to those postulated to occur in weightlessness, a shift away from the lower body. If it is confirmed that LBNP tends to restore body fluid toward the normal prebed rest (prespace flight) status, it will tend also therefore to confirm the postulated mechanism by which weightlessness effects a redistribution of body fluid. Although it is unlikely that it will be necessary for 45-60 day missions, the foregoing suggests the possibility that in very long flights LBNP could be employed to supplement exercise as a countermeasure to the body fluid adaptive responses, as well as to changes in blood vessel regulatory mechanisms.

Obviously, the space environment can be better controlled to minimize body fluid losses than has been the case in flights up to date. Factors of special importance are: providing a shirt sleeve mode of operation, designing those tasks which require physical activity in such a way as to impose only moderate levels of exertion, improving the regulation of temperature and humidity, providing improved (conductive) cooling of crewmen in pressure suited operations, and providing more adequate food and water systems. These factors have been recognized in the current design criteria for long duration spacecraft, and improvements in most of them are apparent in Apollo.

The significance of the body fluid losses to the physiologic capacity to tolerate the space environment is largely manifest in the effect upon the circulation and the blood volume as described in previous sections. It is highly unlikely that the functional reserve of any body system will be significantly reduced by body fluid changes, provided that the changes are limited to those resulting from weightlessness and a degree of relative physical inactivity, and that changes resulting from environmental transients or from periods of vigorous physical activity are compensated by appropriate replacement in the form of water and food.

Bone and Muscle Metabolism

Data from the attempts in Gemini VII to determine changes in bone and muscle metabolism by metabolic balance studies are not conclusive. This resulted from operational difficulties. The data that are available suggest that there were losses in nitrogen, calcium and phosphorus during the flight.(22) The time course and rate of these losses cannot be interpreted. Attempts to quantify changes in the mineralization of the bones by X-ray densitometry have been carried out postflight in Gemini and Apollo crewmen. The results are somewhat equivocal, but suggest the possibility of demineralization.(4, 5)

In bed rest and other forms of immobilization of the human body losses of minerals and nitrogen indicative of skeletal demineralization and muscular atrophy consistently have been observed.(11) Quantitatively the mineral losses are very small relative to the total skeletal content, but some evidence is present (principally in animals) that the osseous demineralization is selective, that is, that it affects to a disproportionate degree the trabecular bone of the spine and other weight bearing structures.[23] The time course of the loss of mineral is not completely established in the ground based studies, although some degree of negative bone mineral balance is still present at 6-7 weeks. The increase in rate of mineral loss ends after about 3-4 weeks. Figure 7, taken from the classic paper of Dietrick, Whedon, and Schorr, illustrates these points.[11] In that study the subjects were immobilized by the use of body casts, a form of inactivity restriction far more rigorous than that to be expected in space flight.

The alterations of musculoskeletal metabolism are thought to be primarily a result of physical inactivity. The absence of gravitational stresses and strains, expecially in the weight bearing regions of the body may be an important aspect of this inactivity. Attempts to eliminate the negative bone mineral balances by physical stress and bed rest exercise have not been successful. However, in the research aimed at the study of skeletal metabolism, the amount and intensity of exercise imposed has been relatively small. Exercise of the proper form, wherein a force loading similar to that imposed by gravity, and of enough duration and intensity to establish benefit to skeletal metabolism has not been applied as yet to the bed rest model.

In order to prevent a rapid rate of muscle catabolism, two provisions must be supplied for long duration space flights. The first of these is an adequate intake of calories and protein, to avoid the use of the astronaut's own muscle tissue to provide essential nutrients. The second is to provide exercise in the proper form, intensity and duration to maintain muscle strength and work capacity at a level sufficient to enable the astronaut to deal with his normal mission activities and with contingencies, e.g., extravehicular activities, survival situations, etc. The former is readily available by appropriate design of space feeding systems and control of food consumption. The latter can be provided by the use of devices which will provide exercise of the total body. Furthermore, it is felt that exercise of the proper form, intensity and duration will impede muscle catabolism and maintain adequate muscle strength and work capacity.

Cellular Metabolism

There are only a few clues that metabolic processes involving energy production and its regulation at the cellular level may be affected by space flight. Obviously no measurements of endocrine secretory rates at rest or during metabolic stresses have been made in space flight. Postflight analyses of urine for adrenal cortical hormone (17-hydroxycorticoids) and catecholamine excretion have been done and have shown increases.[4, 5] It is probable that these findings represent the endocrine response to the stress of reentry and recovery rather than that due to the prior space environment. Blood glucose determinations, supposedly in the fasting state, in the early postflight period have been obtained in some of the Gemini and Apollo astronauts and in some of the cosmonauts. The values have been considerably greater than preflight, in the high normal range. Glucose loading tests or post prandial blood sugar determinations unfortunately have not been accomplished.

Definite evidence exists that decreased tolerance to glucose results from bed rest.[11] Until very recently blood secretory rates of endocrine substances have not been measured in bed rest subjects, either at rest or during metabolic provocative tests. Early results of studies now underway indicate that measurable changes in pituitary, adrenal cortical and catecholamine responses to tests which stress cellular biochemical processes follow two week periods of bed rest. These appear to represent quantitative, not qualitative alterations, and presumably involve skeletal muscle cells.[24]

The mechanisms by which such changes occur and their time course are unknown. Physical inactivity may be a key aspect, producing what may be termed a "biochemical atrophy" as a result of disuse of the skeletal muscle cells. For this reason it will be important after further confirmation and clarification of these phenomena, to attempt to modify or prevent the diminution of biochemical capacity by imposing physical exercise during bed rest.

The significance of these effects to prolonged space flight is unknown, but a reasonable interpretation is that they would represent a part of the overall loss of ability to accomplish intense and prolonged physical exertion. There is nothing in these findings to imply that a loss of physiological capacity for normal activities and for other of the space environmental stresses than heavy physical work would be affected.

Central Nervous System

Vestibular Function

Soviet space medical scientists first raised the possibility that the weightless state might produce dysfunction of the central nervous system, especially of the vestibular apparatus. In their view this has been confirmed by evidence such as motion sickness and illusions of body motion during weightlessness, either at rest or upon motion of the head. These effects have been observed in several cosmonauts in flight.[25] The worst instance occurred in the pilot of the second Vostok flight, where some degree of motion sickness was present through most of day-long flight. This may have been contributed to by a rather severe degree of vehicle tumbling, presumed to result from attitude control system malfunction.

Symptoms of possible vestibular origin have been much less in evidence in the astronauts. Early in flight a few crewmen have reported the illusion of being upside down. Attempts on the part of the Gemini astronauts to elicit illusions of body motion by moving the head with and without visual inputs failed.(4) Quantitative measurement of otolith function in Gemini V and VII was successfully obtained preflight, inflight and postflight, and demonstrated no abnormality.(26) In two Gemini flights rapid rates of vehicle rotation were tolerated without motion sickness or other evidence of abnormal vestibular response.(4) More recently, some of the Apollo astronauts have had transient nausea and a few episodes of vomiting.(5) This has occurred in three flights, involved five crewmen early in flight, and has been attributed by some of the astronauts themselves to the fact that they are able to and did move around rapidly inside the larger Apollo spacecraft. The symptoms subsided early in the flights. It seems that vestibular adaptation to weightlessness may have developed and suggests that no further difficulty should be anticipated.

It is possible that certain individuals may be more susceptible to vestibular phenomena of this type, and that difficulties would persist for a longer period. Such susceptibility is highly unlikely in successful test pilots, who have been effectively selected by their career activities not to be motion sickness prone.

Soviet and American space crewmen agree that muscular coordination is nearly immediately and completely adapted to weightlessness.

In short, no problem in the function of the vestibular apparatus, related to weightlessness or other space environmental factor is expected to limit space missions of 45-60 days.

Sleep

A sleep evaluation, employing electroencephalography, was attempted in the Gemini VII flight in one crewman.[3, 4, 27] The value of the results is limited by the fact that failure of the electrode system occurred early, and by the fact that the data was obtained in the first 2 1/2 days of the flight, a period of intense activity and excitement. The sleep obtained during this period consisted of electroencephalographically normal stages (depths) of sleep, but the periods of sleep obtained were shorter than normal.

Most of the information available about sleep in space is descriptive and subjective.[2, 4, 5, 8] There has been great individual variation in the ability to sleep in space flight, some astronauts saying it is not difficult, others that it is a great problem. Generally, sleep has been grossly inadequate in the first 48 hours of flight, due in part to long work schedules beginning prior to launch, and in part to nonphysical stresses involved with the onset of a mission. Early American multiman flights were scheduled to have one crewman "on duty" at all times. This was found to be totally unsatisfactory, at least in a very small spacecraft, because of distractions to the sleeping crewman arising from the activities of his partner. More important, it forced the abandonment of the normal earth surface sleep cycle by at least one crewman. As a result of this experience, the sleep periods of American flights, beginning in Gemini V, have been scheduled to coincide with launch site sleep times for nearly all crewmen. When exceptions to this plan have been required as a result of the mission, (as in the early Apollo flights) sleep interference has resulted.

Noise, cabin lighting, sunlight through the windows and temperature fluctuations all have interfered frequently with sleep. There has been a tendency for the command pilot, responsible for the mission, to sleep less well than other crewmen.

In spite of careful preflight scheduling, the planned sleep cycles have been abbreviated, shifted several hours from launch site time, and interrupted due to unforeseen requirements of the mission.

All of the foregoing has resulted in some degree of fatigue, often severe, being present in most astronauts at some phase of their flights. In some instances, continuous fatigue has been described.

In contrast, the Soviet scientists have claimed that the cosmonauts have not had any difficulty with sleep.[7, 8] Two factors are emphasized as responsible for this success, that the schedule of sleep periods coinciding with Moscow time are rigorously followed, and that the cosmonauts are "conditioned" to fall asleep easily. Autohypnotic techniques to induce sleep have been described in some space medical reports, although it is not known whether they were actually used by the cosmonauts.

Ground-based research on sleep-work cycles for space flight is of very limited value, since the study of sleep as a psychophysiologic function is so dependent on the accuracy of environmental and psychological simulations. The nonphysical stress aspect of space flight, contributed to both by the actual flight conditions and by the psycho-intellectual makeup of space crewmen obviously cannot be reproduced in a ground laboratory.

The significance of this area to long duration flight is obvious. Fatigue arising from inadequate sleep may well be the most probable biomedical threat to the effectiveness of crewmen in 45-60 day flights. It is essential that everything possible be done to establish a "normal" sleep environment, and that the sleep period be scheduled to coincide with that to which the crewman is adjusted preflight. Alterations in the sleep schedule should be minimized, and must be compensated by appropriate added rest periods. The use of drugs to induce sleep is undesirable, but it is conceivable that in some crewmen it could be of occasional value.

In short, there is no reason to suspect that the basic nature of sleep changes in the space environment. Difficulties in sleep have arisen because of deficiencies in the control of the sleep environment and in the management of work-sleep schedules. These deficiencies will be alleviated by improvements in sleep station design (being accomplished for the Apollo Applications Program--AAP) and by better management of work-sleep schedules based primarily on careful study of this aspect of Apollo flights.

Mission Performance Capacity

Space flight to date has been characterized by the fact that the flight crewmen have not demonstrated significant failures in mission performance.[4, 5] Critically demanding tasks, complex control functions and contingency judgements have all been superbly performed, even at the end of the longer missions where physiologic space adaptation and fatigue have been present.

None of the known physiologic effects of the space environment has or is expected to degrade the astronauts intellectual or motor capacities, with the possible exception of fatigue. Ground-based research in this area is not very rewarding. Attempts have been made to demonstrate human performance decrements, employing synthetic (and occasionally real) tasks, in relation to changes in physiologic status induced by various environmental loads. Generally these attempts have been found to fail, until either the physiologic decrement is very severe or the subjective reaction to the situation (pain, extreme fatigue, sleep deprivation, etc.) overshadows the subject's motivation to continue performing. The impossibilities of extrapolating from such studies to the real question of 45-60 day space flight are readily apparent.

Sleep deprivation and fatigue deserve special consideration, however, since they have occurred frequently in flight. The majority of subjects who are deprived of sleep for 24-36 hours demonstrate performance decrements.[28] That sleep is required to maintain normal brain function (from a biochemical standpoint) is clear, although the mechanisms by which the maintenance and restoration of function is accomplished are not. Generally, it has been found that sleep deprived subjects fail earliest in the performance of routine, repetitive types of tasks.

Fatigue and sleep problems as potential sources of difficulty in space flight to date have been hedged by the ability to execute changes in the flight plan in real time to allow the crewmen to "catch up on sleep" when required to prepare for tasks of major importance to the overall mission. In flights of 45-60 days, where the substance of the missions is involved with relatively routine repetitive tasks it will become critical that our management of crew sleep-work cycles is perfected. This can only be accomplished through careful analysis of the effectiveness of the planning of crew time lines in current programs, Apollo and AAP.

Flights of 45-60 days may present problems in maintaining the crewmen at peak mental capacity. If the crew is to continue successful performance psychological factors must receive as careful attention and planning as has been outlined for the physiological maintenance of the astronaut. The long duration mission presents a potential problem in maintaining the constant high-level crew attention demanded by the daily workload which is likely to consist of tasks that are routine or repetitive in nature. This may lead to decay in attention and interest, and subsequently in performance.

Much effort has been made to insure that the spacecraft is safely habitable by the crewmen; however, the provisions still provide only a relatively "Spartan" existence and therefore may impose additional psychological stress.

Based upon the experiences of men on earth who have performed similar long periods of isolated duty (i. e., polar expeditions, DEW line and submarine duty, etc.), the requirement for new fundamental knowledge in habitability appears to be minimal. The problem of providing the proper psychological support for each program is more one of carefully selecting and applying the best approaches for the specific mission, considering the vehicle to be used and the proposed operational plan. Some promising areas based upon earth-developed data, include the provision of some degree of privacy up to and including separate quarters for each crewman; the provision of mental and physical recreation and relaxation; increased free volume in both the work and living areas as crew sizes increase; increased options in the selection of food items; and provision for communications with friends and family. An unusual event, or a change in the mission routine may offer welcome relief for the crew and may present an effective operational tool for restimulating or enhancing the crew's attention and performance. Even the associated crew actions required to meet an emergency event may produce, as a by-product, a resurgence of crew attention and interest.

Although the earth experiences of man while on isolated duty do suggest many good approaches for providing psychological support and the data base appears adequate, the final demonstration of the solutions for space missions must be tested in actual flight.

In short, from the physiological adaptation standpoint, there is little risk that crewmen will not be completely capable of continuing top-level performance. From the standpoint of planning work-maintenance-sleep cycles and psychological support for long missions consisting heavily of repetitive tasks, we have much to learn. This information will have to come from actual flight experience.

IV - Information Requirements

Although it is apparent from the previous discussion that our knowledge of the human physiological adaptations to the space environment is far from comprehensive, it is adequate to predict that missions of as much as 60 days duration may be undertaken with a good chance of success. In part this prediction is based upon the anticipations (1) that environmental control and life support systems will be more effective than they have been in previous programs, (2) that crew conditioning (countermeasures) in flight can be provided in a potent form producing an adequate compensation for the adverse effects of weightlessness and physical inactivity, (3) that monitoring of the crew and his environment will be adequate to detect and correct undesirable physiologic changes and deficiencies in life support, and (4) that space flight and ground biomedical research programs accomplished in the next few years will clarify and confirm the important hypotheses alluded to in the foregoing sections and recapitulated in the following.

Environmental Control and Life Support Systems

Frequent references have been made in the previous sections to transient or long term lack of ideal control of the spacecraft environment by those systems provided to make the spacecraft habitable by man. These fluctuations have clearly contributed heavily to the physiologic effects of space flight. To recapitulate an outstanding example, that of temperature-humidity control, a brief review of Mercury and Gemini experience follows. In Mercury, the crewmen wore space suits in all missions. The thermal regulation system was not adequate to provide effective convective cooling, but imposed evaporative cooling often with frank sweating. It has been estimated by NASA that the pilot of MA-9 lost about 2 1/2 liters of body fluid by sweat. He did not have adequate drinking water available for replacement.[2]

In Gemini, the thermal system was much better, but still not ideal.[4] The major difficulty was still the requirement to wear pressure suits, continuing the requirement for evaporative cooling. This was true of all Gemini flights except for GT-VII where the crew doffed their suits for part of the flight. Frequent episodes of uncomfortably warm or cold suit ventilation were reported, some of which lasted for several hours. These were related to the status of the heat load to the thermal regulation system from electronic and other equipment, and to crew activity. Frank sweating was reported. Problems with fluid and electrolyte replacement were encountered, due to failure of the water system, time constraints, and problems of unacceptability of some of the food items and procedural complexity of its consumption.

In current and future programs evidences of very great improvement in environmental control/life support (EC/LS) systems are apparent. The crewmen are in shirt sleeves, providing the opportunity for a more normal pattern of physiologic thermal regulation. In MOL, equipment panels surrounding the crew work areas were to have been conductively cooled by water lines. This would have provided for increased radiative heat transfer from the men, and diminished the requirement for evaporative cooling. In Apollo, conductive cooling by a water cooled garment is provided during planned operations in a pressurized suit. Food and water systems have been greatly improved.

In short, the great improvements in the effectiveness of the current generation of EC/LS systems, and the further refinements to be expected in future systems, in themselves will serve to minimize to a great extent many of the physiologic effects of space flight.

Crew Conditioning

In Gemini and Apollo programs exercise devices have been supplied, in part to assess the status of the circulatory system, and in part to afford programmed physical exertion. These devices have consisted of an elastic cord and a rope-variable friction device. Neither has provided much of a physiologic challenge to the crewmen, in part because of the nature of the equipment and in part because of the confinement imposed by the spacecraft. The astronauts have also performed optional exercise, usually isometric, consisting of pressing between couch and bulkheads, etc. It is fair to say that this amount and type of exercise was inadequate to control "deconditioning."

In two of the longer Gemini flights, an automatic cuff inflation device was provided to one crewman. This was designed to occlude cyclically the return of blood from the legs. The purpose was to provide a pooling effect in the legs, simulating the effects of gravity. No beneficial effect was found, perhaps in part due to the fact that there were problems with the function of the equipment. There is also doubt about the effectiveness of a regimen wherein the pooling effect was intermittent and occupied a relatively small fraction of time.

As has been discussed previously, ground-based research has provided assurance that exercise can be effective in modifying space environmental physiologic effects if it is of adequate intensity and duration and in the proper form. The Aerospace Medical Division (AMD) has designed a space borne exerciser which can provide for a range of loads, for various exercise regimens involving either the whole body or body regions and for relatively large enery expenditure rates (Fig. 8).

The flight prototype of the exerciser has been tested during Keplerian trajectory flights producing weightlessness (Fig. 9). These tests have validated the principles of mechanical operation and have defined the crew body motion patterns and restraint requirements. Figure 9 is a sequence of three photos showing one-half of a total stroke of the exerciser.

Physiologic validation of the concept is underway in training studies and bed rest research. This research will provide guiding information to design the exercise program of astronauts. A ground simulation version of the exerciser is available, both for the astronaut conditioning in the preflight period, and for the ground-based research (Fig. 10). It incorporates into a partial weightlessness simulating platform an identical exercise apparatus to the flight equipment in order to provide the same "feel" and relative body motion pattern as would occur in space flight.

For 45-60 day flights, it will be very important to instrument the exercise apparatus in order to document during the mission via recorded and telemetered data, the specific nature of the conditioning exercise performed by the crew. This can be accomplished easily in the case of the AMD total body exerciser by the measurement of force on and displacement of the handle against time. This is being accomplished in the ground-based studies. Simultaneous measurement of heart rate during each exercise period and perhaps oxygen intake on a periodic basis will provide an accurate means of determining the work capacity status of the astronaut, and afford the basis for adjustments in the conditioning program if indicated.

Although exercise alone will probably be adequate for deconditioning control in 45-60 day flights, studies along other avenues involving the addition of other techniques are being pursued, for possible use in flights of very long duration.

Biomedical Monitoring in 45-60 Day Flights

As is implied in previous sections the physiology of man is extremely responsive to the status of his environment, (note the discussion of the temperature-humidity control in Mercury and Gemini above). For this reason it will be mandatory in all space flight programs to obtain not only data descriptive of the crew's physiologic status, but also of the environment surrounding him.

This implies that at least the following named parameters should be monitored adequately to give a running history of the environmental status; atmospheric pressure, oxygen partial pressure, carbon dioxide partial pressure, water vapor pressure, cabin air temperature, wall temperatures, air flow rate, toxic agent levels and radiation dose and dose rates. The systems peculiar to a given spacecraft must be analyzed to identify other parameters of importance to the biomedical flight controller, including those that may be predictive of environmental changes.

Data from the man must include the capability to record and telemeter heart beat interval continuously, to obtain the electrocardiogram on demand in a form providing clinical diagnostic capability, and body temperature. In addition, the astronaut's intake and output of fluid must be measured, and his food intake documented. The ability to measure body mass must be provided, which together with the intake and output information provides the critically important capability to establish fluid balance and its regulation, and helps to confirm the adequacy of caloric intake. The data on body mass, water and solid material intake, and fluid output in combination provide a means to evaluate the adequacy of life support and are indicative and predictive of the biomedical/physiologic state of the crew. Together with environmental system data, they provide the basis for recognition of life support inadequacies and provide guides to their correction.

The importance of the capability to communicate directly with the crew for biomedical purposes cannot be overestimated.

It will also be necessary to the purposes of 45-60 day flights that a specific means of quantifying the crew performance be provided.

V - Space Flight and Ground-Based Biomedical Research

Circulatory System

1. It will be very important to confirm that exercise during bed rest can preserve the physiologic capacity for physical exertion. Studies for this purpose are underway within the Aerospace Medical Division (AMD).

2. It is desirable that the effectiveness of exercise as a countermeasure be documented in actual space flight. The best opportunity to accomplish this will be in the Apollo Applications Program (AAP) SIVB Workshop flights. One crewman who performs programmed exercise should be compared with his two crewmates to determine the benefit to circulatory (physical working capacity) performance. NASA currently does not have plans to accomplish this research.

Hematopoietic System

1. It will be desirable that the changes in the red blood cell mass seen in some of the Gemini and early Apollo data be further explored by making appropriate measurements in succeeding Apollo flights.

2. It will be important to confirm that 5-6 weeks of bed rest produces only a small decline in red blood cell mass, and to disclose the protective effect of exercise during bed rest on red cell kinetics. Such research is underway within the AMD.

3. It will be important that careful red blood cell studies be accomplished in the crewmen of the AAP flights. NASA does have plans to make these measurements.

Metabolism

1. It will be important to confirm and further elucidate the effects of bed rest upon water and electrolyte balance and distribution within the body. The modifying effects of programmed exercise should be documented. Similar data concerning bone and muscle metabolism is desirable. This research is underway within AMD.

2. It will be very important to pursue the question of cellular metabolic effects of bed rest, using appropriate provocative biochemical tests, and to evaluate the effectiveness of exercise in modifying these effects.

3. It is desirable that metabolic studies similar to those described in 1. and 2. above be carried out in the AAP flights. NASA has approved experiment protocols to accomplish preflight, inflight, and postflight metabolic measurements of the AAP crewmen. The use of metabolic provocative tests is not currently planned for AAP.

Sleep

1. It will be extremely important to quantify sleep in space flight in whatever missions this can be accomplished, specifically the AAP

flights. Such an experiment has been proposed to NASA, and is receiving favorable consideration.

Performance of the Crew

It is mandatory that careful study of the effectiveness of the planning of the work-rest cycles in providing adequate rest (and preventing fatigue), an assessment of the adequacy of the provisions for maintaining high levels of crew attention and interest throughout the flight, and the overall evaluation of crew performance be accomplished in all space flights; and reasons for success or failure analyzed.

VI - Summary

The principle effects of the space flight environment upon the physiologic function of human subjects have been reviewed. The validity and results of biomedical ground-based simulation research have been discussed. Where known the time courses of the physiologic changes, considered to be normal adaptive responses to a new set of environmental conditions, have been described.

In general, it is concluded that in flights of up to 14 days duration the alterations in the physiologic reserves of space crewmen have not developed to the point of compromising their ability either to live and function in the 'normal' space environment, or to withstand frequently occurring instances of unforeseen environmental stress. The time courses of most of the biomedical changes are such that significant further diminution of physiologic capacities is felt to be unlikely after about 4 weeks of flight provided that life support systems are adequate. Our ability to modify the effects of space flight has been discussed from the standpoints (1) of improving the effectiveness of environmental control and life support systems to minimize the physiological "deconditioning" resulting from sustained or transient environmental loads, and (2) of providing countermeasures (especially exercise) as a means of modifying the effects of the "obligatory" environmental factors such as weightlessness and a degree of

physical inactivity. Results of ground research testing of this ability to modify or control these effects are encouraging.

Insofar as it may be affected by physiologic adaptive changes, there is little reason to be concerned about the continuing ability of the astronaut to perform normally in 45-60 day missions. However, past space flight experience indicates that the management of work-sleep cycles needs more concentrated study. Work-sleep cycles may pose highly significant problems in long missions involving routine, repetitive tasks.

In addition, extension of mission duration and the demand for continuing high-level crew performance will require detailed studies of the adequacy of the provisions made for improving vehicle habitability and of the planning to maintain crew attention and interest. An improved ability to understand and deal with the interrelations between the physiological and psychological areas must come from analysis of actual flight experience, rather than ground-based research. There is a clear-cut need specifically to quantify crew performance in flight.

Continuation of the measurement of the status of the environmental factors artificially controlled by the vehicle systems has been identified to be required for biomedical purposes in 45-60 day flights. Its scope for this purpose is outlined. Measurement of the physiologic status of the crewman as it may be affected by his environment also must be continued, and it is recognized that the scope of such measurements must be tailored to meet the requirements of a 45-60 day flight.

Overall it is strongly felt that the current status of all of these factors enables us to predict with confidence that 45-60 day manned space flights will not be limited by the physiologic effects of the space environment.

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VIII. GLOSSARY

Atelectasis - collapse of lung tissue due either to externally applied pressure or to absorption of gases from the collapsed segment

Catabolism - the process by which the complex substances of body tissues are converted by living cells into more simple compounds, destructive metabolism

Conditioning - as used in this paper, the act of preparing all body systems to peak readinesss to perform and respond to physical and mental stresses

Deconditioning - In space flight a decrease in the peak readiness to meet and to perform in the space environment. Generally related to physiologic changes due to the absence of earth gravity, reduction in levels of activities or energy requirements for performing activities. Also used to refer to changes that may be completely appropriate for the space environment but abnormal as related to the 1 g reference on the earth. Frequently used synonyms are: accommodation, acclimatization, adjustment, adaptation

Electrocardiogram - the record obtained by recording the electrical voltages emanating from the heart associated with the process of muscle contraction.

Electroencephalogram - the record obtained by recording the electric voltages developed in the brain by the use of electrodes applied to the scalp

Erythropoietic - pertaining to the formation of red blood cells

Extra cellular space - the space occupied by body fluids outside of the body cells, including that within the blood vessels

Extra vascular space - the space occupied by body fluid outside the walls of the blood vessels

Hematocrit - a measurement of the percentage of the volume of the whole blood consisting of the blood vessels

Hematopoietic - pertaining to the formation of blood cells

Hemoconcentration - decrease of the fluid content of the blood with an increase in the cellular segment of the blood

Hyperoxia - an increase of oxygen partial pressure in the body tissues.

Intra cellular space - the collective volume inside the cell membranes occupied by body fluid

Intrathoracic Hypervolemia - an increase in the volume of fluids within the thoracic cavity. In this paper, it refers specifically to the increased volume of blood that collects in the circulatory system within the thorax following the reduction of the effects of gravity.

Isometric - contraction of muscle without motion of the body part which may or may not be applied against an external immovable object

Lower Body Negative Pressure (LBNP) - a test procedure which uses a box into which the lower part of the body of the test subject is sealed. The external pressure surrounding the lower part of the body is reduced relative to the upper part of the body and the outside of the box. As the pressure on the lower body is reduced, there is movement of the fluids into the extravascular spaces and an increase in blood volume of that part of the body, especially in the veins of the lower limbs.

Metabolism - the chemical and physical processes continuously going on in living organisms and cells

Orthostatic tolerance - the ability of man to automatically maintain adequate circulation when the body is shifted from the horizontal to standing erect in the earth gravity field.

Osseous - pertaining to bone

Otolith - a sensory structure of the inner ear which responds to linear acceleration, including the force of gravity

Post prandial - after eating

Red cell kinetics - the process of the turnover or rate of change in the red blood cell development, use and destruction

Renal - pertaining to the kidney

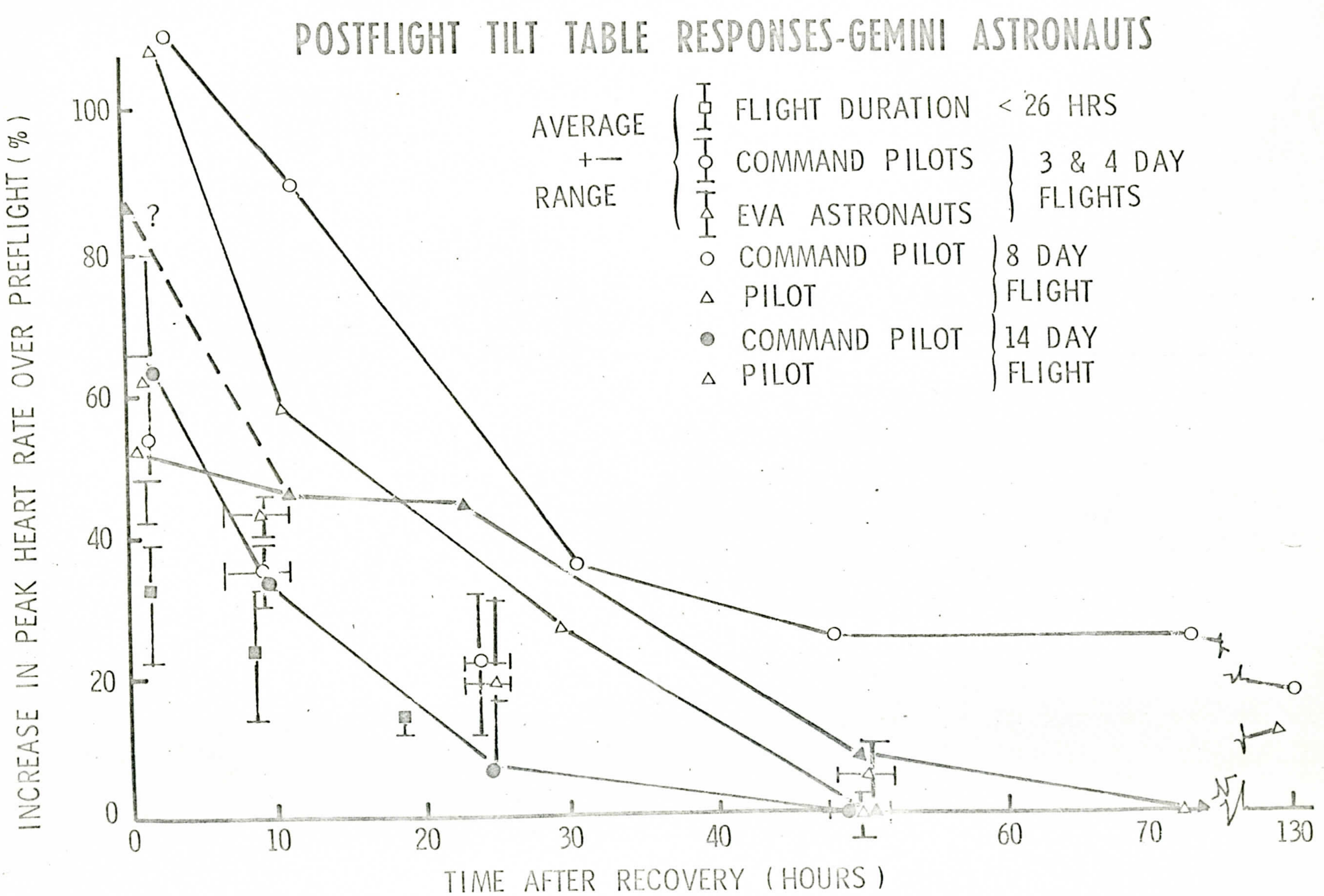
Simulation - as used in this paper, a laboratory or mechanical reproduction of an event or sequence that may have biological impact upon the man and will be encountered in space flight

Trabecular bone - referring to the structure of certain bones or parts of bones. These bones are characterized by a structure of bridges that effectively separate the bone into anatomical compartments. Most of the weight bearing bones of the body have this characteristic

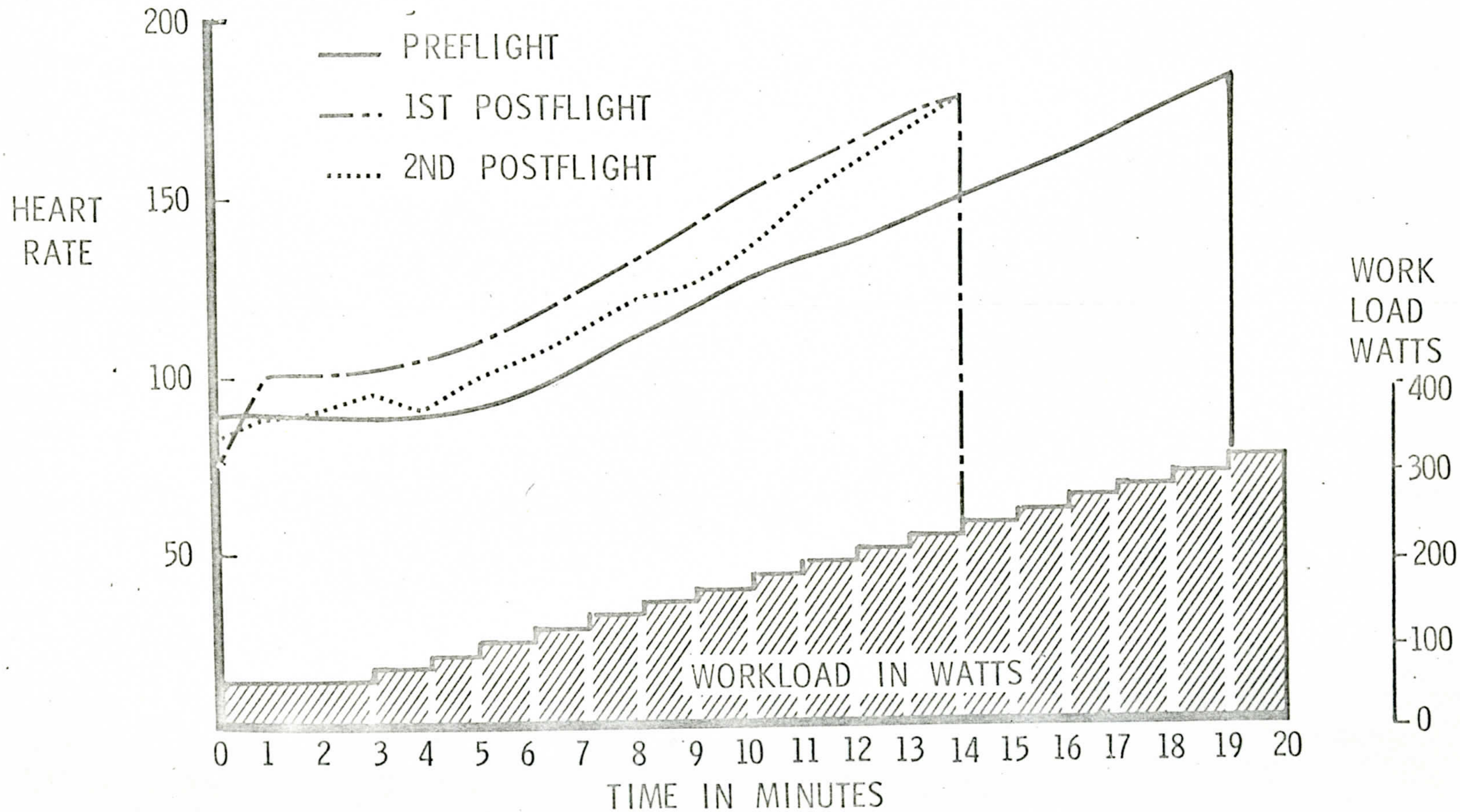
BIOMEDICAL RESEARCH GROUND SIMULATION CAPABILITY

ENVIRONMENTAL FACTOR	CAPABILITY
ACCELERATION	GOOD
VIBRATION	GOOD
NOISE	GOOD
CONFINEMENT (INACTIVITY)	GOOD
WEIGHTLESSNESS	PARTIAL
RADIATION	NOT PERMISSIBLE
WORK-REST CYCLES (BIORHYTHMS)	GOOD
TEMPERATURE	GOOD
EMOTION PRODUCING	NOT GOOD
FOOD AND WATER	GOOD
ATMOSPHERE	GOOD
HYGIENE/WASTE MANAGEMENT	GOOD

FIG. 1


POSTFLIGHT TILT TABLE RESPONSES-GEMINI ASTRONAUTS
AVERAGE
+—
RANGE
FLIGHT DURATION < 26 HRS
COMMAND PILOTS
EVA ASTRONAUTS
3 & 4 DAY FLIGHTS
COMMAND PILOT
PILOT
8 DAY FLIGHT
COMMAND PILOT
PILOT
14 DAY FLIGHT
?
INCREASE IN PEAK HEART RATE OVER PREFLIGHT (%)
0
20
40
60
80
100
0
10
20
30
40
60
70
130
TIME AFTER RECOVERY (HOURS)

GEMINI VII ERGOMETRY STUDIES [29]



WEIGHT	PERFORMANCE			
PRE	76.88 KG	PRE	290 WATT	
POST	74.55 KG	POST I	215 WATT	25.9%
	▲2.33 KG		▲75 WATT	

FIG. 3

GEMINI BLOOD VOLUME STUDIES [29]

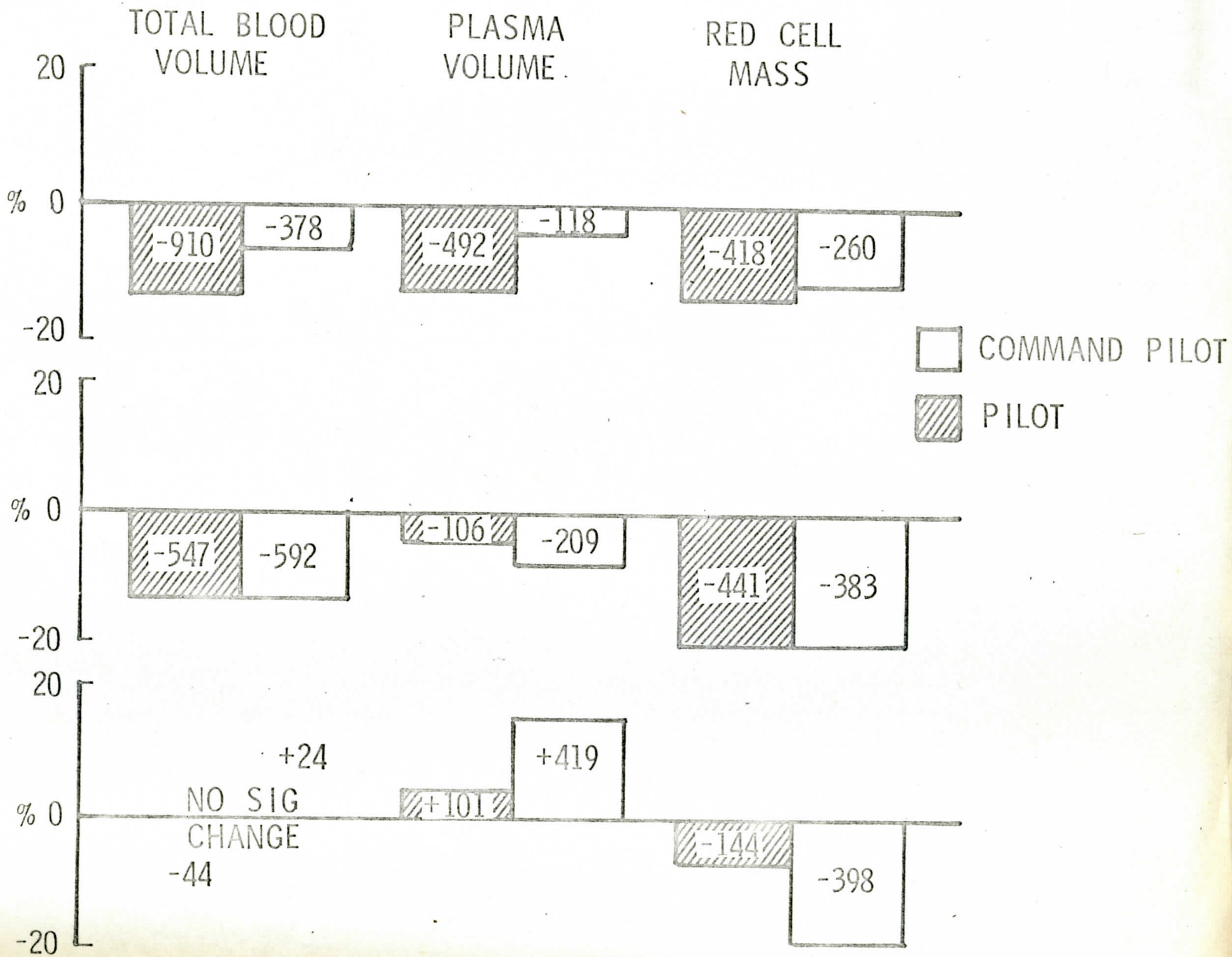
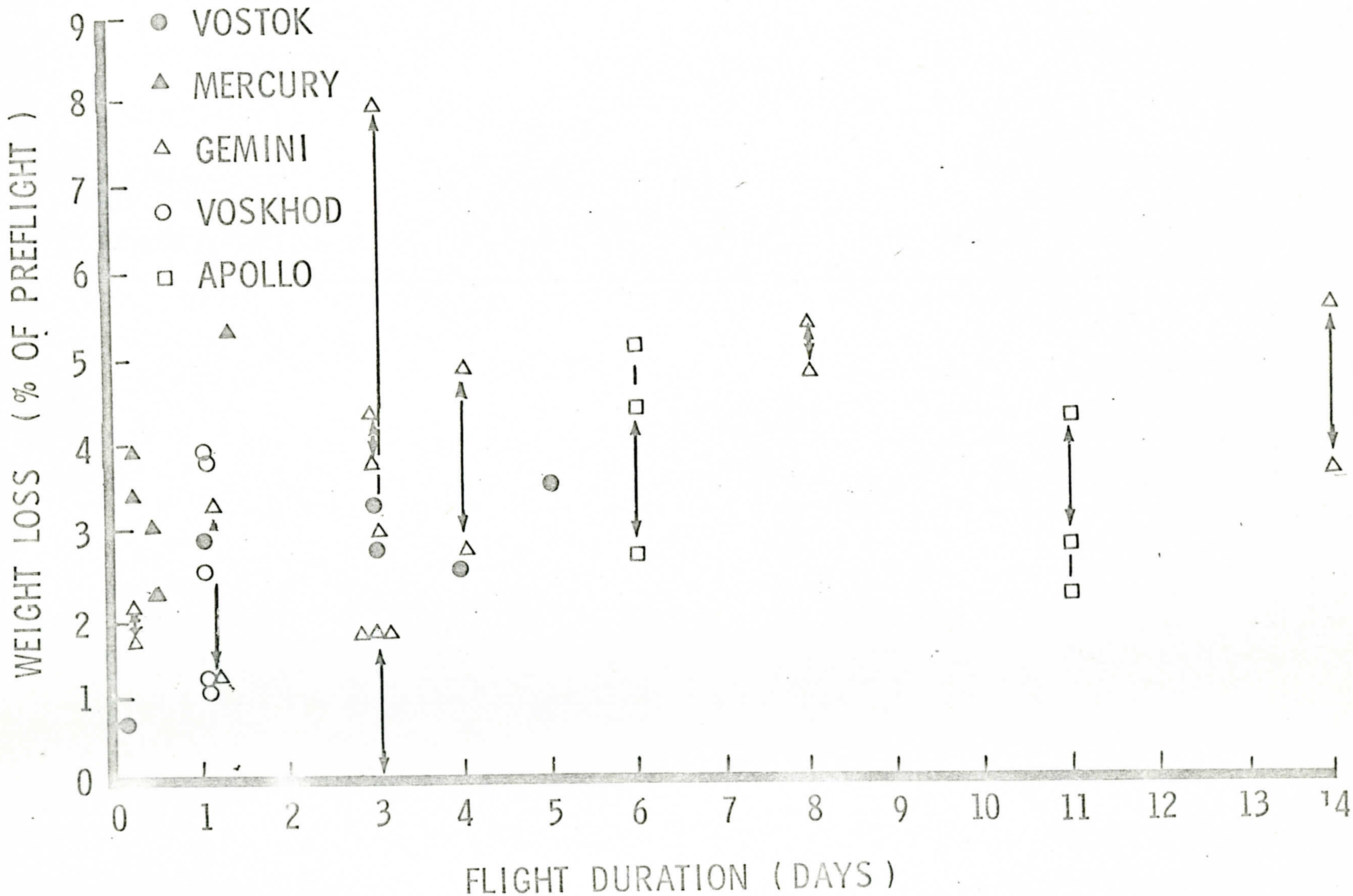


FIG 4

FLIGHT CREW WEIGHT LOSS



ASTRONAUT POST FLIGHT WEIGHT CHANGES

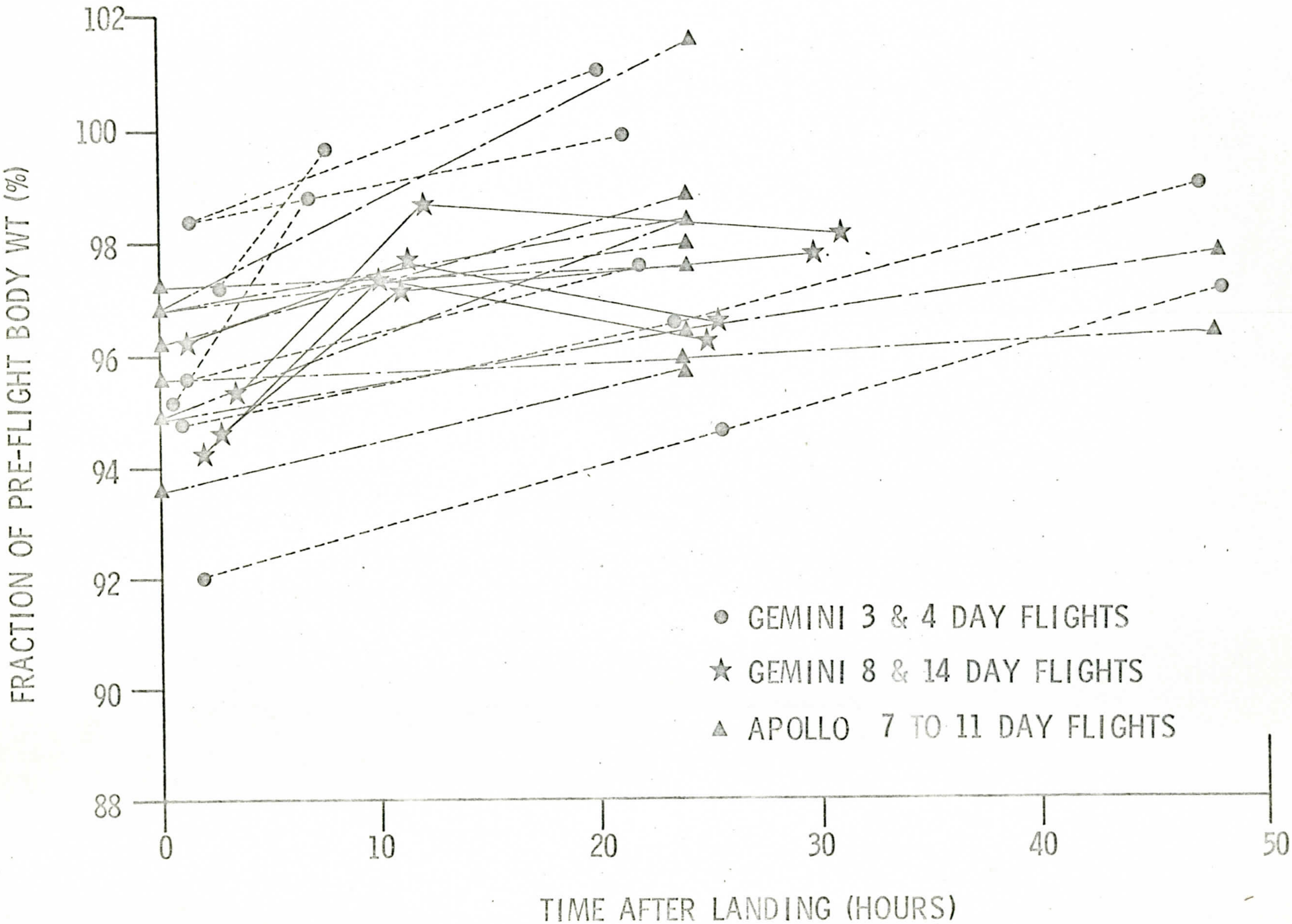


Fig. 6

CALCIUM METABOLISM[22]

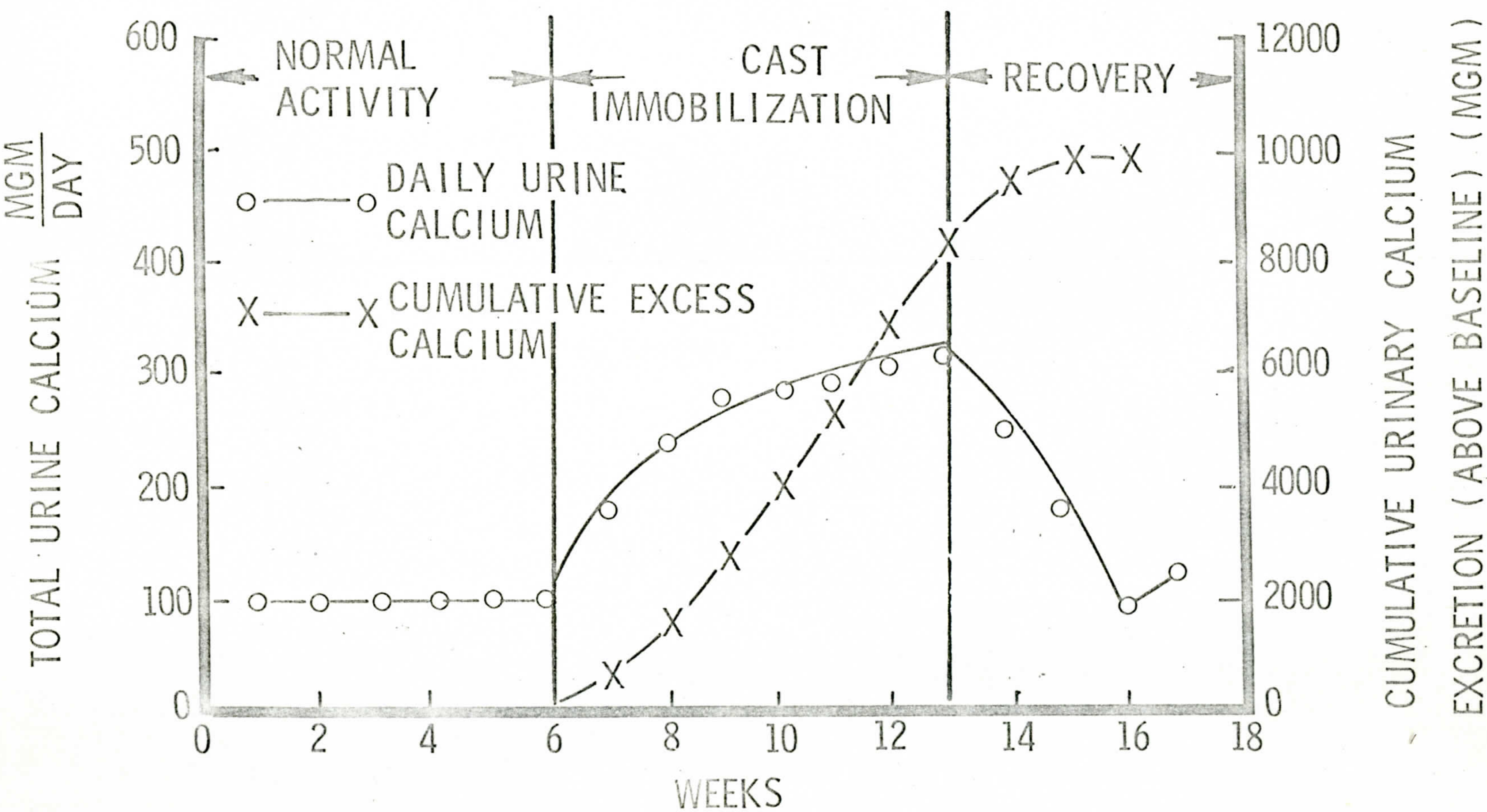


FIG 7.

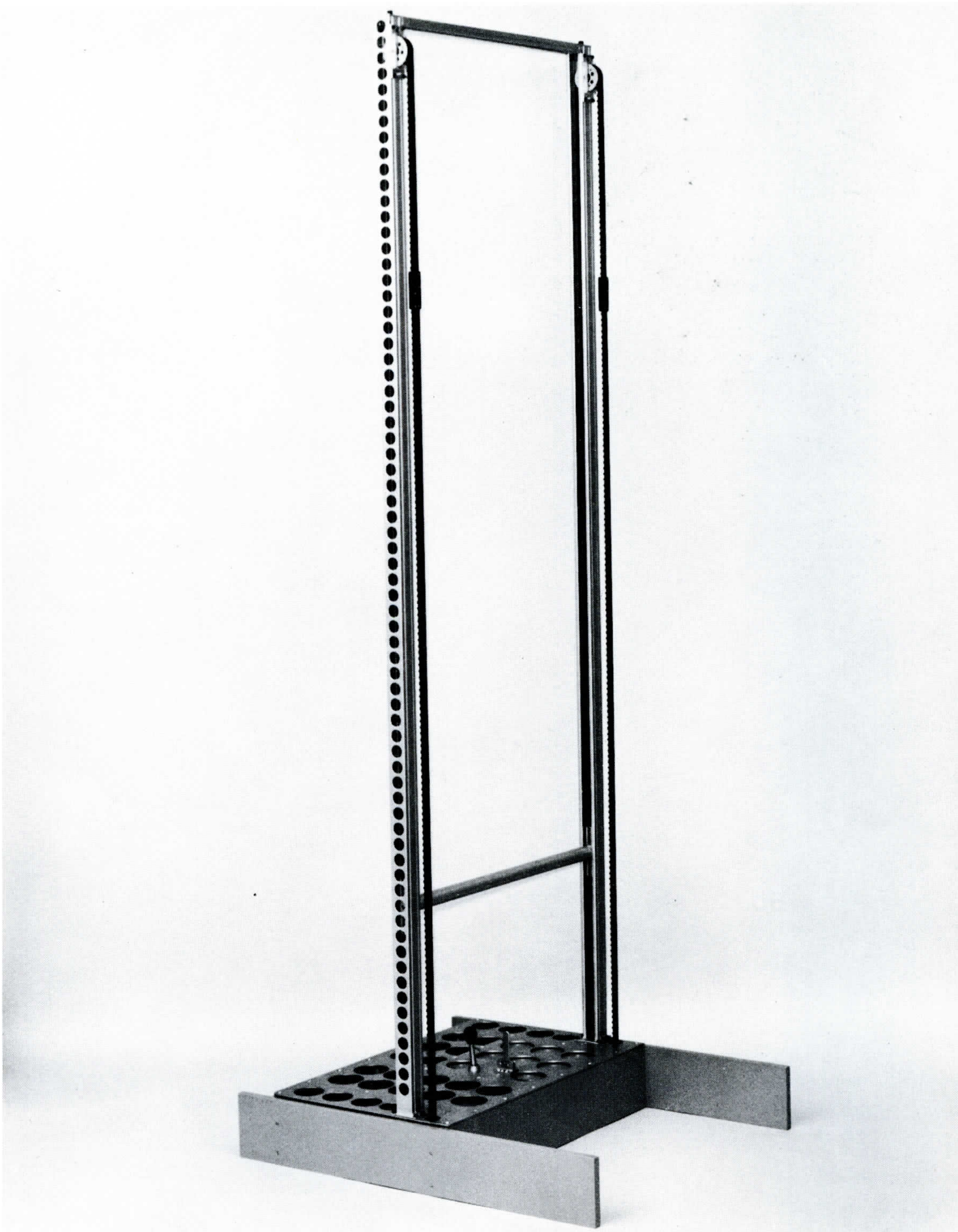
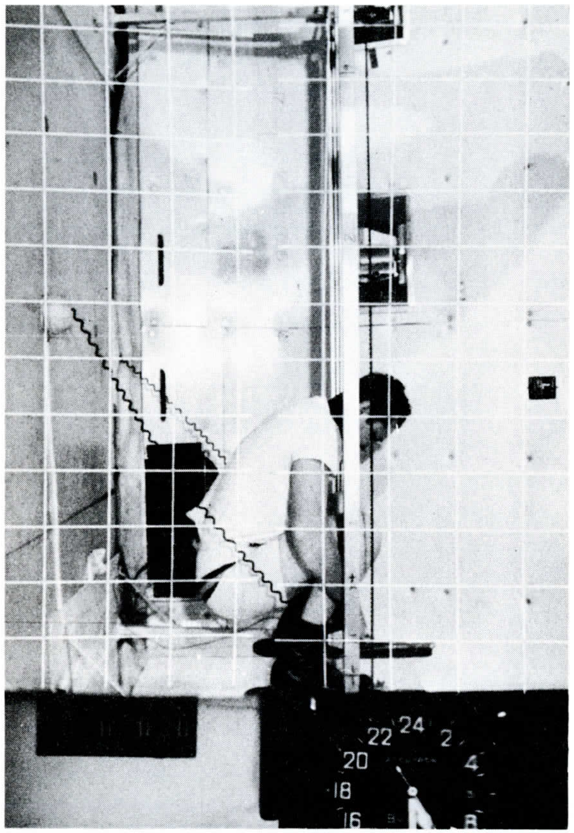


Fig. 8



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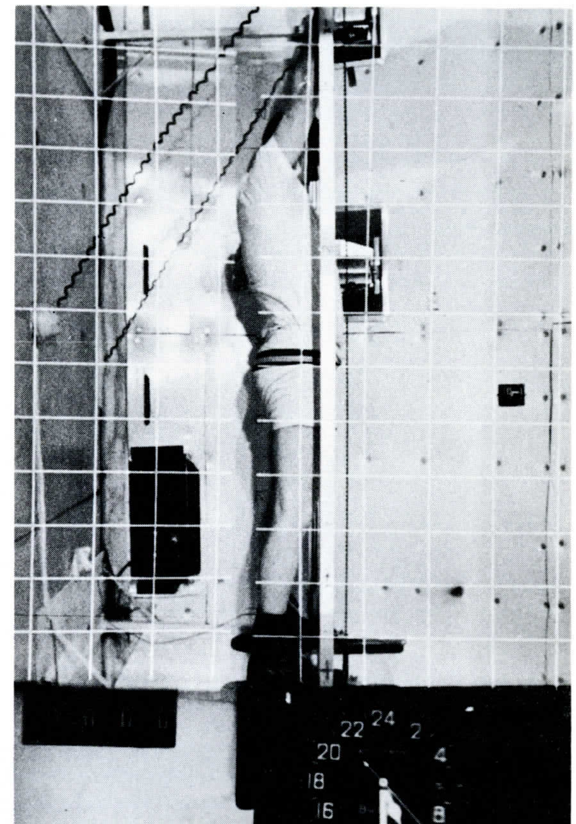
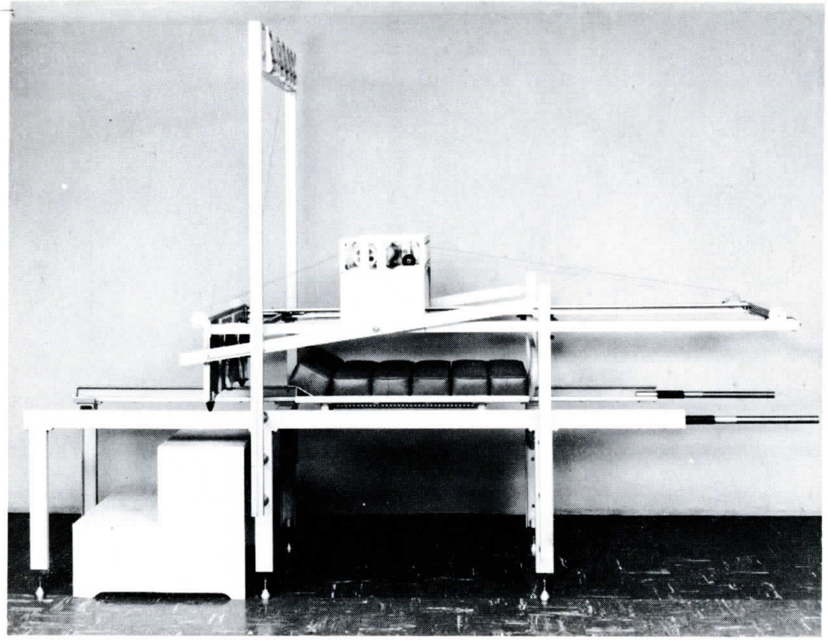
2



3

Fig. 9



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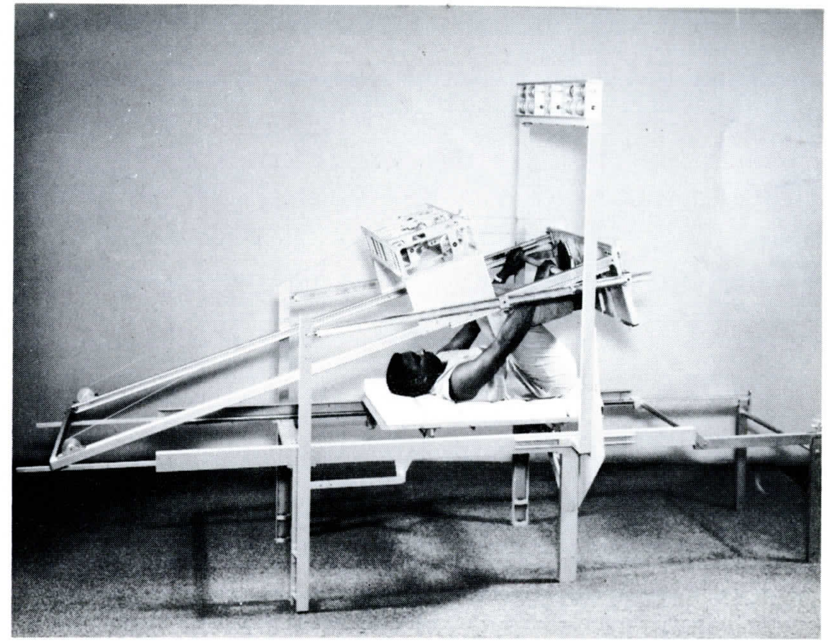

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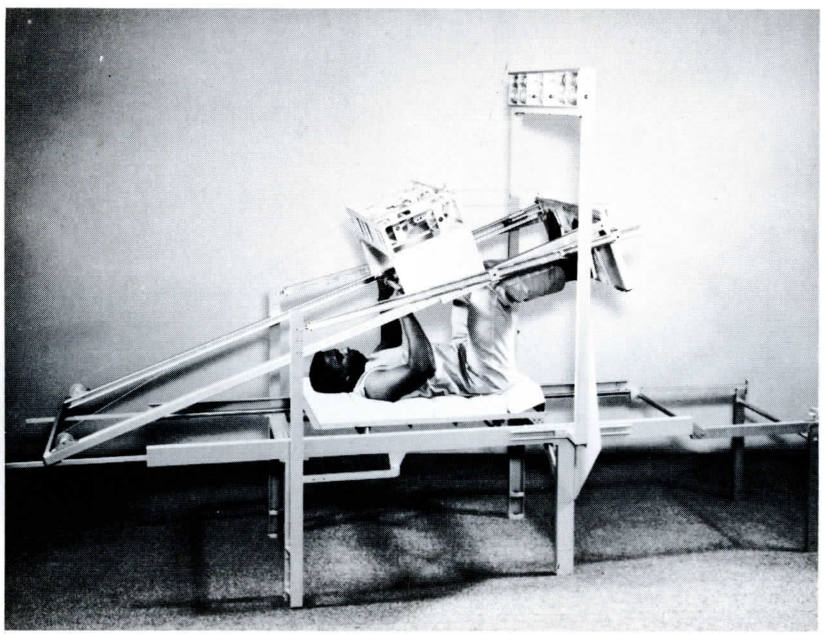

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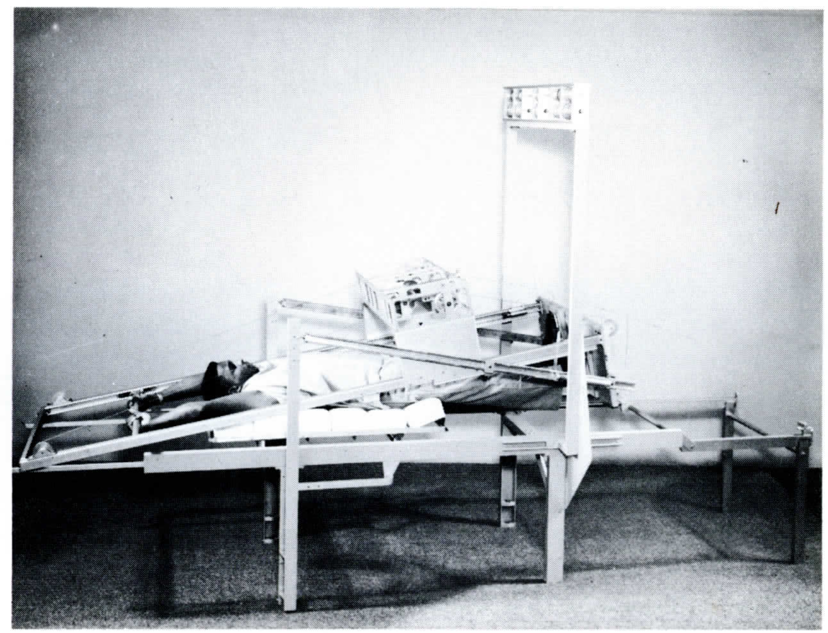

4

FIG. 10