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# BIOMEDICAL ACCEPTABILITY OF 45- TO 60-DAY SPACE FLIGHT

JOHN W. ORD, Colonel, USAF, MC *
STANLEY C. WHITE, Colonel, USAF, MC †

* Chief, Clinical Sciences Division, USAFSAM, Brooks AFB, Texas
† Office of Manned Space Flight, Office of Life Sciences, Hq NASA, Washington, D.C.

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John W. Ord, Colonel, USAF, MC
Stanley C. White, Colonel, USAF, MC

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13. ABSTRACT

The principal known effects of the space flight environment upon the physiologic function of human subjects have been reviewed as have the results and validity of biomedical ground-based simulation. Where known, the time courses of these physiologic changes have been described.

Our ability to modify the deconditioning effects of space flight has been discussed from the standpoints (1) of improving the effectiveness of environmental control and life support systems and (2) of providing countermeasures (especially exercise) as a means of modifying the effects of weightlessness and a degree of physical inactivity.

Biomedically, the current status of knowledge enables the prediction that 45-60 day manned space flights can be successfully accomplished.

It is clear, however, that complete knowledge of the mechanisms involved in space environmental physiologic adaptation and the time course of these changes is not available. To provide an adequate basis for managing the biomedical aspects of space flights of very long duration (greater than 60 days), much space-borne and earth-based biomedical research remains to be accomplished.

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## GLOSSARY

The paper was initially 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 the following brief glossary is provided:

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 readiness 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.

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 electrical voltages developed in the brain by the use of electrodes applied to the scalp.

Erythropoietic - pertaining to the formation of red blood cells.

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

Extravascular 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 blood cells.

Hematopoietic - pertaining to the formation of blood cells.

Hemoconcentration - decrease of the fluid content of the blood with a resulting relative increase in the cellular segment of the blood.

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

Intracellular space - the collective volume inside the cell membranes occupied by body fluid.

Intrathoracic hypervolemia - an increase in the volume of blood 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.

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 atmospheric pressure surrounding the lower part of the body is reduced relative to the upper part of the body and to that present outside the box. As the pressure on the lower body is reduced, fluids move into the extra-vascular spaces and blood volume increases, 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 passively from the horizontal to 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.

Postprandial - 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 biologic 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 anatomic compartments. Most of the weight-bearing bones of the body have this characteristic.

# BIOMEDICAL ACCEPTABILITY OF 45- TO 60-DAY SPACE FLIGHT

## 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 biologic 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 attempts 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 considers information developed by environmental physiologic 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 among individuals and the net effect of multiple stresses may vary; therefore, 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 (MOL) 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 is 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.

## SUMMARY

The principal known effects of the space flight environment upon the physiologic function of human subjects have been reviewed. The results and validity 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, diminution in the physiologic reserves of space crewmen has 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.

Our ability to modify the effects of space flight has been discussed from the standpoints of (1) improving the effectiveness of environmental control/life support (EC/LS) systems to minimize the physiologic "deconditioning" resulting from sustained or transient environmental loads, and (2) 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.

On this basis, physiologic adaptive changes probably will not diminish significantly the continuing ability of the astronaut to perform normally in 45- to 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 physiologic and psychologic 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 as a requirement for biomedical purposes in 45- to 60-day flights. Its scope for these purposes is outlined. Measurement of the physiologic

status of the crewman as it may be affected by his environment also must be continued, and the scope of these measurements (tailored to meet the requirements of a 45- to 60-day flight) is presented.

Overall, it is strongly felt that the current status of all of these factors enables us to predict with confidence that from the biomedical standpoint 45- to 60-day manned space flights can be successfully accomplished.

It is clear, however, that complete knowledge of the mechanisms involved in physiologic adaptation to the space environment and the time course for these changes is not available. To provide an adequate basis for managing the biomedical aspects of space flights of very long duration (greater than 60 days), much spaceborne and earth-based biomedical research remains to be accomplished.

## SPACE ENVIRONMENT

The environment to which the crewman in space flight 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, review of experiments, 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 1 G conditions and to 100% oxygen breathing to eliminate the nitrogen from his body, thus preventing decompression sickness. This is followed at launch by the psychologic inputs, acceleration, vibration, and noise associated with powered flight and orbital insertion.

In orbital flight he is weightless and 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 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. Since these factors 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, they are discussed in detail in this paper.

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 effects of the radiation environment are not discussed in this paper because of 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 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 depends upon the success of the systems to accomplish these functions now undergoing testing for the Skylab Workshop.

This paper does not deal with contingency situations imposed by the failure or malfunction of spacecraft systems. 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 their physiologic adaptation to the space environment, but rather to their normal vulnerability to the effects of failure or malfunction of the environmental control and life support hardware.

As isolated entities, most of the factors contributing to the space environment can be simulated accurately in earth-based research with a few exceptions: (1) weightlessness; (2) radiation, to which human beings cannot be deliberately exposed because of the production of permanent injurious effects; and (3) nonphysical (emotion-producing) stresses, because equivalency of the ground models departs radically from actual flight in that similar nonphysical stresses cannot be produced in the laboratory and because the special psychointellectual structure of the astronaut is not available in the usual laboratory research subject.

Multienvironmental simulations pose problems of two types. The first is the logistical impossibility of assembling all of the factors into single research efforts, and the second is the difficulty of 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. Neither is a completely effective model. 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 in actual space flight. The results of the bed rest research are more cohesive and interpretable than those of water immersion mostly because artifactual physiologic responses produced by technical difficulties (i.e., thermal effects, breathing pressure variations) are encountered in the latter. 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 and contaminants. Additionally, this model may be designed to impose a degree of physical inactivity somewhat less than that of bed rest, thereby enabling the environmental physiologist to fill in other points on the curves of adaptive responses to that factor of space flight. The resulting physiologic data are 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. The achievement of this goal will entail 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 in flight 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 body system response patterns to space flight environmental inputs and their operational significance to 45- to 60-day missions, and to extend the findings to deal with much longer missions of the future.

## 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 (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 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 the Apollo program, to lower body negative pressure (LBNP), 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 to counteract the pooling of blood in the lower part of the body. Without exception, a degradation of this control response, as measured by abnormal increases in heart rate and changes in blood pressures, has been observed in the astronauts following flight, with return to the preflight patterns in 48 to 72 hours. A few of the astronauts have fainted or approached that state in the first postflight test. This represents 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.

Inadequate intake of water and solute has been observed, both absolute and relative to excessive losses of body fluid. The excessive losses of body fluid have been incurred through active sweating or by the requirement to lose body heat by evaporation of fluid from the skin during prolonged periods of wearing spacesuits. Such body fluid losses may produce orthostatic intolerance through an effect on blood volume or on the properties of blood vessel walls 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 finding 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 for durations of 45 to 60 days will not continue to increase orthostatic intolerance as long as the environmental milieu remains relatively constant. Improvements in EC/LS systems, "shirtsleeve" operation, provisions for sleep, management of work-rest schedules, and ability to monitor and maintain adequate crew water intake and output and food consumption should reduce the inputs eliciting the orthostatic intolerance.

Preliminary evidence indicates that exercise and other methods of conditioning may partially prevent the orthostatic effect of bed rest. This finding may be applicable to space flight as well, although the type of conditioning device and the intensity, frequency, and 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 affected by the orthostatic intolerance; however, physical activity (or lying down) overcomes the peripheral pooling of blood and tends to stabilize the circulation.

In short, the orthostatic tolerance tests should be considered as laboratory procedures used to detect and quantify alterations in circulatory regulation, and not as procedures 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, and other factors.

Exercise tolerance. A highly reproducible form of exercise test has been employed pre- and postflight in some of the Gemini astronauts (2-4). 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 greater. 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 preflight status.

The Russians have used exercise in the postflight period in the physiologic evaluation of the cosmonauts. The test employed was apparently a milder form of exercise, but a diminished 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, decline in circulating red blood cell mass, 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 to 900 kcal., has been the only regimen tested to date which prevented loss of exercise capacity during 3 weeks of bed rest (15). Programmed exercise at a rate of 500 to 600 kcal. 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 substantially the deconditioning effects has yet to be carried out.

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 activity (EVA), 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. An interdependent adaptation to heat loading accompanies physical fitness. 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 environmental control system function, suited operations, and 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.

In most American flight crewmen and in the Russians (where data are available), hemoglobin, red cell count, and hematocrit values of peripheral blood have been elevated immediately postflight (2, 3, 8). This elevation most probably reflects hemoconcentration due to a relative loss of the 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 section entitled "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 erythropoiesis. Hemoconcentration does in itself diminish the stimulus to red cell production, and hence may be a factor in the apparent loss of red cells.

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 cellular element of the blood 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. 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 disparate body of data is extremely difficult to interpret even though certain differences in environmental factors are present among the flights.

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, 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 p. s. i.) oxygen breathing occurred during training; this has been minimized (but not totally eliminated) 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 and was followed by about 7 days of flight in pure oxygen (at a pressure of about 5 p. s. i.).

The possibility that thermal loading, acceleration (reentry), or physical activity (especially after landing) may impose destructive trauma to the red cells is suggested 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 the blood volume to the recumbency 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- to 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 pre-bed-rest condition is complete after about 3 to 4 weeks of normal activity.

The effect of moderate diminution of red cell volume on physiologic function is not apparent at rest, but only when relatively intense physiologic 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 tolerance to acceleration (especially transverse) is not diminished by red cell changes to the degree seen in the studies discussed earlier in this paper.

Ground-based research indicates that adaptation of the red cell mass to new and constant environmental conditions is nearly complete in 4 to 6 weeks, thus suggesting that changes in physiologic capacities dependent on alterations in the red blood cell mass beyond those present at the end of 30 days will not be great. Furthermore, the RBC-stimulating effect of physical exertion indicates that programmed exercise will be beneficial in modifying the decline of red cell volume. The form and amount of exercise required are 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 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 the determination of 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 that results in a maldistribution of ventilation relative to blood flow through the lungs. In turn, part of the blood passes through the pulmonary circulation without being normally oxygenated, so that the arterial blood does not have the normal quality 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 psychophysiologic functional status during the acceleration exposure. The transverse acceleration 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. This is especially true at reduced atmospheric pressure where the number of oxygen molecules per unit volume available for absorption is reduced. The presence of even small amounts of an inert diluent gas (nitrogen or helium) diminishes strikingly the tendency to the production of atelectasis. 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- to 60-day flights.

## Metabolism

For the purpose of this paper, body metabolism will be considered in three segments: (1) body fluid metabolism, (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 largely 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% to 5% of the preflight weight in crewmen of missions longer than 1 day's duration and has ranged from about 2% to 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 losses in crewmen of short flights and a major part of those occurring in crewmen of the long flights are restored in the first few days. 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, especially 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 an acute renal loss of fluid is induced 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 is 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 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 decrease 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.

Loss of body weight has not often occurred in bed rest research subjects. 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 by normal water and sodium balances, slight increases in plasma volume, and presumably 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.

Exercise adequate to counteract the effects of bed rest has not been imposed in the research where body fluid metabolism has been measured in detail and should be studied. One report suggests that the application of 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 pre-bed-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- to 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, certain factors of the space environment contributing to excessive body fluid loss can be better controlled than has been the case in space flights to date. Factors of special importance are providing a shirtsleeve 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. Limited data are available from the analysis of body waste samples taken in flight and measurement of food and water intake during flight. These data suggest that losses in nitrogen, calcium, and phosphorus occur during space 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 to 7 weeks. The increase in rate of mineral loss ends after about 3 to 4 weeks, as determined by the classic work of Dietrick et al. (11). In that study the subjects were immobilized by the use of body casts, a form of restriction of activity more rigorous than that to be expected in space flight.

The alterations of musculoskeletal metabolism are thought primarily to be a result of physical inactivity. The absence of gravitational stresses and strains, especially 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 have been relatively small. Exercise of the proper form (with 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 so that the astronaut's own muscle tissue will not have 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., EVA and survival situations. 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. 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. Analyses of urine samples taken immediately postflight have shown increased concentrations of adrenocortical hormone (17-hydroxycorticoids) and catecholamines (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 in the early postflight period, in the fasting state, 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 postprandial blood sugar determinations unfortunately have not been accomplished.

Definite evidence exists that decreased tolerance to glucose results from bed rest (11, 24). 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. Results of studies in 2-week periods of bed rest indicate that measurable changes occur in pituitary, adrenocortical, and catecholamine responses to tests which stress cellular biochemical processes. 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.

Nothing in these findings suggests that a loss of physiologic capacity for normal activities would occur, or that a reduction of tolerance to the space environmental stresses other than heavy physical work would be expected.

## 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 the daylong flight. A contributory factor may have been a rather severe degree of vehicle tumbling, presumed to result from malfunction of the attitude control system.

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 more freely 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 susceptible to motion sickness.

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 to 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 were 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, 3, 5, 8). Great individual variation in the ability to sleep in space flight has been observed; some astronauts say sleep is not difficult, others that it is a great problem. Generally, sleep has been grossly inadequate in the first 48 hours of flight, because of long work schedules beginning prior to launch and nonphysical stresses involved with the onset of a mission. Early American multimanned 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. The command pilot, who is responsible for the mission, has a tendency 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 because of unforeseen requirements of the mission.

All of the foregoing have contributed to a 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: the schedule of sleep periods coinciding with Moscow time is rigorously followed, and the cosmonauts are "conditioned" to fall asleep easily. Autohypnotic technics to induce sleep have been described in some Soviet space medical reports, although it is not known whether they were actually used by the cosmonauts.

Ground-based research on work-sleep 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 psychologic simulations. The nonphysical stress aspect of space flight, contributed to both by the actual flight conditions and by the psychointellectual 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- to 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 at this time 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 Skylab Program) and by better management of work-sleep schedules, based primarily on careful study of this aspect of Apollo flights.

Mission performance capability

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 judgments 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 (with the possible exception of fatigue) have degraded or are expected to degrade the astronauts' intellectual or motor capacities. 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, or sleep deprivation) overshadows the subject's motivation to continue performing. The impossibilities of extrapolating from such studies to the real question of 45- to 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 to 36 hours demonstrate performance decrements (28). That sleep is required to maintain normal brain function is clear, although the mechanisms by which the maintenance and restoration of function are accomplished are not clear. 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 to 60 days, where the substance of the missions is involved with relatively routine repetitive tasks, it will become critical that our management of crew work-sleep 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 Skylab.

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

Based upon the experience 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 psychologic 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 experiences of man while on isolated duty on earth do suggest many good approaches for providing psychologic 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 standpoint of physiologic adaptation, there is little risk that crewmen will not be completely capable of continuing top-level performance. From the standpoint of planning work-sleep cycles and psychologic support for long missions consisting heavily of repetitive tasks, we have much to learn. This information will have to come from actual flight experience.

## INFORMATION REQUIREMENTS

Although it is apparent from the previous discussion that our knowledge of the human physiologic 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 anticipation that (1) environmental control/life support systems will be more effective than they have been in previous programs, (2) crew conditioning (countermeasures) applied in flight will produce an adequate compensation for the adverse effects of weightlessness and physical inactivity, (3) monitoring of the crewman and his environment will be adequate to detect and correct undesirable physiologic changes and deficiencies in life support, and (4) 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/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 spacesuits 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 Mercury flight 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 drinking water system, time constraints, unacceptability of some of the food items, and procedural complexity of food consumption.

In current and future programs evidences of very great improvement in EC/LS systems are apparent. The crewmen are in shirtsleeves, 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 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 because of the nature of the equipment and the confinement imposed by the spacecraft. The astronauts have also performed optional exercise, usually isometric, consisting of pressing between couch and bulkheads. It is fair to say that this amount and type of exercise were inadequate to modify "deconditioning."

In two of the longer Gemini flights, an automatic cuff-inflation device was provided to one crewman. This was designed to impede 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 because of 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 many of the 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 spaceborne exerciser which can provide for a range of loads, various exercise regimens involving either the whole body or body regions, and relatively large energy expenditure rates.

The flight prototype of the exerciser has been tested during Keplerian trajectory flights producing weightlessness. These tests have validated the principles of mechanical operation and have defined the crew body motion patterns and restraint requirements.

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. Simulation versions (1 G) of the exerciser have been fabricated and are suitable both for astronaut conditioning in the preflight period and for the ground-based research. An identical exercise apparatus to the flight equipment is incorporated into a partial weightlessness-simulating platform in order to provide the same "feel" and relative body motion pattern as would occur in space flight.

For 45- to 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 with 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- to 60-day flights, studies along other avenues involving the addition of other technics should be pursued, for possible use in flights of very long duration.

## Biomedical monitoring in 45- to 60-day flights

As is implied in previous sections, the physiology of man is extremely responsive to the status of his environment (note the previous discussion of the temperature-humidity control in Mercury and Gemini flights). 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.

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 heartbeat interval continuously, to obtain the electrocardiogram on demand in a form providing clinical diagnostic capability, and to record body temperature. In addition, the astronaut's intake and output of fluid must be measured, and his food intake documented. The measurement of body mass, together with the intake and output information, provides the critically important capability to establish fluid balance and its regulation and 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 the 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- to 60-day flights that a specific means of quantifying the crew performance be provided.

## FLIGHT AND GROUND-BASED BIOMEDICAL RESEARCH

The following presents a list of the more important general areas of research in space physiology to provide greater assurance of success in accomplishing long-duration manned space flight.

### Circulatory system

It will be very important to confirm that exercise during bed rest can preserve the physiologic capacity for physical exertion and to accomplish further research on the benefits of exercise in preventing other manifestations of circulatory deconditioning.

It is mandatory that the effectiveness of exercise and other promising modalities as countermeasures be documented in actual space flight. Crewmen who perform programmed exercise should be compared with crewmates to determine the benefit to circulatory functional integrity (such as physical working capacity and orthostatic tolerance).

### Hematopoietic system

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 detailed measurements of red cell mass and kinetics in succeeding flights.

It will be important to confirm that 5 to 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.

### Metabolism

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. Similiar data concerning bone and muscle metabolism are desirable.

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.

It is desirable that metabolic studies similar to those described above be carried out in actual space flight.

### Sleep

It will be extremely important to quantify sleep in space flight in whatever missions this can be accomplished, and to correlate sleep with mission events and sleep environment.

### 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.

### Comparison of flight with ground-based physiologic models

It will be completely impossible to carry out the research required to disclose all of the required specific information concerning physiologic adaptations to the space environment in actual flight. Most of the research will have to be accomplished in the ground laboratory. Therefore, a major objective in designing flight research should be to accomplish confirmation of the validity of ground laboratory physiologic models and methods.

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