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# CHAPTER 4
# APOLLO FLIGHT CREW CARDIOVASCULAR EVALUATIONS

*by*

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## Introduction

The Apollo Program was designed to fulfill the specific operational goals of landing man safely on the moon, enabling him to explore the lunar surface, and successfully returning him to Earth. The engineering and operational complexity of this effort necessarily limited inflight physiological studies of man to those measurements considered vital to crew safety and health assessment. Limited availability of astronaut time during busy preflight and postflight periods constrained evaluations significantly; therefore, only examinations believed to have the greatest relevance to the understanding of man's physiological responses to the space flight environment were undertaken.

Reductions in orthostatic tolerance following space flight were first observed with the late flights of Project Mercury. Tilt table tests revealed moderate orthostatic hypotension in the Mercury-Atlas 9 Pilot after only 34 hours of orbital flight. Because of this finding, tilt table tests for orthostatic tolerance were incorporated into routine preflight and postflight evaluations and continued throughout the Gemini Program. The results of these tests confirmed consistent but variable losses of orthostatic tolerance following three- to fourteen-day flights. Elevated heart rate, reduced pulse pressure, and increased pooling of fluid in the lower extremities were found consistently during 70° upright tilts in the early postflight period. Responses to this stress usually returned to normal within 50 hours after splashdown, regardless of flight duration (NASA, 1963; 1967).

The advent of the Apollo Program presented new questions and uncertainties. Fundamental differences in the Apollo spacecraft, in its operational environment, and in program goals were expected to produce physiological responses that differed from those

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seen after the Gemini flights. The two-gas (oxygen and nitrogen) atmosphere and the capability to move about in the spacecraft led to speculation that returning Apollo crewmen might show little or no change in orthostatic tolerance. On the other hand, there was some concern regarding the ability of the cardiovascular system to withstand acceleration stresses associated with lunar descent and ascent. Headward acceleration ($+G_z$) was imposed during the Lunar Module descent after three to four days of weightlessness, and a near one-g ($+G_z$) force was produced by the ascent profile after a day or more of 1/6-g exposure. Also, the results of postflight tests were expected to show important differences in cariovascular responsiveness between crewmen who walked on the moon and those who remained in weightless flight. These speculations and many other unanswered questions emphasized the need to gain as much understanding as possible about the cardiovascular system and its adaptation, first to zero g and, later, to one g.

For several years before the first manned Apollo flight, investigators had studied the effects on the cardiovascular system of the application of lower body negative pressure (LBNP). Lower body negative pressure involves the application of reduced pressure usually to that portion of the body below the level of the iliac crests. Evaluations of its use as a simulator of orthostatic stress (Samueloff et al., 1966; Brown et al., 1966; Gilbert et al., 1966; Murray et al., 1967) and as a preventer of cardiovascular deconditioning (Stevens et al., 1966a; 1966b) had been made. Lower body negative pressure, at levels ranging from -40 to -60 mm Hg ($-53 \times 10^2$ to $-80 \times 10^2$ N/m$^2$) as determined by individual tolerance, produced changes in heart rate and blood pressure similar to those resulting from upright tilting. Clearly, the cardiovascular responses initially induced by either stress procedure depended primarily on displacement of blood, chiefly from central blood volume reservoirs, to the lower extremities.

Although qualitatively alike, differences in the magnitude of cardiovascular compensatory responses induced by LBNP have been reported. Stevens (1966) and Stevens and Lamb (1965) found a greater increase in heart rate during upright tilting than during LBNP adjusted to produce the same cardiac output reduction (-19 percent). Later, Musgrave and co-workers (1969; 1971) reported that even though LBNP at -40 mm Hg ($-53 \times 10^2$ N/m$^2$) and the upright posture displaced essentially equal volumes of blood to the lower extremities, negative pressure levels of -50 mm Hg ($-67 \times 10^2$ N/m$^2$) were required to produce equivalent elevations of heart rate. Both groups of investigators attributed the smaller heart rate response during LBNP to the absence of stimulation of carotid and other baroceptors by gravity-induced hydrostatic pressure and flow changes. Further, the absence of hydrostatic pressure gradients along the lower extremities during LBNP caused displaced blood to be distributed differently than during tilt.

In addition to the capability to induce cardiovascular responses similar to those resulting from orthostasis, several advantages over the tilt table test were offered by the LBNP procedure. No movement of the subject was required; therefore, instrumentation was easier to apply and maintain, and physiological signals remained more stable. Stress could be applied at several levels and the magnitude of stress could be adjusted with greater ease and precision with the LBNP procedure. Because it could be used in weightless conditions and tilt table testing could not, LBNP testing of Apollo crewmen furnished a valuable data base for future application to the understanding of Skylab results. LBNP studies were performed for most Apollo crewmen for missions not encumbered by postflight quarantine restrictions. In some instances, a static stand procedure was performed in conjunction with, or instead of LBNP evaluations. Admittedly, these techniques had limitations. The response of the cardiovascular system during weightlessness can only be inferred from studies performed before and after flight. In addition, many variables, including climatic and emotional factors, complicated interpretation of the results (Hoffler et al., 1974).

On the last two Apollo missions, experimental antihypotensive garments were tested. Although the Gemini and earlier Apollo missions revealed no need for such postflight support, planners of the 28- and 56-day Skylab flights envisioned the possible need for such postflight protection. This concern was in part engendered by reports that crewmen of the 18-day Soyuz 9 orbital mission had to be assisted from their spacecraft after flight because of difficulty standing, and that anti-G suits had been provided for Soyuz 11/Salyut crewmen for use following flight if necessary.

In this chapter, the results of the lower body negative pressure and passive stand tests are presented, and the efficacy of the experimental antihypotensive garments is evaluated. Many answers will be required before the entire picture of man's cardiovascular adaptation to weightlessness can be clarified and understood. The Apollo cardiovascular studies constitute a small but important step in the acquisition of this knowledge.

## Methods and Conditions

As noted previously, an LBNP protocol was used in conjunction with missions not encumbered by postflight quarantine restrictions. To assess the comparability of the LBNP and passive stand procedures, both tests were performed on the Apollo 9 crewmen. The passive stand protocol alone was used for evaluating the orthostatic tolerance of the Apollo 10 and 11 crewmen. The Apollo 10 to 14 missions included postflight quarantine, which precluded use of the LBNP. The types and durations of each of the eleven manned Apollo missions and the orthostatic evaluation techniques employed for each are described in table 1. Total mission duration varied from 143 to 302 hours; for the lunar landing missions, the length of crew time in 1/6 g varied from 22 to 75 hours.

The Command Module Pilot (CMP), his backup crewmember, and two control subjects were fitted for Jobst waist-length leotards before the flight of Apollo 16. These garments were to be donned during postflight orthostatic evaluations to assess their antihypotensive effect. A garment employing the capstan principle for the application of lower body positive pressure was designed to be worn by the Apollo 17 CMP during postflight tests.

The following subsections will describe the methodological aspects and conditions affecting orthostatic evaluation with and without the use of countermeasure garments.

### Equipment and Measures

***Lower Body Negative Pressure Device.*** The device for accomplishing LBNP consisted of a chamber of sufficient size to accommodate the lower body, an airtight waist seal, and

Table 1

Apollo Mission Characteristics and Orthostatic Evaluation Techniques Employed

| Apollo Mission | Type of Mission | Time From Lift-off to Lunar Landing, Hr | Length of Lunar Stay, Hr | Time From Lunar Lift-off to Splash-down, Hr | Total Mission Duration | | Type of Orthostatic Evaluation Performed |
|---|---|---|---|---|---|---|---|
| | | | | | Hours | Days | |
| 7 | Earth orbital | | | | 260.1 | 10.8 | LBNP |
| 8 | Lunar orbital | | | | 147.0 | 6.1 | LBNP |
| 9 | Earth orbital | | | | 241.0 | 10.0 | LBNP, Stand |
| 10 | Lunar orbital | | | | 192.0 | 8.0 | Stand |
| 11 | Lunar landing | 102.7 | 22.2 | 70.9 | 194.0 | 8.1 | Stand |
| 12 | Lunar landing | 110.5 | 31.5 | 102.0 | 244.5 | 10.2 | – |
| 13 | Lunar-abort | | | | 142.9 | 6.0 | – |
| 14 | Lunar landing | 108.2 | 33.5 | 74.3 | 216.0 | 9.0 | – |
| 15 | Lunar landing | 104.7 | 67.0 | 123.6 | 295.0 | 12.3 | LBNP |
| 16 | Lunar landing | 104.5 | 71.0 | 90.3 | 265.8 | 11.1 | LBNP |
| 17 | Lunar landing | 110.3 | 75.0 | 116.5 | 301.8 | 12.6 | LBNP |

a regulated vacuum source (Wolthuis et al., 1970; Wolthuis et al., 1972). The LBNP device is shown in figure 1. The type of physiological measurements taken during the LBNP protocol varied slightly from mission to mission. Measurements made in conjunction with the Apollo 7 to 9 missions included continuous axillary and sternal lead electrocardiograms, indirect blood pressure taken every 30 seconds by the Korotkov sound technique [using the NASA Gemini blood pressure measuring system (NASA, 1968)], and changes in calf circumference measured by double-strand, mercury-in-Silastic strain gages.

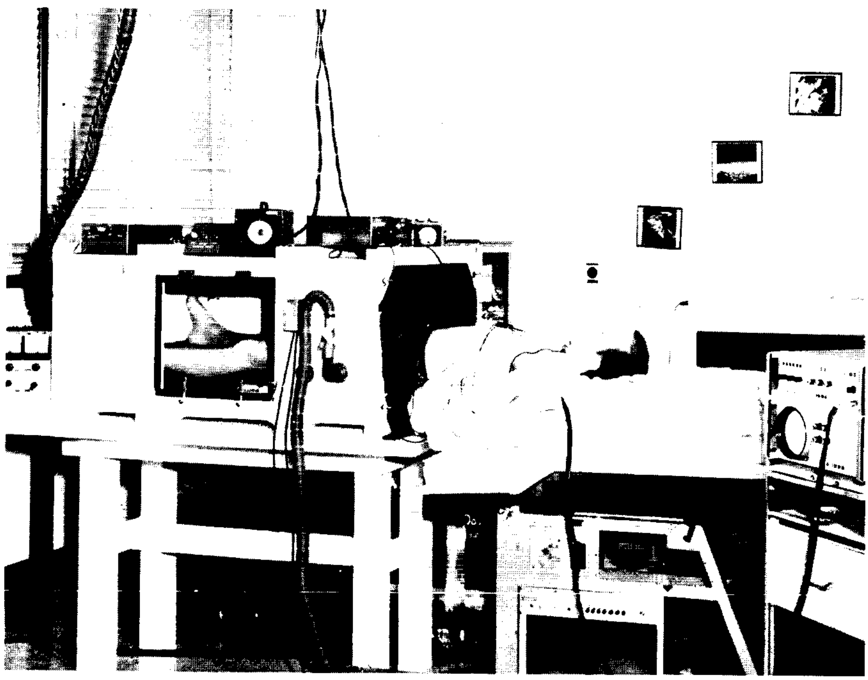

Figure 1. Subject undergoing test in lower body negative pressure device.

For the Apollo 15 to 17 evaluations, the limited two-lead electrocardiogram (ECG) was replaced with a modified Frank lead vectorcardiogram (VCG), and wide-band precordial heart sounds (vibrocardiogram) were recorded with a capacitance microphone system (LTV Research Center, Anaheim, Calif.). The respiration rates of the Apollo 16 and 17 crewmen were measured with a mercury strain gage attached to the lower thorax. The carotid pulse trace was recorded for Apollo 17 crewmen.

***Antihypotension Garments.*** A Jobst waist-length elastic leotard was used in conjunction with the Apollo 16 mission. This garment was designed to produce a pressure at the ankle of 40 to 45 mm Hg ($53 \times 10^2$ to $60 \times 10^2$ $N/m^2$) that decreased linearly to approximately 10 mm Hg ($13 \times 10^2$ $N/m^2$) at the waist. To accommodate the reduction in limb size expected to occur during flight, garments in three separate sizes were made for the CMP. They were, respectively, 0.5, 1, and 1.5 cm smaller in circumference at the calf with proportionate reductions throughout the lower limbs.

A lower body garment using the capstan principle to apply pressure to the lower limbs was designed, fabricated, and sized for the Apollo 17 CMP to use following splashdown. The garment is pictured diagrammatically in figure 2. Capstan pressure was read from an aneroid gage and the capstan was inflated with a hand bulb, both of which were concealed in a zippered pocket. The capstan exerted the pressure of the garment over the skin at the ankle in a 2:1 ratio. This pressure diminished linearly to approximately 10 mm Hg ($13 \times 10^2$ $N/m^2$) at the waist. Preflight testing with pressure sensors between the garment and the skin verified the ratio and the diminishing gradient of pressure from ankle to waist. To accommodate anticipated loss of limb girth, laces were provided for reducing the garment size slightly before stowage in the Command Module. The capstan itself accommodated moderate changes (±2.5 cm) in limb girth.

## Physical Examinations

Major medical examinations of space flight crewmembers were performed at approximately 30, 15 and 5 days before flight (F-30, F-15 and F-5, respectively). Orthostatic tolerance evaluations performed as an integral part of these medical examinations provided baseline information for comparison with postflight evaluation results. These preflight orthostatic tolerance evaluations took place at the NASA Lyndon B. Johnson Space Center (JSC) Cardiovascular Laboratory, Houston, Texas, and at the NASA John F. Kennedy Space Center (KSC) Medical Operations Facility, Kennedy Space Center, Florida. As part of the major medical examinations, postflight orthostatic tolerance evaluations were performed shortly after splashdown and at intervals of approximately 24-hours thereafter. The number of postflight evaluations and the time at which they were performed (table 2) were dictated partly by operational constraints and partly by the length of time required for individual crewmembers to regain their preflight status. As indicated in table 2, either two or three postflight orthostatic evaluations were completed on each crewman; a fourth evaluation of the Apollo 15 to 17 crewmembers differed in that it did not necessarily include orthostatic stress tests. Immediately postflight, the first evaluations took place on the recovery ship; subsequent postflight evaluations were performed on the recovery ship, at KSC, or at the JSC Cardiovascular Laboratory.

## Control Subjects

To ensure comparability of test conditions and operability of test equipment, several members of the attending support team assigned to each Apollo mission participated in preflight and postflight orthostatic evaluations identical to those used on crewmembers. These control subjects were evaluated a day or two before the Apollo crewmen were evaluated. The data collected helped ensure the validity of postflight changes observed in space flight crewmembers and the operational readiness of test teams and equipment.

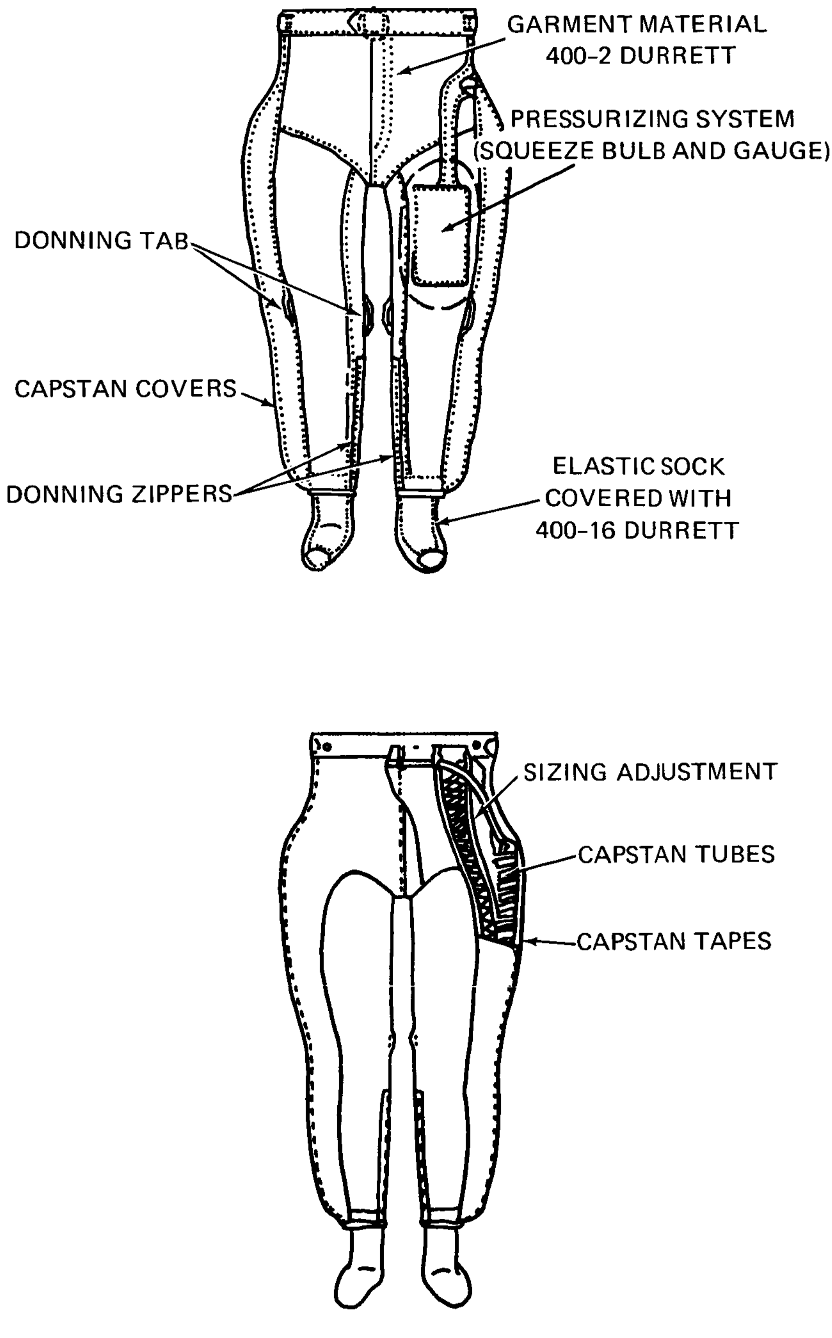


Figure 2. Lower body positive pressure garment employing the capstan principal.

Table 2

Time of Apollo Postflight Orthostatic Tolerance Evaluations

| Apollo Mission | Crew-member | Time of Postflight Evaluations (hours following splashdown) | | | |
|---|---|---|---|---|---|
| | | First | Second | Third | Fourth |
| 7 | CDR | 3 | 34 | | |
| | CMP | 2 | 35 | | |
| | LMP | 5 | 32 | | |
| 8 | CDR | 3 | 26 | 51 | |
| | CMP | 4 | 27 | 53 | |
| | LMP | 5 | 26 | 52 | |
| 9 | CDR | 2 | 31 | 53 | |
| | CMP | 4 | 33 | 55 | |
| | LMP | 3 | 32 | 54 | |
| 10 | CDR | 2 | 26 | | |
| | CMP | 3 | 27 | | |
| | LMP | 2 | 28 | | |
| 11 | CDR | 6 | 25 | | |
| | CMP | 7 | 25 | | |
| | LMP | 8 | 26 | | |
| 15 | CDR | 3 | 43 | 73 | 122 |
| | CMP | 4 | 42 | 71 | 121 |
| | LMP | 5 | 44 | 72 | 137 |
| 16 | CDR | 4 | 24 | 68 | 162 |
| | CMP | 6 | 26 | 70 | 162 |
| | LMP | 5 | 25 | 71 | 162 |
| 17 | CDR | 6 | 24 | 48 | 90 |
| | CMP | 5 | 26 | 50 | 91 |
| | LMP | 7 | 25 | 51 | 91 |

**Test Protocols**

The protocols for the two orthostatic stress procedures are shown in figure 3. The supine LBNP protocol consisted of a five-minute resting control period, a five-minute period at each of three distinct reduced-pressure levels, and a five-minute recovery period. The first five-minute period of reduced pressure included one minute at -8 mm Hg ($-11 \times 10^2$ N/m$^2$) and one minute at -16 mm Hg ($-21 \times 10^2$ N/m$^2$), followed by three minutes at -30 mm Hg ($-40 \times 10^2$ N/m$^2$). The two short-duration, relatively low levels of reduced pressure were adopted to obtain additional information regarding the responsiveness of lower limb capacitance vessels. The three levels of sequentially applied reduced pressure used were chosen on the basis of previous experience in the JSC Cardiovascular Laboratory (Wolthuis et al., 1970). As reported, the use of an incremental LBNP protocol produced physiological responses for each level of reduced pressure applied and ensured a measurable, quantitative stress response in both the normal preflight and the orthostatically intolerant postflight conditions.

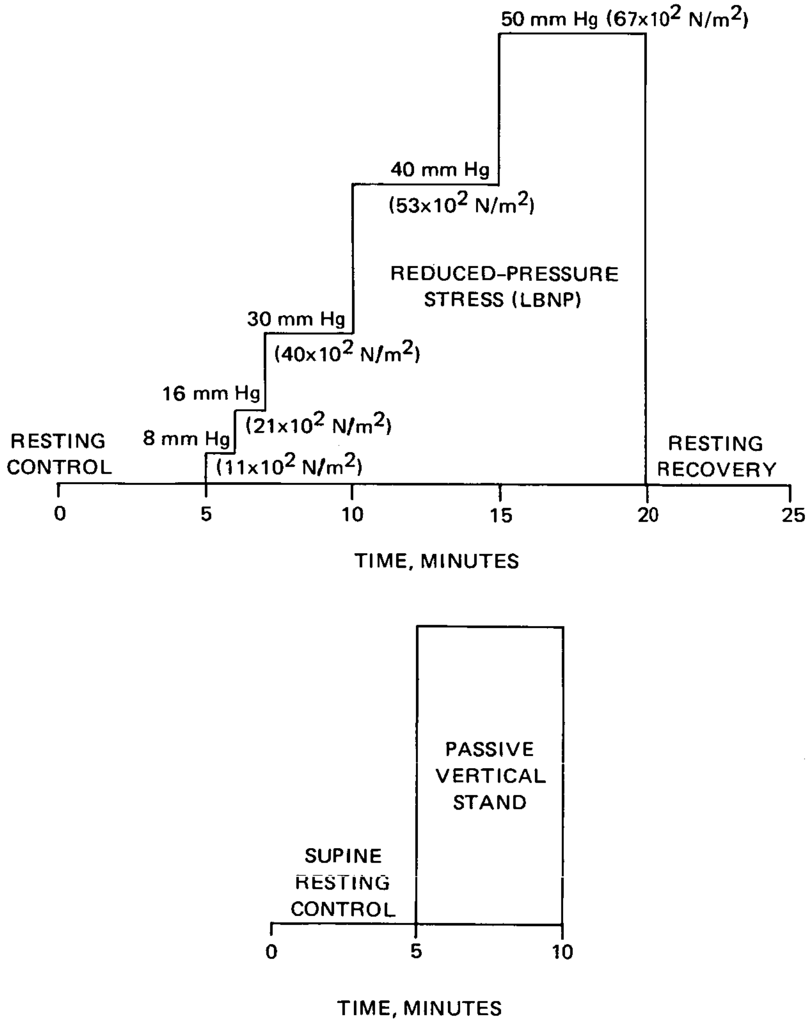


Figure 3. Orthostatic stress procedure protocols.

The passive stand protocol consisted of a five-minute resting supine control period followed by a five-minute passive stand. For the passive stand, the subject leaned against a wall in a relaxed manner with his heels spaced 15 cm (6 in.) away from the wall. Physiological measurements made during this protocol included continuous sternal and axillary lead ECG's, and indirect blood pressure taken by the Korotkov sound technique at 30-second intervals.

The Apollo 16 tests, utilizing the Jobst leotard, were performed pre- and postflight. Passive stand tests were performed at the F-15 tests on the Command Module Pilot, the backup CMP, and the two control subjects, and were repeated on the CMP and the controls at their respective recovery day examinations. The tests followed the LBNP test and consisted of a five-minute supine rest period followed by a five-minute stand period in the manner of the earlier Apollo passive stand tests. The leotards were then donned, and, after a ten-minute period of supine rest, the stand test was repeated. Blood pressure and heart-rate data were obtained by using the instrumentation of the earlier LBNP test.

Approximately one-half hour before Apollo 17 deorbit, the Command Module Pilot donned but did not inflate the antihypotensive garment. After splashdown, while still reclining in the couch, he inflated the capstan to a pressure of 130 mm Hg ($173 \times 10^2$ N/m$^2$) and, thus, furnished 65 mm Hg ($87 \times 10^2$ N/m$^2$) pressure over the ankle region. This pressure was maintained until a stand test could be performed. The suit was tested by performing a stand test four hours after splashdown and before LBNP testing. Crew time restraints prohibited repetition of the preflight protocol, which included separate tests with and without the garment, each separated by an appropriate recovery period. Therefore, the crewman spent five minutes in the supine position with the capstan inflated, five minutes passive standing with the capstan inflated, five minutes standing with the garment depressurized, and four minutes standing with the capstan reinflated to the original capstan pressure of 130 mm Hg ($173 \times 10^2$ N/m$^2$). The total duration of the continuous stand was 15 minutes, including approximately 45 seconds for reinflation of the capstan. Heart rate was obtained continuously from the VCG; blood pressure was measured every 30 seconds by a Skylab automatic blood pressure measuring system.

## Ancillary Indicators of Orthostatic Tolerance

Accessory cardiovascular and related measurements were made in conjunction with orthostatic evaluations. Before orthostatic evaluation of the Apollo 7 to 11 and 15 to 17 crewmen, the circumference of the calf at its maximum girth was measured during supine rest. An assessment of total lower limb volume made on the Apollo 16 and 17 crewmembers consisted of multiple leg circumference measurements at discrete intervals from the ankles to the groin while the crewman was supine with the legs extended and slightly elevated. Limb volume was computed by summing sequential, truncated, assumed-circular cones. Standard 1.8-m (6-ft) posterior-anterior chest X-rays were taken of every crewmember at his last major preflight medical examination and first postflight evaluation. The cardiothoracic (C/T) ratio was determined by standard clinical methods. The ambient temperature and the oral temperature and body weight of each crewman were recorded at each evaluation.

## Ambient Conditions and Other Variables

Ambient temperatures and oral temperatures were recorded during preflight and postflight orthostatic evaluations because sufficiently high temperatures can affect orthostatic tests in an adverse way. While ambient temperatures during preflight orthostatic evaluations were acceptably low, temperatures during the first postflight evaluations were generally markedly higher. Ambient temperatures during orthostatic evaluations for the Apollo 15 Commander are illustrative. During preflight testing, the mean ambient temperature derived from measurements made on three separate days of testing was 297°K (24°C). On the first postflight day, the ambient temperature during orthostatic evaluation was 301°K (28°C). The significant elevation in group mean ambient temperature at the first postflight evaluation reflected the recovery zone climate (usually tropical) and inadequate air conditioning of the recovery ships. Group mean ambient temperatures for subsequent postflight evaluations were not significantly different from preflight temperatures.

Preflight examinations employing the Apollo 16 antihypotensive garment were performed under adequately controlled temperatures of 295° to 296°K (22° to 23°C). However, environmental temperatures during the first and second postflight examinations were the highest of any encountered during the Apollo shipboard tests, ranging from 305° to 306°K (32° to 33°C) during the postflight stand tests of the CMP. Apollo 17 crewmen were exposed to high environmental temperatures during transfer to the recovery vessel and during subsequent ceremonies, but their tests were performed in the air-conditioned Skylab Mobile Laboratory at a temperature of 296°K (23°C).

Table 3 is a tabulation of group mean oral temperature. Here, too, the preflight mean was based on three separate determinations, thirty, fifteen and five days before flight. The elevation in this parameter noted at the first postflight evaluation continued for succeeding postflight days.

The effects of elevated ambient and oral temperatures within the postflight evaluation periods may be altered by the presence of certain additional variables. For example, although most Apollo crewmembers reported a normal amount of sleep before each preflight evaluation, there was a significant group mean reduction in the amount of sleep on the night before splashdown. Further, the interval between venipuncture for biochemical analysis (30 to 80 $cm^3$ withdrawn) and time of orthostatic evaluation varied widely (15 minutes to many hours) within preflight and postflight time frames. Finally, the interval between food ingestion and orthostatic evaluation also varied widely (15 minutes to 17 hours).

### Data Collection and Reduction

The various physiological measurements were recorded in real time on a strip chart recorder and on frequency modulation magnetic tape. The strip chart data were used for real-time assessment of crewmember well-being and safety. The appearance of presyncopal symptoms in some crewmen during orthostatic stress caused early termination of the procedure. Analog tape data were subsequently converted to digital data and analyzed by specially developed software on a Sigma 3 computer system.

Minute heart rates were derived from an analysis of electrocardiogram or vectorcardiogram R-R intervals; systolic blood pressure and diastolic blood pressure values were read at the appearance of the first and last Korotkov sounds, respectively, on the calibrated descending arm cuff pressure ramp. Percentage change in calf volume was measured by calculating the change from initial, resting-calf circumference and converting this value to percentage change in calf volume using the method of Eagan (1961). Two

Table 3

Tabulation of Apollo Group Mean Oral Temperatures
(Arrows Indicate $p<0.05$)

| Apollo Mission | Crew-member | Preflight Summary | | | Postflight Evaluations | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | | ±SD | First | | Second | | Third | |
| | | °K | (°C) | | °K | (°C) | °K | (°C) | °K | (°C) |
| 7 | CDR | 309.6 | (36.5) | 0.12 | 310.7 | (37.6) ↑ | 309.9 | (36.8) ↑ | | |
| | CMP | 309.8 | (36.7) | 0.12 | 309.7 | (36.6) | 310.1 | (37.0) ↑ | | |
| | LMP | 309.6 | (36.5) | 0.38 | 310.5 | (37.4) | 309.9 | (36.8) | | |
| 8 | CDR | 309.6 | (36.5) | 0.17 | 310.2 | (37.1) ↑ | 309.7 | (36.6) | 309.9 | (36.8) |
| | CMP | 309.9 | (36.8) | 0.32 | 310.2 | (37.1) | 310.2 | (37.1) | 310.0 | (36.9) |
| | LMP | 309.7 | (36.6) | 0.25 | 309.9 | (36.8) | 309.7 | (36.6) | 309.8 | (36.7) |
| 9 | CDR | 309.5 | (36.4) | 0.15 | 309.5 | (36.4) | 309.3 | (36.2) | 310.3 | (37.2) ↑ |
| | CMP | 309.4 | (36.3) | 0.15 | 309.7 | (36.6) | 309.3 | (36.2) | 309.6 | (36.5) |
| | LMP | 309.7 | (36.6) | 0.21 | 309.9 | (36.8) | 310.3 | (37.2) ↑ | 309.9 | (36.8) |
| 10 | CDR | 309.6 | (36.5) | 0.36 | 309.3 | (36.2) | 309.4 | (36.3) | – | – |
| | CMP | 309.8 | (36.7) | 0.31 | 309.9 | (36.8) | 309.9 | (36.8) | – | – |
| | LMP | 309.6 | (36.5) | 0.15 | 310.2 | (37.1) ↑ | 309.7 | (36.6) | – | – |
| 11 | CDR | 309.6 | (36.5) | 0.12 | 309.5 | (36.4) | – | – | – | – |
| | CMP | 309.6 | (36.5) | 0.49 | 309.8 | (36.7) | – | – | – | – |
| | LMP | 309.8 | (36.7) | 0.06 | 310.2 | (37.1) ↑ | – | – | – | – |
| 15 | CDR | 309.4 | (36.3) | 0.23 | – | (37.1) | 309.2 | (36.1) | 309.4 | (36.3) |
| | CMP | 309.6 | (36.5) | 0.17 | – | (36.9) | – | – | 310.4 | (37.3) ↑ |
| | LMP | 309.6 | (36.5) | 0.21 | – | (36.9) | 309.8 | (36.7) | 309.7 | (36.6) |
| 16 | CDR | 308.9 | (35.8) | 0.40 | – | (37.1) | – | – | 309.6 | (36.5) |
| | CMP | 309.1 | (36.0) | 0.10 | – | (36.7) | – | – | 309.7 | (36.6) ↑ |
| | LMP | 308.8 | (35.7) | 0.46 | – | (36.4) | – | – | 310.2 | (37.1) ↑ |
| 17 | CDR | 309.8 | (36.7) | 0.40 | 309.8 | (36.7) | 309.7 | (36.6) | 309.8 | (36.7) |
| | CMP | 310.0 | (36.9) | 0.35 | 310.4 | (37.3) | 309.8 | (36.7) | 310.5 | (37.4) |
| | LMP | 309.4 | (36.3) | 0.46 | 309.9 | (36.8) | 310.0 | (36.9) | 309.3 | (36.2) |
| Group Mean | | 309.61 | (36.42) | | 310.01 | (36.86) | 309.81 | (36.66) | 309.92 | (36.77) |
| ±SD | | 0.334 | | | 0.345 | | 0.316 | | 0.353 | |
| | | t-Test | | | $p<0.001$ | | n.s | | $p<0.005$ | |

successive heart sound complexes were analyzed from the vibrocardiogram each minute; computation of stroke volume followed the method of Agress and co-workers (1967).

For each crewman evaluation, heart rate, systolic blood pressure, diastolic blood pressure, pulse pressure, and stroke volume values were averaged within each of the five five-minute LBNP periods and within the two five-minute passive stand periods to produce the respective mean values within each of these periods. These mean values for each crewmember, during each period and by each measurement, were subsequently used as the best estimate of measurement within that period in the compilation of data tables. In the case of percentage, maximal calf volume change rather than mean values within each level of LPNP was used.

### Data Analysis

Data were analyzed statistically by individual crewmember and by group mean. For individual crewmembers, the mean and the standard deviation of the three preflight values for each measurement in each distinct protocol condition were calculated (preflight summary). From these values, fiducial limits of the normal range at the 95-percent confidence level were determined. Individual postflight values lying outside these limits were defined as statistically significant changes and are indicated appropriately in the tables. Group means and standard deviations were calculated for each discrete measurement within each protocol condition for every evaluation day and for the preflight summaries. Preflight summary group means were compared with each postflight counterpart by using the independent *t*-test.

It should be noted that four astronauts flew two Apollo missions each. The Apollo 8 Command Module Pilot (CMP) flew as the Apollo 13 Commander (CDR); the Apollo 9 CMP flew as the Apollo 15 CDR; the Apollo 10 CMP flew as the Apollo 16 CDR; and the Apollo 10 Lunar Module Pilot (LMP) flew as the Apollo 17 Commander.

## Results

### Heart Rates

Of the various cardiovascular measurements obtained from Apollo crewmembers during their evaluations, heart rate was the most easily measured and yielded the most accurate and predictable values. Table 4 contains heart-rate data on individual crewmembers during three conditions of orthostatic stress evaluations: (1) resting supine control, (2) the highest level of LBNP [-50 mm Hg (-67 x $10^2$ N/$m^2$)], and (3) passive standing. Resting supine heart rate is elevated significantly in 13 of 24 crewmen (54 percent) at the first postflight evaluation; the group response is elevated at the two-percent level of confidence. A trend toward preflight values is subsequently evident. By the third postflight evaluation, only three of fifteen individuals (20 percent) show significant elevations in resting supine heart rate, and the group mean value is not statistically different from the preflight group mean heart rate (n = 15, paired).

Following the same comparisons, the application of -50 mm Hg (-67 x $10^2$,N/$m^2$) LBNP produced significantly elevated heart rates in 14 of 17 Apollo crewmen (82 percent) at the first postflight evaluation, with a group elevation significant at the 0.1-percent level. The Apollo 15 LMP experienced presyncope during the last seconds of

Table 4
Individual Apollo Crewmember Heart Rate Data
(Arrows Indicate $p<0.05$)

| Protocol Condition | Apollo Mission | Crew member | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | First | Second | Third |
| Resting Supine Control Period | 7 | CDR | 56 | 59 | 54 | 56 | 2.6 | 77 ↑ | 59 | |
| | | CMP | 81 | 74 | 78 | 78 | 3.1 | 78 | 76 | |
| | | LMP | 57 | 64 | 66 | 62 | 4.4 | 75 ↑ | 70 | |
| | 8 | CDR | 74 | 69 | 70 | 71 | 2.6 | 87 ↑ | 70 | 80 ↑ |
| | | CMP | 84 | 69 | 66 | 73 | 9.7 | 94 | 76 | 66 |
| | | LMP | 77 | 74 | 72 | 74 | 2.4 | 91 ↑ | 81 ↑ | 71 |
| | 9 | CDR | 76 | 63 | 68 | 69 | 6.8 | 64 | 78 | 80 |
| | | CMP | 56 | 59 | 58 | 57 | 2.0 | 57 | 54 | 53 |
| | | LMP | 59 | 55 | 57 | 57 | 2.1 | 50 ↓ | 50 ↓ | 50 ↓ |
| | 10 | CDR | 62 | 70 | 59 | 64 | 5.7 | 81 ↑ | 73 | – |
| | | CMP | 65 | 59 | 55 | 60 | 5.0 | 65 | 62 | – |
| | | LMP | 59 | 62 | 52 | 58 | 5.1 | 80 ↑ | 79 ↑ | – |
| | 11 | CDR | 61 | 62 | 67 | 63 | 3.2 | 69 | 79 ↑ | – |
| | | CMP | 53 | 46 | 51 | 50 | 3.6 | 67 ↑ | 65 ↑ | – |
| | | LMP | 68 | 69 | 70 | 69 | 1.0 | 62 ↓ | 81 ↑ | – |
| | 15 | CDR | 51 | 50 | 55 | 52 | 2.6 | 54 | 50 | 52 |
| | | CMP | 66 | 69 | 70 | 68 | 2.1 | 83 ↑ | 84 ↑ | 73 |
| | | LMP | 52 | 56 | 57 | 55 | 2.6 | 66 ↑ | 66 ↑ | 66 ↑ |
| | 16 | CDR | 57 | 57 | 55 | 56 | 1.2 | 70 ↑ | 60 ↑ | 61 ↑ |
| | | CMP | 49 | 49 | 45 | 48 | 2.1 | 56 ↑ | 48 | 56 ↑ |
| | | LMP | 60 | 53 | 54 | 56 | 3.9 | 57 | 61 | 60 |
| | 17 | CDR | 55 | 62 | 59 | 59 | 3.2 | 67 ↑ | 70 ↑ | 64 |
| | | CMP | 78 | 76 | 68 | 74 | 5.1 | 67 | 64 | 69 |
| | | LMP | 50 | 50 | 51 | 50 | 0.6 | 55 ↑ | 56 ↑ | 52 |
| | Group Mean | | 62.8 | 61.5 | 60.7 | 61.6 | | 69.7 | 67.2 | 63.5 |
| | ±SD | | 10.47 | 8.53 | 8.41 | 8.60 | | 12.19 | 10.90 | 9.88 |
| | LMP | | | | | t-Test | | $p<0.02$ | n.s. | n.s. |

Table 4 (Continued)
Individual Apollo Crewmember Heart Rate Data
(Arrows Indicate $p<0.05$)

| Protocol Condition | Apollo Mission | Crew-member | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | First | Second | Third |
| −50 mm Hg* LBNP | 7 | CDR | 72 | 61 | 59 | 64 | 6.7 | 90 ↑ | 67 | – |
| | | CMP | 94 | 92 | 90 | 92 | 2.1 | 137 ↑ | 94 | – |
| | | LMP | 76 | 74 | 76 | 75 | 1.1 | 108 ↑ | 87 ↑ | – |
| | 8 | CDR | 100 | 86 | 94 | 93 | 6.7 | 159 ↑ | 108 | 101 |
| | | CMP | 116 | 89 | 94 | 99 | 14.5 | 129 | 121 | 88 |
| | | LMP | 97 | 105 | 106 | 103 | 4.8 | 146 ↑ | 137 ↑ | 102 |
| | 9 | CDR | 82 | 67 | 78 | 76 | 7.9 | 100 ↑ | 94 | 93 |
| | | CMP | 63 | 73 | 76 | 71 | 6.9 | 81 | 70 | 68 |
| | | LMP | 74 | 70 | 67 | 70 | 3.3 | 87 ↑ | 75 | 65 |
| | 15 | CDR | 62 | 59 | 61 | 61 | 1.5 | 76 ↑ | – | 65 |
| | | CMP | 79 | 81 | 81 | 80 | 1.2 | 131 ↑ | 109 ↑ | 93 ↑ |
| | | LMP | 58 | 56 | 64 | 59 | 4.2 | – | 84 ↑ | 78 ↑ |
| | 16 | CDR | 79 | 71 | 72 | 74 | 4.1 | 109 ↑ | 101 ↑ | 83 |
| | | CMP | 62 | 67 | 58 | 62 | 4.2 | 99 ↑ | 74 ↑ | 79 ↑ |
| | | LMP | 82 | 72 | 83 | 79 | 5.9 | 112 ↑ | 98 ↑ | 98 ↑ |
| | 17 | CDR | 67 | 78 | 71 | 72 | 5.3 | 112 ↑ | 91 ↑ | 78 |
| | | CMP | 87 | 86 | 79 | 84 | 4.3 | 87 | 78 | 90 |
| | | LMP | 59 | 69 | 60 | 63 | 5.4 | 82 ↑ | 80 ↑ | 60 |
| | Group Mean ±SD | | 78.3 15.97 | 75.3 12.61 | 76.1 13.70 | 76.5 13.27 t-Test | | 108.5 24.58 $p<0.001$ | 92.2 18.85 $p<0.02$ | 82.7 13.76 n.s. |

* $-67 \times 10^2$ N/m$^2$

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Table 4 (Continued)
Individual Apollo Crewmember Heart Rate Data
(Arrows Indicate $p<0.05$)

| Protocol Condition | Apollo Mission | Crew-members | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | First | Second | Third |
| Passive Stand | 9 | CDR | 81 | 73 | 79 | 78 | 4.2 | 93 ↑ | 100 ↑ | 96 ↑ |
| | | CMP | 66 | 75 | 72 | 71 | 4.6 | 88 ↑ | 72 | 70 |
| | | LMP | 71 | 67 | 69 | 69 | 2.0 | 93 ↑ | 79 ↑ | 65 |
| | 10 | CDR | 86 | 93 | 86 | 88 | 4.0 | 111 ↑ | 92 | – |
| | | CMP | 88 | 85 | 70 | 81 | 9.6 | 100 | 81 | – |
| | | LMP | 80 | 74 | 70 | 75 | 5.0 | 121 ↑ | 109 ↑ | – |
| | 11 | CDR | 73 | 83 | 85 | 80 | 6.4 | 112 ↑ | 105 ↑ | – |
| | | CMP | 76 | 69 | 65 | 70 | 5.6 | 91 ↑ | 88 ↑ | – |
| | | LMP | 73 | 76 | 79 | 76 | 3.0 | 89 ↑ | 100 ↑ | – |
| | Group Mean | | 77.1 | 77.2 | 75.0 | 76.4 | | 99.8 | 91.8 | 77.0 |
| | ±SD | | 7.22 | 8.29 | 7.48 | 6.11 | | 11.99 | 12.71 | 16.64 |
| | | | | | | t-Test | | $p<0.001$ | $p<0.001$ | n.s. |

-40 mm Hg (-53 x $10^2$ N/$m^2$) LBNP and was not tested at -50 mm Hg (-67 x $10^2$ N/$m^2$) LBNP on recovery day. Five other crewmembers (the Apollo 8 CMP, the Apollo 8 LMP, the Apollo 9 LMP, the Apollo 16 CMP, and the Apollo 16 LMP) developed presyncopal symptoms at some point before protocol completion during their immediate postflight -50 mm Hg (-67 x $10^2$ N/$m^2$) stress; the Apollo 15 Commander experienced similar symptoms during his second postflight evaluation. Although more crewmembers, immediately postflight, demonstrated a larger heart rate increment over preflight values during LBNP stress than during the resting control period, statistically significant group differences disappeared by the third postflight evaluation. Passive vertical standing results indicated a similar increase in heart rate immediately postflight, with eight of nine crewmembers (89 percent) having heart rates above their 95-percent preflight envelope, and the group mean value being elevated at the 0.1 percent level.

In table 5, heart rates of Apollo crewmembers are compared with those of control subjects for three protocol conditions. Significant "postflight" heart rate changes among the control subjects onboard the recovery ship were not observed. Although the control subjects were exposed to similar environmental conditions, all had a five- to ten-day acclimatization period onboard the recovery ship preceding their evaluations.

Table 5

Apollo Crewmember Versus Control Subject Heart Rate Data

| Protocol Condition | Apollo Group | Preflight Summary | | | | Postflight Evaluations | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Response | | | | First | | | Second | | |
| | | N | $\overline{X}$ | $SD_i$ | $SD_t$ | N | $\overline{X}$ | p | N | $\overline{X}$ | p |
| Resting supine | Crew | 24 | 61.6 | 8.60 | 1.06 | 24 | 69.7 | 0.02 | 24 | 67.2 | 0.05 |
| | Controls | 22 | 69.7 | 6.93 | 1.00 | 22 | 69.4 | n.s. | 10 | 70.4 | n.s. |
| −50 mm Hg* LBNP | Crew | 18 | 76.5 | 13.27 | 1.55 | 17 | 108.5 | 0.001 | 17 | 92.2 | 0.02 |
| | Controls | 16 | 85.1 | 8.14 | 1.49 | 14 | 87.3 | n.s. | 9 | 84.2 | n.s. |
| Stand | Crew | 9 | 76.4 | 6.11 | 1.24 | 9 | 99.8 | 0.001 | 9 | 91.8 | 0.01 |
| | Controls | 7 | 79.6 | 6.40 | 2.72 | 7 | 81.1 | n.s. | – | – | – |

*−67 x $10^2$N/$m^2$

Note: N = Number of subjects

$\overline{X}$ = Group mean

$SD_i$ = Standard deviation of crewmember preflight summary means

$SD_t$ = Standard deviation of three preflight group means

p = Probability level

## Heart Rate and Other Measures During Several LBNP Protocols

Table 6 contains group mean values for several physiological measurements by protocol condition. Preflight summary group means are shown with two different standard deviations. The first ($SD_i$) is an expression of variability between the crewmember preflight summary means; the second ($SD_t$) is a measure of variability among the three preflight group means. Accompanying each postflight evaluation group mean is the $t$-test probability that it differs from the preflight summary group mean. For the resting supine control condition, heart rate is significantly elevated at the first and second postflight evaluations. The reciprocal of this response is seen in the stroke volume data. No significant differences are noted after flight in the resting systolic, diastolic, or pulse pressures. During the three conditions of reduced pressure [-30, -40, and -50 mm Hg ($-40 \times 10^2$, $-53 \times 10^2$ and $-67 \times 10^2$ $N/m^2$) LBNP], heart rates are significantly elevated at the first postflight evaluation, with a trend toward preflight summary response values in subsequent postflight evaluations. Again, stroke volume followed a reciprocal pattern. Significant decreases in systolic and pulse pressures are seen during LBNP only in the first postflight evaluations. Changes during the passive stand condition parallel changes during LBNP. Postflight changes during the recovery condition are not significant. All postflight alterations return to preflight summary values by the third postflight evaluation.

### Calf Volume Changes Induced by LBNP

No significant postflight changes in calf volume are observed during the three conditions of reduced-pressure stress at any of the postflight evaluations (table 6). Table 7, which includes data on individual calf volume change during Apollo LBNP maximal stress, is presented because plethysmographic data from Gemini tilt table tests indicated increased postflight calf volume during tilt stress. Seven of seventeen Apollo crewmembers (41 percent) showed significantly decreased postflight calf volume changes during the maximal [-50 mm Hg ($-67 \times 10^2$ $N/m^2$)] LBNP level, and the total group mean also decreased from the preflight value, although not to a statistically significant degree.

### Body Weight Changes

Significant body weight changes occurred in virtually all astronauts regardless of flight duration. If a significant part of the weight change is due to a reduction in blood volume or loss of body fluids, cardiovascular function might be affected. Consequently, weight changes were considered in conjunction with orthostatic evaluations. Table 8 contains data on individual body weights at each evaluation date. Preflight summary means are based on three weights taken on the days of the major medical examinations. Launch day (F-0) weights are also listed because the postflight weight of United States space crewmen has been previously based on these data (Berry, 1973). The launch day group mean is clearly decreased (0.7 kg) from the preflight summary group mean. The $t$-test probability for postflight weight change is referenced to the preflight summary group mean rather than to the single launch day group mean, because the preflight mean is more representative of true crew weight change. The first postflight group mean weight shows a 3.4-kg (4.4 percent) decrement that is not regained at 90 to 160 hours after splashdown by the nine crewmen (Apollo 15 to 17 missions) weighed that long after recovery.

### Resting Calf Circumference and Volume of the Lower Limbs

The simple and relatively accurate supine measurement of maximal calf circumference was performed before and after flight on 24 crewmen. The first section of table 9

Table 6

Apollo Group Mean Values for Preflight Summary and Postflight Orthostatic Evaluations

| Measurement | Protocol Condition | Preflight Summary | | | | Postflight Evaluations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Response | | | | First | | | Second | | | Third | | |
| | | N | $\overline{X}$ | $SD_i$ | $SD_t$ | N | $\overline{X}$ | p | N | $\overline{X}$ | p | N | $\overline{X}$ | p |
| Heart rate (bpm) | Control | 24 | 61.6 | 8.60 | 1.06 | 24 | 69.7 | 0.02 | 24 | 67.2 | n.s. | 15 | 63.5 | n.s. |
| | −30 mm Hg* LBNP | 18 | 65.7 | 11.11 | 1.42 | 18 | 84.3 | 0.005 | 18 | 72.7 | n.s. | 15 | 68.5 | n.s. |
| | −40 mm Hg* LBNP | 18 | 70.7 | 11.20 | 1.40 | 18 | 96.7 | 0.001 | 18 | 79.8 | 0.05 | 15 | 74.5 | n.s. |
| | −50 mm Hg* LBNP | 18 | 76.5 | 13.27 | 1.55 | 17 | 108.5 | 0.001 | 17 | 92.2 | 0.02 | 15 | 82.7 | n.s. |
| | Recovery | 18 | 59.1 | 8.66 | 1.08 | 18 | 67.4 | n.s. | 18 | 64.1 | n.s. | 15 | 60.5 | n.s. |
| | Stand | 9 | 76.4 | 6.11 | 1.24 | 9 | 99.8 | 0.001 | 9 | 91.8 | 0.001 | 3 | 77.0 | n.s. |
| Systolic blood pressure (mm Hg*) | Control | 24 | 115.3 | 8.31 | 0.74 | 24 | 111.6 | n.s. | 24 | 118.0 | n.s. | 15 | 118.5 | n.s. |
| | −30 mm Hg* LBNP | 18 | 110.5 | 10.04 | 1.86 | 18 | 101.5 | 0.02 | 18 | 112.3 | n.s. | 15 | 112.7 | n.s. |
| | −40 mm Hg* LBNP | 18 | 107.7 | 10.66 | 1.15 | 18 | 96.3 | 0.01 | 18 | 109.7 | n.s. | 15 | 109.3 | n.s. |
| | −50 mm Hg* LBNP | 18 | 104.8 | 11.09 | 1.86 | 17 | 91.5 | 0.01 | 17 | 107.4 | n.s. | 15 | 107.2 | n.s. |
| | Recovery | 18 | 117.1 | 10.03 | 1.55 | 18 | 116.4 | n.s. | 18 | 123.2 | n.s. | 15 | 120.5 | n.s. |
| | Stand | 9 | 118.8 | 6.24 | 3.40 | 9 | 105.8 | 0.001 | 9 | 123.9 | n.s. | 3 | 120.7 | n.s. |
| Diastolic blood pressure (mm Hg*) | Control | 24 | 67.0 | 6.61 | 1.51 | 24 | 67.1 | n.s. | 24 | 67.7 | n.s. | 15 | 66.3 | n.s. |
| | −30 mm Hg* LBNP | 18 | 69.7 | 6.63 | 1.31 | 18 | 66.5 | n.s. | 18 | 67.4 | n.s. | 15 | 67.9 | n.s. |
| | −40 mm Hg* LBNP | 18 | 70.7 | 6.21 | 1.25 | 18 | 66.3 | 0.05 | 18 | 68.3 | n.s. | 15 | 70.0 | n.s. |
| | −50 mm Hg* LBNP | 18 | 71.8 | 6.84 | 2.01 | 17 | 66.6 | n.s. | 17 | 69.1 | n.s. | 15 | 70.9 | n.s. |
| | Recovery | 18 | 71.0 | 6.32 | 0.89 | 18 | 73.4 | n.s. | 18 | 70.9 | n.s. | 15 | 69.4 | n.s. |
| | Stand | 9 | 81.0 | 5.22 | 4.46 | 9 | 80.2 | n.s. | 9 | 82.8 | n.s. | 3 | 80.7 | n.s. |

*1 mm Hg = $1.33 \times 10^2$ N/m$^2$

Note: N = Number of subjects
$\overline{X}$ = Group mean
$SD_i$ = Standard deviation of crewmember preflight summary means
$SD_t$ = Standard deviation of three preflight group means
p = Probability level

Table 6 (Continued)

Apollo Group Mean Values for Preflight Summary and Postflight Orthostatic Evaluations

| Measurement | Protocol Condition | Preflight Summary Response | | | | Postflight Evaluations First | | | Second | | | Third | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N | $\overline{X}$ | $SD_i$ | $SD_t$ | N | $\overline{X}$ | p | N | $\overline{X}$ | p | N | $\overline{X}$ | p |
| Pulse Pressure (mm Hg*) | Control | 24 | 48.3 | 6.34 | 0.81 | 24 | 44.6 | n.s. | 24 | 50.2 | n.s. | 15 | 52.1 | n.s. |
| | −30 mm Hg* LBNP | 18 | 40.9 | 6.09 | 0.61 | 18 | 35.2 | 0.01 | 18 | 44.8 | n.s. | 15 | 44.8 | n.s. |
| | −40 mm Hg* LBNP | 18 | 37.2 | 6.52 | 0.06 | 18 | 30.2 | 0.02 | 18 | 41.4 | n.s. | 15 | 39.4 | n.s. |
| | −50 mm Hg* LBNP | 18 | 33.1 | 6.59 | 0.06 | 17 | 24.8 | 0.02 | 17 | 38.2 | n.s. | 15 | 36.3 | n.s. |
| | Recovery | 18 | 46.4 | 6.76 | 1.07 | 18 | 43.1 | n.s. | 18 | 52.2 | 0.05 | 15 | 51.0 | n.s. |
| | Stand | 9 | 37.8 | 6.44 | 7.47 | 9 | 25.6 | 0.02 | 9 | 41.0 | n.s. | 3 | 40.0 | n.s. |
| Calf circumference (cm) | Control | 24 | 37.47 | 1.626 | 0.072 | 24 | 36.38 | 0.05 | 21 | 36.85 | n.s. | 15 | 37.05 | n.s. |
| Calf volume Change (% Δ) | −30 mm Hg* LBNP | 18 | 1.62 | 0.512 | 0.060 | 18 | 1.45 | n.s. | 18 | 1.49 | n.s. | 15 | 1.45 | n.s. |
| | −40 mm Hg* LBNP | 18 | 2.32 | 0.597 | 0.050 | 18 | 2.09 | n.s. | 18 | 2.26 | n.s. | 15 | 2.21 | n.s. |
| | −50 mm Hg* LBNP | 18 | 3.08 | 0.679 | 0.042 | 18 | 2.71 | n.s. | 17 | 3.04 | n.s. | 15 | 3.04 | n.s. |
| | Recovery | 18 | 0.54 | 0.270 | 0.029 | 17 | 0.27 | 0.02 | 18 | 0.66 | n.s. | 15 | 0.53 | n.s. |
| Stroke volume (ml) | Control | 9 | 85.8 | 4.49 | 0.15 | 7 | 74.1 | 0.02 | 9 | 79.2 | 0.05 | 9 | 80.4 | n.s. |
| | −30 mm Hg* LBNP | 9 | 73.7 | 6.00 | 1.05 | 7 | 60.3 | 0.01 | 9 | 64.9 | 0.05 | 9 | 66.3 | n.s. |
| | −40 mm Hg* LBNP | 9 | 63.8 | 6.96 | 1.58 | 6 | 49.3 | 0.025 | 9 | 56.4 | n.s. | 9 | 58.0 | n.s. |
| | −50 mm Hg* LBNP | 9 | 57.6 | 7.02 | 0.78 | 5 | 41.4 | 0.05 | 8 | 47.9 | n.s. | 9 | 50.2 | 0.05 |
| | Recovery | 9 | 86.9 | 3.37 | 1.36 | 7 | 79.4 | n.s. | 9 | 81.6 | n.s. | 9 | 82.7 | n.s. |

*1 mm Hg = $1.33 \times 10^2$ N/m$^2$.

Note: N = Number of subjects

$\overline{X}$ = Group mean

$SD_i$ = Standard deviation of crewmember preflight summary means

$SD_t$ = Standard deviation of three preflight group means

p = Probability level.

Table 7

Individual Calf Volume Percent Change Data During Apollo LBNP Maximal Stress. (Arrows Indicate $p<0.05$).

| Apollo Mission | Crew-member | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | |
|---|---|---|---|---|---|---|---|---|---|
| | | F-30 Days | F-15 Days | F-5 Days | Mean | SD | First | Second | Third |
| 7 | CDR | 1.74 | 1.73 | 2.24 | 1.90 | 0.294 | 2.21 | 2.01 | |
| | CMP | 2.49 | 2.30 | 2.50 | 2.43 | 0.120 | 1.96 ↓ | 2.21 | |
| | LMP | 3.60 | 3.41 | 2.85 | 3.13 | 0.392 | 2.78 | 3.87 | |
| 8 | CDR | 3.06 | 2.86 | 2.54 | 2.83 | 0.262 | 2.37 | 2.75 | 2.91 |
| | CMP | 2.74 | 2.98 | 2.98 | 2.90 | 0.140 | 2.29 ↓ | 2.54 ↓ | 2.55 |
| | LMP | 3.54 | 4.09 | 3.45 | 3.70 | 0.350 | 2.61 ↓ | 4.25 | 3.34 |
| 9 | CDR | 2.45 | 2.16 | 2.42 | 2.34 | 0.159 | 2.72 | 2.53 | 2.40 |
| | CMP | 2.59 | 3.86 | 2.16 | 2.87 | 0.884 | 3.40 | 2.83 | 2.71 |
| | LMP | 2.90 | — | 3.50 | 3.20 | 0.424 | 2.31 | 2.59 | 2.55 |
| 15 | CDR | 4.16 | 3.93 | 4.28 | 4.12 | 0.178 | 3.55 ↓ | — | 3.28 ↓ |
| | CMP | 2.71 | 2.85 | 3.03 | 2.86 | 0.160 | 3.27 ↑ | 3.50 ↑ | 2.91 |
| | LMP | 3.98 | 3.86 | 4.28 | 4.04 | 0.216 | — | 3.90 | 3.94 |
| 16 | CDR | 4.02 | 4.02 | 3.90 | 3.98 | 0.069 | 3.37 ↓ | 3.98 | 4.18 ↑ |
| | CMP | 3.69 | 3.78 | 3.16 | 3.54 | 0.335 | 2.32 ↓ | 3.11 | 4.03 |
| | LMP | 3.89 | 3.94 | 3.68 | 3.83 | 0.135 | 2.99 ↓ | 3.37 ↓ | 3.71 |
| 17 | CDR | 2.47 | 2.81 | 3.08 | 2.79 | 0.306 | 2.71 | 2.85 | 2.84 |
| | CMP | 1.97 | 1.84 | 2.13 | 1.98 | 0.145 | 2.37 ↑ | 2.44 ↑ | 1.58 ↓ |
| | LMP | 3.05 | 2.92 | 3.25 | 3.07 | 0.166 | 2.80 | 2.98 | 2.69 |
| Group Mean | | 3.06 | 3.14 | 3.08 | 3.08 | | 2.71 | 3.04 | 3.04 |
| ±SD | | 0.729 | 0.796 | 0.679 | 0.679 | | 0.472 | 0.666 | 0.708 |
| | | | | | t-Test | | n.s. | n.s. | n.s. |

Table 8
Individual Body Weights at Each Orthostatic Evaluation Date
(Arrows Indicate $p<0.05$)
(Values are in kg)

| Apollo Mission | Crew-member | Preflight Evaluations | | | Preflight Summary | | Launch Day | Postflight Evaluations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | | First | Second | Third | Fourth |
| 7 | CDR | 87.1 | 88.0 | 88.2 | 87.8 | 0.59 | 88.0 | 86.1 ↓ | 86.4 | | |
| | CMP | 69.4 | 69.4 | 69.8 | 69.5 | 0.23 | 71.2 ↑ | 66.7 ↓ | 68.3 | | |
| | LMP | 69.4 | 71.8 | 70.8 | 70.7 | 1.21 | 70.8 | 67.8 | 69.6 | | |
| 8 | CDR | 76.2 | 76.4 | 77.1 | 76.6 | 0.47 | 76.8 | 72.8 ↓ | 74.0 ↓ | 75.1 ↓ | |
| | CMP | 76.4 | 77.6 | 76.4 | 76.8 | 0.69 | 78.0 | 74.4 ↓ | 74.7 ↓ | 75.2 | |
| | LMP | 66.0 | 67.1 | 66.0 | 66.4 | 0.64 | 64.4 ↓ | 62.6 ↓ | 62.8 ↓ | – | |
| 9 | CDR | 73.5 | 72.8 | 72.8 | 73.0 | 0.40 | 72.1 | 69.6 ↓ | 70.9 ↓ | 71.7 ↓ | |
| | CMP | 82.8 | 82.5 | 80.7 | 82.0 | 1.14 | 80.7 | 78.2 ↓ | 82.1 | 81.2 | |
| | LMP | 74.7 | 74.4 | 73.7 | 74.3 | 0.51 | 72.1 ↓ | 69.4 ↓ | 71.3 ↓ | 72.3 ↓ | |
| 10 | CDR | 80.1 | 79.4 | 78.9 | 79.5 | 0.60 | 77.6 ↓ | 76.4 ↓ | 77.4 ↓ | | |
| | CMP | 76.6 | 77.1 | 76.6 | 76.8 | 0.29 | 74.8 ↓ | 72.3 ↓ | 73.1 ↓ | | |
| | LMP | 79.4 | 79.5 | 79.4 | 79.4 | 0.06 | 78.5 ↓ | 73.9 ↓ | 74.6 ↓ | | |
| 11 | CDR | 78.0 | 78.2 | 79.1 | 78.4 | 0.59 | 78.0 | 74.4 ↓ | 77.1 | | |
| | CMP | 74.4 | 75.3 | 77.1 | 75.6 | 1.37 | 75.3 | 72.1 ↓ | 72.1 ↓ | | |
| | LMP | 77.6 | 78.9 | 77.9 | 78.1 | 0.68 | 75.7 ↓ | 75.3 ↓ | 77.1 | | |
| 12 | CDR | 66.2 | – | 66.9 | 66.6 | 0.49 | 67.7 | 65.8 | 66.7 | 66.7 | |
| | CMP | 71.0 | 70.3 | – | 70.7 | 0.49 | 70.4 | 67.1 | 68.9 | 68.9 | |
| | LMP | 69.4 | – | 70.3 | 69.9 | 0.64 | 69.1 | 63.5 ↓ | 64.9 | 64.4 | |
| 13 | CDR | 79.8 | 77.8 | 78.5 | 78.7 | 1.01 | 80.5 | 74.2 ↓ | | | |
| | CMP | 89.1 | – | 89.7 | 89.4 | 0.42 | 89.3 | 84.4 ↓ | | | |
| | LMP | 71.0 | 70.3 | 71.2 | 70.8 | 0.47 | 70.8 | 67.8 ↓ | | | |

Table 8 (Continued)
Individual Body Weights at Each Orthostatic Evaluation Date
(Arrows Indicate p<0.05)
(Values are in kg)

| Apollo Mission | Crew-member | Preflight Evaluations | | | Preflight Summary | | Launch Day | Postflight Evaluations | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | | First | Second | Third | Fourth |
| 14 | CDR | 78.0 | 78.5 | 78.7 | 78.4 | 0.36 | 76.2 ↓ | 76.6 ↓ | 77.1 ↓ | | |
| | CMP | 74.2 | 76.2 | 75.5 | 75.3 | 1.01 | 74.8 | 69.4 ↓ | 72.6 ↓ | | |
| | LMP | 83.5 | 83.1 | 83.2 | 83.2 | 0.26 | 79.8 ↓ | 80.3 ↓ | 80.7 ↓ | | |
| 15 | CDR | 80.5 | 81.2 | 81.5 | 81.1 | 0.51 | 80.2 | 78.9 ↓ | – | 81.0 | 80.7 |
| | CMP | 73.7 | 73.2 | 74.0 | 73.6 | 0.40 | 73.5 | 72.1 ↓ | – | 72.6 | 72.3 ↓ |
| | LMP | 74.3 | 73.9 | 74.8 | 74.3 | 0.45 | 73.2 | 70.8 ↓ | – | 73.7 | 73.1 ↓ |
| 16 | CDR | 80.8 | 80.5 | 78.9 | 80.1 | 1.02 | 78.9 | 75.5 ↓ | 76.6 ↓ | – | 76.4 ↓ |
| | CMP | 63.2 | 61.9 | 62.6 | 62.6 | 0.65 | 61.5 | 58.5 ↓ | 59.9 ↓ | – | 60.3 ↓ |
| | LMP | 73.1 | 73.8 | 72.6 | 73.2 | 0.60 | 73.0 | 70.5 ↓ | 71.7 ↓ | – | 71.3 ↓ |
| 17 | CDR | 81.0 | 80.3 | 80.7 | 80.7 | 0.35 | 80.3 | 76.1 ↓ | 76.0 ↓ | 78.0 ↓ | 78.5 ↓ |
| | CMP | 78.2 | 76.6 | 77.0 | 77.3 | 0.83 | 75.7 | 74.6 ↓ | 73.9 ↓ | 73.9 ↓ | 74.8 ↓ |
| | LMP | 76.0 | 76.6 | 75.3 | 76.0 | 0.65 | 74.8 | 72.9 ↓ | 71.8 ↓ | 73.4 ↓ | 72.8 ↓ |
| Group Mean | | 75.90 | 75.09 | 76.12 | 75.96 | | 75.26 | 72.45 | 73.05 | 73.44 | 73.36 |
| ±SD | | 5.849 | 5.213 | 5.786 | 5.792 | | 5.727 | 5.866 | 5.763 | 4.781 | 5.787 |
| | | | | | t-Test | | | p<0.02 | n.s. | n.s. | n.s. |

contains values of the average of both calves for individual crewmembers at each test date. In the first postflight evaluation, 16 of 24 crewmembers (67 percent) showed significantly reduced calf circumference. Group mean values showed a statistically significant probability ($p < 0.05$) immediately postflight of a decrement of 1.1 cm (3 percent) that was not totally regained at approximately 120 hours after splashdown by two of the three crewmen tested at that time.

Total leg volume was calculated for the six crewmen of the last two Apollo missions (Apollo 16 and 17). The last section of table 9 contains data on total leg volume as the sum of both legs. Although not statistically significant, a one-liter (5.8 percent) group mean decrement was seen in the first two postflight evaluations. No clear trend toward restitution was seen as late as 90 to 160 hours after splashdown; subsequent measurements were not performed.

### Cardiothoracic Ratios

To determine whether a change in heart size had occurred, cardiothoracic (C/T) ratios were calculated. Once before and once after flight, posterior-anterior chest X-rays were taken of each crewmember. The C/T ratios given in table 10 provided a measure of heart size to amplify the preceding weight and leg-size data. Accurate cardiothoracic ratios could not be obtained from three postflight films. Synchronization at peak systolic and peak diastolic cardiac phases for X-rays taken on the last six Apollo crewmembers (Apollo 16 and 17 missions) enabled achievement of greater accuracy by providing two films for each preflight and postflight comparison, and by eliminating random X-ray exposure in the cardiac cycle. Twenty-four of thirty crewmembers (80 percent) showed a decrease in postflight C/T ratios with a group mean cardiothoracic ratio decrement of 0.021 (5 percent), highly significant at $p < 0.001$. The Apollo 17 CMP, who showed a postflight increase in C/T ratio, wore a special antihypotensive pressure garment from splashdown until LBNP evaluation five hours later.

### Special Measures for Apollo 15, 16, and 17

Vectorcardiographic data for Apollo 15, 16, and 17 crewmen showed no changes of clinical significance. An analysis of the phonocardiographic findings derived from the vibrocardiogram and of the systolic time intervals obtained with carotid pulse and VCG measurements was incomplete at the time of this writing.

### Antihypotensive Garment Efficacy

Seven hours after splashdown, orthostatic evaluations were made of the Apollo 16 CMP wearing the antihypotensive garment. The garment was 0.5 cm smaller at the calf than the one worn during preflight testing to compensate for the expected loss of lower limb girth from disuse in zero g. The results are shown in table 11. Blood pressure and heart rate data are expressed as mean values with one standard deviation, for each five-minute period.

As noted earlier, ambient temperatures during postflight testing of Apollo 16 astronauts were high [305°K (32°C) to 306°K (33°C)]. During the same tests on two control subjects one day earlier, the temperature was somewhat lower: 301°K (28°C) for

Table 9

Individual Resting Supine Calf Circumference and Lower Limb Volume Data (Arrows Indicate $p<0.05$)

| Apollo Mission | Crew-member | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | First | Second | Third | Fourth |
| Resting Supine Mean Calf Circumference, cm | | | | | | | | | | |
| 7 | CDR | 40.7 | 40.9 | 40.8 | 40.8 | 0.10 | 40.1 ↓ | 40.1 ↓ | – | – |
| | CMP | 35.9 | 35.9 | 35.9 | 35.9 | 0.00 | 34.7 | 35.6 | – | – |
| | LMP | 36.6 | 36.9 | 36.1 | 36.5 | 0.40 | 35.1 ↓ | 36.0 | – | – |
| 8 | CDR | 35.2 | 35.3 | 35.4 | 35.3 | 0.10 | 34.9 ↓ | 35.2 | 34.4 ↓ | – |
| | CMP | 39.7 | 39.4 | 39.4 | 39.5 | 0.17 | 39.1 | 39.1 | 39.1 | – |
| | LMP | 37.3 | 36.8 | 37.2 | 37.1 | 0.26 | 36.8 | 36.7 | 37.2 | – |
| 9 | CDR | 37.0 | 37.0 | 36.8 | 36.9 | 0.12 | 35.2 ↓ | 35.9 ↓ | 36.4 ↓ | – |
| | CMP | 40.5 | 40.2 | 40.1 | 40.3 | 0.21 | 38.9 ↓ | 40.2 | 40.4 | – |
| | LMP | 36.4 | – | 36.2 | 36.3 | 0.14 | 34.7 ↓ | 38.1 ↑ | 36.1 | – |
| 10 | CDR | 36.3 | 35.1 | 35.9 | 35.8 | 0.61 | 34.6 ↓ | 35.6 | – | – |
| | CMP | 37.8 | 37.1 | 37.0 | 37.3 | 0.44 | 36.2 | 37.1 | – | – |
| | LMP | 38.1 | 37.5 | 37.0 | 37.5 | 0.55 | 35.6 ↓ | 36.5 | – | – |
| 11 | CDR | 36.6 | 36.0 | 36.2 | 36.3 | 0.31 | 35.6 | – | – | – |
| | CMP | 37.2 | 36.8 | 38.1 | 37.4 | 0.67 | 37.0 | – | – | – |
| | LMP | 37.9 | 38.3 | 37.6 | 37.9 | 0.35 | 37.6 | – | – | – |
| 15 | CDR | 40.3 | 40.5 | 40.5 | 40.4 | 0.12 | 39.3 ↓ | 39.4 ↓ | 40.1 | 40.8 ↑ |
| | CMP | 36.5 | 36.3 | 36.5 | 36.4 | 0.12 | 35.6 ↓ | 35.1 ↓ | 35.9 ↓ | 35.9 ↓ |
| | LMP | 37.5 | 37.1 | 37.4 | 37.3 | 0.21 | 36.0 ↓ | 36.5 ↓ | 36.7 ↓ | 36.3 ↓ |
| 16 | CDR | 38.1 | 37.9 | 38.0 | 38.0 | 0.10 | 36.6 ↓ | 36.6 ↓ | 36.5 ↓ | – |
| | CMP | 34.4 | 34.4 | 34.8 | 34.5 | 0.23 | 33.5 ↓ | 33.5 ↓ | 33.2 ↓ | – |
| | LMP | 36.3 | 36.3 | 36.3 | 36.3 | 0.00 | 35.5 | 35.6 | 35.4 | – |

Table 9 (Continued)
Individual Resting Supine Calf Circumference
and Lower Limb Volume Data (Arrows Indicate $p<0.05$)

| Apollo Mission | Crew-members | Preflight Evaluations | | | Preflight Summary | | Postflight Evaluations | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | F-30 Days | F-15 Days | F-5 Days | Mean | ± SD | First | Second | Third | Fourth |
| Resting Supine Mean Calf Circumference, cm (Continued) | | | | | | | | | | |
| 17 | CDR | 38.0 | 38.2 | 38.5 | 38.2 | 0.25 | 37.3 ↓ | 36.6 ↓ | 38.1 | 37.3 ↓ |
| | CMP | 38.8 | 38.1 | 38.6 | 38.5 | 0.36 | 37.0 ↓ | 37.0 ↓ | 38.1 | 37.0 ↓ |
| | LMP | 38.6 | 39.1 | 38.9 | 38.9 | 0.25 | 37.4 ↓ | 37.5 ↓ | 38.1 ↓ | 37.6 ↓ |
| Group Mean | | 37.57 | 37.44 | 37.45 | 37.47 | | 36.43 | 36.85 | 37.05 | 37.48 |
| ±SD | | 1.621 | 1.724 | 1.625 | 1.634 | | 1.688 | 1.719 | 1.995 | 1.743 |
| | | | | | t-Test | | $p<0.05$ | n.s. | n.s. | n.s. |
| Lower Limb Volume, ml | | | | | | | | | | |
| 16 | CDR | 15 929 | 15 485 | 15 669 | 15 694 | 223 | 14 108 ↓ | 14 146 ↓ | 13 770 ↓ | 13 812 ↓ |
| | CMP | 12 577 | 12 492 | 12 798 | 12 622 | 158 | 12 150 ↓ | 11 898 ↓ | 12 005 ↓ | 12 146 ↓ |
| | LMP | 14 556 | 14 794 | 14 741 | 14 697 | 125 | 14 482 | 14 033 ↓ | 14 068 ↓ | 13 806 ↓ |
| 17 | CDR | 17 265 | 17 685 | 17 991 | 17 647 | 365 | 16 772 | 16 427 ↓ | 17 238 | 16 706 ↓ |
| | CMP | 17 426 | 17 132 | 17 357 | 17 305 | 154 | 15 964 ↓ | 16 366 ↓ | 17 028 | 16 424 ↓ |
| | LMP | 17 944 | 18 542 | 18 030 | 18 172 | 323 | 17 084 ↓ | 17 692 | 17 878 | 17 189 ↓ |
| Group Mean | | 15 950 | 16 022 | 16 098 | 16 023 | | 15 093 | 15 094 | 15 331 | 15 014 |
| ±SD | | 2 059 | 2 218 | 2 089 | 2 113 | | 1 873 | 2 116 | 2 371 | 2 035 |
| | | | | | t-Test | | n.s. | n.s. | n.s. | n.s. |

Table 10

Apollo Crewmen Cardiothoracic Ratios
During Orthostatic Evaluations
(Ratios based on X-radiographs)

| Apollo Mission | Crew-member | Preflight F-5 Days | First Post-flight | Change in C/T |
|---|---|---|---|---|
| 7 | CDR | 0.46 | 0.44 | –0.02 |
| | CMP | 0.45 | 0.41 | –0.04 |
| | LMP | 0.39 | 0.36 | –0.03 |
| 8 | CDR | 0.44 | 0.40 | –0.04 |
| | CMP | 0.44 | 0.41 | –0.03 |
| | LMP | 0.38 | 0.32 | –0.06 |
| 9 | CDR | 0.37 | 0.36 | –0.01 |
| | CMP | 0.43 | 0.39 | –0.04 |
| | LMP | 0.36 | 0.33 | –0.03 |
| 10 | CDR | 0.43 | 0.39 | –0.04 |
| | CMP | 0.43 | 0.39 | –0.04 |
| | LMP | 0.50 | 0.40 | –0.10 |
| 11 | CDR | 0.40 | 0.40 | 0.00 |
| | CMP | 0.35 | – | – |
| | LMP | 0.40 | 0.39 | –0.01 |
| 12 | CDR | 0.37 | 0.39 | +0.02 |
| | CMP | 0.41 | – | – |
| | LMP | 0.40 | – | – |
| 13 | CDR | 0.42 | 0.41 | –0.01 |
| | CMP | 0.43 | 0.42 | –0.01 |
| | LMP | 0.43 | 0.39 | –0.04 |
| 14 | CDR | 0.39 | 0.42 | +0.03 |
| | CMP | 0.41 | 0.40 | –0.01 |
| | LMP | 0.46 | 0.44 | –0.02 |
| 15 | CDR | 0.42 | 0.43 | +0.01 |
| | CMP | 0.40 | 0.37 | –0.03 |
| | LMP | 0.48 | 0.51 | +0.03 |
| 16 | CDR | 0.41 | 0.40 | –0.01 |
| | CMP | 0.44 | 0.41 | –0.03 |
| | LMP | 0.36 | 0.34 | –0.02 |
| 17 | CDR | 0.50 | 0.44 | –0.06 |
| | CMP | 0.43 | 0.45 | +0.02 |
| | LMP | 0.37 | 0.36 | 0.00 |
| Group Mean | | 0.417 | 0.399 | –0.021 |
| | ±SD | 0.0383 | 0.0384 | 0.0281 |
| | | t-Test | n.s. | p<0.001 |

control subject 1, and 303°K (30°C) for control subject 2. The results of their tests also appear in table 11.

Table 11

Preflight and Postflight Passive Stand Test Data With and Without Jobst Antihypotensive Garment

| Subject Position | Measurement | Without Garment Preflight Mean ±SD | Without Garment Postflight Mean ±SD | With Garment Preflight Mean ±SD | With Garment Postflight Mean ±SD |
|---|---|---|---|---|---|
| | | Apollo 16 Command Module Pilot | | | |
| Supine | Heart rate, bpm | 45.8 ± 0.96 | 57.8 ± 0.84 | 44.8 ± 0.84 | 54.6 ± 0.89 |
| | SBP, mm Hg* | 113.5 ± 2.64 | 119.2 ± 4.80 | 117.9 ± 7.09 | 112.6 ± 6.17 |
| | DBP, mm Hg* | 74.3 ± 2.00 | 80.8 ± 2.90 | 67.2 ± 4.21 | 67.5 ± 3.89 |
| Erect | Heart rate, bpm | 55.8 ± 1.79 | 87.6 ± 0.89 | 55.2 ± 3.56 | 78.4 ± 1.34 |
| | SBP, mm Hg* | 121.6 ± 5.62 | 112.6 ± 6.17 | 117.8 ± 4.02 | 110.2 ± 5.24 |
| | DBP, mm Hg* | 77.2 ± 4.37 | 67.5 ± 3.89 | 77.8 ± 5.27 | 75.2 ± 6.02 |
| | | Control Subject 1 | | | |
| Supine | Heart rate, bpm | 77.6 ± 0.89 | 60.2 ± 1.30 | 81.4 ± 1.52 | 63.4 ± 2.70 |
| | SBP, mm Hg* | 118.0 ± 2.71 | 102.8 ± 4.77 | 118.4 ± 2.50 | 111.3 ± 4.47 |
| | DBP, mm Hg* | 57.4 ± 2.95 | 62.1 ± 2.81 | 58.0 ± 4.45 | 58.4 ± 4.12 |
| Erect | Heart rate, bpm | 85.8 ± 0.84 | 76.8 ± 1.48 | 78.4 ± 2.70 | 70.4 ± 1.34 |
| | SBP, mm Hg* | 119.1 ± 0.72 | 104.4 ± 8.38 | 122.7 ± 4.79 | 109.6 ± 3.95 |
| | DBP, mm Hg* | 74.9 ± 2.66 | 75.8 ± 4.02 | 75.1 ± 3.60 | 76.5 ± 3.24 |
| | | Control Subject 2 | | | |
| Supine | Heart rate, bpm | 67.2 ± 0.84 | 72.4 ± 0.89 | 64.0 ± 1.87 | 71.2 ± 1.30 |
| | SBP, mm Hg* | 134.3 ± 3.11 | 127.7 ± 5.58 | 137.1 ± 2.85 | 124.2 ± 5.55 |
| | DBP, mm Hg* | 71.8 ± 5.03 | 74.9 ± 5.21 | 81.3 ± 5.01 | 75.0 ± 1.63 |
| Erect | Heart rate, bpm | 76.8 ± 2.05 | 92.2 ± 2.17 | 70.6 ± 1.95 | 85.0 ± 1.22 |
| | SBP, mm Hg* | 145.0 ± 7.44 | 132.7 ± 8.74 | 149.7 ± 5.25 | 136.0 ± 8.01 |
| | DBP, mm Hg* | 82.8 ± 2.57 | 81.4 ± 5.52 | 90.4 ± 3.47 | 84.4 ± 7.95 |

*1 mm Hg = 1.33 x $10^2$ N/$m^2$

The Apollo 17 CMP, as noted previously, inflated his antihypotensive garment one-half hour before deorbit and kept it inflated [which provided a pressure of 65 mm Hg ( 87 x $10^2$ N/$m^2$) over the ankle area] until a standard orthostatic evaluation could be made. Under the conditions of testing, his heart rate increased slightly and tended to climb after the garment was deflated. Heart rate declined slightly upon reinflation (figure 4). Heart rate and blood pressure data are shown in table 12 as mean values for the three five-minute periods and for the single four-minute period.

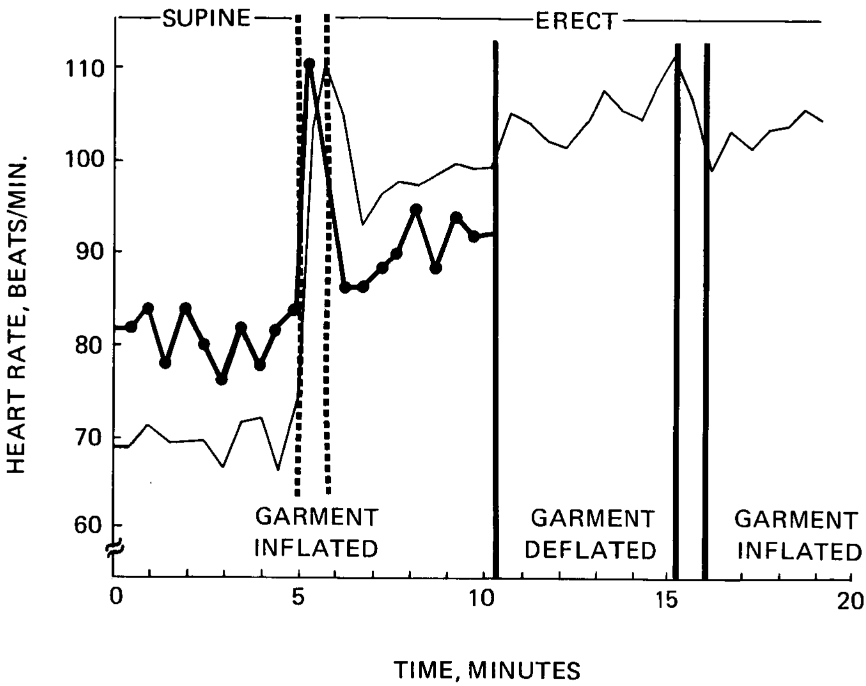


Figure 4. Passive Stand test with antihypotensive garment – Apollo 17 CMP.

Table 12

Heart Rate and Blood Pressure Data for Apollo 17 Command Module Pilot During Passive Stand Test Utilizing Antihypotensive Garment

| Measurement | Supine | Erect | | |
|---|---|---|---|---|
| | Garment Inflated | Garment Inflated | Garment Deflated | Garment Reinflated |
| | Mean ±SD | Mean ±SD | Mean ±SD | Mean ±SD |
| Heart rate, bpm | 70.1 ± 3.50 | 98.3 ± 3.43 | 105.2 ± 3.82 | 103.5 ± 3.72 |
| SBP, mm Hg* | 115.5 ± 8.28 | 128.8 ± 3.27 | 131.0 ± 3.89 | 129.1 ± 5.92 |
| DBP, mm Hg* | 64.6 ± 3.92 | 82.7 ± 4.22 | 84.4 ± 4.93 | 85.4 ± 2.88 |
| Pulse pressure, mm Hg* | 49.4 ± 6.90 | 46.9 ± 7.25 | 46.6 ± 5.46 | 43.3 ± 7.16 |

*1 mm Hg = $1.33 \times 10^2$ N/m$^2$.

## Discussion

The objective of Apollo preflight and postflight cardiovascular evaluations was to determine the effects of space flight on human physiological functions. These studies were performed within the context of transporting man safely to the moon and returning him to Earth while ensuring his well-being and functional capability in an unnatural environment. It would be naive, however, to ascribe the cardiovascular findings reported here to the effects of weightlessness alone. The observed postflight cardiovascular changes reflect the total effect of the environmental conditions encountered by each crewman within a given space flight mission. In addition to stresses of the weightless state, these conditions included stresses of launch, inflight deviations from normal work and rest cycles, variations in duration and magnitude of lunar activity, changes in diet, and stresses of entry, splashdown, and recovery. Unfortunately, the relative contribution of each of these environmental conditions cannot be established.

Significant postflight changes in cardiovascular measurements have included elevated resting and orthostatically stressed heart rate, similar but reciprocal decreases in stroke volume, and decreases in pulse pressure during orthostatic stress caused almost exclusively by decreases in systolic blood pressure. These changes are characteristic of decreased orthostatic tolerance. In addition, several presyncopal episodes occurred postflight during orthostatic stress. To properly assess the postflight decrease in crew orthostatic tolerance, however, one must consider the set of variables that existed during the recovery period.

1. Crewmen were launched and maintained in a temperate environment but were recovered and evaluated immediately after flight at significantly elevated ambient temperatures (Apollo 10, 11, and 17 missions excepted).
2. Crewmen were physically more active in the time periods immediately preceding and following splashdown. This activity tended to augment any postflight thermal stress.
3. Preflight evaluations were always performed in the morning hours, whereas postflight evaluations were usually performed in the afternoon or evening hours with respect to the preflight work and rest cycles established at the Kennedy Space Center and normally maintained in flight. This change in the time of day postflight evaluations were performed could have produced diurnal variations in body temperature, heart rate, and orthostatic tolerance.
4. Returned crewmen were exposed for varying time periods to orthostatic stress in one-g prior to orthostatic testing.
5. Vestibular effects associated with readaptation to the one-g environment were compounded by sea motion (not expressly evaluated).
6. Neurohumoral forces were altered by the excitement and the emotion of return to Earth.

These stresses and uncontrolled variables undoubtedly affected the postflight cardiovascular changes reported here.

Certain relationships suggest that all the factors listed contributed significantly. A positive, though statistically insignificant, correlation (r = 0.27) exists between change (preflight to postflight) in resting heart rate and change in oral temperature (figure 5). Also, there is a significant positive correlation (r = 0.52) between postflight change in orthostatically stressed heart rate and postflight change in resting heart rate (figure 6). In concert with similar data from Gemini crew evaluations, these Apollo findings suggest that, for flights of eight to fourteen days, postflight resting or orthostatically stressed heart rates do not increase in conjunction with increasing mission duration.

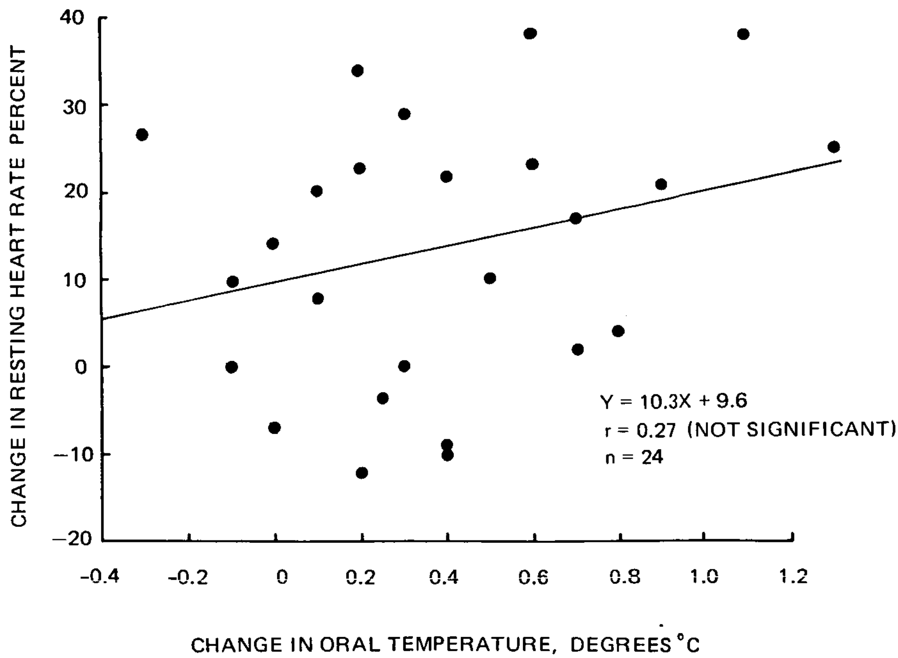


Figure 5. Positive correlation between preflight to postflight change in oral temperature and change in resting heart rate.

Weight loss was a universal finding among Apollo flight crews, but the cause and the specific body tissues involved are not readily apparent. A positive correlation between weight loss and change in total blood volume (r = 0.77) was obtained from Apollo data. Fluid losses or changes, however, did not fully explain the weight loss. The relatively inactive role of the lower extremities during space flight predisposes them to significant loss of tissue substance, especially in muscle; consistent postflight reductions in maximal calf girth on 24 Apollo crewmen and in total leg volume on the last six Apollo crewmen showed significant soft-tissue decrements (table 9). The magnitude of these decrements in the maximal calf circumference measurement taken immediately after recovery showed a positive correlation (r = 0.42) with the time of the measurement following splashdown (figure 7). Assuming rapid changes to be due to fluid shifts to the lower extremities postflight, a better correlation would be expected had the physical activities of the crewmen between splashdown and time of calf measurement been controlled. Continued decrements in leg size for several days after splashdown indicate that they were not exclusively caused by fluid changes. On the other hand, a true flight-related tissue deterioration was suggested by a negative and significant correlation (r = -0.47) between the decrement in calf size and the length of exposure to weightlessness (figure 8). When both Apollo data and Gemini data (from missions shorter and longer than Apollo missions) are used, weight loss reveals a leveling off with flight duration, if not a reversed trend, after a peak at approximately 200 hours of flight time (figure 9). The relative contributions of muscle, fatty, and interstitial tissues to weight loss have not yet been determined.

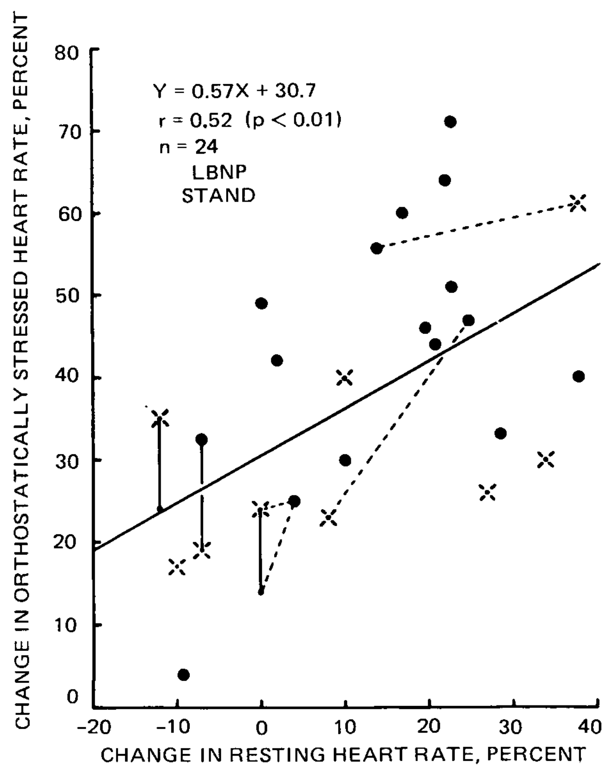


Figure 6. Positive correlation between postflight change in orthostatically stressed heart rate and postflight change in resting heart rate.

Perhaps more specific are data obtained from preflight and postflight chest roentgenograms. Although a decrease in the frontal plane cardiac silhouette size may

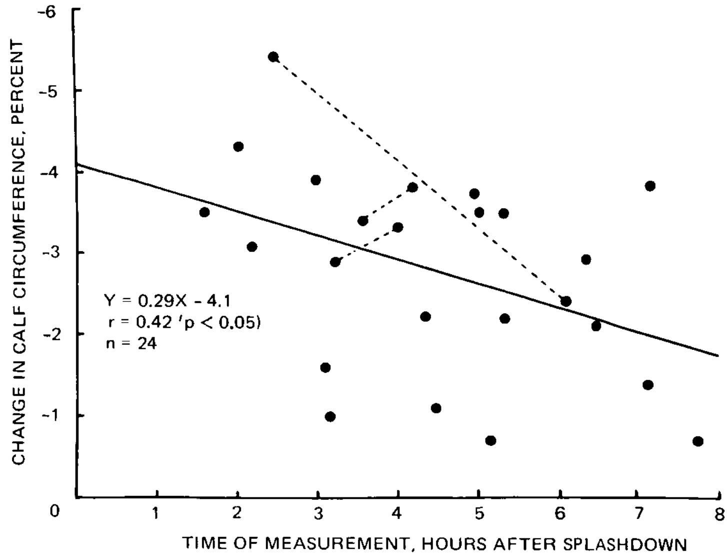


Figure 7. Positive correlation between maximal calf circumference taken immediately after recovery and time of measurement following splashdown.

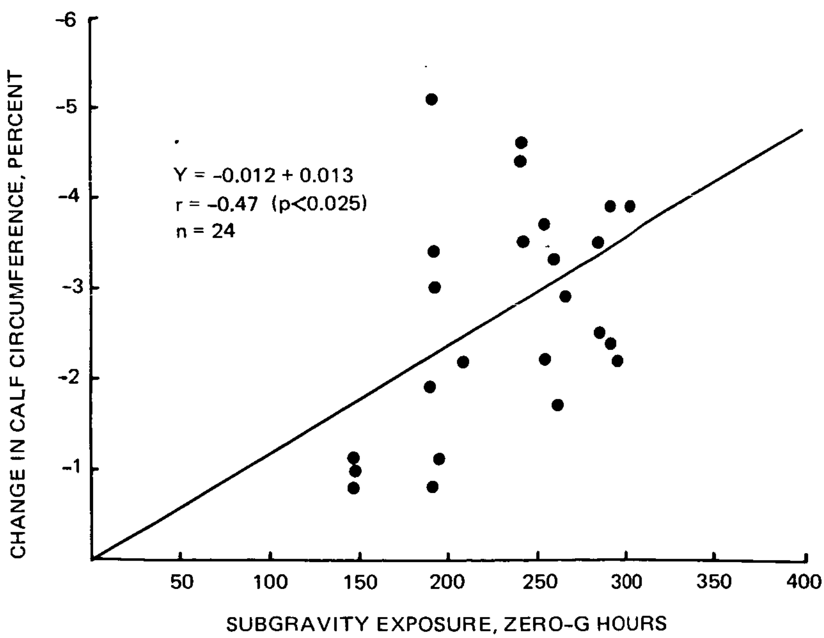


Figure 8. Negative correlation between decrement in calf size and length of exposure to weightlessness.

represent either a decrement of myocardial tissue, a decrement of intrachamber blood content, or positional change such as rotation of the heart with reference to the chest wall, changes in the cardiothoracic ratio show a very definite rise and subsequent reversal with the duration of zero-g exposure; the peak decrement occurs between 100 and 200 hours (figure 10). The relationship between the cardiothoracic ratio and the duration of zero-g exposure is definite, whereas correlations of the C/T ratio with weight loss or change in blood volume are only vaguely suggested. A most unexpected finding, however, is the significant difference ($p<0.01$) between the mean C/T ratio of the 12 lunar explorers and the mean of those Apollo crewmen who were continuously exposed to weightlessness. With 11 useful postflight data points, the lunar-walking group mean postflight cardiothoracic ratio was essentially unchanged from the preflight ratio, whereas the other 19 Apollo crewmen incurred a decrease in the group mean C/T ratio of -0.03. Because changes explicitly caused by exposure to the space environment are of great importance and concern, any opportunity to detect them is eagerly explored. Other similar comparisons between these same groups have revealed no difference in postflight weight loss or changes in resting and stressed postflight heart rate. Despite some use of the lower extremities on the lunar surface, no difference in resting-calf circumference changes was detected between the groups. These findings imply that exposure to the lunar environment somehow maintains the preflight cardiothoracic ratio.

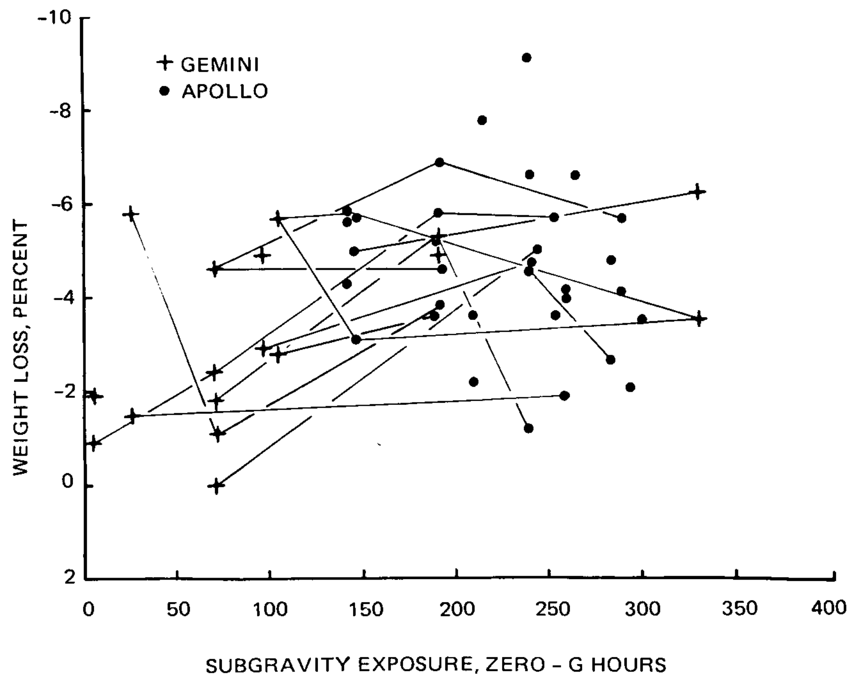


Figure 9. Apollo and Gemini data indicating a leveling off of weight loss after 200 hours of flight.

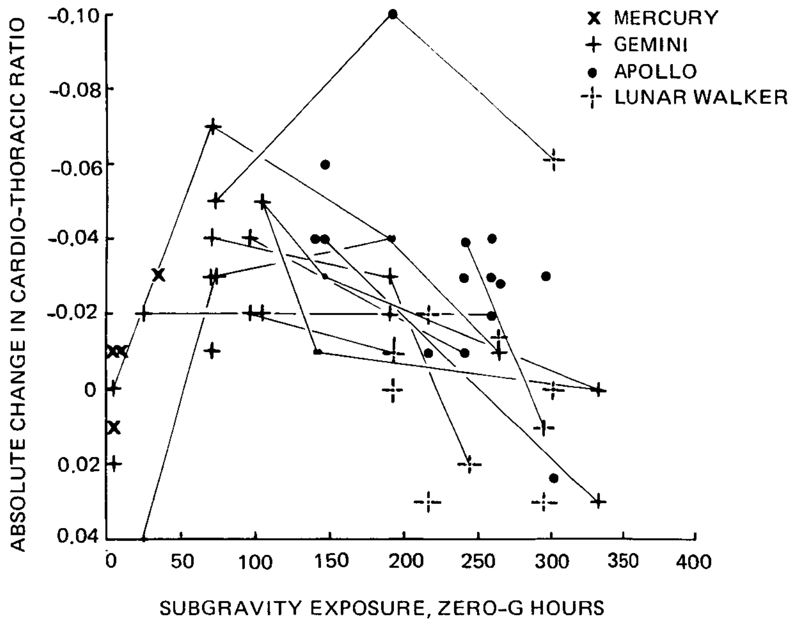


Figure 10. Roentgenogram showing peak decrement in cardiothoracic ratio.

These Apollo data have also provided a comparison of cardiovascular responses to LBNP and to vertical passive standing (the true orthostatic stress reference). For 18 crewmen evaluated with -50 mm Hg (-67 x $10^2 N/m^2$) LBNP and for nine tested with the passive stand (both procedures for three of each group), heart rates were almost identical before flight, and postflight values for LBNP stress were slightly greater. In contrast, and as noted in prior studies comparing orthostatic techniques, preflight and postflight systolic and diastolic blood pressure values were higher during stand stress than during LBNP. Thoracic and carotid pressure sensors differentially responding to the two stressors may partly account for the difference. Pulse pressure during LBNP, however, differed very little from pulse pressure during passive stand. These findings supported the use of LBNP as an orthostatic stress procedure and provided a reference for the integration of data from the Skylab inflight LBNP evaluations.

Of the two garments designed to offer protection against orthostatic hypotension, the garment employing the capstan principle proved to be the more suitable for use in the space flight environment. Although the elastic garment worn by the Apollo 16 CMP appeared to furnish moderate protection against orthostatic hypotension following weightless flight and heat stress, this type of garment seemed to be unsuitable for use in the operational setting. The crewman was unable to don the leotards in zero g before reentry or following splashdown in the confined volume of the spacecraft. Consequently, any protection the garment afforded could not be made available until the postflight testing phase. It was also impossible to ensure a garment of proper fit for postflight use because the decline in limb girth was neither uniformly distributed nor predictable in magnitude.

The design of the pressurized garment used by the Apollo 17 CMP included features intended to overcome the difficulty of predicting change in limb girth during flight. The CMP reported that the garment was easier to don in flight than he had anticipated, due in part perhaps to a relatively large reduction in limb girth. He wore the garment for more than four hours and reported it relatively comfortable.

The heart rate while reclining with the suit inflated was ten beats per minute slower than during the preflight test 15 days before launch (70.1 ± 3.5 compared to 81 ± 2.12 beats per minute). Although uncommon, a reduction of the supine resting heart rate from preflight values had been seen previously in Apollo crewmen. Mean heart rate during the first five minutes of standing with the garment inflated after flight was 98.3 ± 3.43 beats per minute compared to 91 ± 2.35 beats per minute in the preflight test.

When the garment was deflated, heart rate increased and was still increasing after five minutes. Garment reinflation, which required approximately 40 seconds, was associated with an interruption of the rising slope of heart rate and a modest reduction of mean heart rate, suggesting a protective effect from the garment.

Aside from the antihypotensive effect of using the garment, other physiological processes that occurred during readaptation to one g may have been modified. The Apollo 17 CMP was the only crewman of the 18 tested whose mean heart rate at R+0 during exposure to a pressure of -50 mm Hg ($-67 \times 10^2 N/m^2$) was within the preflight envelope. In the other stress procedure, bicycle ergometry, he again showed no decrement of performance from preflight levels. His pattern of postflight limb volume changes, estimated from multiple circumferential measurements, was somewhat different from that shown by the other five crewmen who received such measurements. Postflight X-rays, taken before deflation of the garment, showed an increased cardiothoracic ratio in contrast to the other 20 Apollo crewmen exposed to continuous weightlessness, for whom data exist demonstrating postflight decreases in C/T ratios.

## Summary and Conclusions

In summary, postflight orthostatic evaluations during the Apollo Program appear to indicate that reduction in orthostatic tolerance is a consequence of space flight exposure. Heart rate, the most reliable index, was increased, while systolic and pulse pressures were decreased during immediate postflight evaluations using lower body negative pressure and passive standing as the orthostatic stress. Elevation in resting heart rate was a less frequent finding. There was considerable variability in the magnitude of these changes between individual crewmembers and in the persistence of the changes over subsequent postflight evaluations. Postflight changes in leg volume during LBNP were equal to or less than those seen during preflight baseline evaluations. Body weight, resting calf girth, supine leg volume, and cardiothoracic ratios were all diminished immediately postflight, and return to preflight values was not complete within the postflight testing time frame.

The reported changes in orthostatic tolerance and other related measurements must be interpreted with care in view of the conditions under which the data were obtained.

The priority of operations during Apollo missions did not allow optimal control over a number of important variables during preflight and postflight evaluations. Preflight evaluations had to be scheduled and completed within narrow time limits and in competition with the training and launch preparation of crewmembers. Postflight evaluations were performed among intensive debriefing sessions, public appearances, and other ceremonies. Relative degrees of sleep loss and high ambient temperatures also undoubtedly influenced the findings.

Wearing of a lower body positive pressure garment during the reentry and immediate postflight period appeared to offer some protective benefit by way of reducing extravascular lower body pooling of fluid. It would, however, be premature to conclude that the garment was the primary factor responsible for improved orthostatic tests for the Apollo 17 Command Module Pilot. As was the case in all missions and for all crewmen, individual variables cloud interpretation of the data. Other studies will be necessary to determine the effects of such protective garments under space flight-type readaptive conditions.

Man's physiological adaptation to the space environment and his readaptive alterations upon return to Earth are complex. The orthostatic evaluations performed in conjunction with the Apollo missions provide some insight into these changes. But a more complete understanding of the physiological role, especially for missions of longer duration, requires a thorough analysis of the effects of the space environment with special emphasis upon inflight evaluations, control of environmental conditions, and interrelating findings from many study disciplines.

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