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CHAPTER 7
SKELETAL RESPONSE

by

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Introduction

Derangements of bone mineral metabolism can be considered to be one of the major threats to the health of crewmen on prolonged missions.

The integrity of bone and the maintenance of a skeleton capable of resisting the stresses of everyday life are functions of several factors (Hattner & McMillan, 1968):

1. The pulling forces that are exerted on bone by its attached muscles.
2. The forces that are exerted along the longitudinal axis of the skeletal system by gravity.
3. The piezoelectric forces.
4. The hydrostatic forces that permit the proper flow of blood with its nutrient materials to, and the waste products from, the bone.

This complex set of stimuli is balanced to provide a bone structure capable, by its chemical composition as well as by its architectural deployment of these materials, of supporting the organism and resisting the forces against which the organism must function. Bone is a living organ that is continuously remodeling itself. When mechanical forces applied to the skeleton during normal activity in a one-g environment are removed, bone mineral is lost because bone resorption is allowed to outstrip bone formation. This factor represents a danger not only because of the risk of fracture in demineralized bones, but also because the associated increased urinary calcium excretion might lead to the formation of kidney stones.

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*Now with Bureau of Foods, Food and Drug Administration.

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Early radiographic densitometric studies in Gemini by Mack and co-workers (1967) revealed significant bone mineral losses in the os calcis, radius, and phalanges of crewmen who were exposed to varying short periods of weightlessness. Because the degree of loss appeared excessive for such short periods of weightlessness, further evaluation of the data led to a lower estimate of loss (Vose, 1974).

It is necessary, however, to view the Gemini and early Apollo results with an appreciation of the problems inherent in the measurement techniques used in Gemini 4, 5, and 7, and Apollo 7 and 8. X-ray densitometry – with its attendant problems of a polychromatic energy beam, film characteristic changes, film development variables, and ultimate translation of film density to digital analysis – has many sources of error. Many of the problems associated with the radiographic technique are amplified when measurements are to be made at a variety of locations with wide differences in temperature, humidity, power sources, and equipment, as was the case with the earlier studies.

A photon absorptiometric technique (Witt et al., 1970; Vogel & Anderson, 1972) that does not suffer from these problems was investigated by applying it to a series of bed rest studies (Donaldson et al., 1970; Hulley et al., 1971; Hantman et al., 1973). The results showed the technique to be suitable for the measurement of later Apollo crews (Rambaut et al., 1972). Apollo 14 was to include postflight quarantine, and neither the X-ray densitometric nor photon absorptiometric techniques had previously been adapted to these conditions. Because the crew was to be isolated preflight and quarantined postflight, a device had to be designed that was compact, required minimal storage area, was adaptable to measuring mineral in representative upper and lower extremity bones, and was sufficiently portable for use preflight at the Lyndon B. Johnson Space Center and the John F. Kennedy Space Center, and postflight in the Mobile Quarantine Facility aboard the recovery carrier and in the quarantine area of the Lunar Receiving Laboratory (LRL) at JSC. Because no changes were seen, the procedure was not applied to Apollo 17 crewmen.

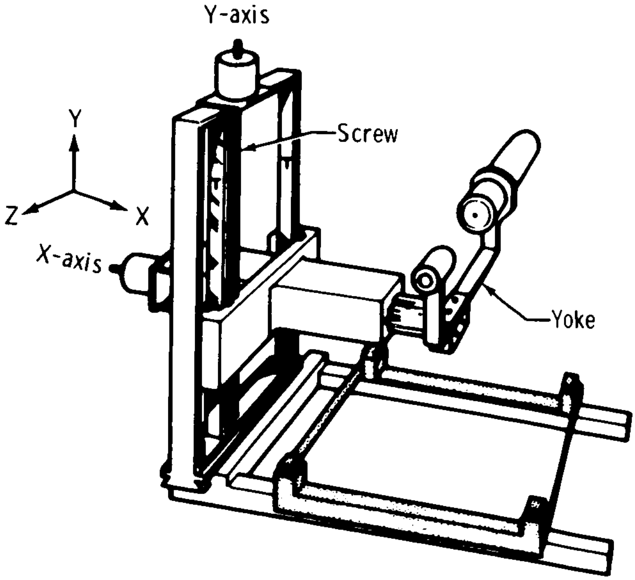
Methods and Materials

The rectilinear bone mineral scanner designed and built for the Apollo missions was compact, easily disassembled, and had the capacity for operation in two configurations: heel scanning (figure 1) and arm scanning (figure 2). The unit consisted of a scanning yoke, an apparatus for moving the yoke, and devices for positioning the limb to be scanned.

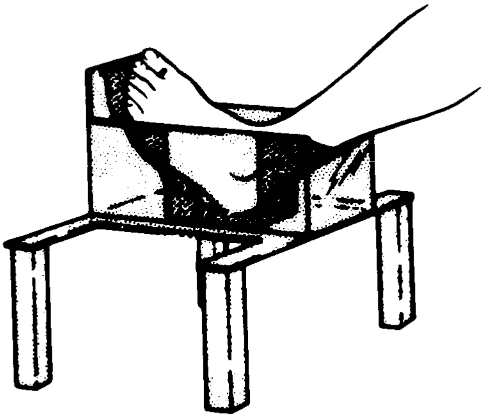
The scanning yoke held a collimated source and collimated detector 13 cm apart with the apertures aligned in direct opposition. The source contained 1480 x 10^{10} disintegrations/second (400-millicurie) iodine-125 and was shielded, except for a 3 mm-diameter collimator output hole. The detector was a sodium iodide scintillator mounted in a housing collimated to 3 mm. The limb to be scanned was placed between the source and detector. The yoke was attached to a movable ram by means of a special mounting stud that allowed for two different mounting configurations [figures 1(a) and 2(a)].

Rectilinear scanning was accomplished by moving the yoke sequentially in two directions. First, a traverse of the ram into and out of its housing constituted a row during which data were collected (X-axis). Second, a movement by the Y-axis unit at the completion of each row constituted an increment during which no data were collected.

The beam of radiation was oriented parallel to the Z-axis. The conversion of the scanner from one configuration to the other required a 90° rotation of the frame with respect to the base and a 90° rotation of the yoke with respect to its mounting stud.

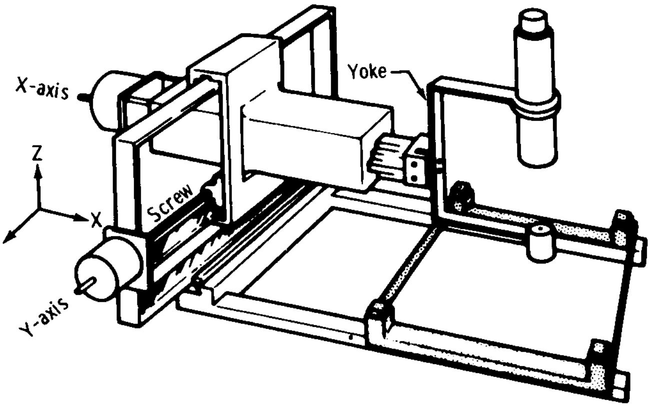


(a) Diagram of heel scanner

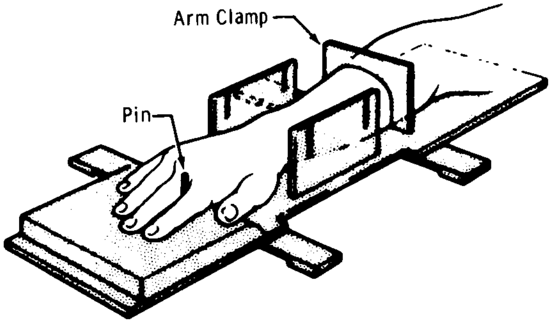


(b) Diagram showing heel mounted and ready for scanning

Figure 1. Heel scanner.



(a) Diagram of arm scanner



(b) Diagram showing arm mounted
and ready for scanning

Figure 2. Arm scanner.

A row of data collected during the X-axis traverse contained 256 points, each point representing an interval of 0.397 mm for a total row width of 10.16 cm. After the completion of each row, the ram and yoke were moved by 3.0 mm increments along the Y-axis. (This length is standard for Y-axis increments.) A full scan was completed when 16 rows of data or 4096 data points had been collected.

The devices that held the limbs stable and in position for scanning consisted of two interchangeable tables on a common base that slid on the scanner legs for positioning. The base was locked into position by locking thumbscrews.

All scans were made of the left os calcis, with the heel resting in a foot mold mounted in a plastic box on a table [figure 1(b)]. The plastic foot mold was fashioned from an impression of each subject's foot made before the study. The box was filled with water to provide a constant tissue-equivalent path length. The scan was started at a point determined from an initial radiograph to include the entire central os calcis in 16 parallel rows, each spaced 3 mm apart (figure 3).

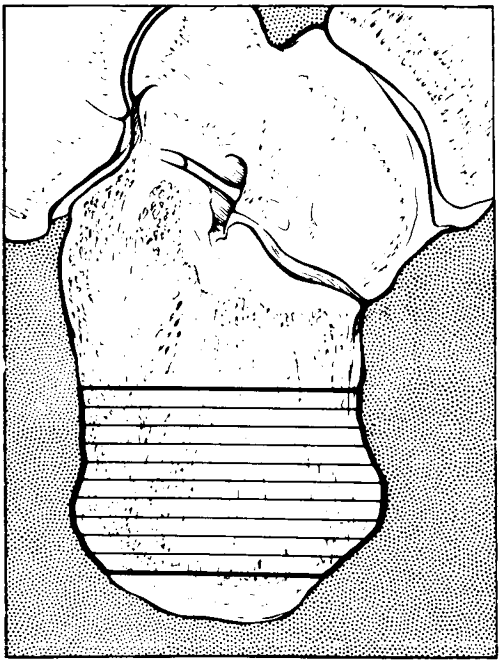


Figure 3. Schematic representation of os calcis scan rows.

During arm scanning, the arm lay horizontally between two plastic vertical uprights on the arm table top [figure 2(b)]. Pegs in a movable handrest positioned and held the arm with the ulnar styloid opposite a reference point in the upright. To maintain a constant tissue-equivalent path length, the arm was surrounded by Superstuff (Oil Center Research, Lafayette, Louisiana) and covered with a thin sheet of plastic. Sixteen rows were scanned at 3-mm intervals beginning 2 cm proximal to the level of the ulnar styloid.

Bone scans using the photon absorptiometry technique were made for the crews of Apollo 14, 15, and 16 approximately one month, two weeks, and one week before flight. Four postflight measurements were made for each crew. No bone studies were performed on the crews of Apollo 9 through 13. During the postflight period of Apollo 14, because of the space restrictions in the Mobile Quarantine Facility and the isolation restrictions of the Lunar Receiving Laboratory, only a single scanner could be deployed in each of these areas. For this reason, arm and heel scans were performed separately using the same scanner in each of the two configurations. The scanner setup was performed by the Flight Surgeon. The data acquisition electronics were located outside of the quarantine area with passthrough cable connectors installed previously in the bulkhead of the Mobile Quarantine Facility and the wall of the crewmen's communication and visiting area of the Lunar Receiving Laboratory. On the two subsequent missions, arm and heel studies were performed simultaneously both preflight and postflight, because quarantine was no longer required.

Results

In general, no mineral losses were observed in the os calcis, radius, and ulna during the 10-day Apollo 14 flight (tables 1, 2, and 3). The Lunar Module Pilot (LMP) had a change of mineral in the central os calcis of +3.5 percent when immediate preflight and postflight measures were compared, in contrast to the -0.7 percent for the Commander (CDR), and +1.5 percent for the Command Module Pilot (CMP). The preflight measurements varied from +0.8 to -1.1 percent of mean baseline for all three crewmembers. In contrast, there was a greater variation in the three controls of +1.8 to -2.8 percent. Postflight measurements for control subjects 1, 2, and 3 were +2.9, -3.1, and -1.0 percent of mean baseline.

Table 1

Apollo 14 Left Os Calcis Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	LMP	CMP	1	2	3
F – 26	+0.7	+0.2	+0.2	–1.8	+0.6	+1.0
F – 15	–1.1	– .3	+ .8	+1.5	–1.5	–2.8
F – 6	+ .3	+ .2	+1.0	+ .3	+ .9	+1.8
R – 8	–	–	–	– .5	+ .9	–
R – 2	–	–	–	.0	–	–
R + 10**	– .4	+3.7	+ .5	–	–	–
R + 30**	–	+3.3	–	–	–	–
R + 6	–2.6	+5.9	+ .2	+2.9	–	–
R + 16	–1.0	+4.8	+1.2	.0	–	–
R + 18	–	–	–	–	–3.1	–1.0

*Based on hydroxyapatite equivalency in mg/cm^2: mean value for nine rows scanned.
**Hours.

The radius measurements postflight ranged within the values obtained preflight (table 2). When immediate preflight values were compared to postflight values, there were -0.7, +2.2, and -0.3 percent changes for the CDR, LMP, and CMP, respectively.

The ulna mineral content was somewhat more variable, but postflight values were essentially within the preflight range (table 3). When immediate preflight and postflight values were compared, there were -3.6, -2.9, and -5.2 percent changes for the CDR, LMP, and CMP. These changes appear to be large; however, there was a ±2.5 to 3.0 percent variation preflight for the CDR and LMP and a -7.2 to +5.7 percent variation for the CMP. This latter variation appears to be instrumental rather than real.

Table 2

Apollo 14 Right Radius Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	LMP	CMP**	1	2	3
F – 26	–0.7	–3.5	–5.3(– –)	–1.6	–1.5	–3.9
F – 15	+ .1	+4.1	+3.5(+ .8)	+ .3	+ .1	+1.1
F – 6	+ .6	– .7	+1.8(– .8)	+1.3	+1.0	+2.8
R – 6	–	–	–	– .6	+ .5	–
R + 1	– .1	+1.5	+1.5(–1.1)	–	–	–
R + 6	– .4	+1.4	+3.5(+ .9)	+2.3	–	–
R + 16	+ .3	+3.4	+3.3(+ .7)	+1.8	–	–
R + 18	–	–	–	–	+2.2	+4.7

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*Based on corrected computer unit values.

**Percent values in parenthesis based on only 2 baseline values; the first being omitted.

Table 3

Apollo 14 Right Ulna Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	LMP	CMP**	1	2	3
F – 26	–2.1	–0.1	–7.2(– –)	–1.5	–1.5	–0.1
F – 15	+ .1	–2.5	+1.5(–2.0)	+1.8	– .9	+1.1
F – 6	+2.0	+2.6	+5.7(+2.0)	– .3	+2.3	– .9
R – 6	–	–	–	–1.0	+3.4	–
R + 1	–1.6	– .3	***	–	–	–
R + 6	+3.0	–2.7	+ .3(–3.2)	+1.1	–	–
R + 16	– .3	0	– .5(–3.8)	–2.0	–	–
R + 18	–	–	–	–	– .5	–2.0

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*Based on corrected computer unit values.

**Percent values in parenthesis based on only two baseline values; the first being omitted.

***No match in ulna width. Data not valid.

A significant increase in fat was observed on the plantar side of the os calcis. Changes were seen in all crewmen immediately postflight. The most significant change was in the CMP's measurement at ten hours after recovery (R+10). There was a 34 percent increase in fat equivalence when compared to the immediate preflight measurement. This increase would have resulted in a 4.3 percent overestimation of bone mineral if the soft tissue contribution had not been measured. In contrast, the CDR had an 8.4 percent increase and the LMP an 8.1 percent increase with a potential 2.2 to 2.5 percent overestimation in mineral.

As with the Apollo 14 crew, no mineral losses were observed during the 11-day Apollo 16 flight. The left os calcis mineral values immediately postflight were +1.2, +0.4, and +0.4 percent of mean baseline for the CDR, CMP, and LMP, respectively (table 4). The four controls measured on the day before recovery were -0.6, +1.5, +2.5, and -0.3 percent of mean baseline. Therefore, no changes can be attributed to the flight.

Table 4

Apollo 16 Left Os Calcis Mineral Content Change
(Percent change from mean baseline)

Time (Days)	Crewmen			Control Subjects			
	CDR	CMP	LMP	1	2	3	4
F – 30	–0.4	–0.5	+1.0	–0.1	+2.3	–0.8	+1.9
F – 15	– .1	+ .1	– .9	+1.4	– .5	+1.7	–1.2
F – 5	+ .5	– .3	– .2	–1.3	–1.8	–1.0	– .7
R – 2	—	—	—	+ .4	– .3	0	– .1
R – 1	—	—	—	– .6	+1.5	+2.5	– .3
R + 4 to 7*	+1.2	+ .4	+ .4	—	—	—	—
R + 24*	–1.0	–1.5	+1.4	—	—	—	—
R + 3	– .4	–2.5	– .8	– .7	– .2	+ .5	–1.1
R + 7	—	–1.4	—	+2.4	+1.6	+2.4	+ .3

*Hours

The distal radius mineral measurements immediately postflight were +1.0, +2.1, and +1.5 percent of mean baseline for the CDR, CMP, and LMP, respectively (table 5). The four controls were +0.1, +0.1, +0.5, and 0.0 percent of mean baseline on the day before recovery. These values are within the ±2 percent accuracy of the technique, and no radius mineral losses can therefore be attributed to the flight. The distal right ulna values immediately postflight were -2.2, -3.5, and -3.3 percent of mean baseline for the CDR, CMP, and LMP, respectively (table 6). Similar values (-2.8, -2.9, -0.5, and -2.7 percent) were observed in the controls on the day before recovery. It is, therefore, reasonable to conclude that there were no significant changes from preflight in the Apollo 16 crew.

The Apollo 15 data differed somewhat from that obtained on Apollo 14 and 16 in that two crewmen lost mineral from the left central os calcis during this mission (table 7).

When compared with the mean baseline values, there were -6.6, -7.3, and -0.5 percent changes in the CDR, CMP, and LMP, respectively. The changes for control subjects 1, 2, and 3 were +0.3, -0.2, and -2.8 percent, respectively. The CDR regained his mineral more rapidly than the CMP, and both were near baseline values by the end of two weeks. The magnitude of these losses must be evaluated in terms of the variability in the controls observed during the postflight period. Taken in this context, the losses exhibited by the CDR and CMP could more likely reflect losses of about 5 to 6 percent.

Table 5

Apollo 16 Right Radius Mineral Content Change
(Percent change from mean baseline)

Time (Days)	Crewmen			Control Subjects			
	CDR	CMP	LMP	1	2	3	4
F – 30	+0.3	+0.2	+1.6	–0.2	–0.2	+0.8	+2.7
F – 15	+ .1	+1.2	– .3	+ .3	0	+ .3	– .7
F – 5	– .4	–1.4	–1.3	– .1	+ .3	–1.1	–2.0
R – 2	–	–	–	– .5	–1.6	–1.6	+ .1
R – 1	–	–	–	+ .1	+ .1	+ .5	0
R + 4 to 7*	+1.0	+2.1	+1.5	–	–	–	–
R + 24*	– .9	+2.0	–1.4	–	–	–	–
R + 3	+1.0	– .9	– .2	+1.0	–1.0	–1.2	+1.3
R + 7	–	+1.1	–	+ .5	–1.2	+ .6	– .3

*Hours

There were essentially no changes in radius mineral during flight, namely -1.1, -2.3, and -1.0 percent for the CDR, CMP, and LMP, respectively (table 8). Changes for control subjects 1, 2, and 3 were -1.6, -0.9, and +0.1 percent, respectively. Also, the crew's ulna mineral changes were not significant when compared with the control subjects (table 9). Immediate postflight values differed from the mean preflight by -1.4, -3.6, and -1.8 percent for the CDR, CMP, and LMP, respectively. Changes for control subjects 1, 2, and 3 were +0.6, +0.1, and -2.2 percent, respectively. The -3.6 percent mineral change in the CMP may be significant, but he was +1.4 percent of the mean baseline the following day. As noted in the Apollo 14 and 16 crews, there is a greater variation in the ulnar mineral determinations, the cause of which is unknown.

Whereas there were signficant changes in the soft tissue composition in the CMP of Apollo 14, there were no significant changes in any of the Apollo 15 or 16 crewmembers.

Table 6

Apollo 16 Right Ulna Mineral Content Change
(Percent change from mean baseline)

Time (Days)	Crewmen			Control Subjects			
	CDR	CMP	LMP	1	2	3	4
F – 30	–1.3	+0.4	+1.2	+0.8	+0.4	+0.5	+2.5
F – 15	+ .1	– .5	+1.6	– .4	– .5	+1.0	–2.1
F – 5	+1.2	+ .2	–2.8	– .4	+ .1	–1.4	– .4
R – 2	–	–	–	–3.2	–5.2	+1.7	– .8
R – 1	–	–	–	–2.8	–2.9	– .5	–2.7
R+4to7*	–2.2	–3.5	–3.3	–	–	–	–
R + 24*	–1.1	+1.5	+1.7	–	–	–	–
R + 3	–1.0	+ .3	–4.7	+1.1	– .6	+1.8	+2.6
R + 7	–	–1.8	–	+ .6	–1.4	+3.2	+2.5

*Hours

Table 7

Apollo 15 Left Os Calcis Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	CMP	LMP	1	2	3
F – 27	+0.1	–0.9	+0.1	–0.7	–1.7	0
F – 13	– .2	+ .4	– .2	+ .6	+2.0	+ .3
F – 5	+ .1	+ .5	+ .1	+ .1	– .3	– .3
R – 2	–	–	–	–2.2	–1.1	–1.0
R + 0	–6.6	–7.3	– .5	–	–	–
R + 1	–3.1	–5.7	–1.0	+ .3	– .2	–2.8
R + 5	–2.4	–3.5	– .08	–1.7	–1.3	–2.4
R + 14	–1.4	–1.7	–	–	+2.0	+ .5

*Based on mg/cm^2 of hydroxyapatite in nine rows of the central os calcis.

Discussion

The purpose of this study was to determine the effect of weightlessness on bone during prolonged space exploration. Ground-based studies designed to mimic the altered physiologic state were used to construct a time-effect curve. Bed rest, which most closely models the weightless state at least as far as the musculoskeletal system is concerned, has served as an experimental model to assess the bone mineral changes observed during bed rest periods of up to 36 weeks, and to determine what remedial measures might be used to stem the tide of bone mineral loss. The loss of bone mineral in the bedridden patient has long been recognized. Contrary to previous reports, total recovery does occur (Donaldson et al., 1970). Because of the combined effects of immobility and weightlessness, losses of bone mineral in flight were expected to be, if anything, more severe than were seen in bed rest.

Table 8

Apollo 15 Right Radius Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	CMP	LMP	1	2	3
F – 27	+0.4	+0.7	+0.2	+0.9	+2.5	+1.7
F – 13	+ .8	– .3	+ .1	–1.0	–1.7	0
F – 5	–1.1	– .4	– .3	0	– .8	–1.7
R + 2	–	–	–	–3.5	–4.0	–1.1
R – 0	–1.1	–2.3	–1.0	–	–	–
R + 1	–4.7	–2.6	–3.3	–1.6	– .9	+ .1
R + 5	– .1	– .6	+1.6	–2.5	– .5	–1.3
R + 14	+ .1	– .3	–	–	–1.3	–2.5

*Based on gm/cm of bone mineral as derived by Cameron.

Table 9

Apollo 15 Right Ulna Mineral Content Change
(Percent change from mean baseline*)

Time (Days)	Crewmen			Control Subjects		
	CDR	CMP	LMP	1	2	3
F – 27	+0.6	+0.4	+0.5	+1.3	+2.1	+3.7
F – 13	– .8	+ .1	–2.1	+2.4	– .7	–3.2
F – 5	+ .3	– .5	+1.7	–3.8	–1.3	– .4
R – 2	–	–	–	–1.3	–2.8	–1.2
R + 0	–1.4	–3.6	–1.8	–	–	–
R + 1	0	+1.4	+2.1	+ .6	+ .1	–2.2
R + 5	+ .9	+ .5	–2.1	–3.3	–5.0	+ .4
R + 14	0	+1.4	–	–	–1.0	+ .7

*Based on gm/cm of bone mineral as derived by Cameron.

The early reports of significant bone mineral losses in the five- to fourteen-day Gemini and Apollo flights served to emphasize the need for correlating the bed-rest-induced mineral losses with those observed during varying periods of weightlessness. Time-effect curves for both situations needed to be established so that better estimates could be obtained on the risk of prolonged space flight as translated from the ground-based bed rest studies.

Using a gamma photon absorptiometric technique, a time-effect curve was constructed for the bed rest state. The following conclusions were derived:

1. Periods of up to 36 weeks of bed rest can account for a 40 percent mineral loss from the central os calcis (Donaldson et al., 1970). This bone is highly trabecular, as well as weight bearing. In contrast, the ulna and the radius (primarily cortical and non-weight-bearing bones) failed to exhibit mineral losses during periods of up to 30 weeks of bed rest (Vogel et al., 1974). It is acknowledged that the muscular forces may not have been reduced in the case of the radius and that the hydrostatic forces may not have been sufficiently altered to result in a breakdown in homeostasis.

2. The amount of initial mineral content in the os calcis can influence the rate of mineral loss (Vogel et al., 1974). In a study of 19 subjects on 17 to 36 weeks of bed rest, two groups of subjects emerged: those who exhibited a high mineral content at the onset and eventually lost the least mineral both in percent and in quantity, and those who exhibited a low mineral content at the onset and lost at a greater rate than the other group.

3. The rate of mineral loss in general, but not in all cases, was greatest during the second 12 weeks of bed rest and the least after the 24th week.

4. The mean rate of mineral loss in the os calcis was approximately 5 percent per month, in contrast to a whole body calcium loss of 0.5 percent per month (Donaldson et al., 1970). Therefore, the os calcis is not representative of all the bones in the body, and weight-bearing bones are more inclined to lose mineral in the recumbent state than the non-weight-bearing bones.

5. The rate of mineral regain after reambulation follows a pattern roughly similar to that of the loss; that is, if the maximal loss took 24 weeks, regain to baseline also took approximately 24 weeks.

6. Little or no os calcis mineral loss was observed in less than 21 days of bed rest and often was not observed until after 15 weeks (table 10).

From these data, a predictive model was established for the bed rest situation. In this model, the ratio of initial mineral content to the initial 24-hour urinary hydroxyproline excretion is related to observed losses (Lockwood et al., 1972). The greater this ratio, the slower and smaller the losses and, conversely, the smaller the ratio, the faster and greater the losses. The accurate measurement of baseline 24-hour urinary hydroxyproline excretion is, therefore, an essential requirement for this prediction term.

Because of the limited available data, no time-response curve could be established for the weightless state. It appears, however, that the time-response curve obtained from the bed rest studies may be more prolonged with respect to the time of onset of demineralization than is observed in true weightlessness (Donaldson et al., 1970; Hulley et al., 1971; Hantman et al., 1973). Yet, this does not appear to be true for all crewmen; in particular, the Apollo 14 and 16 crewmen and the LMP of Apollo 15 had no mineral losses in the os calcis in 10 to 21 days.

Table 10

Left Os Calcis Mineral Content Changes During Bed Rest
(19 subjects – 29 measurements)

Days of Bed Rest	Subject	Percent of Baseline	Days of Bed Rest	Subject	Percent of Baseline
7	G.F.	+2.1	23	A.D.	−4.5
7	B.L.	− .6	24	R.B.	+ .8
7	R.W.	0	24	J.F.	−2.4
8	T.A.	−1.5	24	D.M.	− .6
8	A.K.	−1.4	24	M.H.*	+1.0
9	R.G.	−1.2	25	F.C.	+ .2
10	M.H.	− .8	25	J.C.	−1.9
14	J.G.	−2.3	25	W.R	+2.1
16	F.K.	− .5	28	G.M.	+1.2
17	F.B.	0	30	F.B.*	+ .4
17	R.R.	+ .5	30	J.G.*	−2.5
21	G.F.*	− .2	30	R.R.*	−1.3
21	B.L.*	−5.1	31	R.G.*	−3.2
22	T.A.*	+3.3	31	F.K.*	−4.1
22	A.K.*	−2.6			

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*Os calcis mineral change was measured twice for particular subject.

Repetitive studies of normal ambulatory males carried out over six to eight months exhibited a 0.9 to 1.5 percent standard deviation from the mean in repetitive measurements performed every two to three weeks (table 11). Furthermore, control subjects 1 and 2 studied during the Apollo 14, 15, and 16 missions had maximal variations from their mean values of -2.7 to +2.1 percent for control subject 1 and -2.4 to +2.1 percent for control subject 2 (table 11). Therefore, it seems reasonable that not only did the six Apollo 14 and 16 crewmen and the LMP of Apollo 15 fail to lose calcaneal mineral (table 12), but that the 2.9 and 2.8 percent losses for the Gemini 7 crewmen, 2.1 and 3.0 percent losses for the CDR and CMP of Apollo 8 and 0.8 and 2.3 percent gains for the LMP and CMP of Apollo 7 could also represent minimal or no losses from this bone (table 13).

These data must be contrasted to the 7.8 and 10.3 percent losses in Gemini 4, 15.1 and 8.9 percent losses in Gemini 5, 7.0 percent loss for the LMP on Apollo 8, 5.4 percent

Table 11

Bone Mineral Content of Left Os Calcis

Control Subject	Date	Mineral Content, mg/cm^2	Mean ± Standard Deviation in —	
			mg/cm^2	Percent
		Apollo 14		
1	Jan. 4, 1971	493.74	488.70 ± 8.8	1.8
	Jan. 15, 1971	483.29		
	Jan. 24, 1971	495.37		
	Feb. 2, 1971	495.39		
	Feb. 27, 1971	475.69		
2	Jan. 4, 1971	634.68	625.63 ± 11.71	1.9
	Jan. 15, 1971	610.30		
	Jan. 24, 1971	639.77		
	Feb. 18, 1971	621.27		
	Feb. 27, 1971	622.12		
		Apollo 15		
1	June 27, 1971	476.45	483.89 ± 7.1	1.5
	July 13, 1971	493.93		
	July 20, 1971	482.95		
	Aug. 5, 1971	478.88		
	Aug. 9, 1971	483.61		
	Aug. 12, 1971	478.12		
	Aug. 19, 1971	493.86		
2	June 27, 1971	632.03	626.17 ± 8.3	1.3
	July 12, 1971	633.73		
	July 19, 1971	630.16		
	Aug. 5, 1971	625.81		
	Aug. 9, 1971	614.26		
	Aug. 12, 1971	616.69		
	Aug. 20, 1971	635.17		
		Apollo 16		
1	Mar. 16, 1972	486.49	487.74 ± 6.4	1.3
	Mar. 30, 1972	493.58		
	Apr. 9, 1972	480.22		
	Apr. 25, 1972	488.29		
	Apr. 26, 1972	483.82		
	Apr. 30, 1972	483.36		
	May 4, 1972	498.59		
2	Mar. 16, 1972	631.03	617.90 ± 6.7	1.1
	Mar. 30, 1972	611.61		
	Apr. 9, 1972	614.42		
	Apr. 25, 1972	618.43		
	Apr. 26, 1972	616.96		
	Apr. 30, 1972	611.95		
	May 4, 1972	620.87		

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loss for the CDR on Apollo 7 (table 13), and the reported losses of 6.6 and 7.3 percent for the CDR and CMP of Apollo 15 (table 12). The 6.7 and 7.3 percent mineral losses for the 12-day mission (Apollo 15) are in line with losses observed during the 18-day Soyuz 9 mission where there was no interlude of lunar gravity (1/6 g) (Biriukov & Krasnykh, 1970).

Table 12

Bone Mineral Changes During Apollo 14, 15, and 16
(Photon absorptiometric technique, percent change)
from mean baseline)

Mission	CDR	LMP	CMP
Central Left Os Calcis			
Apollo 14	−0.4	−3.7	+0.5
Apollo 15	−6.6	− .5	−7.3
Apollo 16	+1.2	+ .4	− .4
Distal Right Radius			
Apollo 14	−0.1	+1.5	+1.5
Apollo 15	−1.1	−1.0	−2.3
Apollo 16	+1.0	+1.5	+2.1
Distal Right Ulna			
Apollo 14	−1.6	−0.3	+0.3*
Apollo 15	−1.4	−1.8	−3.6
Apollo 16	−2.2	−3.3	−3.5

*R + 1 measurement

Losses of this magnitude did not occur in bed rest subjects until after the tenth week; very little significant change was evident until the fourth to sixth week of bed rest. This appears to be similar to the comparisons made by Biriukov and Krasnykh (1970) who considered the Soyuz 9 flight to be similar to their 62- to 70-day bed rest confinement. Krasnykh's studies of 70- to 73-day bed rest subjects (1969) resulted in an observed average loss of 11.1 percent in five subjects, without total recovery occurring after 20 to 40 days of reambulation. This observation appears to be similar to the authors' studies where an average loss of 10.5 percent was observed in eight subjects after ten weeks of bed rest, with recovery after reambulation requiring a time approximately equivalent to the duration of bed rest.

Clearly, there are no known experimental differences to account for all of these observations. Only in Apollo 14, 15, and 16 were there exposures to 1/6 g for short periods of time. Of the six crewmen who experienced such an exposure, only the CDR of Apollo 15 had mineral losses in the os calcis, and he experienced a more rapid recovery than the CMP who had no such exposure. Yet, the CMP for Apollo 14 and 16 did not experience any mineral losses. Of the nine crewmen studied, the CDR and CMP of Apollo 15 had the greatest baseline mineral content; that is, 706.2 and 704.7 mg/cm^2, respectively, while the LMP had 576.3 mg/cm^2. The Apollo 14 crew had 562.0, 520.4, and 673.1 mg/cm^2, and the Apollo 16 crew had 606.3, 601.4, and 532.6 mg/cm^2. The losses experienced during Apollo 15 are at variance with the bed rest observations.

Table 13

Gemini 4, 5, and 7 and Apollo 7 and 8
Bone Mineral Changes During Flight

Mission	CP* (percent)	P** (percent)	CDR (percent)	LMP (percent)	CMP (percent)
Central Os Calcis					
Gemini 4	− 7.8	−10.3			
Gemini 5	−15.1	− 8.9			
Gemini 7	− 2.9	− 2.8			
Apollo 7			−5.4	+ 0.8	+ 2.3
Apollo 8			−2.1	− 7.0	− 3.0
Distal Radius					
Gemini 5	−25.3	−22.3			
Apollo 7			−3.3	+ 3.4	− 3.6
Apollo 8			−8.8	−11.1	−11.4
Distal Ulna					
Apollo 7			−3.0	+ 2.1	− 3.4
Apollo 8			−6.4	−12.4	−16.2

*Command Pilot
**Pilot

The level of dietary calcium and phosphorus appears to have some effect on the rate of mineral loss in bed rest subjects (Mack & LaChance, 1967). Some initial protective effect is observed when supplemental calcium and phosphorus are administered (Hantman et al., 1973). In examining the data available, the calcium intake could be considered low only in the case of the crews of Gemini 4 and 5, the crew of Apollo 8, the CDR of Apollo 7, and the CMP of Apollo 16; all others had an excess of 700 mg of calcium in their diet (table 14). Additional exercise could have been a factor during Gemini 7 and the Apollo missions as well as on Soyuz 9. Nevertheless, at this time, no clear-cut pattern can be developed from the data available.

The results of the later Apollo studies contrast most sharply with the previously reported flight mineral data in Gemini and Apollo in the case of the radius and ulna. In none of these missions were there any significant losses in either of these bones for any of the crewmen or controls. In these studies, the most distal area of the ulna and radius, where the two bones are distinctly separated, was measured. This is the more trabecular area of these bones. As shown in table 13, there were variations in Apollo 7 of -3.3, +3.4, and -3.6 percent for the radius and -3.0, +2.1, and -3.4 percent for the ulna. These data are not particularly different from the data of -0.1, +1.5, and +1.5 percent for the radius and -1.6, -0.3, and +0.3 percent for the ulna on Apollo 14; 0.0, -0.7, and -1.9 percent for the radius and -1.7, -3.5, and -3.1 percent for the ulna on Apollo 15; and +1.0, +1.5, and +2.1 percent for the radius and -2.2, -3.3, and -3.5 percent for the ulna on Apollo 16 (table 14). In contrast, the reported values for Gemini 5 were -25.3 and -22.3 percent for the radius with no data available for the ulna, and those for Apollo 8 were -8.8, -11.1, and -11.4 percent for the radius and -6.4, -12.4, and -16.2 percent for the ulna. Data for these two bones have not been reported for Soyuz 9, and, to date, no data have been reported for Soyuz 11.

Table 14

Bone Mineral Change Related to Calcium Intake

Mission	Crewmen	Calcium (mg)	Os Calcis (percent)	Radius (percent)	Ulna (percent)
Gemini 4	CP	679	– 7.8	–	–
	P	739	–10.3	–	–
Gemini 5	CP	373	–15.1	–25.3	–
	P	333	– 8.9	–22.3	–
Gemini 7	CP	945	– 2.9	–	–
	P	921	– 2.8	–	–
Apollo 7	CDR	644	– 5.4	– 3.3	– 3.0
	LMP	925	+ .7	+ 3.4	+ 2.1
	CMP	938	+ 2.3	–	–
Apollo 8	CDR	427	– 2.1	– 8.8	– 6.4
	LMP	366	– 7.0	–11.1	–12.4
	CMP	479	– 2.9	–11.4	–16.2
Apollo 14	CDR	802	– 0.4	– 0.1	– 1.6
	LMP	843	+ 3.7	+ 1.5	– .3
	CMP	809	+ .5	+ 1.5	+ .3*
Apollo 15	CDR	857	– 6.7	0	– 1.7
	LMP	778	– .6	– .7	– 3.5
	CMP	725	– 7.8	– 1.9	– 3.1
Apollo 16	CDR	805	+ 1.2	+ 1.0	– 2.2
	LMP	705	+ .4	+ 1.5	– 3.3
	CMP	468	+ .4	+ 2.1	– 3.5

*R + 1 measurement

It is not possible at this time to attempt any correlations on these conflicting data. Clearly, Gemini 7 and Apollo 7 had the greatest similarity to the Apollo 14, 15, and 16 results and Gemini 4 and 5 and Apollo 8 had the least. Based on the bed rest experience, one would not have expected significant losses from the upper extremity bones. The differences between the photon absorptiometric and X-ray densitometric techniques can account partly for these differences. The accuracy of the radiographic technique has been considered to approach 10 percent, whereas the photon absorptiometric technique can claim a 2 percent accuracy (Cameron et al., 1969). It would appear that the forces generally applied to the upper extremity bones are still applied during flight, although they are significantly reduced. In contrast, except for the lunar excursion periods, compression forces, most vital to the integrity of the os calcis, are completely removed from that bone.

Reliable calcium balance data for these missions are not available. During Gemini 7 when a metabolic balance technique was used, the net calcium balance was distinctly less positive for both crewmen (Lutwak et al., 1969). The mean urinary calcium increased during the second week by 23 percent for the Command Pilot (CP) and 9 percent for the Pilot (P), the latter not being significant. However, the changes in calcium balance were appreciable. In addition to weightlessness, investigators speculate that high oxygen atmosphere, low pressure, exercise, and dietary protein reduction were factors that contributed in varying degrees to the calcium balance changes in these two crewmen. The greater negativity of the CP was supported by a slightly greater mineral loss in the hand phalanx 4-2 (-6.55 percent compared to -3.82 percent) and distal talus (-7.06 percent compared to -4.0 percent) but not by the os calcis (-2.9 percent compared to -2.8 percent), capitate (-4.31 percent compared to -9.3 percent), or the hand phalanx 5-2 (-6.78 percent compared to -7.83 percent) (tables 13 and 15).

The CDR on Apollo 8 is estimated to have had a 1.01 gm/day mass balance deficit, and the average for all three crewmen on Apollo 7 was a 0.59 gm/day deficit (Brodzinski, 1971). These data are based on the examination of fecal calcium only, and are only approximate because the fecal calcium excretion was assumed to be a constant 80 percent of the daily total. This value has been shown to vary between 69.4 and 91.6 percent. In bed rest studies (Donaldson et al., 1970; Hulley et al., 1971; Hantman et al., 1973), the calcium balance became negative almost immediately and reached a peak in the fifth to eighth week with a range of about 250 ± 200 mg/day (two standard deviations) (Hantman et al., 1973). These Apollo data reflect a greater negative balance that might account for an earlier onset of the mineral loss.

Other bones were studied by X-ray densitometry, and the results obtained are listed in table 15 for completeness. No specific pattern can be ascribed to these results on the basis of duration of weightlessness, calcium intake (table 14), or physical activity. The crew of Gemini 5 appears to have had the greatest losses in all of the bones studied.

Conclusions

It is concluded that loss of mineral from bone incident to periods of weightlessness is comparable to that observed in bed rest subjects but that the magnitude is not severe. If these losses were allowed to continue unabated for a prolonged period of time, the consequences might be more serious because the losses are probably not confined to the bones described. Because of either biological variability between subjects or factors not yet identified, not all crewmen were similarly affected during the ten- to twelve-day missions. These studies can be used to construct a time-effect curve that can be compared with the bed rest data, thus permitting a reasonable degree of prediction for longer space missions.

Table 15

Mineral Changes in Other Bones Studied by X-Ray Densitometry

Mission	Bone	CP (percent)	P (percent)	CDR (percent)	CMP (percent)	LMP (percent)
Gemini 7	Distal talus	– 7.06	– 4.00			
	Capitate	– 4.31	– 9.30			
	Phalanx 4-2	– 6.55	– 3.82			
	Phalanx 5-2	– 6.78	– 7.83			
Gemini 5	Distal talus	–13.24	– 9.87			
	Capitate	–17.10	–16.80			
	Phalanx 4-2	– 9.86	–11.80			
	Phalanx 5-2	–23.20	–16.98			
Gemini 4	Distal talus	–10.69	–12.61			
	Capitate	– 4.48	–17.64			
	Phalanx 4-2	– 4.19	– 8.65			
	Phalanx 5-2	–11.85	– 6.24			
Apollo 7	Central talus			–3.6	+ 1.8	+2.9
	Phalanx 4-2			–9.3	+ 2.0	–6.5
	Capitate			–4.1	+ 3.3	–3.4
Apollo 8	Central talus			–2.6	– 2.8	–3.2
	Phalanx 4-2			–2.2	– 2.4	+4.8
	Capitate			–9.6	–12.1	–6.7
Soyuz 9	Phalanx II	–	– 4.1			
	Phalanx III	– 5.0	– 5.0			
	Phalanx IV	– 3.1	– 4.3			
	Phalanx V	– 4.7	– 8.9			

References

Biriukov, E.N.; and Krasnykh, I.G.: Changes in the Optical Density of Bone Tissue and in the Calcium Metabolism of the Astronauts. A.G. Nikovaev and V.I. Sevastianov, Moscow, Kosmicheskaia Biologiia i Meditsina, vol. 4, Nov.-Dec. 1970, pp. 42-45.

Brodzinski, R.L.; Rancitelli, L.A.; Haller, W.A.; and Dewey, L.S.: Calcium, Potassium, and Iron Loss by Apollo VII, VIII, IX, X, and XI Astronauts. Aerospace Med., vol. 42, no. 6, June 1971, pp. 621-626.

Cameron, John R.; Jurist, John M.; Sorenson, James A.; and Mazess, Richard B.: New Methods of Skeletal Status Evaluation in Space Flight. Aerospace Med., vol. 40, no. 10, Oct. 1969, pp. 1119-1122.

Donaldson, Charles L.; Hulley, Stephen B.; Vogel, John M.; Hattner, Robert S.; Bayers, J.H.; and McMillan, D.G.: Effect of Prolonged Bed Rest on Bone Mineral. Metab., vol. 19, no. 12, 1970, pp. 1071-1084.

Hantman, D.A.; Vogel, J.M.; Donaldson, C.L.; Friedman, R.J.; Goldsmith, R.S.; and Hulley, S.B.: Attempts to Prevent Disuse Osteoporosis by Treatment with Calcitonin, Longitudinal Compression and Supplementary Calcium and Phosphate. J. Clin. Endocrinol. Metab., vol. 36, no. 12, 1973, pp. 29-42.

Hattner, R.S.; and McMillan, D.E.: Influence of Weightlessness Upon the Skeleton: A Review. Aerospace Med., vol. 39, no. 8, Aug. 1968, pp. 849-855.

Heuck, F.; and Schmidt, E.: Die quantitative bestimmung des mineralgehaltes des knochen aus dem Rontgenbild. Fortschr. Roentgenstr., vol. 93, 1960, pp. 523-554.

Hulley, Stephen B.; Vogel, John M.; Donaldson, Charles L.; Bayers, Jon H.; Friedman, Ronald J.; and Rosen, Sheldon N.: Effect of Supplemental Oral Phosphate on the Bone Mineral Changes During Prolonged Bed Rest. J. Clin. Inv., vol. 50, no. 12, 1971, pp. 2506-2518.

Krasnykh, I.G.: Mineral Saturation of Bone Tissue Under Conditions of Prolonged Hypodynamia. NASA TT F-639, 1969.

Lockwood, D.R.; Lammert, J.E.; Vogel, J.M.; and Hulley, S.B.: Bone Mineral Loss During Bed Rest. Proceedings of the Clinical Aspects of Metabolic Bone Disease, Excerpta Medica Foundation (Amsterdam), 1972, pp. 148-151.

Lutwak, Leo; Whedon, G. Donald; LaChance, Paul A.; Reid, Jeanne M.; and Lipscomb, Harry S.: Mineral, Electrolyte and Nitrogen Balance Studies of the Gemini-VII Fourteen-Day Orbital Space Flight. J. Clin. Endocrinol. Metab., vol. 29, Sept. 1969, pp. 1140-1156.

Mack, Pauline B.; LaChance, Paul A.; Vose, George P.; and Vogt, Fred B.: Bone Demineralization of Foot and Hand of Gemini-Titan IV, V and VII Astronauts During Orbital Flight. Am. J. Roentgenology, Radium Therapy, and Nuclear Medicine, vol. 100, no. 3, 1967, pp. 503-511.

Mack, Pauline B.; and LaChance, Paul A.: Effects of Recumbency and Space Flight on Bone Density. Am. J. Clin. Nutr., vol. 20, no. 11, 1967, pp. 1194-1205.

Rambaut, Paul C.; Deitlein, Lawrence F.; Vogel, John M.; and Smith, Malcolm C., Jr.: Comparative Study of Two Direct Methods of Bone Mineral Measurement. Aerospace Med., vol. 43, no. 6, June 1972, pp. 646-650.

Vogel, John M.; and Anderson, Jerome T.: Rectilinear Transmission Scanning of Irregular Bones for Quantification of Mineral Content. J. Nucl. Med., vol. 13, no. 1, 1972, pp. 13-18.

Vogel, J.M.; Rambaut, P.C.; and Smith, M.C.: Bone Mineral Measurement from Apollo Experiment M078, NASA TMX-58110, 1974.

Vose, G.P.: Review of Roentgenographic Bone Demineralization Studies of the Gemini Space Flights. Am. J. Roentgenology, Radium Therapy and Nuclear Medicine, vol. 121, 1974, pp. 1-4.

Witt, R.M.; Mazess, R.B.; and Cameron, J.R.: Standardization of Bone Mineral Measurements. Proceedings of Bone Measurement Conference, Atomic Energy Commission Conference 700515, 1970, pp. 303-307.