BIOMEDICAL FINDINGS ON AMERICAN ASTRONAUTS PARTICIPATING IN SPACE MISSIONS

Man's Adaptation to Weightlessness

Presented by

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TABLE OF CONTENTS

	Page
Introduction	1
Performance in Zero Gravity	1
Locomotion	1
Orientation	2
Sleep	3
Adaptation to Zero Gravity	5
Cardiovascular Adaptation	5
Weight Loss	6
Endocrine and Electrolyte Response	9
Fluid Balance	11
Skeletal Responses	13
Muscular and Neuromuscular Changes	14
Work Capacity	15
The Nature of the Adaptive Response: An Hypothesis	16
Projections for Future Missions	20
References	21

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Introduction

Fifty-four persons now have been exposed to the environment of space, some for periods lasting up to 22 days. Returning space travelers have shown no apparent lasting ill effects as a result of exposure to the rigors of the space environment, although many signs of adaptive changes are apparent. The implication of these changes for prolonged space flight cannot be assessed until a number of questions are answered, although it is clear that man adapts to space flight at some physiological cost.

At this time, data from space missions are too limited to reveal the full extent of adaptive trends, partly because of the relatively small number of individuals involved and the extensive variability among these individuals, and partly because of limited inflight measurements. However, the complex of data is beginning to afford clues as to the mechanism, if not the full extent, of the zero gravity adaptive response.

Performance in Zero Gravity

The totally different nature of the world without gravity results in two kinds of change in the human space traveler. Of primary concern to medical scientists are the *adaptive* changes which take place in the basic physiological systems of the body. However, there also are a number of *operative habitational* changes which confront the astronaut simply because the gravity factor is no longer present. We are accustomed to living, working, and moving in a world in which there is a constant one-gravity force. When this force is removed, many things must be done differently.

Locomotion

The absence of gravity has been found to represent a bonus for locomotion within the spacecraft cabin. Locomotion in zero g appears to require much less work than in the unit gravity environment. Movement is accomplished with minimal effort, frequently in a swimming manner. Acrobatic maneuvers, such as rolling, tumbling, and spinning, are done without difficulty. An additional feature of the zero gravity environment, the capability to impart minimal velocities to objects, also has been used repeatedly by crewmen as an aid in performing inflight activities.

The ability to move freely through all parts of a space cabin during weightlessness has implications for general vehicle habitability. Apollo astronauts have commented that the Command Module, which seemed rather cramped during ground tests, was more comfortable in flight due to the increase in usable living and working space. This observation has raised the question of the validity of volumetric studies which attempt to extrapolate from habitation in other confined areas such as submarines or low pressure chambers the volume of living space required for astronauts in long duration missions. Locomotion in three dimensional space, as opposed to two, appears to be a positive factor in determining vehicle habitability.

Orientation

Prior to the first manned space flights, it was feared that exposure to weightlessness might produce significant functional disruption of the body's principal orientation mechanism, the vestibular system. Fortunately, there have been no episodes of debilitating disorientation or serious impairment of vestibular function. Almost all crewmembers have, however, experienced a fullness-of-the-head sensation upon *initial* entry into zero gravity. Although this frequently produces the sensation of hanging upside down, the phenomenon is transient and does not impair the general orientation of the astronaut.

In addition to the initial subjective sensations, there have been a number of instances in which crewmembers have developed symptoms of motion sickness varying in degree of severity. Table 1 shows that all instances in the American space program have occurred in Apollo flights. This may be a function of the increased ability to move around the cabin and to move the head prior to orbital adaptation.

Table 1
Summary of Vestibular-Related Symptoms and Signs
in U. S. Space Flights

Program	Total Crewmembers	Stomach Awareness	Nausea/ Vomiting	Spatial Disorientation/ Tumbling Illusions	Debilitating Disorientation
Mercury	6	0	0	0	0
Gemini	20	0	0	0	0
Apollo	27	6	2	3	0

NOTE: One crewman could experience more than one class of symptoms.

The absence of orientation problems or vestibular symptoms in early space flights has allowed more realistic medical standards to be used in recent Apollo missions (Berry, 1971). For example, one member of the Apollo 14 crew had been afflicted with Meniere's disease some years earlier, with symptoms including episodes of serious vertigo, a partial hearing loss, and tinnitus. The condition was alleviated through the surgical implacement of an endolymphatic shunt, resulting in the crewmember's becoming totally asymptomatic.

Prior to the Apollo 14 mission, this astronaut was thoroughly evaluated through clinical observation, a number of centrifuge tests, altitude chamber simulations, and many zero gravity parabolic aircraft flights. All results were excellent. During the lunar flight, this crewmember experienced no symptoms of vestibular dysfunction. Pre- and postflight audiograms and vestibular tests showed no change. The preflight medical evaluation program was completely successful in predicting inflight results.

Sleep

The ability to obtain proper rest becomes of considerable importance as space missions increase in length and complexity. During the Gemini program, it became obvious that orbital flights could result in conditions which did not permit adequate sleep. Among the many sleep-disrupting factors are cyclic noise disturbances from such events as thruster firings, communications,or movement in the spacecraft; staggered sleep periods; significant alterations of preflight diurnal cycles; the so-called "Command Pilot syndrome;" the unfamiliar sleep environment; and excitement. Obviously, it becomes quite difficult to isolate weightlessness *per se* as a factor influencing the quality of sleep.

The Gemini sleep difficulties continued into the Apollo series. Apollo 7 work/sleep cycles were rather irregular, and staggered sleep periods shifted considerably from preflight bedtime. The crew never adapted to these cycles, reporting very poor sleep during the first three days of flight. One crewmember fell asleep on his watch, and, on another occasion, took five milligrams of dextroamphetamine to stay awake during his work period.

By the time of the Apollo 11 lunar landing flight, increased confidence had been gained in spacecraft systems, and sleep periods were improved. In fact, as Figure 1 shows, rest periods were close to ideal prior to lunar orbit insertion. These sleep periods, described from the study of telemetered heart and respiration rates, were deemed adequate for medical approval of an earlier start of the scheduled extravehicular activity on the lunar surface than was originally planned. However, during the actual lunar stay, the quality of sleep deteriorated. The Lunar Module environment was too noisy and the space suit too cold to permit adequate sleep. In general, accommodations for sleeping in the Lunar Module are less than ideal—a condition which has continued to the present time. Apollo 14 crewmembers, for example, reported they obtained little, if any, sleep between their two lunar extravehicular activity periods. The lack of an adequate place to rest the head, discomfort of the pressure suit, and the seven-degree starboard list of the Lunar Module caused by the lunar terrain were held to be contributory. Concern over the list of the vehicle was such, in fact, that the crewmen looked out the window several times during the sleep period and used a hanging upright as a plumbob for reassurance that the vehicle was not beginning to tip over.

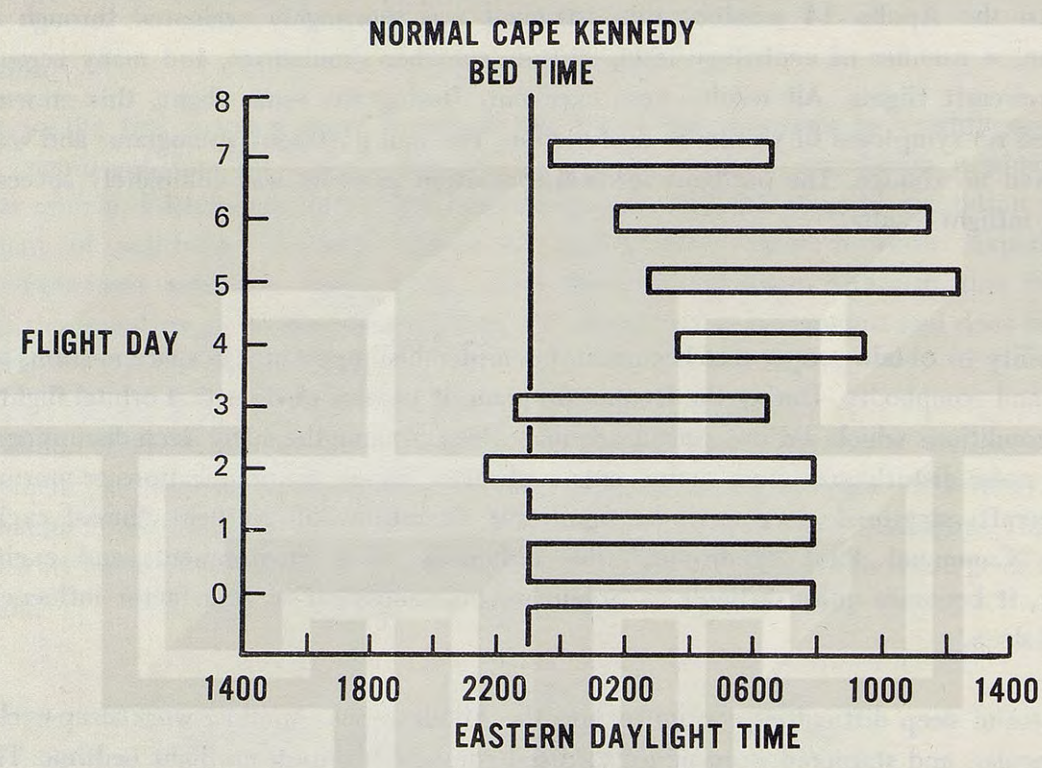

Figure 1. Crew Sleep Periods during Apollo 11 Mission

In missions longer than those of the Apollo series to date, significant attention must be given to sleep conditions. Facilities must be provided so that astronauts working on the lunar surface can obtain more normal and comfortable sleep while resting in the lunar vehicle. Although task performance has not as yet been significantly affected by the fatigue brought on through lack of proper rest, the situation is serious enough to warrant close attention in future missions. However, it does seem that poor quality of sleep to date is largely a function of operational factors and cannot be attributed to any basic inability to sleep in a weightless environment.

A number of astronauts have complained of backache as one effect of living under weightless conditions. While the cause is not known with certainty, it has been conjectured that these symptoms arise as a result of crewmen assuming a fetal position during sleep, a position which seems most comfortable within the present space cabin constraints. The use of improved sleep restraint systems on future missions might alleviate this problem.

Adaptation to Zero Gravity

The first indication that the transition from zero gravity to earth's gravity exacted a physiological toll appeared as early as the first orbital mission in the American space program. On that mission, and on all subsequent missions with very few exceptions, weight losses have been observed. With the last two project Mercury missions, a more distressing phenomenon was seen. Both the Mercury 8 and 9 astronauts exhibited signs of reduced orthostatic tolerance after reentry which persisted up to 19 hours postflight. This phenomenon, along with weight loss, has since been a consistent finding. These signs had been anticipated in view of the alteration in hemodynamics expected with weightless exposure and were closely watched. Endocrine and electrolyte studies were also performed to obtain corroborative biochemical information.

The principal physiological responses to the weightless environment observed in American astronauts are summarized in the following sections.

Cardiovascular Adaptation

Cardiovascular indices have been monitored during all American space flights and have been within expected physiological ranges. No significant changes have been noted inflight for heart rate or blood pressure. Only in the Apollo 15 crew have any irregularities been noted in electrocardiographic recordings. Postflight, reduced orthostatic tolerance has been observed with regularity. This phenomenon has also been seen following Russian space missions. Petukhov and coworkers (1970), for example, reported severe orthostatic intolerance in Soyuz 8 cosmonauts. Since the full extent of orthostatic hypotension is not always obvious in the resting state, several provocative tests have been employed. These have included tilt table tests, lower body negative pressure tests, and static standing tests. The techniques involved in each method will not be described here, since these descriptions appear in the literature (Berry et al., 1966; Wolthus, Hoffler, & Johnson, 1970; Berry, 1971).

Whatever the factors causing evidence of cardiovascular adaptation to zero gravity, heart rate appears to be the most sensitive index of reduced orthostatic tolerance available at the present time.

Figure 2 shows a typical heart rate response during orthostatic tolerance testing. In this case, the passive standing test was employed. Blood pressure data are not given since blood pressure has not proven a reliable index of deconditioning. Blood pressure responses to the application of lower body negative pressure and 90 degree passive standing, for example, have been quite variable (Berry, 1969).

In the earthbound environment, the gravity gradient results in a tendency for blood to pool in the limbs. When the gradient is removed during weightlessness, blood becomes more evenly distributed throughout the body. Should vascular tone decrease during this period, it would be reasonable to expect a postflight increase in pooling of blood in the lower limbs. Calf circumference measurements made in conjunction with tilt table tests in the Gemini mission series indicated that pooling did occur, with leg volumes universally greater by 12 to 82 percent postflight (Berry et al., 1966). Distention of blood vessels corroborated this finding. In the Apollo mission series, with lower body negative pressure used as the test for orthostatic tolerance, similar changes in leg volume were not observed. The reason for the divergence of findings is unclear but may simply be indicative of a basic difference in the two tests.

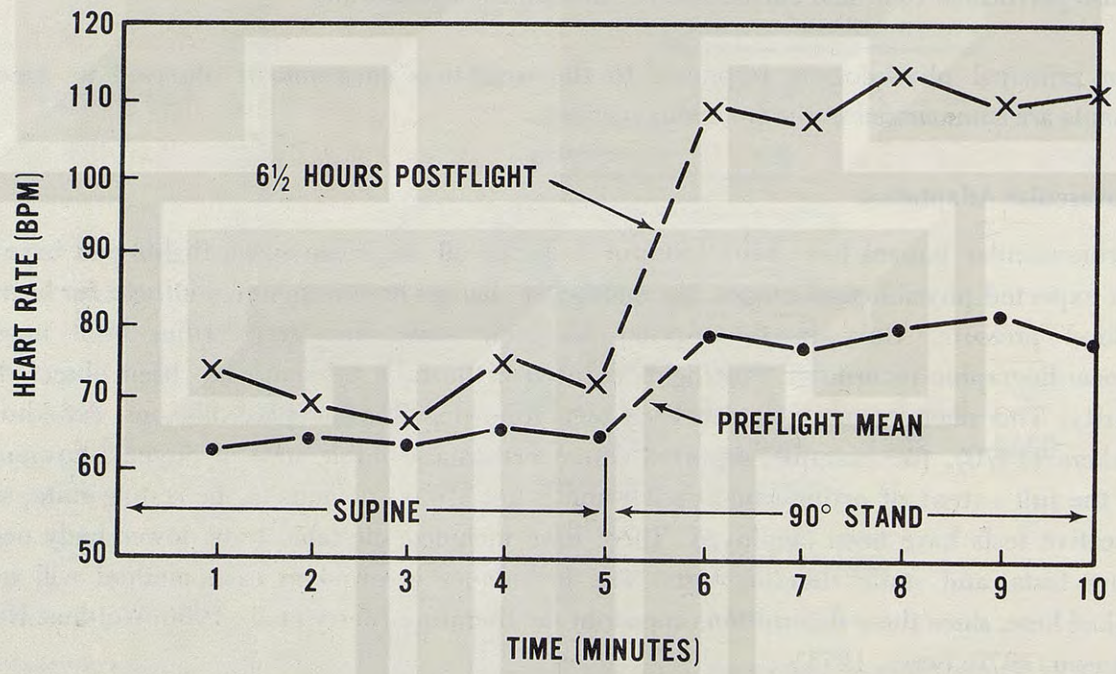

Figure 2. Representative Changes of Heart Rate during 90° Passive Standing Preflight and Postflight (Berry, 1970)

Weight Loss

Table 2 indicates average postflight weight losses recorded to date for American astronauts. Similar effects have been reported by Russian investigators (Gazenko & Gyurdzhian, 1965; Volynkin & Vasil'yev, 1969). Most, but not all, of these weight losses have been regained within one day after reentry. This is illustrated by the Apollo mission data presented in Table 3. This is a clear indication that the bulk of weight loss was fluid and electrolyte loss. Endocrine and electrolyte data have borne this out. Obviously, caloric intake and energy expenditure data must be precisely known in order to determine to what extent space flight–induced loss of tissue mass is involved. Attempts will be made in the remaining Apollo missions to evaluate the precise extent of tissue loss. It should be noted that although weight loss has occurred on all missions, it has not been proportional to increasing mission duration.

Table 2
Average Weight Loss Immediately Postflight
for American Space Missions

		Weight Loss (lb)
Mercury	6	6.3
	7	6.0
	8	4.5
	9	7.8
Gemini	3	3.3
	4	6.5
	5	8.0
	6A	5.3
	7	8.0
	8	not available
	9A	9.5
	10	3.0
	11	1.3
	12	6.8
Apollo	7	8.1
	8	6.8
	9	5.7
	10	8.5
	11	9.0
	12	8.0
	13	10.5
	14	4.0*
	15	3.2

*Weight changes were −12 lb, −1 lb, and +1 lb. Widely divergent losses were associated in part with increased fluid intake on the part of two of the men.

Table 3
Weight Changes—Apollo 7 to 15

	Weight Loss	Percent Change	Weight Regained (R + 24 hr)	Percent Change
Apollo 7				
CDR	– 6.3 llbs	–3.2	+2.5 lbs	+1.3
CMP	–10.0 lbs	–6.4	+3.5 lbs	+2.2
LMP	– 8.0 lbs	–5.1	+5.5 lbs	+3.5
Apollo 8				
CDR	– 8.7 lbs	–5.1	+2.7 lbs	+1.6
CMP	– 7.8 lbs	–4.5	+0.7 lbs	+0.4
LMP	– 4.0 lbs	–2.8	+0.5 lbs	+0.3
Apollo 9				
CDR	– 5.2 lbs	–3.3	+2.7 lbs	+1.7
CMP	– 5.7 lbs	–3.2	+8.5 lbs	+4.8
LMP	– 6.1 lbs	–3.8	+4.2 lbs	+2.6
Apollo 10				
CDR	– 2.0 lbs	–1.1	+2.0 lbs	+1.1
CMP	– 5.0 lbs	–3.0	+1.0 lbs	+0.6
LMP	–10.0 lbs	–5.8	+2.0 lbs	+1.2
Apollo 11				
CDR	– 8.0 lbs	–4.7	+6.0 lbs	+3.7
CMP	– 7.0 lbs	–4.2	+0.0 lbs	+0.0
LMP	– 1.0 lbs	–0.6	+4.0 lbs	+2.4
Apollo 12				
CDR	– 4.2 lbs	–2.8	+2.0 lbs	+1.4
CMP	– 7.2 lbs	–4.7	+4.0 lbs	+2.7
LMP	–12.5 lbs	–8.2	+3.0 lbs	+2.1
Apollo 13				
CDR	–14.0 lbs	–8.1	———	———
CMP	–11.0 lbs	–5.6	———	———
LMP	– 6.5 lbs	–4.2	———	———
Apollo 14				
CDR	+ 1.0 lbs	+0.5	+1.0 lbs	+0.6
CMP	–12.0 lbs	–7.2	+7.0 lbs	+4.8
LMP	+ 1.0 lbs	+0.5	+1.0 lbs	+0.6
Apollo 15				
CDR	– 1.2 lbs	–0.7	+1.0 lbs	+0.5
CMP	– 3.0 lbs	–1.9	+2.0 lbs	+1.3
LMP	– 5.5 lbs	–3.4	+5.0 lbs	+3.2

Endocrine and Electrolyte Responses

Assay of urine samples collected pre- and postflight in the Apollo mission series and inflight during the Gemini 7 mission have provided valuable insight into the nature of the adaptive response to weightlessness which is clearly evidenced by the weight loss phenomenon. Endocrine and electrolyte studies indicate that weight loss is principally accounted for by fluid loss.

Electrolytes. Urine and plasma electrolyte studies have revealed postflight retention of electrolytes. Decreases have been noted in potassium levels, indicative of decreases in total body potassium, and in urinary sodium and chloride levels. These changes have paralleled the time course of body water changes.

Figure 3 shows the results of urinary potassium studies for the Gemini 7 Pilot. In flight, potassium excretion appeared depressed, and this depression was still apparent by 24 hours postflight. Similar decreases were found in both serum and urinary potassium levels for Apollo crewmen. These changes were, in fact, suggestive of a decrease in total body potassium, an hypothesis that was supported by K^{40} evaluations in the Apollo 13 and 14 crews. Total body gamma spectrometry indicated a significant decrement of total body potassium for Apollo 13 crewmen compared with preflight values. In Apollo 14 crewmen, similar decreases in total body potassium were seen 17 days after recovery versus the astronauts' preflight values. These decreases were noted when control subjects showed increased total body potassium levels. This potassium loss is presumptive evidence of intracellular water and cation loss, for which there is other supporting evidence. Decrements in total exchangeable potassium also were seen in Apollo 15 crewmen when evaluated postflight by K^{42}.

Consistently diminished excretions of sodium and chloride have also been observed in the immediate postflight period. Figure 4 indicates urinary electrolyte levels for the Command Module Pilot of the Apollo 14 mission. This figure also shows his pre- and postflight potassium levels. Although some individual variation has been observed, these urinary electrolyte measures are typical following space flight exposure and clearly indicate efforts on the part of the body to retain fluid to compensate for inflight fluid volume loss.

Endocrine Responses. Endocrine responses have been evaluated principally to determine whether hormones related to body fluid regulation reflect the observed postflight fluid and electrolyte changes. Attempts have also been made to evaluate stresses related to space flight by measuring certain postflight steroid levels. These results, based on very limited data, appear to indicate that the reentry and recovery periods may be the most stressful. It is, however, admittedly difficult to evaluate "stress" on the basis of endocrine assay since many hormones which are believed to be indicative of certain stresses are also related to other physiological functions, for example, vasoconstriction or vasodilation and electrolyte regulation.

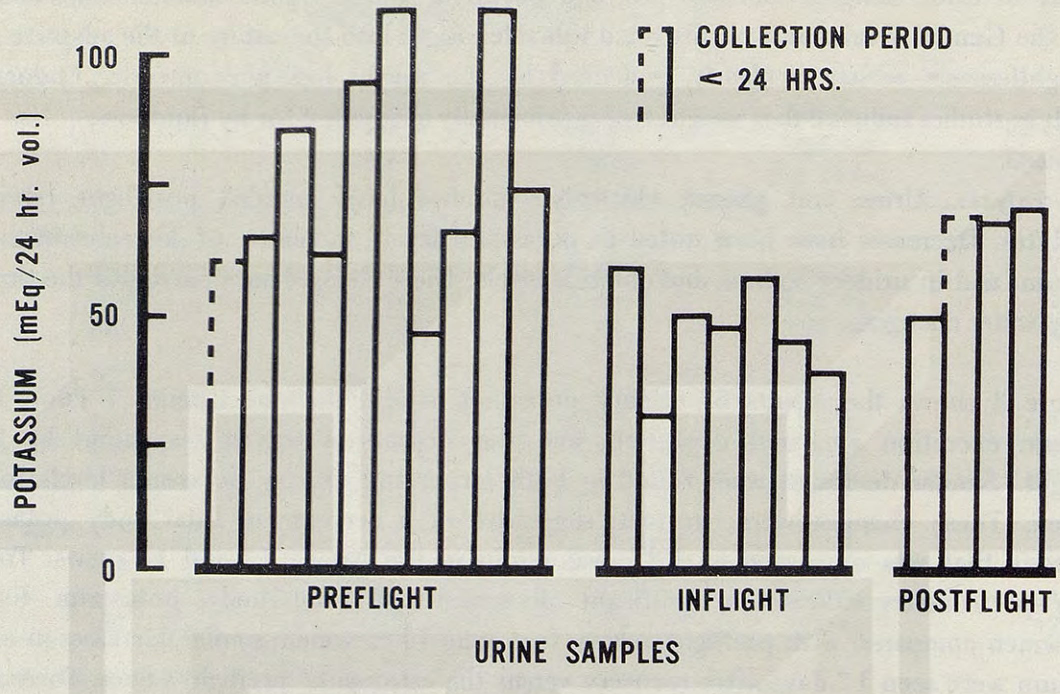

Figure 3. Urine Potassium, Gemini 7 Pilot

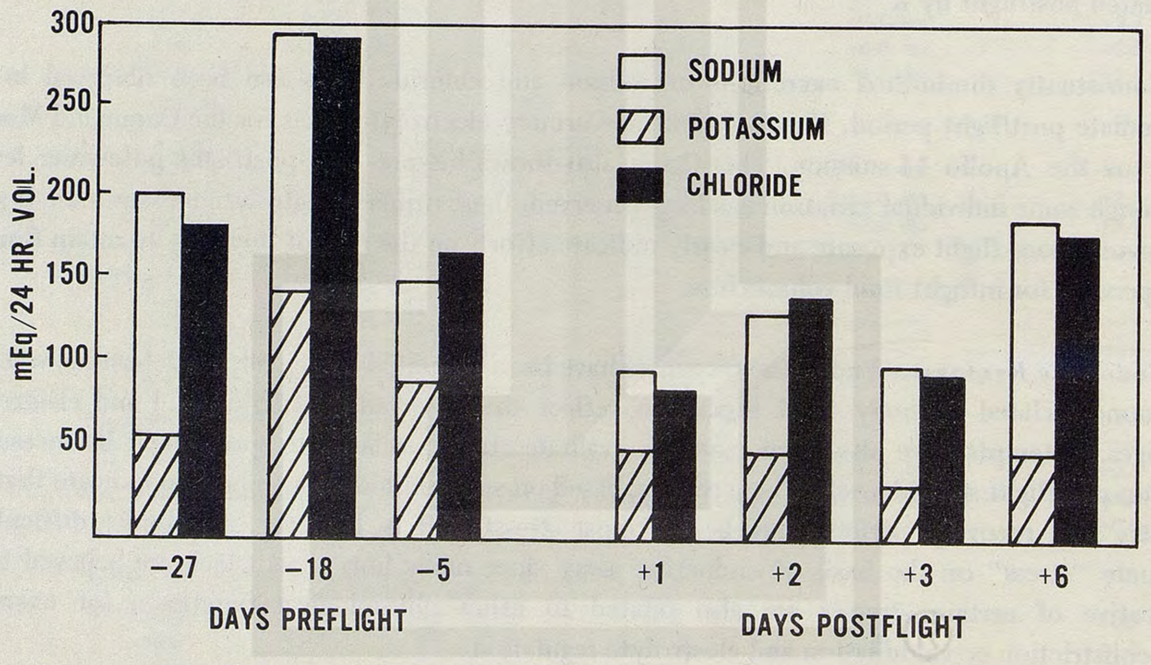

Figure 4. Urinary Electrolyte Levels Pre- and Postflight
for Apollo 14 Command Module Pilot

Pre- and postflight measures of hormones related to electrolyte and fluid balance support the hypothesis that readily recoverable weight losses immediately postflight are primarily the result of inflight water loss. Postflight elevations have been noted for (1) antidiuretic hormone, (2) aldosterone, (3) plasma angiotensin which indicates renin activity, and (4) catecholamines.

Increased levels of antidiuretic hormone, which regulates water resorption through the distal renal tubule, and increased aldosterone levels resulting in resorption of sodium in the proximal tubule are consistent with the electrolyte retention noted and the rapid weight gain postflight. Plasma angiotensin levels, an index of renin activity, show significant increases postflight. Since renin stimulates the adrenal gland to secrete aldosterone upon sensing decreased blood volume or salt concentration (which is uncertain) in the kidney, the elevations in aldosterone levels observed postflight are consistent with cardiovascular and fluid/electrolyte findings. Elevated catecholamine levels may be indicative of a stress response. However, since these hormones are responsible for many metabolic processes, preflight levels must also be taken into account in interpreting the significance of this finding.

Fluid Balance

At least 60 to 70 percent of the weight loss noted immediately postflight is regained by 12 to 24 hours after reentry into the earth's gravitational field. This definitely indicates that water loss is a significant component in overall body weight reduction. Extensive studies have therefore been performed to determine the etiology of these consistently observed negative fluid balances.

Plasma Volume. Plasma volume changes have been observed, but these have been small. Significant decreases in plasma volume were found in the Gemini 4 and 5 missions (13 percent and 6 percent, respectively). On the 14-day Gemini mission, however, no decrease was noted.

Plasma volume decreases after weightless exposure have been variable in the Apollo mission series. They have ranged from virtually no change to an average decrease of 13 percent during the Apollo 8 mission while red blood cell mass for the Apollo 8 crewmembers remained unchanged.

Since the mean weight loss of the crews has been several times larger than the decreases in plasma volume, fluid loss other than plasma loss was occurring and was, therefore, subsequently measured.

Intracellular Versus Extracellular Fluid Loss. Prior to the Apollo 14 mission, it was suspected that extracellular fluid loss accounted for the major part of the total body water deficit. The absence of any significant clinical symptomatology and the small changes in plasma volume both pointed to fluid loss from other fluid compartments. Since vascular and intracellular fluids are typically conserved at the expense of the relatively less critical interstitial fluid, interstitial fluid volume loss was suspected. Results of fluid volume assessments made on the Apollo 14 crew revealed, however, that intracellular fluid accounted for the greater part of total body water deficit. Prior to the mission and at 15 days after the flight, total body water, extracellular fluid, plasma volume, and red blood cell mass were measured by the techniques and with the results indicated in Table 4. Intracellular fluid volume was calculated by subtracting extracellular water from total body water (ICW = TBW – EWC). The astronauts served as their own controls and were also compared with three control subjects who followed the same protocol, except, of course, for space flight.

Table 4

Percentage Change in Body Fluid Volumes
(Preflight Versus Immediately Postflight)

	Measurement Technique	CDR	CMP	LMP	Controls		
RBC	Cr^{51}	−1.7	− 9.1	−4.0	+4.4	−3.5	+ 0.3
Plasma Volume	I^{125}alb.	+1.2	− 9.7	+0.1	+6.0	+6.1	+10.7
Extracellular Fluid	SO_4	−0.5	0.0	−0.5	+4.2	−2.8	+ 3.3
Total Body Water	H_2^3O	−1.9	−17.7	−1.8	+1.6	−2.1	+ 3.0
Intracellular Fluid	(TBW – ECF)	−2.7	−27.0	−2.6	0.0	−1.6	+ 2.9

(Berry, 1971)

The data in Table 4 indicate that extracellular fluid volume remained virtually unchanged for all three Apollo 14 crewmen. The decrease in plasma volume noted in the case of the Command Module Pilot was accentuated by an almost equal loss in red blood cell mass. The total body water deficit for each of the three crewmembers therefore is, as noted, accounted for principally by a loss of intracellular rather than extracellular fluid volume.

Postflight indications of total body potassium deficit on the Gemini 7 and Apollo 13, 14, and 15 missions further support the loss of intracellular fluid. Potassium deficit, however, may also result from the loss of bone minerals and/or muscle mass. Future Apollo missions will examine the fluid shift phenomenon again to confirm the findings of the Apollo 14 mission and to determine to what extent tissue loss is involved in postflight weight losses.

Skeletal Responses

The reduction of mechanical forces on weight bearing bones and muscles in the zero gravity environment can result in a loss of calcium and other related elements. If such losses were to continue unabated over a long period of time, it is conceivable that demineralization, leading to loss of skeletal strength, could ultimately occur. At the present time, however, there is no evidence to indicate that bone mineral depletion increases with increasing space flight duration.

To minimize both muscle and skeletal deterioration during weightlessness, vigorous exercise routines have been adhered to by American astronauts and Russian cosmonauts. During the 18-day Soyuz 9 flight, cosmonauts exercised up to 60 minutes a day employing rubber bungee cords attached from their suits to the space cabin floor to provide increased loads. The exercise levels were apparently great enough for the cosmonauts to report a feeling of "muscular exhilaration" after exercise which lasted the entire work day (Vorob'yev et al., 1970). Similar, but less extensive exercise routines were followed by American astronauts. Despite this regimen, both groups experienced loss of bone mass, with the exception of the Apollo 14 crew.

Losses in bone mass observed in the Gemini and Apollo missions were directly demonstrable using the bone densitometric X-ray technique. Table 5 indicates bone density changes for the Gemini 7 (14-day) crew. When compared with changes observed during bed rest studies, calcium losses for the 14-day Gemini mission were far lower than for the four- and eight-day Gemini missions. An adequate dietary calcium intake (approaching 1000 mg per day) and routine exercise doubtless had a salutary effect on the Gemini 7 crew.

Apollo 14 bone mineral content determinations have not confirmed earlier findings. Pre- and postflight examinations of the left central os calcis and the right distal radius and ulna by means of a monoenergetic photon absorption technique revealed no significant mineral losses during the 10-day mission.

The reason for the divergence of these results is unclear. Mineral balance data have shown a negative balance trend indicative of calcium loss from the bones. Further, although no overall changes in calcium or magnesium levels have been noted, there have been instances of elevated urinary calcium and magnesium. In addition, elevated bound plasma hydroxyproline levels immediately following the 14-day Gemini mission are consistent with resorptive changes in bone matrix. Subsequent mission data will be needed to clarify the reason for the disparity in bone mineral data; it may be simply a matter of improved technique.

One final point regarding reduced bone mineral content should be made. Although functional underloading of skeletal muscle and the decrease in energy expended during muscular work in the weightless state are undoubtedly closely linked to skeletal muscle changes, other possibilities must be taken into account. Biryukov and Krasnykh (1970) suggest that "calcium metabolic mechanisms associated with general impairment in regulatory processes under the influence of space flight stress factors may be involved." These might include the endocrine mechanisms responsible for regulating the general metabolism of the body. It is possible, for example, that calcium ions are mobilized from the bone cation pool in order to correct the electrolyte balance changes occurring in weightlessness. Changes in parathormone and calcitonin levels will be investigated in subsequent missions to further clarify the mechanisms of mineral loss from the bones.

Table 5
Bone Density Changes in Gemini 7
(Percentage Decrease)

	Command Pilot	Pilot
Conventional os calcis scanning section	– 2.91	– 2.84
Overall os calcis involving multiple traces over 60% of bone	– 2.46	– 2.54
Section through distal end of talus	– 7.06	– 4.00
Multiple traces covering hand phalanx 4-2	– 6.55	– 3.82
Multiple traces covering hand phalanx 5-2	– 6.78	– 7.83
Greatest change in any section of os calcis	– 5.17	– 7.66
Greatest change in hand phalanx 4-2	– 9.11	– 8.00
Greatest change in hand phalanx 5-2	–12.07	–14.86

(Mack, Vogt, & LaChance, 1966)

Muscular and Neuromuscular Changes

Muscle, like bone, can reasonably be expected to deteriorate in the absence of gravity and countergravitational effort. Dietrick, Whedon, and Shorr (1948) noted increased urinary nitrogen excretion and muscle atrophy from two to 12.5 percent in the arms and thighs of their bed rested subjects. The muscular system and its neuromuscular correlates have been examined closely after all manned space flights, since these are gravity-influenced systems and therefore likely to be affected by null gravity.

Fourteen days' exposure to weightlessness has not resulted in muscle atrophy or any impairment in coordination (Berry, 1967b). Mineral balance studies for astronauts exposed to two weeks of space flight, however, indicated slightly negative nitrogen balances which persisted postflight despite increased dietary nitrogen intake (Berry, 1967a). After 18 days of space flight, however, the picture apparently differed considerably. Upon return to earth, the Soyuz 9 cosmonauts exhibited significant changes in the motor sphere. They reported that their limbs felt unusually heavy and they had difficulty walking and lifting objects. When in the prone position, they sensed "being pressed" into their beds. On the second to the fifth day postflight, muscle soreness was reported. Muscle tone and strength as well as the circumference of the lower extremities were diminished. Cherepakhin and Pervushin (1970) reported that the reflex excitability of the neuromuscular system, determined by recording the bioelectric activity of the muscles during knee tendon reflexes, was increased.

Cherepakhin and Pervushin (1970) also surmised that the principal cause of decrease in muscle tone during 18 days of space flight was weightlessness *per se*. Since this condition makes it unnecessary to maintain anti-gravity posture, postural muscle tone is reduced. This cause/effect relationship, these investigators suggest, is confirmed by the fact that those muscle groups subjected to a lesser inflight load show the greatest degree of decremental change. Shoulder muscle tone in the Soyuz 9 crew was somewhat improved postflight, but lower leg and hip tone decreased significantly. "Since neuromuscular tone plays an important part in regulating many body functions," they contend, "deterioration of tone following exposure to weightlessness plays an important part in determining the characteristics of the readaptation period. Apparently, too, the longer the space flight the more stressful will be the adaptation to earth's gravity."

Exercise is undoubtedly helpful. This seems to be particularly true if the exercise is coupled with a temporary exposure to a partial gravity field. The lunar explorers of the Apollo 14 mission showed far less degradation of gravity-influenced physiological systems than have those astronauts who have not been exposed to one-sixth gravity. Exposure to artificial gravity supplied intermittently by a centrifuge or some other means might provide the answer. Other preventive techniques require further exploration. Drugs have not yet in our experience proved effective but this avenue might still be fruitful to pursue.

Work Capacity

In assessing the physiological cost of manned space flight, it is essential to determine to what extent the many factors inherent in the weightless environment affect the capability to do physical work. Significant deterioration in physical work capacity is a phenomenon noted in individuals subjected to bed rest. For this reason, exercise capacity tests are routinely performed following space flights.

A reduction in work capacity has been noted following all missions in the Gemini and Apollo series. For the most part, work capacity tests have employed an electronic bicycle ergometer capable of producing a fixed workload. The load is increased in regular increments until elevated heart rates, usually 160 or 180 beats per minute, are reached. Table 6 shows decrements in terms of oxygen consumption during these tests for Apollo 7–11 crewmen immediately postflight. All these crewmen exhibited a significant reduction in the ability to utilize oxygen, and consequently in their capacity to perform work. Postflight quarantine requirements precluded obtaining work capacity data for the Apollo 12 and 13 crews but, with the elimination of this requirement, the evaluations were reintroduced with Apollo 14.

Table 6

Apollo Exercise Response Test – Oxygen Consumption Immediately Postflight

Heart Rate, bpm	$\bar{X}$, Percent*	σ	No. of Subjects
120	68.6	15.2	15
140	74.5	11.6	15
160	77.8	10.8	15
180	77.0	8.1	3
Over all	73.8	12.7	48

*100 percent = mean of three preflight measurements. (Berry, 1969)

Table 7 shows oxygen consumption and systolic blood pressure changes for the three Apollo 14 crewmembers. It is interesting to note that the pattern found in earlier flights no longer obtains.

Table 7

Work Capacity Indicators for Apollo 14 Crew

		O_2 Consumption/ 160 H. R.	Percent of Preflight	Systolic Blood Pressure/160 H. R.	Percent of Preflight
CDR					
	Preflight	2.40 l/min.	103	233 mm Hg	102
	R + 0	2.48		238	
LMP					
	Preflight	3.05	94	225	92
	R + 0	2.86		207	
CMP					
	Preflight	2.40	75	216	72
	R + 0	1.81 ↓		156 ↓	

↓ = statistically significant decrease. (Berry, 1971)

While a significant reduction in work capacity was exhibited for the Command Module Pilot, only minimal change was noted for the other two crewmembers. It is logical to presume that the absence of the previously noted reduction in work capacity for these two crewmen might be attributable to the moderate work conducted by these men in one-sixth gravity during their lunar stay.

Results of the Apollo 15 mission, while still under evaluation, appear to show a reversal of the findings for Apollo 14. The two Apollo 15 crewmembers who worked on the lunar surface showed a considerably greater reduction in work capacity than did the member who orbited the Moon. It is possible that the greatly increased work activities of the Apollo 15 crew negated the apparently salutary effects of operating in one-sixth gravity noted for the Apollo 14 crew.

The Nature of the Adaptive Response: An Hypothesis

Much information has been gained in American biomedical programs concerning the effects of space flight on man. A number of consistent findings have been observed: some imply a possible alteration of the structure of physiological systems while others indicate merely a change in capacity. These changes, while dealt with as discrete events, undoubtedly are individual elements in a basic adaptive response of the human organism to the unique stresses of space. Sufficient information is presently available to begin to piece together at least a tentative hypothesis concerning the nature of the adaptive process and the manner in which the various changes may be interrelated.

Table 8 is a greatly simplified illustration of the hypothesis now being developed and shows the major classes of body response during the period of adaptation. Figure 5 presents the same hypothesis in diagrammatic form. In each case, the part of the hypothesis presented is that intended to describe factors influencing fluid shifts within the body.

The immediate response of the body upon initial entry into weightlessness is a redistribution of the total circulating blood volume. The increase in right atrial filling of the heart is interpreted by the body as a need to reduce total fluid volume which it does by increased urination. This event is governed by a decrease in antidiuretic hormone and a decrease in aldosterone production. This results in a loss of water, sodium, and potassium through the kidneys with a resulting loss in total body weight. The concomitant decrease in plasma volume tends to reverse the initial aldosterone decrease. The body has now entered a phase of electrolyte and fluid imbalance in which sodium retention increases while potassium loss continues. Intracellular fluid and potassium loss results in a cellular acidosis with a mild (compensated) hypokalemic alkalosis of extracellular fluids.

Table 8

Overview of Current Hypothesis Concerning Processes Involved in Man's Adaptation to Zero Gravity

Event	Response of Body
Entry into zero gravity. Redistribution of circulating blood volume.	Body attempts to reduce volume. ADH decreases, aldosterone production decreases.
Loss of water, sodium, potassium (loss of body weight).	Decrease in plasma volume. Aldosterone increases (secondary aldosteronism).
Increased sodium retention. Potassium loss continues. Cell: acidotic — extracellular fluid: alkalotic.	Intracellular exchange of potassium and hydrogen ions. Decrease in bone density, muscle cell potassium, and muscle mass; possibly including cardiac muscle.
Respiratory and renal compensation. Halt to weight loss trend.	Stabilizes with new effective circulating blood volume. New body fluid and electrolyte balance or "set."

In essence, it is hypothesized that the response of the body to lowered total body potassium is an intracellular exchange of potassium for hydrogen ions. Associated with the potassium deficit is a decrease in bone density and muscle mass. Loss of cellular potassium might possibly include heart muscle with resultant increased irritability and tendency toward disorders of cardiac rhythm.

In the final phase of this adaptation loop, the hyperacidity of the cell stimulates the respiratory system to decrease plasma carbon dioxide by increasing the ventilatory rate. Renal compensation commences as the renal tubules begin to reabsorb potassium. The body weight now stabilizes at a new equilibrium point. This part of the body's overall adaptation process now becomes complete. The new equilibrium establishes an optimal total circulating blood volume or "new load" on the cardiovascular system and a new fluid and electrolyte balance state. It is reasonable to presume that the new stabilized condition is appropriate for long-term performance under space flight conditions.

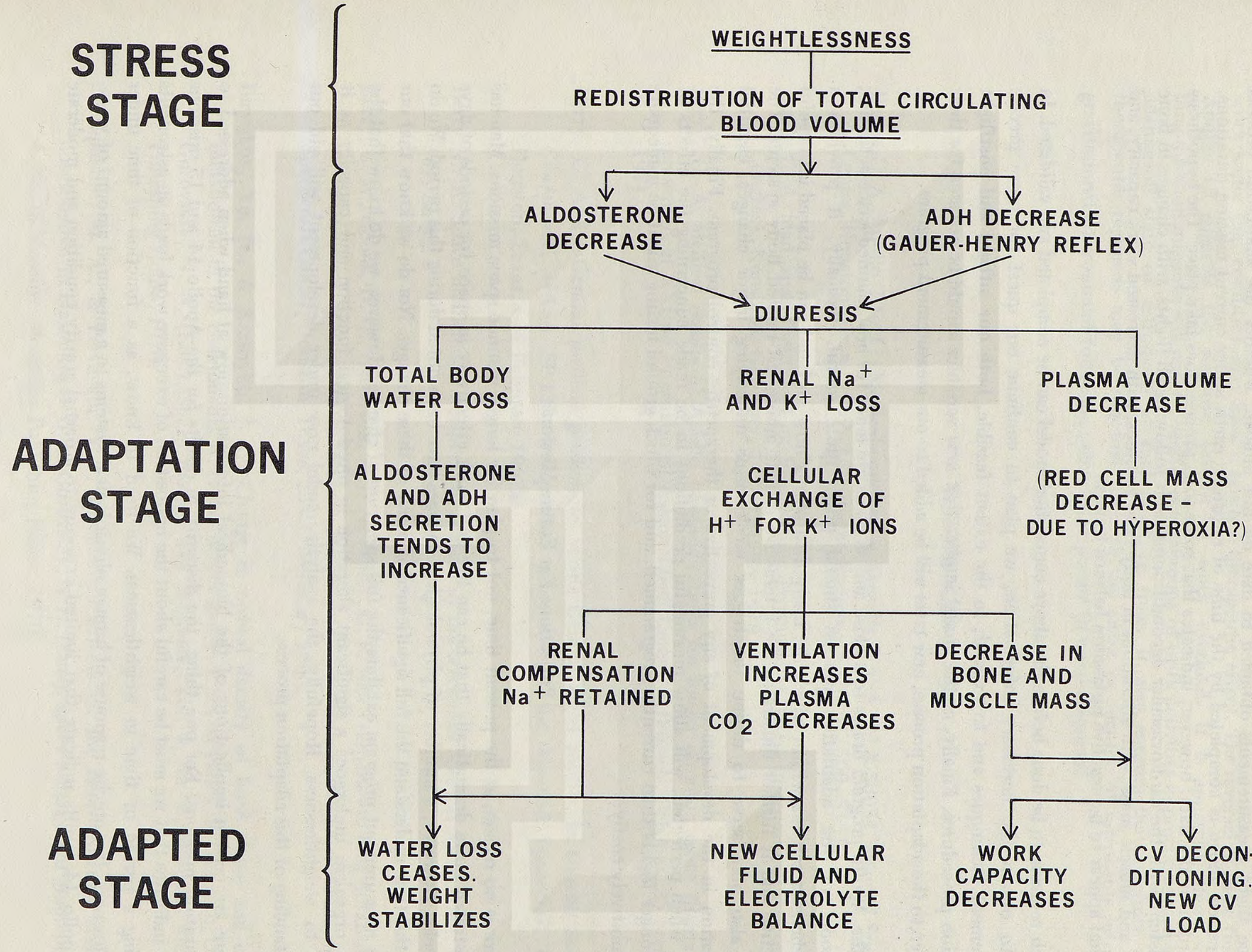

Figure 5. Diagram of the Hypothesized Course of Adaptation to Weightlessness
(Adapted from Leach, Alexander, and Fischer, 1970)

Space flight measurements obtained to date do not indicate whether the adaptation process hypothesized above is completed by the time of return to earth under current mission durations. The burden of the data, however, indicates that some such process does take place. The hypothesis is consistent with the cardiovascular deconditioning seen following all flights, with changes in bone density and muscle mass, with alterations in body fluid volumes, with decreased work capacity, and with what appear to be negative potassium balance trends.

Much remains to be done before the above conceptual model can be completed and validated. In order to obtain the necessary information, we plan to continue our quest for more precise measurement techniques and to expand, to the extent feasible, both our inflight and postflight evaluation procedures. Finally, as the model implies that new variables should be assessed for their relevance to the adaptation process, new tests will be added to our measurement program.

As the Apollo program draws to a close and as plans are made for new manned space activities, the model of the adaptation process should prove quite useful. Basically, it provides a comprehensive schema within which the many data points now on hand can be placed into useful perspective and it further illustrates the interactive effects among all related body systems. The model also may serve to define the trigger mechanisms underlying major changes, essential information in the development of any preventive or therapeutic control program. Finally, the model, when perfected, will allow meaningful predictions to be made concerning the effects of much longer flights than currently programmed, and for which ground testing might be inadequate or prohibitively costly.

Projections For Future Missions

There is no reason, at the present time, not to plan for longer manned space missions. Man has demonstrated quite dramatically that he can live and work effectively in space for periods of days and weeks. However, a number of physiological changes have been noted during this period. We do not at this time understand the full significance of many of these changes. Nor do we know that our current measurement program exhibits the full spectrum of change. However, we do know that the human organism undergoes a significant alteration in physiological function and capacity as it adapts to weightlessness. Hopefully, the analytic model now under development will aid our understanding of this adaptation process.

There are certain implications of the biomedical information now at hand when addressed to long-duration missions. For one thing, the disparity in results for the Apollo 14 and 15 missions clearly indicates that we must be careful about the imposition of excessive work loads on astronauts following a period of time in weightlessness. We need to know, as a function of time under weightlessness, the precise response of human physiological systems to a measured amount of work. The Apollo 14 results indicate that limited exposure to a partial gravity condition and moderate work under that condition may have a positive therapeutic effect. The reversal of these findings in Apollo 15 suggests the negative benefit of work overload. It is apparent, therefore, that long-duration missions will require careful programming of work activities in precise accord with the adaptation state of astronauts at that point in time. It also appears that carefully planned therapeutic regimens may be required prior to the entry or reentry of astronauts into a new gravitational environment following extended exposure to weightlessness.

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