THE MEDICAL LEGACY OF APOLLO

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Paper Presented At

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Introduction

To reach for the Moon in 1961, when man's total orbital flight time was less than two hours, and to specify that it should be gained "before this decade is out," was to strive for the near-impossible. The vehicle for this achievement was to be the Apollo spacecraft, and it served its purpose well. The Apollo Program placed twelve men on the moon, leaving them there for a total of over four man-weeks, and returned all of them safely to earth.

While the Apollo Program now is viewed as one of the greatest engineering and scientific successes of man, there were many moments of uncertainty as new procedures were used and new systems tested. No one who followed the progress of Apollo 8 will forget the tension while awaiting word that the critical lunar orbit insertion had been achieved by firing of the SPS engine while the craft was on the far side of the moon. The sound of "OK, Houston" as Apollo 8 reappeared symbolized the triumph of both man and machine over the great unknown of space.

Indeed, at the beginning of the space program, it is my impression that there were more dire predictions concerning the ability of man to withstand the stresses of space than there were concerning the capabilities of our engineers to build the necessary systems. There was great concern, as is well known, over the ability of the heart to endure the sustained acceleration forces and other stresses of launch. Early tests indicated the heart rate would go to 180 beats per minute, and quite possibly higher, under such conditions. These rates could be a precursor to fibrillation, according to some cardiologists, and recommendations were made that man not be exposed to such obvious risks. Concern over this issue was such that final approval for the launch of John Glenn on the first U.S. orbital flight was delayed until almost the last moment. As it turned out, there was no real problem here, as proved to be true for so many of the other early predictions concerning man's reaction to space. The greatly increased heart rate at launch, and at other critical points in mission profiles, now appears to be a perfectly normal feature and one which in no way impairs the ability of an astronaut to perform.

Many of the early biomedical preconceptions and questions concerning man were answered during the Mercury and Gemini flights. Project Mercury's indispensable legacy was the knowledge that man could survive in space. These missions also proved that he could do useful tasks. The legacy of Gemini was in many respects an even richer one. The 14-day Gemini flight clearly demonstrated that weightlessness caused changes in man. Cardiovascular system changes and bone density changes were just two findings that signaled that the world of zero gravity profoundly affected the human. The Gemini missions also provided a fund of knowledge concerning the measurement of physiological change at a distance. But at the end of the 2,000 man-hours of Gemini, we were faced with two imponderable problems. First, because the number of individuals involved was small, one could not tell whether genuine space-related phenomena were being observed or whether the changes reflected individual variations. Second, if the changes seen were genuine responses to the space environment, one could not say whether they represented the beginning of downward trends, whether they would level off in time, or whether, perhaps, they would be cyclic. This was Gemini's legacy to Apollo and it became the task for the Apollo Program to search for answers.

The Apollo Program provided an opportunity to gain biomedical information in a more orderly manner than was true with Gemini. More definitive data now could be obtained as to man's performance during what could be termed a real space "voyage" and while operating from a more habitable space vehicle. The biomedical information returned from Apollo missions has allowed us to progress significantly toward a detailed scientific description of the behavior of man in space and to describe in some detail the physiological changes which occur.

In order to understand the manner in which Apollo has in turn left us its invaluable medical legacy, it is necessary to review briefly the Apollo mission and the requirements and stresses imposed on Apollo astronauts.

Apollo Environment

Apollo Spacecraft

The Apollo Command Module served as control center and provided living quarters for the three-man crew. It was spacious in comparison to earlier spacecraft, extending almost twelve feet from nose to heat shield and providing 210 cubic feet of operating space. Added to this were the 235 cubic feet of space of the Lunar Module. This contrasts significantly with the 55 cubic feet in which the two-man crew of a Gemini vehicle lived and worked, and the 47 cubic feet of a Mercury capsule. Figure 1 compares the volume of the three manned space vehicles used to date.

The Apollo Command Module, in addition to being much larger than the other two vehicles, afforded still further opportunity for movement when the Lunar Module was first mated to the Command Module for the Apollo 9 mission. For the first time, with the Apollo 9 mission, astronauts were able to move about inside two spacecraft by traversing the tunnel connecting them. Because the Apollo spacecraft was so much larger than earlier craft, astronauts could move freely using no restraints; they could stand and tumble and exercise. Further, with lunar landings, transitions from zero gravity to one-sixth gravity, and back again, were possible. This, as will be discussed in greater detail, may not be without influence on the gravity-dependent otolith apparatus (Berry & Homick, 1973).

The interior of the Command Module contained three couches in which astronauts rode during launch and reentry and in which they slept. The couches were positioned so as to allow the astronaut to withstand reentry accelerations that reached as high as 7 G in Apollo 16. The couches faced the main display console, nearly seven feet long, which contained all displays and controls of the vehicle. The atmosphere was 100 percent oxygen at 5 psi pressure during flight but, in order to reduce fire hazard during launch preparations, was a less flammable 60/40 oxygen/nitrogen mixture at 15 psi during ground tests and countdown. Through a controlled bleed-off process, this was gradually reduced after launch to the normal flight atmosphere. Usual temperatures inside the Command Module were 21 to 24°C.

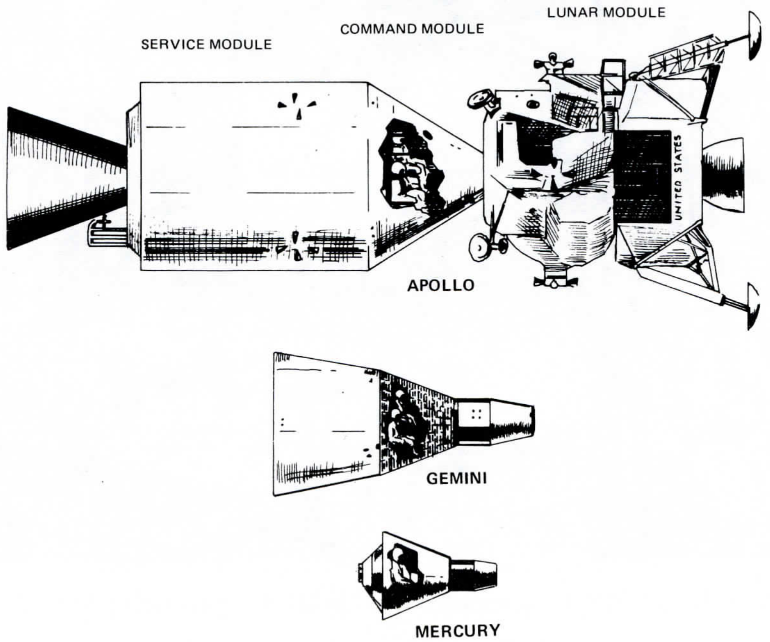

Figure 1. Comparison of Mercury, Gemini, and Apollo Command Module volumes.

The Lunar Module transported two astronauts on each lunar surface mission to and from the Command Module in lunar orbit and provided living quarters and a base of operations on the moon. The LM had essentially the same subsystems as the CSM, including the environmental control, communications, reaction control, and guidance control systems. The volume of the cabin, seen in Figure 2, was sufficient to permit the astronauts to remove pressure suits and to sleep in relative comfort in hammocks while on the moon.

Apollo Space Suits

Two versions of the Apollo space suit were used. The Command Module Pilot version was worn during intravehicular operations in the Command Module and during extravehicular operations as film was retrieved during trans-earth coast (Figure 3). The extravehicular version was worn by the Commander and Lunar Module Pilot for lunar surface EVA's (Figure 4). Both versions of the suit had a central portion called a torso limb suit assembly consisting of a gas-retaining pressure bladder and an outer structural restraint layer. These suits were constructed for a 3.5 psi operating pressure. The integrated thermal meteroid garment worn by the Commander and the Lunar Module Pilot during lunar activities contained a total of eighteen layers of different materials.

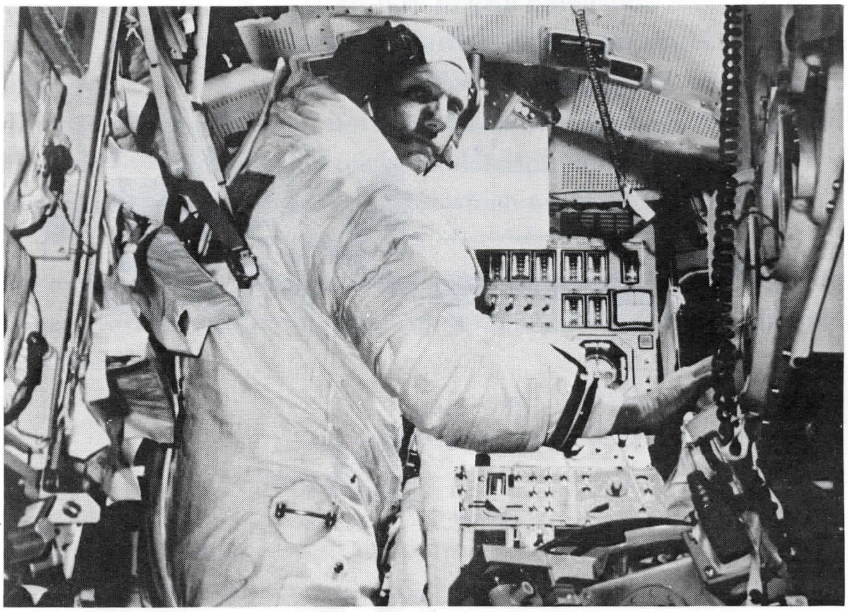

Figure 2. Neil Armstrong, Commander for Apollo 11, practicing lunar landing control.

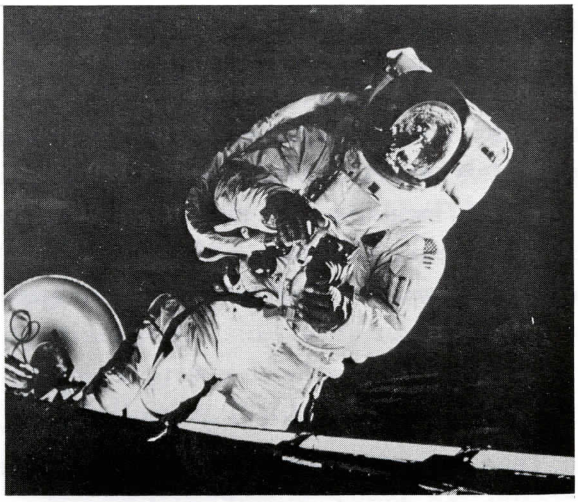

Figure 3. Apollo space suit worn by Command Module Pilot.

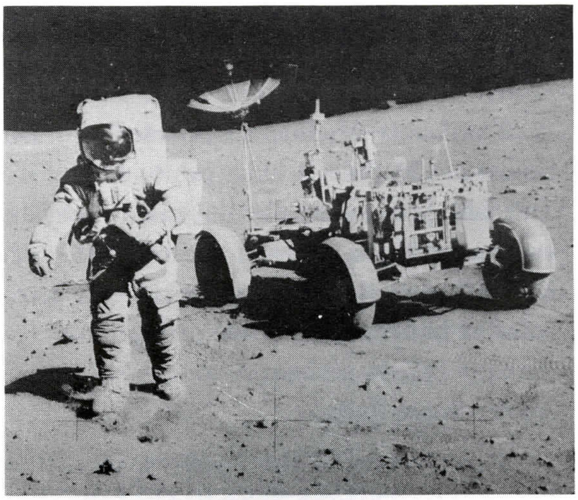

Figure 4. Apollo space suit worn during lunar surface exploration.

The space suit, liquid cooling garment, portable life support system, oxygen purge system, lunar extravehicular visor assembly, gloves, and lunar boots made up the extravehicular mobility unit (EMU) worn as astronauts carried out lunar explorations. The EMU provided an extravehicular crewman with life support for a seven-hour mission outside the Lunar Module without replenishing expendables.

Mission Parameters

Apollo missions were a new order of event in space travel, much expanded in purpose and complexity from any that had taken place before. The missions, which lasted for nearly 14 days, in the case of Apollo 17, required many changes in flight path, reconfiguring of the space vehicle as the position of the Lunar Module was changed, docking while in lunar orbit, and, most critically, a descent to and ascent from the surface of the moon. The total voyage, for Apollo 11, covered 952,700 miles (11,533,225 km). During the trips, astronauts were subjected to deceleration forces as high as 7 G. They also entered regions of possible increased radiation, a cause of some initial concern. However, as shown in Table 1, the measured radiation doses in general were quite low and none was considered to be of hazard or biological significance.

Table 1

Crew Radiation Exposure for Apollo Missions

	RAD		RAD
Apollo 7	.16	Apollo 13	.24
8	.16	14	1.14
9	.20	15	.30
10	.48	16	.51
11	.18	17	.55
12	.58		

Spacecraft Systems

Food Service

The provision of food was given increasing attention as the United States space program developed until, by the conclusion of the Apollo Program, more than 110 different items were included on astronauts' menus. Both the food and the service techniques in Apollo were significantly better than those used during earlier programs. The balanced menus provided approximately 2,500 calories per man per day. Each menu was designed to supply the following specified daily levels of nutrients (Berry & Smith, 1972).

Nutrient	Daily Requirement
Protein	90 to 125 g
Calcium	750 to 850 mg
Phosphorus	1500 to 1700 mg
Sodium	100 to 200 mEq
Potassium	135 to 145 mEq
Magnesium	300 to 400 mg

Food packages were assembled into man-meal units for the first ten days of a mission. Items similar to those in the daily menu were stowed in a pantry fashion, giving the crew a variety of food choices for later meals, snacks, and beverages and menu substitutions. No attempt was made to exercise rigid control over food intake other than to see that balanced meals were provided.

Various types of food were used. These included freeze-dried rehydratables in spoon-bowl packages; thermostabilized foods (wet packs) in flexible packages and metal easy-open cans; bite sized cubes either dried or containing some moisture, and a variety of beverages. Figure 5 illustrates Apollo food items.

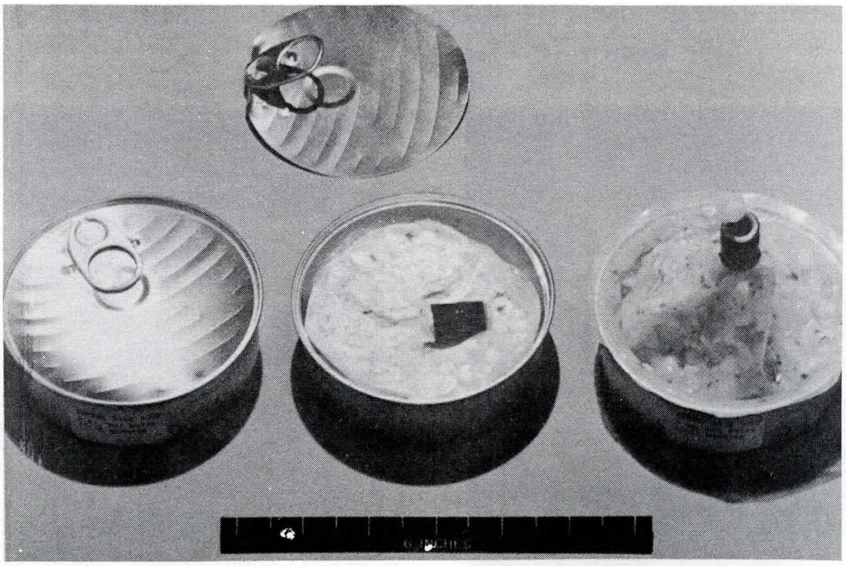

Figure 5. Apollo food packaged in metal easy-open can.

Water for drinking and rehydrating foods was obtained from two sources in the Command Module. A portable dispenser was used for drinking water and a water spigot was used at the food preparation station which supplied water at approximately 145° and 55°F. The portable water dispenser provided a continuous flow of water with the trigger held down, while the food preparation spigot dispensed water in one-ounce increments.

The Lunar Module was equipped with a continuous flow water dispenser similar to the one in the Command Module except that only cold water was provided.

Prescribed amounts of water were injected into food pouches with a pistol-dispenser. The package then was kneaded and allowed to sit for several minutes. Some foods were squeezed through the tube directly into the mouth; for others, the bag top was cut open and the food eaten with the spoon. After the meal, germicide tablets were placed in each bag to prevent fermentation and gas formation. The bags then were rolled and stowed in waste disposal areas in the spacecraft.

Personal Hygiene/Waste Management

Facilities aboard the Apollo spacecraft for personal hygiene were, frankly, primitive. In this area, technology lagged seriously. However, the motivation of Apollo astronauts overcame the hardships of dealing with the systems. The issue was one of ensuring that personal hygiene facilities were as adequate as feasible and that a level of personal cleanliness could be maintained. The Apollo system met these criteria and provided minimal hygiene maintenance that was adequate for the short durations of the missions.

The personal hygiene equipment included a toothbrush and tooth paste, a wet-wipe cleansing towel, dry towels, and tissue dispensers. Shaving supplies were provided and Apollo astronauts discovered that it was a surprisingly simple matter to shave with lather and a safety razor in weightlessness (Figure 6).

Solid body wastes were collected in plastic bags containing a germicide to prevent bacteria and gas formation. The bags were sealed after use and stowed in empty food containers for postflight analysis. Apollo urine collection devices were provided for use with either the inflight coveralls or the EVA pressure suit. With the suit, the system can collect up to 950 cc of fluid at rates up to 30 cc per second. Stored urine can be transferred through the suit wall by a hose to the Command Module or Lunar Module during pressurized or depressurized cabin operations. The urine was dumped overboard through the spacecraft urine dump valve in the Command Module and was stored in the Lunar Module. In Apollo 17, the urine was collected by means of a Biomedical Urine Sampling System for later analysis.

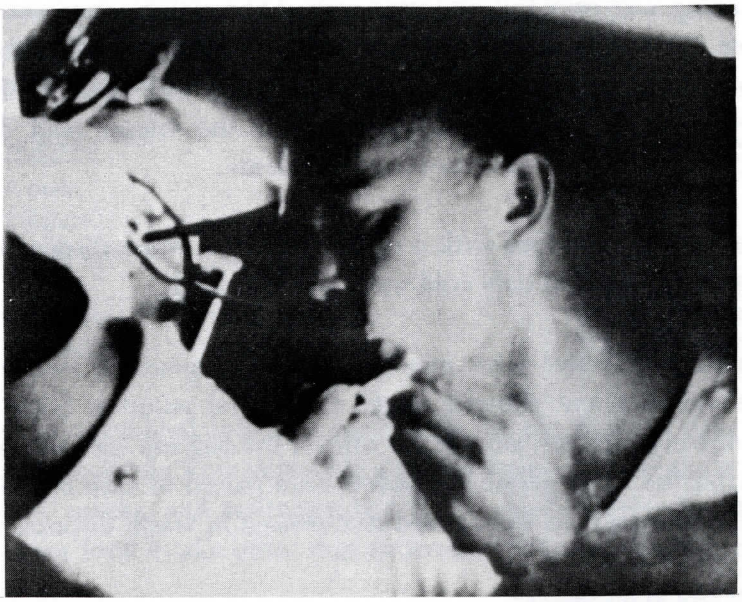

Figure 6. Astronaut Michael Collins shaving on Apollo 11 after almost eight days in space.

Medical Kit

Each Apollo vehicle carried a medical accessory kit stowed in a compartment behind the Lunar Module Pilot's couch. Contents of this kit were reviewed for adequacy following each flight, with appropriate modifications made for the next flight corresponding to changes in mission requirements. Therefore, there was no "standard" medical kit. However, the basic ingredients remained the same for each flight. An abbreviated version of the Command Module kit was carried in the Lunar Module. Table 2 lists the Lunar Module medical kit contents. Note the addition of antiarrhythmic drugs. These were stowed on Apollo 16 and 17.

Bioinstrumentation System

Each Apollo crewman wore a biosensor harness which provided a means of transmitting critical physiological parameters to the ground in real time. Through this system, medical personnel were able to evaluate physiological performance during such critical phases as launch and docking, EVA, and lunar explorations. This real-time telemetry of vital biomedical information also allowed medical personnel to monitor Apollo crewmen in the event of inflight illness.

The operational bioinstrumentation system was designed as an individually adjustable unit worn beneath flight clothing. The biobelt assembly was an electronic system that included sensors, signal conditioners, and telemetry interfaces. The system returned the following data by means of telemetry:

1. Electrocardiogram
2. Heart rate
3. Respiration rate

Table 2
Medications in Lunar Module
Medical Kit – Apollo 17

Medical Package Assembly	Quantity
Rucksack	1
Stimulant pills (Dexedrine)	4
Pain pills (Darvon)	4
Decongestant pills (Actived)	8
Diarrhea pills (Lomotil)	12
Aspirin	12
Band aids	6
Compress bandages	2
Eye drops (Methylcellulose)	1
Antibiotic ointment (Neosporin)	1
Sleeping pills (Seconal)	6
Anesthetic eye drops	1
Nose drops (Afrin)	1
UCTA roll-on cuffs	6
Pronestyl	12
Injectable Drug Kit	
Injectable drug kit rucksack	1
Lidocaine (cardiac)	8
Atropine (cardiac)	4
Demerol (pain)	2

Data from the biotelemetry of the spacecraft were displayed at special consoles at the launch control center, Kennedy Space Center, and at mission control, Johnson Space Center. The consoles were manned continuously by medical personnel during the course of the mission. Heart rate and respiration rate were displayed in digital form with the wave form of the electrocardiograph presented on a cathode ray tube. With telemetered data and voice information, all supplemented by direct readout of environmental parameters, the mission Flight Surgeons were able to make real-time, realistic assessments of the physiological and psychological state of the astronauts.

Biomedical Evaluation

At the close of the Apollo Program, 7,508 man hours had been logged in space over and above the hours Mercury and Gemini astronauts had spent in weightless space flight. Table 3 summarizes the man-hours in Apollo missions, including the number of hours spent by Command Module Pilots alone in lunar orbit. It became clear as a result of this experience that exposure to the space flight environment causes definite, quantifiable physiological effects. None of these changes, however, has been permanent, and none has been sufficiently debilitating or serious to engender any real doubts about the advisability of committing man to space flights of longer duration.

Table 3

Man Hours in Apollo Space Flight

Total man hours	Time	
(Apollo 7 thru 17)	7508 Hrs	03 Min
Total man hours EVA in zero g		
(Apollo 9, 15, 16, 17)	3	45
Total man hours EVA in 1/6 g		
(Apollo 11, 12, 14, 15, 16, 17)	161	02
Total man hours alone in CSM		
Apollo 11 - Collins	31	38
Apollo 12 - Gordon	42	00
Apollo 14 - Roosa	42	50
Apollo 15 - Worden	75	40
Apollo 16 - Mattingly	85	45
Apollo 17 - Evans	87	40
TOTAL	364 Hrs	33 Min

General Adaptation to Null Gravity (Weightlessness) and to Lunar Gravity

In general, Apollo astronauts adapted well to the world of zero gravity. It was, in many respects, a boon. Astronauts were able to move effortlessly about the spacecraft. Moreover, this enhanced locomotion subjectively increased the volume of the spacecraft. Apollo astronauts have commented that the Command Module which seemed rather cramped during ground tests was much more comfortable inflight because of the increase in usable space effected by zero gravity.

The most frequently reported subjective sensation associated with initial orbital insertion is a feeling of fullness of the head. All Apollo crewmen with the exception of the Apollo 16 Command Module pilot reported experiencing this sensation. The outward manifestation which accompanied this feeling was a roundness of the face. This was verified photographically, and crewmen noticed it in one another (Figure 7). Roundness of the face was sometimes but not always accompanied by a puffiness under the eyes that caused some crewmen to squint slightly. A redness of the eyes was also noted in some astronauts. The Apollo 13 Lunar Module Pilot reported experiencing a feeling of "hanging upside down" accompanying the fullness of the head sensation. These symptoms lasted for widely varying lengths of time. Generally, the fullness of the head sensation lasted from one to three days after liftoff. The appearance of a rounded or swollen face persisted throughout most flights, and was apparently an alteration of physiognomy due to the absence of the accustomed effect of the downward pull of gravity on the facial features. The Apollo 12 crew noted that their shoulders tended to assume a squared off, or raised, position rather than being sloped as they normally were.

Figure 7. Astronaut Neil Armstrong during Apollo 11 mission.

Crews rather consistently reported a discomfort or soreness of the lower back muscles. This was attributed to changes in posture during weightlessness and was sufficiently distressing to disrupt the sleep of some astronauts.

Sleep

When one considers the unfamiliar environment of space and the excitement of being in that environment and when these things are coupled with noises and other disturbances peculiar to the spacecraft, it is more surprising to find that Apollo astronauts obtained restful sleep than it is to find that their sleep was disrupted. The sleep periods during the Apollo 7 mission were staggered to permit one crewmember to stand watch. The crewmen never adjusted to this arrangement and never obtained restful sleep. One crewmember, in fact, fell asleep on his watch and dextroamphetamine sulfate had to be prescribed for another to enable him to remain awake during his work period. Apollo 8 crewmembers also followed work/sleep cycles that differed greatly from those which they had followed during the preflight period. Despite the fact that sleep period scheduling was a crew option, the shift in schedule led to fatigue and was associated with minor procedural errors. The Lunar Module Pilot also required secobarbital regularly for sleep.

The quality of sleep improved on the Apollo 9 mission when all crewmembers slept simultaneously. However, during lunar stays, the quality of sleep again deteriorated. Crews have reported the Lunar Module environment to be too noisy and the space suit too cold to permit adequate sleep. The Apollo 14 lunar surface crew had great difficulty sleeping because of anxiety produced by a starboard list of their Lunar Module which had landed on uneven lunar terrain. Most lunar surface astronauts had similar difficulty obtaining restful sleep and, in some cases, this necessitated the prescription of a sleeping medication.

Displacement of the terrestrial sleep cycle during lunar surface activity disrupted sleep for the Apollo 15, 16, and 17 crews. The problem was compounded for the Apollo 15 crew by operational problems, notably a cabin oxygen leak in the Lunar Module which required attention. While the displacement of the terrestrial sleep cycle for the Apollo 16 crew contributed to some loss of sleep, heart rate data obtained during sleep, when compared to preflight heart rates during sleep, indicated that this was the first lunar surface crew to obtain adequate sleep. Likewise, the Apollo 17 crew slept well despite displacement of the sleep cycle and changes in the flight plan which impacted sleep periods. To aid sleep, the Apollo 17 crew were given sleeping medications and used sleep restraints.

In summary, a certain amount of difficulty in sleeping has been experienced by Apollo crewmen. While weightlessness has contributed to this difficulty, it is principally a result of shifts in accustomed sleep periods, and presumably circadian rhythms, and of operational problems and workloads. Crews found it possible to obtain restful sleep with the aid of sleeping medications but emphasized the importance of programming an eight hour sleep period each day. Inflight monitoring of sleep patterns by electroencephalographic and electrooculographic recordings during the Skylab mission undoubtedly will help to clarify the effects of weightlessness on sleep.

Exercise

The planned exercise program for Apollo crews included isometric and isotonic exercises and the use of an exercise device. This was a simple, stretchable, rubberized device with handholds. While the device was not popular with many crewmembers, the Apollo 11 Lunar Module Pilot exercised vigorously with it for two ten-minute periods. The device was sufficiently effective to raise his heart rate to 170 and 177 beats per minute. The Apollo 12 crew used this device for 15 to 30 minutes. The Apollo 14 crew reported that exercise provided relief for the lower back discomfort reported by many crews during weightlessness. The Apollo 17 crew experimented with a novel exercise approach. They did what was effectively running in place by holding the struts of their couches and bracing themselves so that they were able to run in place against the floor. One crewmember performed this exercise so vigorously that he perturbed the spacecraft. This type of exercise proved to be relatively effective. Overall, however, Apollo crews were exercise deficient. As a result of their experience, the Skylab Orbital Workshop has been provided with a bicycle exercise device for both experimental purposes and for the provision of rigorous exercise. This increased exercise level should help to maintain muscular tone and this may aid in reducing the level of cardiovascular deconditioning noted.

Metabolism and Nutrition

Only indirect methods were available for estimating metabolic expenditures for Apollo crews. Inflight metabolic costs were inferred by determining the total production of carbon dioxide for a crew through analysis of the lithium hydroxide canisters carried onboard for carbon dioxide removal. Metabolic rates during lunar surface activities were determined by a number of methods, the best of which proved to be monitoring the inlet and outlet temperatures of the liquid cooling undergarment. The average hourly lunar surface energy production ranged between 900 and 1200 BTU's.

While the techniques used to determine metabolic expenditures were gross, they seemed to indicate that the diet provided for Apollo missions was more than adequate. Balanced diets of approximately 2500 calories per man per day were provided. On the whole, however, Apollo astronauts experienced less hunger inflight than on the ground, particularly in the early periods of weightless flight, and they tended to have hypocaloric intakes when compared with their energy requirements as established preflight.

All Apollo crewmen with the exception of the Apollo 14 Commander lost weight inflight. Table 4 shows the weight changes experienced by the crewmen. Weight loss ranged from one to twelve pounds and averaged about six pounds. Some of this weight loss can be attributed to changes in total body water associated with weightlessness-induced electrolyte changes. The remainder is tissue loss. The deficit in energy requirements resulting from the hypocaloric intakes, approximately

22 kilocalories per kilogram per day inflight versus 35 kilocalories per kilogram per day in ground controls, was made up by metabolizing fat and muscle.

Table 4

Weight Changes for Apollo Astronauts

	Weight Loss	Percent Change	Weight Regained (R + 24 hr)	Percent Change
Apollo 7				
CDR	– 6.3 lbs	–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
Apollo 16				
CDR	–7.5 lbs	–4.3	+3.5 lbs	+2.0
CMP	–6.5 lbs	–4.0	+3.0 lbs	+1.9
LMP	–5.5 lbs	–4.1	+2.5 lbs	+1.8
Apollo 17				
CDR	–9.25 lbs	–5.2	+0.3 lbs	+0.2
CMP	–2.5 lbs	–1.5	–1.5 lbs	–0.9
LMP	–4.25 lbs	–2.6	–2.5 lbs	–1.6

Stereometric body volume measurements performed for the Apollo 16 crew confirmed this pattern of weight loss. Body volume measurements were performed fifteen and five days prior to launch and immediately after recovery. Stereophotographs were analyzed to derive the precise displacement of a large number of coordinates from the body reference plane. From these coordinates, the exact volume of the three-dimensional image of each crewman could be computed. Postflight tests show that the Apollo 16 Lunar Module Pilot had a body volume decrease of 2.5 liters and the Command Module Pilot of 6.9 liters. Unexpectedly, the Commander showed no net loss of body volume although he lost the most weight during the mission. Observation of these body density changes together with the known caloric deficits of the crew would imply that loss of fat tissue predominated in the lunar surface crewmen whereas the Command Module Pilot lost proportionately more body water. Negative nitrogen and potassium balances in the Apollo 17 crew confirmed a loss in total body protein.

In summary, the Apollo diet was adequate in terms of calories, vitamins, and minerals provided. Nevertheless, crewmembers lost weight as a result of a hypocaloric intake and as a result of a tendency to lose some fluid and body tissue under hypogravic conditions.

Workloads

The workloads imposed on Apollo crews were carefully calculated during the preflight period. Especially careful prelaunch estimates were made for lunar surface activities. In general, these correlated well with the metabolic expenditures telemetered from lunar surface crews. Table 5 shows the average metabolic cost in BTU's per hour for the Apollo 17 lunar surface crew and compares these figures with prelaunch predictions for lunar surface activities. Actual metabolic rates tended to be only slightly higher than those predicted. Only in the case of the Apollo 15 crew were lunar surface workloads considered to be excessive. The mission was a strenuous one. In addition to the heavy workloads, the crew was excessively fatigued as a result of sleep difficulties. Because of these and other problems, the postflight responses of this crew are different from other crews in virtually all dimensions. Apollo 15 crew responses stand out as an anomaly.

Heart rates recorded during Apollo 15 lunar surface activities gave no early clues as to the extent to which the crew was drawing on its physiological reserves. During some activities, heart rates reached nearly 160 beats per minute. While this heart rate is relatively high compared to that recorded during most lunar surface activities, it is not outstanding. Similar heart rates were recorded for Apollo 11, 12, and 14 crewmen. The first clue to work overload was provided by cardiac arrhythmias noted in both crewmen on the lunar surface which recurred during the return flight to earth. After splashdown, the crew had marked difficulty in physiological readjustment to earth's gravity environment. Recovery of preflight work performance values was retarded. One crewman reported suffering dizziness postflight. He viewed this as a sign of vestibular disturbance while it was, in fact, more likely related to cardiovascular system dysfunction. This distinction is a very important one to make. The crew also showed a marked potassium deficit which undoubtedly contributed to their physiological problems. These findings led to modifications of the work/rest schedule and the diet for the Apollo 16 and 17 crews which successfully prevented a recurrence of the difficulties experienced by the previous crew.

Table 5

Metabolic Assessment Summary During All Surface Extravehicular Activity in Apollo 17

Activity	Commander		Lunar Module Pilot	
	Actual, Btu/hr	Prelaunch prediction, Btu/hr	Actual, Btu/hr	Prelaunch prediction, Btu/hr
Lunar roving vehicle traverse	479	550	447	550
Geological station activities	1036	950	1189	950
Overhead	1200	1050	1130	1050
Apollo lunar surface experiments package activities	1129	1050	1104	1050
All activities	946	892	950	892

Vestibular Function

Apollo crewmen were the first American spacecrews to report any motion sickness symptoms. It is believed that the increased volume of the Apollo spacecraft which affords additional opportunity to move about freely exacerbates the motion sickness problem. It should be stressed, however, that the problems recorded by Apollo crews with very few exceptions were not severe enough to cause serious debilitation. Most symptoms subsided after two to five days of weightless flight.

In the earth environment, the brain receives its orientation cues from the visual system and the vestibular system. Of the two, only the vestibular system is gravity-dependent. Fortunately, visual cues are sufficient to prevent disorientation in the zero g environment. While disorientation did not prove to be a particular problem, other difficulties were experienced by Apollo crews which were undoubtedly linked to alterations in vestibular function. There were a few reports of tumbling illusions, stomach awareness, nausea, and vomiting. Table 6 summarizes the vestibular-related symptoms noted in Apollo astronauts. Twenty-six individuals experienced such symptomatology.

As the table indicates, there is no clear relationship between motion sickness history and vestibular symptoms in zero gravity space flight.

Table 6

Vestibular-Related Symptoms Experienced by Apollo Astronauts

Mission	Astronaut	Motion Sickness History			Illusions/Motion Sickness Symptoms in Space Flight			
		In Land, Air and Sea Vehicles	In Zero-G Parabola	In S/C Egress or Egress Training	Tumbling Illusions	Stomach Awareness	Nausea	Vomiting
7	A	X						
	B	X	X	X				
	C	X		X	X			
8	D	X				X	X	X
	E	X	X	X		X	X	
	F	X	X			X		
9	G							
	H			X	X	X		
	I	X	X	X		X	X	X
10	J	X						
	K	X						
	L	X				X		
11	M	X	X	X				
	N	X	X	X				
	O	X	X					
12	P	X						
	Q							
	R			X				
13	S(E)	X	X	X				
	T					X	X	X
	U					X		
14	V	X						
	W	X						
	X							
15	Y(H)			X				
	Z		X		X	X		
	AA							
16	BB(X)	X						
	CC	X	X					
	DD	X	X					
17	EE(L)	X	X			X		
	FF	X	X			X		
	GG	X	X					

All data related to vestibular function during Apollo were in the form of subjective reports until the time of the Apollo 16 flight when several quantitative measures were obtained. Two types of tests were performed. The first evaluated postural stability with and without the aid of vision. All crewmen were within normal limits during the preflight tests on this measure. However, three days after recovery, two of the crewmen exhibited a significant decrement when deprived of all visual sensory cues. The astronauts were again tested after one week, at which time preflight baseline levels were reattained. The second test consisted of graphic recordings of nystagmus induced by water irrigation of the auditory canal. Two of the crewmen displayed a semicircular canal hypersensitivity during postflight testing, as evidenced by an increase in the frequency of nystagmus and an increase in the slow-phase velocity of caloric-induced nystagmus. Apollo crews have not reported vestibular-related difficulties with the consistency or of the severity reported by Soviet cosmonauts. This is perhaps attributable to the fact that American astronauts have a considerable amount of test pilot experience, and the test pilot population has a lower incidence of motion sickness than the general population (Clark & Stewart, 1972).

Cardiovascular Response

The cardiovascular system of Apollo astronauts has been studied intensively before flight, during weightless exposure by telemetry, and postflight using various provocative tests. Telemetry equipment made possible real-time measurement of heart rate and electrical activity. In the pre- and postflight periods, additional measures were added to the cardiovascular inventory. Heart size was examined by an X-ray technique; orthostatic tolerance was determined by several methods, including monitoring of heart rate, blood pressure, and lower limb volume during a static stand procedure, during tilt-table testing, and during the application of lower body negative pressure; and, finally, exercise capacity, indicative of cardiopulmonary status, was measured using a bicycle ergometer while heart rate, blood pressure, and other measures were monitored.

Heart Rate. Heart rates, after an initial elevation during the launch period, tended to stabilize at lower than preflight levels during the period of weightlessness. Postflight, resting heart rates were elevated and normalization was inhibited. With the single exception of the Apollo 15 crew for whom normalization required several days postflight, heart rates reached preflight baselines by 30 to 50 hours postflight. Orthostatic hypotension was evidenced by elevated heart rates during the application of lower body negative pressure. Eighteen Apollo crewmen were tested in this manner, and the mean heart rate during the application of 50 mm Hg negative pressure was 109 beats per minute postflight compared with 70 beats per minute preflight. In the same subjects, the mean resting heart rate was 70 beats per minute postflight as compared with 62 beats per minute preflight.

Electrical Activity of the Heart. Inflight monitoring of the electrical activity of the heart relied on one or two bipolar EKG chest leads. Measurements obtained inflight indicated no dramatic changes in cardiac electrical activity with the exception of rare extrasystoles and occasional arrhythmias first noted in the Apollo 15 crew. Twelve bigeminis were recorded as premature auricular and ventricular contractions. In one instance, an arrhythmia recorded during a sleep period was accompanied by a heart rate of 28 beats per minute. These arrhythmias are believed to be linked to potassium deficits, about which more will be said later. Arrhythmias were noted also in two of three Apollo 16 and 17 crewmembers, but these were considered of no medical significance. In each case, the arrhythmias occurred less frequently than once a day, and they were consistent with electrocardiographic data obtained for the same crewmen during ground-based tests.

There is a reasonable basis for suspecting that the Apollo 15 crew was launched potassium-depleted. Prior to their space mission, they received rigorous training for their lunar surface tasks. This training was carried out in the summertime in rather intense heat. In addition, the crew drank considerable amounts of an electrolyte solution which tended to replace sodium, but, at the same time, it leeched out potassium. These factors, coupled with inflight diets that were not particularly high in potassium, undoubtedly contributed to the negative potassium balances in the crewmen.

One of the Apollo 15 crewmen has suffered a coronary infarct since his space flight. He undoubtedly had coronary artery disease at the time of the mission but the condition went undetected. Failure to diagnose this condition is possible despite the careful medical scrutiny to which astronauts are subjected because coronary angiography is not routinely done. This technique is used with great reluctance as a selection measure because it involves invasion of one's body and has some inherent risk. The Apollo 15 crewman suffered serious arrhythmias inflight as a result of potassium deficits and fatigue and, we now speculate, his undetected coronary artery disease. We are, however, unable to relate the flight events to the ensuing coronary.

Decreases occurred postflight for the PR and QT intervals at rest and during the application of lower body negative pressure. In the Apollo 17 crew, the clinical 12-lead electrocardiograms showed evidence of slight right axis QRS rotation (frontal plane) and slight diminution of T wave amplitude (precordial leads) postflight for all three crewmen. Table 7 summarizes the vectorcardiographic data. It is clearly evident that many aspects of the vectorcardiogram were significantly altered in Apollo astronauts after space flight. How and when these changes occurred inflight is still unknown, and it is not possible yet to differentiate whether these changes represent an adaptive response or whether they were pathological effects. Answers to these questions await inflight Skylab data.

Cardiac Silhouette. Examination of pre- and postflight posterior and anterior chest films for Apollo crewmen revealed a significantly decreased heart size postflight. These data were confirmed by X-ray studies in the Apollo 16 and 17 crews. Correlation of X-ray views taken at the same time during cardiac cycle, systole or diastole, also revealed the decreased cardiac silhouette. Chest X-rays of the Apollo 17 crew showed a definite decrease in heart size in only one crewman, the

Commander. Little change of heart size could be seen for the Lunar Module Pilot, and the Command Module Pilot's cardiac silhouette was somewhat larger postflight. This is the individual, the CMP, who wore an antihypotensive garment in the final stages of flight (Berry, in press).

Table 7

Apollo 15, 16, and 17 Vectorcardiographic Data
(Mean of Nine Crewmembers)

VCG Measurement	Reference: Preflight, Resting Control values Mean	±S.D.	Percentage Changes from Reference: Treatment = Flight, Comparison of pre- vs. postflight: Control	−50 mm. Hg LBNP	Treatment = LBNP, Comparison of control vs. −50 mm.Hg: Preflight	Postflight
Heart rate, bpm	57.4	8.6	+11	+34	+22	+47
PR interval, msec	158	28	− 5.1	− 7.8	− 8.5	−11
QRS duration, msec	99	6	− 0.1	+ 1.0	− 5.6	− 4.6
QT interval, msec	416	34	− 6.7	−11	− 7.3	−12
P Max. Magnitude, mv	.135	.033	+10	+32	+30	+56
QRS Max. Magnitude, mv	1.86	.376	+ 3.2	+ 3.3	+ 6.0	+ 6.1
ST Max. Magnitude, mv	.653	.181	−15	−24	−11	−22
J—Offset Magnitude, mv	.067	.0186	−18	−11	+20	+29
ST Slope, mv/msec	1.303	.331	+14	−57	+11	−58
QRS—T Spatial Angle,°	44	22	+12	+ 6.5	+65	+55

Hoffler et al., 1973

Blood Pressure. During the postflight period, Apollo astronauts exhibited labile blood pressure for up to three days, again with the exception of the Apollo 15 crew for whom the recovery period was protracted. Postflight pulse pressures were decreased below the preflight level during the application of lower body negative pressure, evidencing orthostatic hypotension.

Orthostatic Tolerance. Decreased ability of the cardiovascular system to withstand gravitational stress upon reentry following space flight was a consistent postflight finding in Apollo astronauts. This finding was expected as a consequence of the reduction in hydrostatic pressure gradients in zero gravity and is consistent with earlier space flight results. Reduced orthostatic tolerance, as has already been noted, was evidenced by elevated heart rates and decreased pulse pressures during orthostatic tolerance testing. Figure 8 permits a closer look at the heart rate data for the Apollo 14 Command Module Pilot recorded immediately postflight. The graph shows his heart rate during resting and passive standing and also presents a preflight record. In the first minute of the passive standing test immediately after recovery, the CMP'S heart rate reached 115 beats per minute and he became presyncopal. Prior to the test, he also had a presyncopal reaction on assuming the upright position after resting in bed. The CMP completed the test in the seated position. On subsequent tests, the presyncopal reaction did not recur but heart rates were still significantly elevated above preflight levels.

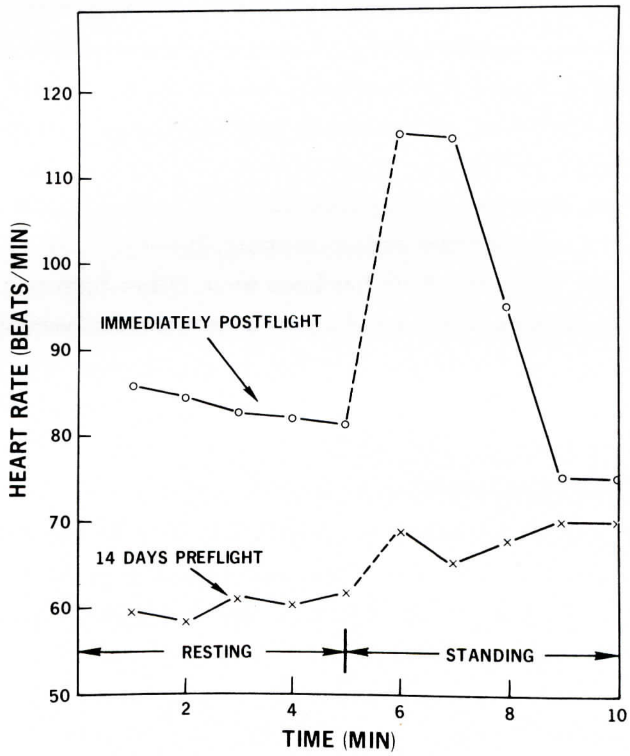

Figure 8. Heart rate data of Apollo 14 Command Module Pilot in static stand test.

An additional measure made during lower body negative pressure response studies was the measurement of lower limb volume. Increased lower limb volume signals venous pooling which is indicative of a certain degree of cardiovascular deconditioning. Measurements of calf size during the application of lower body negative pressure, however, did not show consistent trends postflight.

The other major indicator of the cardiovascular system's status postflight was the crewmen's response to exercise on a heart-rate-controlled bicycle ergometer. The ergometer produced three heart rate stress levels: 120 beats per minute for six minutes; 140 beats per minute for three minutes; and 160 beats per minute for three minutes. Workload, blood pressure, and respiratory gas exchange were measured during each stress level. These tests were performed for all crews with the exception of the Apollo 12 and 13 crews when the requirement for quarantine was in effect. Of the 27 crewmen tested, 18 demonstrated a significant decrease in work performed and oxygen consumed at submaximal heart rate levels. For the three crewmen who could be tested at the maximum workload level (heart rate of 180 to 200), significant decreases in these variables were also noted. No gross changes were noted in mechanical efficiency immediately postflight as reflected by the oxygen required to perform a given amount of work. Systolic and diastolic blood pressures at 160 beats per minute decreased significantly (Rummel, Michel, & Berry, 1973). These data indicate a changed cardiovascular response to workload stresses following return from orbital flight. This decreased exercise capacity persisted in most crewmembers (23 of the 27 tested) from two to three days postflight. Again, the Apollo 15 crew was the slowest to return to normal, with the Commander requiring a full 13 days to reattain preflight exercise capacity levels.

The losses in exercise capacity consistently noted cannot be fully explained at this time. Undoubtedly, they reflect cardiovascular deconditioning. However, these losses in capacity may also reflect the functional disuse atrophy which has been seen. Other factors including stress and fatigue may well be involved. Elucidation of the mechanism awaits the analysis of data obtained during the Skylab missions.

Hematological Effects

One of the striking findings of the Gemini mission series was a marked decrease (ranging from eight to 22 percent) in red blood cell mass postflight. Red blood cell mass was also reduced postflight in virtually all Apollo astronauts. These reductions were, however, noticeably smaller for the crews of Apollo 7 and 8. During the Apollo 7 and 8 missions, there was a small amount of nitrogen in the breathing atmosphere because no operational decompressions eliminated the nitrogen introduced at launch. Since the Gemini spacecraft and the Apollo 7 and 8 spacecraft had effectively 100 percent oxygen breathing atmospheres, it was hypothesized that red blood cell mass changes were the result of increased partial pressure of oxygen in the spacecraft.

A ground-based simulation test was undertaken to determine if hyperoxia was indeed responsible for the reduction in red blood cell mass or if other factors such as the level of activity engaged in by astronauts or exposure to transverse reentry G forces were involved (Richardson, undated). The test was also designed to demonstrate, if hyperoxia were proved to be involved, by what mechanism the red blood cell mass was being reduced: hemolysis or inhibition of erythropoiesis. If hemolysis were occurring, older cells would be likely to be destroyed before younger ones (this could be demonstrated by ^{51}Cr studies with age-density separated red cells). If inhibition of erythropoiesis were occurring, red blood cell survival studies would not show a disproportionate number of young red blood cells. All subjects in the study displayed a significant continuous decline in red blood cell mass during the 30 days of exposure to 100 percent oxygen in an altitude chamber. The decrement in red cell mass appeared to be due to hemolysis and, to a lesser extent, to suppression of erythropoiesis. The consistent postflight finding of elevated haptoglobin levels, however, is not consistent with the concept of intravascular hemolysis.

While a marked increase was seen in the proportion of younger cells during the first week of the test, this increase was probably a consequence of erythropoietic stimulation induced by daily blood sampling. After four to six weeks of exposure, mean red blood cell populations showed an increase in the proportion of more dense, older cells and a trend toward increasing apparent senescence. Evidence from lipid studies performed on the subjects support the hypothesis that anemia induced by exposure to 100 percent oxygen is caused in part by decreased synthesis of cholesteryl esters secondary to an inhibition of the plasma lecithin-cholesterol acyltransferase reaction.

On the other hand, support for the theory that inhibited erythropoiesis was the more important factor in the red blood cell mass decreases and that hemolysis did not occur in Apollo astronauts came from a study of the crews of Apollo 7, 8, 9, 14, and 15 (Johnson & Driscoll, 1972). Table 8 illustrates the findings of this study. As can be seen by comparing pre- and postmission results, ^{51}Cr red cell 50 percent survival times did not differ among the missions. Further, no differences can be observed when the two types of Apollo missions are compared.

Table 8

Red Cell Survival (^{15}Cr Half-Times)

	Apollo	Apollo + LEM
Preflight	25.5 ±0.8	24.1 ±1.1
Inflight	28.3 ±1.3	25.1 ±1.3
Postflight	24.7 ±1.0	28.2 ±1.5

Controls – 23.4 ±2.0

For a time, it appeared that the introduction of nitrogen into the breathing atmosphere retarded the red blood cell mass decreases. When red blood cell mass percentage changes were considered for the Gemini crews versus the Apollo crews on missions which did and did not employ the Lunar Module, a statistically significant difference was noted in the percentage red blood cell mass among the groups, and no such change was seen in controls (Table 9). However, early Skylab results suggest that even greater amounts of nitrogen offer no similar benefit. The precise mechanism of red blood cell mass decrement is still unclear, and Skylab studies have been designed in the hope of clarifying this issue.

In all Apollo crews, again with the exception of the Apollo 15 crew, red blood cell mass losses were recovered in the first few days postflight. Figure 9 shows the postflight response for the Apollo 15 crewmembers.

As has already been noted, plasma volume changes were variable among Apollo crews, with some showing increases and some showing decreases postflight. One of the only persistent hematological changes was transient increases in white blood cell count. This phenomenon is probably a consequence of increased blood epinephrine and steroid levels associated with mission stress, and it was reversible within two days postflight (Berry, 1973).

Table 9

Red Cell Mass Percent Change
(Premission vs Immediately Postmission)

	Gemini	Apollo & LM	Apollo without LM
Crew	−15.6 ±2.3	−7.4 ±1.2	−2.4 ±1.6
Controls		−1.1 ±1.0	+0.1 ±1.6

(From Johnson & Driscoll, 1972)

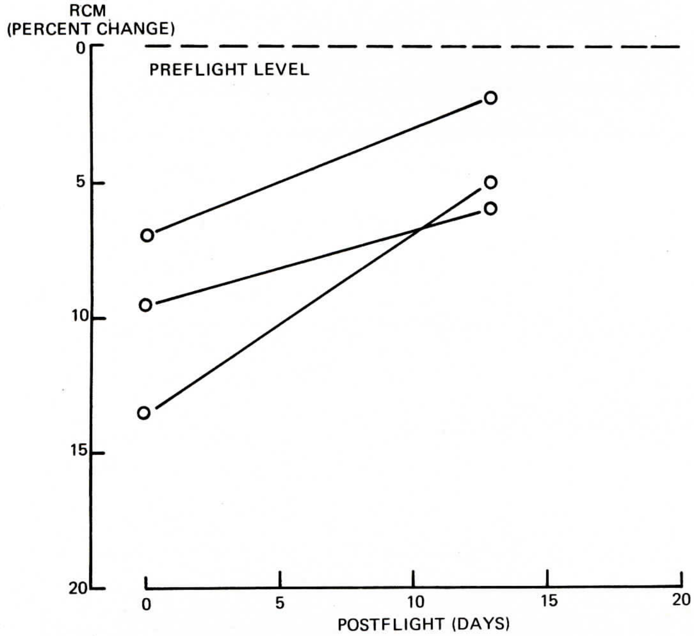

Figure 9. Recovery of red cell mass after Apollo 15 space flight.

Endocrine Homeostasis and Fluid and Electrolyte Balance

A consistent finding, particularly during early Apollo missions, was a significant postflight weight loss. This averaged 6.8 pounds per man. Approximately half this weight loss was regained in the immediate postflight period, indicating that at least half the weight loss was attributable to water loss. Endocrine and electrolyte data confirmed this supposition. It was known, however, that the crewmen had hypocaloric intakes. They reported feeling hungry less frequently in flight and felt their food requirements were satisfied by consumption of about two-thirds of their "normal" dietary intakes (Berry, 1970). Clearly, part of the weight loss was attributable to water loss but from which fluid compartment of the body was unclear. Weight losses were several times larger than decreases in plasma volume, consequently, the remainder of the water loss could have been extracellular fluid loss or intracellular fluid loss. How much of the remaining weight loss was adipose tissue loss and how much was muscle mass loss was unclear.

Gemini and early Apollo data suggested that intracellular water (and tissue mass losses) occurred. Negative potassium balances in the Gemini 7 crew, increased tubular reabsorption of potassium immediately postflight in Apollo 7 through 13 crews at a time when an increased epinephrine, renin, and aldosterone level should produce a potassium diuresis, and a postmission total body potassium deficit (inferred from serum potassium levels) all buttressed this theory (Berry, 1971). The Apollo 14 mission offered the opportunity to investigate the fluid loss and fluid shift phenomenon more closely.

Preflight measurements were made for comparison with postflight findings for the following variables: total body water, extracellular fluid, intracellular fluid, plasma volume, and red blood cell mass. Table 10 shows the results of these investigations and indicates the measurement method used for each. These findings indicated that the body water deficit could be attributed principally to intracellular fluid volume loss. Extracellular fluid volume was essentially unchanged, whereas plasma volume increased to greater than preflight values in the face of decreasing red blood cell mass. With normal if not increased total circulating blood volume and stable extracellular fluid volumes, the only remaining compartment from which fluid could have been lost was the cells. These results also supported the hypothesis that the weight deficit included tissue loss.

Table 10

Percent Change in Body Fluid Volume – Apollo 14
(Preflight vs 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

The next step was to determine the precise nature and extent of tissue loss. To this end, a carefully controlled study was performed in conjunction with the Apollo 17 mission (Johnson, Leach & Rambaut, in press). Measurements were made of the nitrogen, water, and caloric value of the ingested food and the volume and nitrogen content of the excreted urine and feces. These determinations were made during a preflight baseline study and after the flight. Body composition changes were determined from total body water and extracellular fluid volume differences. Table 11 indicates the fluid compartment volume changes and compares these with averaged changes for Apollo 14, 15, and 16 crews. In the Apollo 17 crew, findings were precisely the reverse of those noted for the Apollo 14 crew. In the former crew extracellular fluid volume was decreased, by about five percent, and intracellular fluid volume was slightly increased. There was a slight decrease in total body water and a plasma volume decrease of about eight percent. Total body exchangeable potassium also decreased, by about ten percent. Exchangeable potassium studies were not carried on through normalization in this crew. Determination of the period required to reach preflight baselines awaits Skylab data. Table 12 shows the findings in comparison with data obtained for the Apollo 15, 16, and 17 crews. In addition, negative nitrogen balances were found.

Table 11

Fluid Compartment Volume Change Comparisons

	Apollo XVII	Mean ± S.E. Other Moon Landing Missions (XIV, XV, XVI)
	Mean % Volume Change ASAP	
Red cell mass	−11.2	−9.7 ±1.6
Plasma volume	− 8.1	−3.2 ±1.8
Total body water	− 2.3	−2.7 ±0.4
Extracellular fluid	− 5.1	−1.7 ±0.9
Intracellular fluid	+ 1.6	−3.1 ±0.5
Interstitial fluid	− 4.3	−1.4 ±1.0
	Mean % ml/kg Change ASAP	
Red cell mass	− 7.1	−5.7 ±1.6
Plasma volume	− 4.1	+1.2 ±1.4
Total body water	+ 2.7	+1.2 ±0.4
Extracellular fluid	− 0.8	+2.0 ±0.9
Intracellular fluid	+ 4.9	+0.8 ±0.5
Interstitial fluid	− 0.1	+2.4 ±1.3

Table 12

Total Body Exchangeable Potassium

Mean % Change in Total meq K		
Dilution Time in Hours	24	48
Apollo 15	−15.3	−13.8
Apollo 16	+ 3.8	+ 2.3
Apollo 17	−16.3	− 5.2

Mean % Change in meq K/kg Body Weight		
Dilution Time in Hours	24	48
Apollo 15	−12.7	−12.6
Apollo 16	+ 7.7	+ 7.0
Apollo 17	−13.5	− 0.3

Fluid balance data for the Apollo 17 crew suggested that the major weight loss was body tissue loss and not attributable to water imbalance. The lack of weight gains during the first 24 hours postflight provided additional confirmation. Negative nitrogen and potassium balances confirmed that this tissue loss was principally a loss of body protein, that is, muscle. A loss of calcium and phosphorus also reflected musculoskeletal deterioration. Some of the weight loss observed must be attributed to a loss of fluid because of the slight decrease in total body water noted postflight, confirmed by decreases in urinary electrolytes and antidiuretic hormone. This slightly negative water balance probably reflected an inflight insensible water loss of 800 to 900 cc per day under the conditions of temperature and humidity which prevailed in the spacecraft. Finally, in the case of this crew, as in virtually all previous Apollo crews, a hypocaloric regimen was followed inflight.

The body composition measurements discussed above made it possible to divide the weight loss into lean body mass loss and adipose tissue loss. Since very little water was lost, most of the tissue lost was nonwater containing tissue, that is, adipose tissue. From this division, a caloric equivalent was calculated indicating that the crew's caloric requirements were greater than their caloric intakes. A number of Apollo crewmen had reported no problem with their appetites. They assumed they were eating an adequate amount, they did not feel hungry, and yet they lost weight. In the absence of an apparent reason for restricting caloric intake, for example, nausea, it is necessary to conclude that the stimuli regulating caloric intake in response to energy expenditure are less effective in space (Johnson, Leach, & Rambaut, in press).

Pre- and postflight measures of hormones related to electrolyte and fluid balance were consistent with inflight water loss. Increased levels of antidiuretic hormone, which regulates water resorption through the distal renal tubule, and increased aldosterone levels which result in resorption of sodium in the proximal tubule were consistent with the electrolyte retention noted and the rapid weight gain postflight. Plasma angiotensin levels, an index of renin activity, also showed significant increases postflight. Renin stimulates the adrenal gland to secrete aldosterone upon sensing decreased blood volume or salt concentration (which is uncertain) in the kidney.

Leach, Alexander, and Johnson (1972) report that the increased aldosterone excretion found postflight in the Apollo 15 crew was not accompanied by increases of statistical significance in ACTH, angiotensin I, cortisol, or 17-ketosteroids. These findings suggest that there was stress associated with reentry but that it was not great. If reentry stress was not sufficiently great to raise serum cortisol or urinary cortisol levels significantly, it could not have been expected to elevate aldosterone excretion. Unchanged angiotension I levels showed that aldosterone excretion was not increased by a postrecovery renin response. Therefore, the increased aldosterone excretion found during the first seventeen hours after recovery could best be explained as the remains of an inflight aldosterone elevation. Urine samples collected inflight for Apollo 17 crewmembers confirmed this supposition. These showed aldosterone levels comparable to or higher than preflight baselines. Postflight aldosterone levels were again elevated. Increased aldosterone production appear to be one manifestation of man's adaptation to prolonged weightlessness.

Immunological Evaluations

Significant alterations of the immune mechanism of space crewmen, if these occurred and were of a serious nature, could reduce a crewman's ability to combat infection and repair traumatized tissue in the space flight environment and after return to earth.

Net increases in the number of white blood cells were consistently noted postflight in Apollo astronauts. Similar changes were seen in Gemini astronauts and have been reported for Soviet cosmonauts (Molchanov et al., 1970). The mean lymphocyte number tended to exhibit a significant delayed but fluctuating increase after recovery. Studies were undertaken in the 21 Apollo 7 through 13 crewmen to determine whether any change had occurred in the pattern of cellular division of the human immune system (Fischer et al., 1972). The immunocompetence of lymphocytes was studied *in vitro* by simulation techniques. Lymphocyte reactivity was reflected by RNA and DNA synthesis rates in unstimulated lymphocyte cultures and in cultures stimulated by phytohemagglutinin. The synthesis rates did not differ in the two types of cultures. This finding engenders confidence in the human immune system when it is exposed to space flight if the highly vulnerable small lymphocytes maintain their integrity.

The humoral aspects of the immune system of the same group of astronauts was examined (Fischer et al., 1972a). Definite changes occurred in the concentrations of electrophoretic α_2-globulin and haptoglobin, and α_2-macroglobin, and α_1-acid base glycoprotein. The significance of these findings is unclear, but they do not imply changes that could have proved detrimental to the health of the crewmen.

Microbiological Changes

Another side of the disease-production and disease-resistance picture can be seen by examining the human microflora. Man has evolved in an intimate and constant association with a complex of microflora. Some of these are disease-producing and some are not. Should microfloral shifts occur that permit pathogenic organisms to predominate, the health of the affected individuals could be compromised. For this reason, the microflora of Apollo astronauts have been closely observed.

Certain changes have been observed in the character and distribution of the microflora. Similar changes have been reported for Soviet space crews also. The growth of opportunistic organisms appears to be favored in space flight and certain organisms become less resistant to antibiotics postflight (Berry, 1970). Overall, the changes from the preflight to the postflight period may be summarized in the following way:

1. Anaerobic bacteria decreased in number.
2. Aerobic bacteria increased in number and type.
3. Microorganisms were isolated at more body sites.
4. Organisms tended to spread across crewmembers (especially Staphylococcus aureus).
5. Fungal isolates decreased in number.
6. Higher carrier states for mycoplasma were indicated.

The etiology of the changes is unclear, but they are not surprising against the background in which they occurred. Apollo crews were kept in semi-isolation prior to flight and given diets which carefully restricted their bacterial intake. Furthermore, the atmosphere control system in the spacecraft also limited the number of microbes to which the crews were exposed. In addition to these factors, the distribution of microbe-bearing particles is altered in zero gravity where there are no gravity gradients to cause them to settle out. All of these factors are likely to have a consequence for the microbial burdens of the population involved. Table 13 lists the microflora of possible medical importance which were isolated postflight from Apollo crews.

The crews always harbored potential pathogens, particularly *Candida albicans* in the throat, before, during, and after space flight. A reduction in fungal isolates began during the health stabilization period and continued during flight. The fungal population was usually diverse, which undoubtedly reflected the extensive travel and activities of the crewmembers preflight. A large buildup of pathogens was noted on the inflight urine collection devices; the pathogens most frequently involved were of the *Proteus* and *Pseudomonas* types. Several of the crewmembers had postflight infections. *Tricophyton rubrum* was isolated as the causative agent in the chronic dermatitis of the Apollo 17 Command Module Pilot and Commander. *Haemophylous* was probably a contributory agent to the recurrent urethritis in the Apollo 14 Lunar Module Pilot and *Pseudomonas* was isolated as the causative agent in the urinary tract infection in the Apollo 13 Lunar Module Pilot.

Table 13

Microflora of Possible Medical Importance
Identified Postflight in Apollo Crews

Staphylococcus aureus	Moraxella species
epidermis	Corynebacterium species
faecalis	Enterobacter aerogenes
Klebsiella aerobacter	Haemophilus parahaemolyticus
enterobacter	Herella vaginicola
pneumoniae	E. coli (Throat)
Proteus mirabilis	β – Streptococcus
Pseudomonas aeruginosa	Mycoplasma
Serratia species	Candida albicans (Esp. Throat)
Mima polymorpha	Trichophyton rubrum

It should be noted that microbial loads returned to the preflight norm during the early postflight period.

Musculoskeletal Changes

Muscle changes and bone changes can reasonably be expected in the absence of gravity and the need for countergravitational effort. Dietrick, Whedon, and Shorr (1948) noted increases in urinary nitrogen excretion and muscle atrophy in the arms and legs of their bed rested subjects. Because it was an area likely to manifest effects, the musculoskeletal system was closely examined after space flight.

Losses in bone mass have been demonstrable in some astronauts on early Apollo flights by use of a bone densitometric X-ray technique. A new and more precise method for estimating bone mineral content was initiated with the Apollo 14 crew. This method relied upon an X-ray technique that used an iodine isotope monoenergetic beam with predictable photon absorption characteristics. Surprisingly, the bone mineral content determinations made with this technique in the Apollo 14 crew failed to confirm earlier findings. Pre- and postflight examinations of the left central os calcis and the right distal radius and ulna revealed no significant mineral losses during the ten-day mission.

Findings of the Apollo 15 crew, relying on the same technique, were consistent with earlier observations. These findings are summarized in Table 14. The Apollo 15 Commander regained his mineral content more rapidly than did the Command Module Pilot, but both were within baseline values at the end of two weeks. Overall losses were about four percent.

Table 14

Bone Mineral Content Determinations
Apollo 15 Crewmen

Subject	Change from preflight to postflight value, percent	
	Radius	Os calcis
Crewmen:		
Commander	+0.5	−6.8
Command Module Pilot	−2.0	−7.9
Lunar Module Pilot	−0.7	−0.6
Control subjects:		
A	−0.9	−2.3
B	−0.2	−0.8
C	−2.1	−0.7

Loss of bone mineral was further suggested by examination of plasma and urinary hydroxyproline levels. Large amounts of hydroxyproline are present in collagen which is found in connective tissue and bone. Bioassay revealed that bound plasma hydroxyproline levels were elevated immediately postflight, while larger quantities of calcium were excreted later in the flight than in the early stages. These findings were first noted in the Gemini 14-day flight and were again seen in the Apollo 8 mission (Berry, 1973).

All three members of the Apollo 17 crew were in negative calcium balance during the inflight period. The negative balance was particularly pronounced when compared with a five-day ground-based study which was performed prior to this mission. For two of the crewmembers, the negative calcium balance persisted postflight. Phosphorus balance in these crewmen was also generally negative inflight. This loss of calcium and phosphorus reflects musculoskeletal deterioration. Negative nitrogen and potassium balances in the crew confirmed the finding of a loss in total body protein, that is, muscle mass.

Measurement of the leg size of the Apollo 16 crewmen revealed decreases in both the size of the calf and the thigh. Limb volumes showed consistent postflight decrements from 100 to 800 milliliters. These decrements persisted beyond seven days postflight (Berry, 1972). Reductions in cardiac silhouette were noted by X-ray and may also indicate muscle mass loss.

No gross neuromuscular changes were observed in Apollo spacecrews. This stands in contrast to the findings for the Soviet Soyuz 9 crew who exhibited severe problems in the motor sphere after eighteen days of weightlessness, including muscular pain and alterations in gait (Chekirda et al., 1970).

In summary, musculoskeletal findings for Apollo astronauts were as follows:

1. Slight or no loss of bone mass
2. Decreased leg size
3. Decreased cardiac silhouette
4. Slightly negative nitrogen balances.

Preventive Medicine and Inflight Illness

The problem of communicable disease exposure prior to space flight was recognized as a potential hazard from the beginning of the U.S. Space Program. However, since total isolation of the crew in advance of flight poses enormous operational difficulties, a compromise was reached which called for a program of semi-isolation to minimize the possibility of adverse alterations in the health of crewmembers during the immediate preflight, inflight, and postflight periods. The elements of the program, referred to as the Flight Crew Health Stabilization Program, are illustrated in Figure 10.

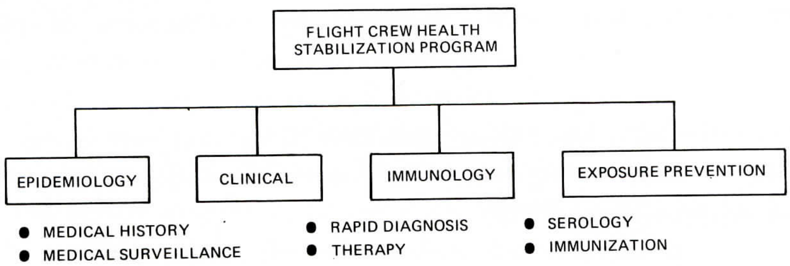

Figure 10. Flight Crew Health Stabilization Program.

The crew's contact with the outside world was limited to encounters with individuals referred to as primary contacts. Three months prior to launch, an epidemiological surveillance was begun on these individuals with the taking of medical histories. Sixty days prior to launch, each was subjected to an extensive physical examination and microbial sampling to identify carriers. The families of the primary contacts were also under medical surveillance from 21 days prior to flight until launch time. During this period, they were instructed to report any illnesses in the family or any known contact with infectious disease.

Apollo crewmembers and their families were immunized against all diseases for which effective immunizations were available. Unfortunately, immunizations are unavailable for the illnesses which are most likely to occur inflight – viral and bacterial infections of the upper respiratory and gastrointestinal tract. Table 15 lists the Apollo immunization requirements.

Table 15

Immunization Requirements

	Astronaut	Astronauts' Children
Diphtheria	Required	Required
Pertussis	–	Required
Tetanus	Required	Required
Typhoid	Required	–
Influenza	Required	–
Mumps	Conditionally Required*	Required
Polio	Required	Required
Rubella	Conditionally Required	Required
Rubeola	Conditionally Required	Required
Smallpox	Required	Required
Yellow Fever	Required	
Others only as indicated for travel to endemic areas	–	As recommended by U.S. Public Health Service/APHA for age group

*Immunize if no serologic response

Since diseases can be transmitted by contaminated inanimate objects, contaminated air, food, or water, and personal contacts, the health stabilization program had an exposure prevention protocol. It included such steps as employing individual headsets and microphones for crewmembers; filtering the air in all crew areas with ultra-high efficiency bacterial filters; performing microbiological evaluations on all foods and water prepared for crew consumption; and daily inspections of the food preparation facilities for cleanliness.

The most important aspect of the disease prevention program was the minimization of exposure to contacts during the critical preflight period. The primary contacts program limited the number of people who had access to the crew to slightly over 100 people with mission-related responsibilities. Actually, in any single day, the crew was exposed to only a very few of these individuals. The crew was isolated from potentially infected carriers at the launch site, and from children, including their own, because they are the most common carriers and transmitters of upper respiratory and gastrointestinal infections.

The clinical phase of the health stabilization program was a continuous one. Crewmembers and their families were provided with routine and emergency physical examinations commencing with the selection of the crewmember for the astronaut corps. Also complete virological, bacteriological, immunological, serological, and biochemical studies were all available.

The enhanced health stabilization program, initiated after the inflight illnesses of Apollo missions 7, 8, and 9, was successful in controlling infectious illness of Apollo crews. Tables 16 and 17 indicate the inflight and postflight medical problems experienced by Apollo astronauts. The influenza syndrome listed was seen in Apollo 8 astronauts. The urinary tract infection was experienced by an Apollo 13 astronaut.

About three years before the Apollo 11 and 12 lunar landing missions, decision was made to conduct a quarantine operation to preclude the possibility, however remote, of contaminating the earth's biosphere with lunar organisms. The quarantine started at closure of the Lunar Module hatch on the lunar surface and continued for a 21-day period. The quarantine program was applied only to the Apollo 11 and 12 crews after meticulous studies revealed that these precautions were unnecessary. The crews kicked lunar dust off their boots on the Lunar Module ladder and used a brush attachment to the suit hoses to vacuum the surfaces of the lunar rock boxes and film containers. The rock boxes and film packs were repackaged after vacuuming, so that little dust was transferred from the Command Module to the Lunar Module. The spacesuits were doffed and packaged in the Command Module and the cabin air constantly filtered during return to earth by lithium hydroxide canisters.

During recovery, swimmers were provided with SCUBA gear. One swimmer wore a biological isolation garment. This swimmer scrubbed the hatch area and postlanding vent with an iodine preparation. He opened the hatch and gave biological isolation garments to the crew who donned them and egressed into the raft. The hatch was closed and again decontaminated, as were the crewmen and swimmer, with the same iodine solution. The astronauts then were transferred by helicopter to the recovery ship, and thence into the Mobile Quarantine Facility (MQF). The microbial sampling and initial examination were completed in the MQF, and the biological samples transferred to the outside through a tank containing a sodium hypochlorite solution.

The crew, a physician, and a recovery technician remained in the MQF during the three days of transit by ship and aircraft to Houston where the MQF was moved to the Lunar Receiving Laboratory. There, the five individuals were transferred to the Crew Reception area (CRA). Daily examinations were conducted on all CRA personnel, and blood and microbiological samples for analysis were obtained at intervals. No evidence of infectious disease was found in the examination of crew or other quarantined personnel. Careful evaluation of the microbiological samples and immunological studies revealed no evidence of bacterial, viral, or fungal growth not noted preflight.

Cultures taken of the lunar dust from the spacesuit showed no growth. Quarantine of the lunar samples continued until 50 days after recovery during which time bacteriological, viral, and fungal studies were performed, again with negative findings (Berry, 1970).

Table 16

Apollo Inflight Medical Problems

Symptoms/Findings	Etiology	Number of Occurrences
Urethral meatal Excoriation (Apollo 13)	Prolong wearing of urine Collection Device (UCD)	2
Inguinal rash	Collection device (UCD)	1
Inguinal rash	Tricophyton rubrum	1
Urinary tract infection Associated with prostatic congestion	Pseudomonas aeruginosa	1
Conjunctival injection	Spacecraft atmosphere	4
Eye irritation	Fiber glass	1
Skin irritation	Fiber glass	2
Skin irritation	Biosensor sites	9
Respiratory irritation	Fiber glass	1
Recurrence of facial rash	Contact dermatitis	1
Stomatitis	Apthous ulcers	1
Stomatitis	Undetermined	1
Nasal stuffiness	Zero g	2
Headache	Spacecraft environment	1
Rhinitis	Oxygen & low humidity	2
Laryngitis	Undetermined	1
Barotitis	Barotrauma	1
Coryza	Undetermined	3
Seborrhea	Activated by spacecraft environment	2
Dermatitis, pustular	Biosensor sites	2
Dehydration (Apollo 13)	Emergency water restriction	2
Cardiac arrhythmia	Undetermined	2
Nausea and vomiting	Undetermined	1
Nausea and vomiting	Labyrinthine	1
Stomach awareness	Labyrinthine	5
Motion sickness	Labyrinthine	1
Shoulder strain	Core drilling	1
Sunbunguinal hemorrhages	Glove fit	5
Flatulence	Undetermined	36

Table 17

Apollo Postflight Medical Problems*

Symptoms/Findings	Etiology
Aerotitis Media	Post-descent
Folliculitis, moderate, right anterior chest	
Gastroenteritis	Possible food poisoning
Herpes simplex, lip	Herpes simplex
Influenza syndrome	Influenza B
	Undetermined
	Influenza A_2
Laceration	Blunt trauma
Nasal discharge, unilateral	Undetermined
Papular lesions, parasacral, multiple (no pustules)	Undetermined
Prostatic congestion, slight	Undetermined
Pulpitis, tooth no. 7	Caries and previous restoration
Pustules, back	
eyelids, left eye	Bacterial
Rhinitis, pharyngitis	Influenza B
	B-streptococcus, not group A
Sinusitis	Post-congestive
Strain, ligament, right shoulder	Lunar core drilling
Urinary infection	Pseudomonas
Vestibular dysfunction, prolonged (7 days)	
mild (head down feeling)	Unknown

*One instance of each symptom found with the exception of prostatitis, of which there were two cases.

The early lunar mission quarantine program provided a considerable amount of experience which can be applied directly to crews and samples returned from future Mars missions.

Psychological Evaluations

All Apollo astronauts were carefully screened psychologically and psychiatrically prior to entry into the astronaut program. An attempt also was made to assess their general ability and their capability to deal with highly stressful situations. The fact that most astronauts were veteran military pilots aided in the selection since this served to indicate that they could keep normal fear reactions under appropriate control and that they were capable of professional behavior under conditions of significant danger.

Results of Apollo flights indicated the initial selection procedures worked well. There were no episodes of inflight emotional disturbance and no untoward postflight reactions. Many astronauts returned, however, with the general manner of a person who has been through a profound personal experience. This is considered quite normal, for indeed they *had* been through a very profound experience.

One feature which was followed with great interest during Apollo dealt with the period of time in which an astronaut was behind the moon, blocked off from all communications and unable to see the earth. Particularly when the Command Module Pilot was in the vehicle alone, he was about as alone as one can possibly imagine. There was no communication of any kind and nothing appeared familiar, with the exception of the small vehicle in which he was riding. Figure 11 is a photograph of the Apollo 11 LM ascent stage returning for docking with the Command Module. The Command Module Pilot took this photograph after nearly three days alone in lunar orbit. Command Module Pilots who had undergone the experience of lunar orbit isolation did not report any depressive or anxiety-type reactions. Further, there was no particular feeling of "detachment," or removal from all earthly ties, as had been predicted by some during the early days of planning for space flight.

An Hypothesis Concerning the Nature of the Adaptive Response to Weightlessness

Much information has been gained concerning the effects of space flight on man as a result of the Apollo experience. A number of consistent findings have been observed, some of which imply a possible alteration in structure of physiological systems and others which indicate merely a change in capacity or functional capability. These changes undoubtedly represent elements in a basic adaptive response of the human organism to the unique environment of space, particularly to weightlessness. Sufficient information is available to form the basis for a tentative hypothesis concerning the nature of the adaptive response. This hypothesis, initially formulated before the Apollo 14 mission, still appears to be basically sound. Inflight data obtained during the Skylab mission will provide evidence to confirm or disprove elements of the theory.

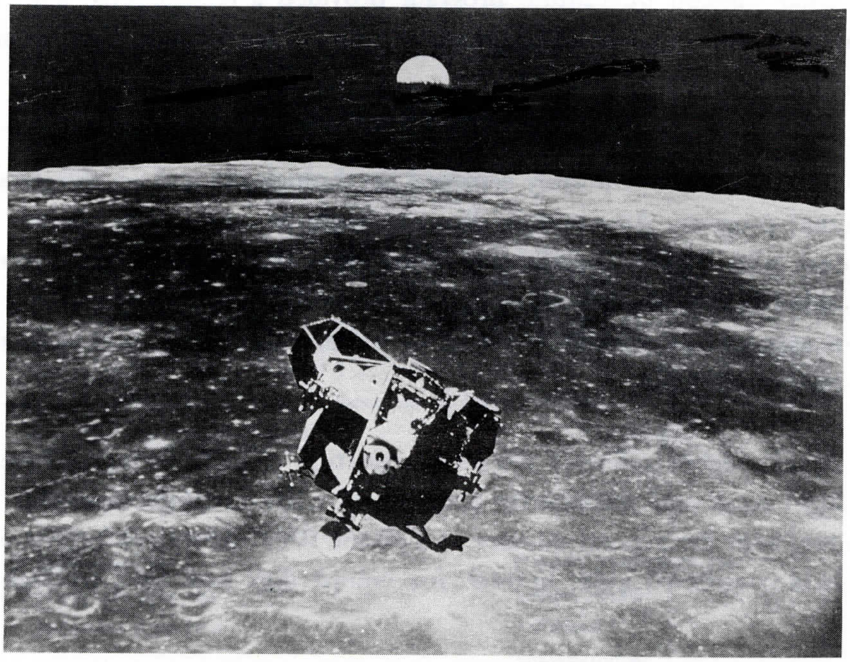

Figure 11. Apollo 11 Lunar Module ascent stage during rendezvous in lunar orbit.

Briefly, the essence of the hypothesis is as follows (Figure 12). Upon initial entry into weightlessness, there is an immediate redistribution in the total circulating blood volume. Reported feelings of fullness of the head, distension of neck veins, and blood volume changes all offer evidence for this phenomenon. Postflight studies of body fluid compartments also confirm that this occurs. The body apparently interprets the resulting increase in right atrial filling as an indication of the need to reduce total fluid volume by increasing urine output. This event would be governed by antidiuretic hormone and a decrease in aldosterone production. While this diuresis has not been directly demonstrated, it can be inferred from the evidence that exists for total body water loss. Inflight weight losses, noted immediately postflight, are partly total body water losses. Diuresis would also be accompanied by a loss of sodium and potassium through the kidneys. Samples being collected during the Skylab mission may offer direct evidence for this, as do postflight urine samples from Apollo missions. A concomitant decrease in plasma volume is postulated. The plasma volume decrease tends to reverse the initial aldosterone decrease. At this point, the body enters a phase of electrolyte and fluid imbalance in which sodium retention increases while potassium loss continues. Intracellular fluid and potassium loss would then result in a cellular acidosis with a mild (compensated) hypokalemic alkylosis of extracellular fluids. While there is no direct evidence of an exchange of hydrogen for potassium ions, this reaction would seem likely.

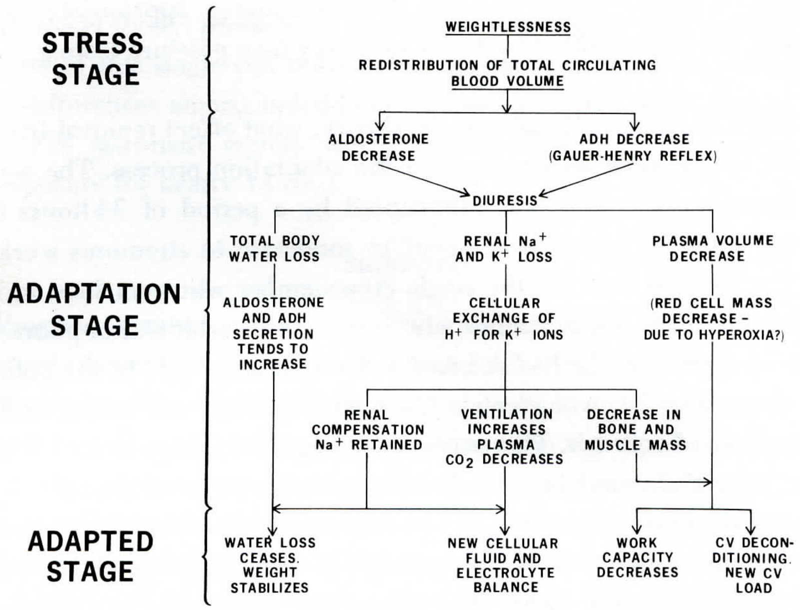

Figure 12. Diagram of the hypothesized course of adaptation to weightlessness.

Associated with the potassium deficit is a decrease in bone density and muscle mass. Both of these situations have been observed postflight. Apollo 17 biochemical data suggest that bone mineral is lost and confirm that muscle mass is lost. Negative nitrogen, potassium, calcium, and phosphorus balances also reflect musculoskeletal deterioration. The loss of cellular potassium can be expected to include the heart muscle. This would cause an increased irritability and a tendency toward disorders of cardiac rhythm. Such arrhythmias have been noted in the Apollo 15 crew.

In the final phase of the adaptation loop postulated, hyperacidity of the cells stimulates the respiratory system to decrease plasma carbon dioxide while increasing ventilatory rate. The Skylab work capacity studies may offer indirect evidence that this occurs. Renal compensation commences as the renal tubules begin to reabsorb sodium. 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, a new load on the cardiovascular system, and a new fluid and electrolyte balance state. It can reasonably be presumed that the new stabilized condition, if unperturbed, is appropriate for long term performance under space flight conditions. If such factors as additional excessive workload, thermal stress, or emotional stress are introduced, the system may be driven beyond the point of equilibrium.

Apollo astronauts upon return from space were, we believe, in this new, adaptive stage. Postflight potassium isotope studies and fluid and other electrolyte data confirm the postulated changes. Work capacity decreases, a part of the adaptive stage, were verified by postflight bicycle ergometry studies. Finally, cardiovascular deconditioning, appropriate to the new, zero g cardiovascular load, has been verified by lower body negative pressure testing.

It was of interest to observe, in light of the theory, what effect removal from zero gravity to the 1/6 g environment of the lunar surface had on the adaptation process. The weightless exposure of the Apollo 14 lunar surface crew was interrupted by a period of 34 hours in the lunar gravity environment, nine hours of which were spent in moderate to strenuous work activity. Postflight comparisons of the medical data for the single crewmember who remained in lunar orbit with the other two indicated that the crewmember who remained in orbit was in poorer physical condition. His weight loss was significant, he had reduced orthostatic tolerance to the point of presyncope, his red blood cell mass decrease was greater, his work capacity was lower, and he showed greater decreases in all body fluid volumes. This experience suggested that perhaps 1/6 g exposure produced some therapeutic benefit. Similar benefit, however, could not be demonstrated for the Apollo 15, 16, or 17 lunar surface crews. However, these crews were exposed to long periods of weightlessness after their lunar exposure. On each of the last Apollo missions, two additional days were spent in lunar orbit performing scientific tasks. It is, therefore, impossible to say whether or not benefit accrued from the 1/6 g exposure because any benefit that might have accrued was undoubtedly neutralized by the extended period of zero gravity exposure.

Countermeasures

The effect of space flight exposure on Apollo astronauts has not clearly indicated a need for countermeasures more elaborate than dietary potassium supplements to prevent potassium deficits and the cardiac arrhythmias associated with these deficits. Nevertheless, because it is difficult to predict at this point the effects of longer term exposure to zero gravity on the cardiovascular system, one potential countermeasure was investigated on Apollo 17. The Command Module Pilot wore an antihypotensive garment during reentry and until the period of postflight orthostatic tolerance testing. Differential heart rate and blood pressure with and without the garment did not substantiate the benefit of the garment. The Command Module Pilot's standing heart rate with the garment was 99 beats per minute compared with 93 beats per minute preflight, while his postflight pulse pressure was 46 mm Hg compared to 34 mm Hg preflight. Upon release of the pressure in the garment, his postflight heart rate reached 104 beats per minute while his pulse pressure held at 47 mm Hg.

Subsequent to removal of the countermeasure garment postflight, the Command Module Pilot's LBNP response showed no heart rate elevation, no pulse pressure decrease, and little diminution of stroke volume compared to his preflight mean response. These data, combined with the large postflight cardiac silhouette of this individual, the known maintenance of his intravascular volume postflight, and the fact that his postflight leg volume decrement was greatest of the three crewmen, inferred a long-term protective effect was afforded by the countermeasure garment. It is speculated that extravascular lower body pooling of fluid was reduced by the wearing of this garment. However, the results of this single test must be interpreted cautiously in view of the well known, marked individual differences among individuals exposed to space flight stresses and it can equally well be said that this astronaut merely was a variant in showing no cardiovascular decrement following zero g exposure for nearly 14 days.

Summary

The Apollo Program spanned a five-year period during which some of the most astounding "firsts" in the history of mankind were scored. The Apollo 8 crewmen were the first humans to see the dark side of the moon. The Apollo 11 Lunar Module Pilot and Commander were the first men to set foot on earth's satellite. The 27 astronauts engaged in the Apollo Program spent a total of 7,508 hours in flight. Six of these astronauts orbited the moon alone while their companions carried out their scientific experiments on the lunar surface. On the longest mission, this period of isolation lasted nearly four days. Surprisingly, the psychological break-off phenomenon long suspected to accompany such periods of isolation never occurred. While lunar exploration was felt by all astronauts to be an intense, profound experience, very few individuals experienced any psychological problems after flight, and those few problems that did occur were mild and not unexpected.

The Apollo Command Module provided a greater living and working volume for the space crews than any previous space vehicles. In general, the astronauts adapted well to operating in this environment. They found that zero g made locomotion in the craft simple and enjoyable. The only problems associated with movement in a vehicle of this volume were occasional transient motion sickness symptoms which rarely lasted beyond the first few days of flight, and some degree of lower back pain resulting from the tendency to assume the fetal position in sleep. On the lunar surface, the 1/6 g environment also enhanced locomotion, and the lunar surface crews employed a loping gait in adaptation to it. New suits and a lunar surface vehicle enhanced mobility. The radiation exposures experienced were benign. It is suspected, but not clearly confirmed, that the occasional reports of seeing light flashes were associated with heavy radiation particles.

New and better foods were enjoyed by the Apollo crews. For the first time, warm food was provided and the astronauts ate with ordinary earth-like utensils in zero g with much success. Interestingly, however, they required less food in space than was predicted, and, partly as a consequence of this, lost weight.

Because of space limitations and technological difficulties, hygiene provisions for the Apollo crews were not markedly better than they were for any previous spacecrew. Crews did find, however, that some hygiene maintenance tasks like shaving were easier in space than they expected. As in previous flights, a medical kit was provided, but this time, because of the arrhythmias experienced by the Apollo 15 crew, injectable antiarrhythmic drugs were stowed. Fortunately, these were never used. In this mission, as in previous missions, vital signs were telemetered from space and from the lunar surface to earth. These signs were monitored at all times, including during sleep periods, which tended on the whole to be slightly shorter and slightly less restful than would have been ideal. With the aid of sleeping medications, however, most crews obtained relatively restful sleep. The few crewmen who performed inflight exercises found these aided in obtaining restful sleep. On the whole, however, the crews were exercise deficient.

The Apollo mission answered the questions raised by the medical legacy of Gemini and Mercury concerning whether the physiological changes seen were a result of confinement or a result of exposure to zero gravity. Since Apollo crews enjoyed a considerable amount of freedom of movement and experienced many of the same problems as earlier crews, confinement had to be ruled out as a factor in the etiology of physiological problems characteristic of space flight exposure. Those physiological problems which did occur during the Apollo mission were reversible postflight within two to three days in almost all crewmen with the single exception of the Apollo 15 crew. The postflight responses, and some of the inflight responses, of this crew were an anomaly in the Apollo Program. In almost all measures, this crew returned to preflight baselines more slowly than any others. They were not fully back to normal until about two weeks after splashdown.

The Apollo mission was a mission of many physiological firsts as well. For the first time, vestibular-related problems were noted. These ranged from feelings of stomach awareness to frank motion sickness with nausea and vomiting. In one instance, however, the most severe symptoms may have been related less to vestibular function than to illness. The Apollo 8 crew, two of whom experienced severe symptoms, had viral illnesses inflight. This was the first occasion on which an astronaut was ill inflight. Other minor illnesses were reported, but these were all manageable with medications available onboard and consultations with ground-based Flight Surgeons.

The other unexpected inflight disorder was a rather alarming series of cardiac arrhythmias experienced by two of the Apollo 15 crew. These arrhythmias have been linked to potassium deficits and fatigue. In one crewman, coronary artery disease also may have played a part. A program involving potassium enriched diets preflight and inflight for the Apollo 16 and 17 crews appears to have had substantial benefit in preventing the serious consequences of potassium deficits. While occasional preventricular contractions were seen in these crews, these were within the normal range, and no serious arrhythmias were noted. Crews of Apollo 11 and 12, and lunar samples from these missions, were quarantined postflight against the remote possibility of contamination of the earth's biosphere with lunar organisms. After 21 days of isolation and testing, no organisms could be identified. The experience with quarantine philosophy and procedures gained will help immeasurably when the quarantine requirement for a Mars mission must be met.

Among the physiological changes noted postflight, the most important have been (1) decreased cardiovascular responsiveness, (2) reduced red blood cell mass, (3) musculoskeletal deterioration, and (4) the vestibular changes already noted.

In the cardiovascular sphere, heart rates have tended to stabilize at lower levels in zero g. Postflight, heart rates have been elevated and normalization inhibited. With the exception of the arrhythmias mentioned, cardiac electrical activity recorded inflight has been normal. Postflight studies of the last three Apollo crews, however, suggest that some alteration takes place in electrical activity, but how and when these changes occurred inflight awaits elucidation from Skylab data. Cardiac silhouette size has been found to be decreased postflight for virtually all crewmen except the Apollo 17 Lunar Module Pilot who, incidentally, wore an antihypotensive garment during the final phases of flight. The garment may have aided in warding off cardiovascular deconditioning in this individual or, on the other hand, we may be seeing another example of the individual variability which has been a hallmark of spacecrews. Blood pressure measured postflight has been labile, generally for up to three days, again with the exception of the Apollo 15 crew who required a markedly longer normalization period. Orthostatic tolerance tests and work capacity tests which reveal cardiovascular and cardiopulmonary status postflight have consistently indicated transient deterioration. Inflight orthostatic tolerance testing and work capacity testing in Skylab should shed light upon the time course and nature of these changes as they occur during weightlessness.

The only persistent hematological changes which have occurred were transient increase in postflight white blood cell count and reduced red blood cell mass loss. The former is of little significance, but the latter may be very important. In the Apollo 15 crew these losses were not recorded until about two weeks postflight. The precise mechanism of red blood cell mass decrement is still unclear. There is evidence to suggest that both hemolysis and suppression of erythropoiesis occur, with perhaps hemolysis being the more important factor. Here, too, Skylab data should bring us closer to the answer.

Muscle mass deterioration clearly occurs during weightless space flight. This is confirmed postflight by reduced limb girth and negative nitrogen and potassium balances. Inflight samples collected on Apollo 17 confirm a loss of body protein. There is some evidence, using various investigative tools, to suggest that slight losses of bone minerals are also occurring.

The vestibular problem already discussed occasioned some concern for the future. Future spacecrews may be even more prone to vestibular disturbance than Apollo crews have been because many will be drawn from the nonmilitary, scientist population and cannot be expected to have the required resistance to motion sickness that people with test pilot experience, like the Apollo astronauts have. As a consequence, the possibility of preadapting the vestibular responses of such individuals to the effects of zero gravity is being studied. Additional studies are needed in this area to provide definitive answers.

In addition to the key physiological findings discussed above, other changes have been seen in conjunction with space flight experience.

The diet of Apollo astronauts was adequate in terms of calories, vitamins, and minerals provided. However, crewmembers lost weight as a result of a hypocaloric regimen inflight and as a result of the tendency to lose body tissue under hypogravic conditions. Apollo crewmen lost an average of about six pounds per man. About 60 percent of this weight loss can be attributed to water loss, about 30 percent to fat loss, and about 10 percent to loss of muscle mass. Because of the deficits in total body potassium noted postflight, Skylab foods have been designed so that they are naturally richer in potassium. These diets are providing between 85 and 100 meq per day of potassium. Metabolism was measured only indirectly for Apollo crews during weightless space flight. On the lunar surface, energy production was inferred from the heat produced in the liquid cooling garment of the lunar activity suit. The hourly average energy production on the moon was estimated to be between 900 and 1200 BTU's.

Characteristic features of the endocrine-electrolyte response to space flight in Apollo crews were elevated aldosterone production and fluid compartment shifts. Increased aldosterone production appears to be one manifestation of man's adaptation to prolonged weightlessness. Fluid compartment losses have varied from crew to crew. A comparison of Apollo 14 and 17 fluid shifts illustrates this variability. In Apollo 14 the principal fluid loss was intracellular fluid. Apollo 17 findings were diametrically opposed, with intracellular fluid actually increasing in volume.

No changes have been seen in the immunological sphere which would suggest any alteration in man's ability to combat infection or repair traumatized tissue in a space flight environment or after return to earth. His microflora have undergone some changes. There seems to be a general decrease in anaerobic bacteria and an increase in aerobic bacteria. Organisms, especially Staphylococcus aureus, tend to spread across crewmembers. Fungal isolates have decreased in number and higher carrier states are indicated for mycoplasma. Twenty organisms of medical significance have been isolated from Apollo crews. While the etiology of the changes is unclear, they are not of a character to cause any undue concern. It should be noted, however, that the microbial loads returned to preflight norms during the early postflight period.

At the close of the Apollo Program, sufficient information was available to form the basis of a hypothesis concerning man's adaptive response to weightlessness. This is basically a three stage process. The first stage is a "stress" stage wherein the body responds to a redistribution in circulating blood volume by decreasing antidiuretic hormone secretion and aldosterone production in an effort to reduce fluid volume. This presumably would result in a diuresis. Inflight samples, however, taken on Apollo 17, showed no evidence of this postulated diuresis. The next stage of the process, the adaptation stage, is thought to be characterized by a loss of water and salt, and a concomitant loss of body weight. This produces a secondary aldosteronism. Again, however, Apollo samples indicated no saluresis. Following the increase in aldosterone production, salts are thought to be retained while potassium loss continues with an intracellular exchange of potassium and hydrogen ions. This change might affect cardiac muscle. Respiratory and renal compensation are then thought to halt the weight loss trend at which point the body enters the adaptive stage wherein it is stabilized with a new effective circulating blood volume and electrolyte balance. We believe it is in this stage that we find man after about two weeks of space flight exposure. Clearly, certain contradictions exist in this theory. It is hoped that Skylab results will qualify these and give us a clear picture of man's adaptive response to zero g. In order to do this, it will be necessary to follow each of these changes from the baseline for a sufficient time following flight to ensure return to the preflight baseline. This has not always been done.

Data from the Apollo Program has provided a sound basis upon which to commit man to two months of space flight. After two months' exposure during the Skylab mission, we should have a sufficiently sound basis upon which to predict if man can tolerate space flight habitation for the period of time required to complete a Mars mission, about two and one-half years. I personally believe that six months of inflight data would provide an adequate basis for safe projection. In this time, all physical changes of a progressive nature could be identified. Certainly any aspects of the environment which have deleterious effects, both physiological and psychological, would become obvious. Once we understand the mechanism of man's response to space, and the Apollo Program has provided a fund of information toward this end, we will be able to provide man with the proper biomedical support to enable him to venture still further into the solar system.

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