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ANTHROPOMETRIC CHANGES AND FLUID SHIFTS

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ABSTRACT

Several observations of body size, shape, posture, and configuration were made to document changes resulting from direct effects of weightlessness during the Skylab 4 mission. These measurements constitute two broad, overlapping categories: anthropometric changes and fluid shifts. Direct anthropometric measurements of limbs and trunk were made from each crewman before, during, and after flight. At the same time, photographs were made of each crewman in the anatomic and relaxed position. Infrared augmented film, which emphasized superficial venous patterns, was used for these photographs. Center-of-gravity and center-of-mass determinations were also made.

After the crewmen were placed in orbit, a number of anatomical and anthropometric changes occurred including a straightening of the thoracolumbar spine, a general decrease in truncal girth, and an increase in height. Relaxed posture resembles that of a quadruped. Some slight trends toward preflight morphology were seen during the latter half of the mission with a prompt return to preflight configuration on recovery.

The series of accurately located limb girth measurements allowed volume determinations of arm and leg segments. By the time of the earliest in-flight measurement on mission day 3, all crewmen had lost more than two liters of extravascular fluid from the calf and thigh. The puffy facies, the "bird legs" effect, the engorgement of upper body veins, and the reduced volume of lower body veins were all documented with photographs. Center-of-mass measurements confirmed a fluid shift cephalad. This shift remained throughout the mission until recovery, when a sharp reversal occurred; a major portion of the reversal was completed in a few hours.

The anatomical changes are of considerable scientific interest and of import to the human factors design engineer, but the shifts of blood and extravascular fluid are of more consequence. It is hypothesized that the driving force for the fluid shift is the intrinsic and unopposed lower limb elasticity that forces venous blood and then other fluid cephalad. This shift may be the driving force for a number of other phenomena, including blood volume loss and changes in leg hemodynamics, and should be considered in the vestibular area and

other problem areas. This phenomenon should also receive proper cognizance in bed-rest and other future simulation studies.

INTRODUCTION

Man's body, both as a species and as an individual, has been shaped by continuous exposure to gravity and a large portion of it is dedicated to more or less continuously opposing gravitational forces. One could confidently predict that placing the human body in weightlessness would produce changes in size, shape, and composition. Many of these changes and their effects were described by astronauts from the earliest days of space flight, for example; puffy faces, stuffy noses, engorged head veins, low back discomfort, and the "bird legs" of space.

The anthropometric studies in American space programs prior to Skylab were:

- °Preflight and postflight leg volume measurements on the later Apollo flights.
- °Stereophotogrammetry of the crew preflight and postflight on Apollo 16.

On Skylab only leg volume measurements, and stereophotogrammetry preflight and postflight, and maximum calf girths in-flight were originally scheduled.

In an effort to obtain the most comprehensive and coherent picture of changes under weightlessness, we initiated a set of measurements on Skylab 2 and, at every opportunity, added additional studies. All pertinent information from ancillary sources, even news photographs was gleaned and collated.

On Skylab 2, the initial anthropometric studies were scheduled in conjunction with the muscle study presented at the session this morning and consisted of direct limb girth measurements for limb volume and trunk girths. A single set of facial photographs was made in-flight. Like measurements were continued on Skylab 3, with additional photographs and truncal and limb girth measurements in-flight.

Prior to Skylab 4, a few of us felt there was considerable evidence for large and rapid fluid shifts, so a series of in-flight volume and center of mass measurements and infrared photographs were scheduled to be conducted as early as possible in the Skylab 4 mission.

A number of changes were properly documented for the first time, most important of which were the fluid shifts. The following description of Skylab anthropometrics will address work done on Skylab 4 primarily.

PROCEDURE

The series of direct anthropometric measurements shown in figure 1 were made preflight and postflight on all missions, and in-flight on the Skylab 4 mission. Leg and arm girth measurements were made every three centimeters by means of a calibrated tape jig attached to the limb to insure accurate location. As part of their experimental protocol, Drs. G. W. Hoffler and R. L. Johnson made such leg measurements preflight and postflight on Apollo and Skylab and, to avoid repetition, data from these measurements were shared on Skylab. We extended their technique of measurement to include the arms on all Skylab missions and preflight and postflight. The in-flight limb measurements on Skylab 4 were made with an unattached single tape and a calibrated longitudinal tape.

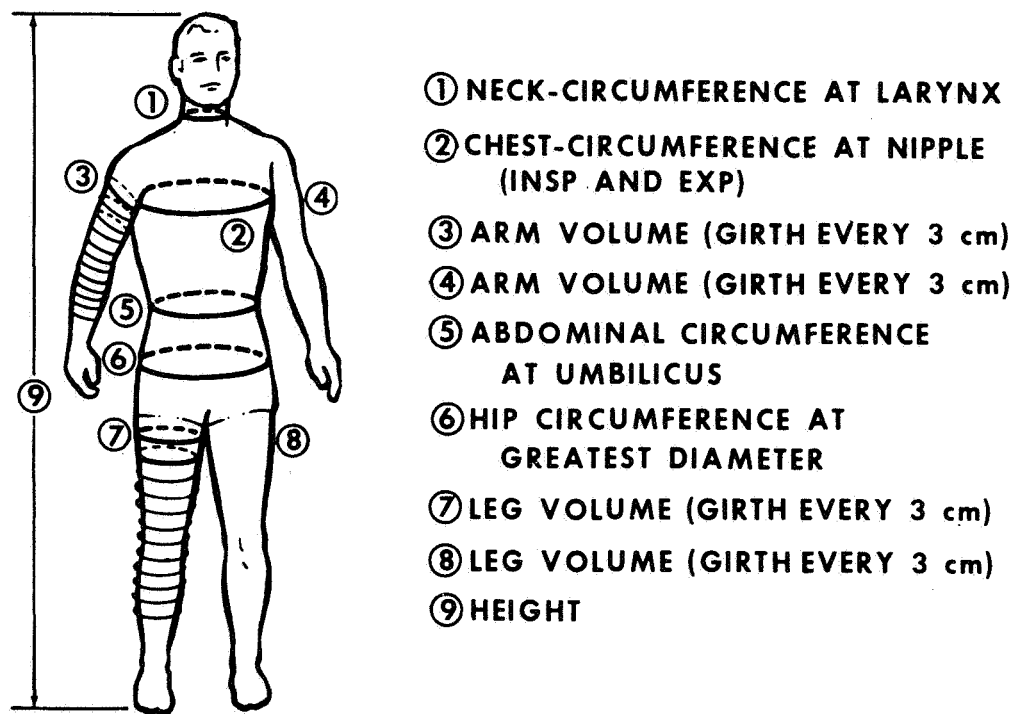


Figure 1. Anthropometric measurements of Skylab crewmen.

For general documentation, a series of preflight, in-flight and postflight front, side and back photographs were made with the crewmen in standard anatomical position; and to note postural changes, an in-flight series of photographs were made with the crewman completely relaxed and free-floating. An infrared sensitive color film was used in an attempt to document the superficial venous blood distribution.

The infrared film had poor resolution and at the last minute, 35 mm was substituted for 70 mm film further reducing resolution. Quality of the in-flight anatomical and postural photographs suffered. However, with diligence, a good deal of vascular detail could be determined that would not have been available on ordinary film.

In an effort to devise a simple way to indicate fluid shifts, center of mass and center of gravity measurements were made (fig. 2). A teeter board was used for these measurements on Earth.

In-flight it was possible to obtain center of mass directly by tying a cord around the subject and then pulling the cord at right angles to the subject. If the cord was anywhere off the center of mass the subject would tilt. The crew claimed this scheme was accurate to a few millimeters.

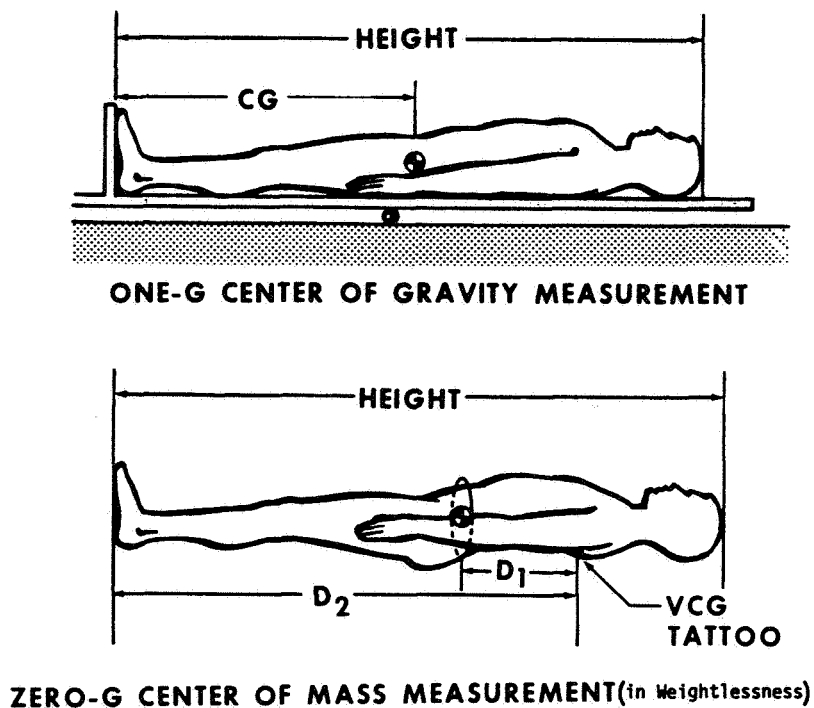


Figure 2. Techniques used to measure center of gravity and center of mass at one-g and in weightlessness (Skylab 4).

Let's look first at the in-flight changes that occur.

OBSERVATIONS AND DATA

Figures 3 and 4 show a preflight and postflight front view of a Skylab 4 crewmen. Although these are third generation copies, one is able to see arm venous pattern clearly.

The Commander of Skylab 3 is shown in-flight in figure 5. In one of the anatomical films, I thought that he had done a military brace in spite of his denials, for he isn't that trim and erect under one-g. Note the abdomen and ram rod spine. Also note, the jugular full to the angle of the jaw and other head veins.

Figure 6 is an in-flight photograph of the subject free-floating and relaxed. Relaxed postural changes varied somewhat throughout the flight and from individual to individual; tracings, figure 7, from in-flight photographs of the Scientist Pilot of Skylab 4 are typical of changes seen.

The spinal column was flexed with loss of the thoracolumbar curve but with retention of the cervical curvature, such that the head is thrust forward. Both upper and lower limbs have moved toward a quadruped position. Postflight, there was surprisingly little change from preflight posture.

Figure 8 are plots showing what gravitational unloading does to truncal size. The Pilot of Skylab 4 had the largest changes with gain of some two inches in height and loss of four inches in abdominal girth. Chest girth was also initially reduced in both inspiration and expiration, but trended toward "normal" in-flight. Postflight, which is poorly shown in these figures, there was a more or less rapid trend toward preflight values. It seems that most of the increase in height was caused by expansion of the intervertebral discs which were unloaded. This stretched the torso and probably aided in reduction of abdominal girth. Abdominal viscera may be considered semiliquid, and when their weight was removed the normal tone of abdominal muscles moved them in and upward. Changes in chest girth are not so easily explained, but if the spinal column moved upward without a similar anterior elevation of the sternum, then the rib (costovertebral) angles is increased, effectively reducing thoracic girth. Changes noted in the Commander were virtually the same as those noted in the Scientist Pilot.

There was considerable evidence of large and rapid shifts in fluid from the lower to upper body prior to Skylab 4. Indeed, no subject has

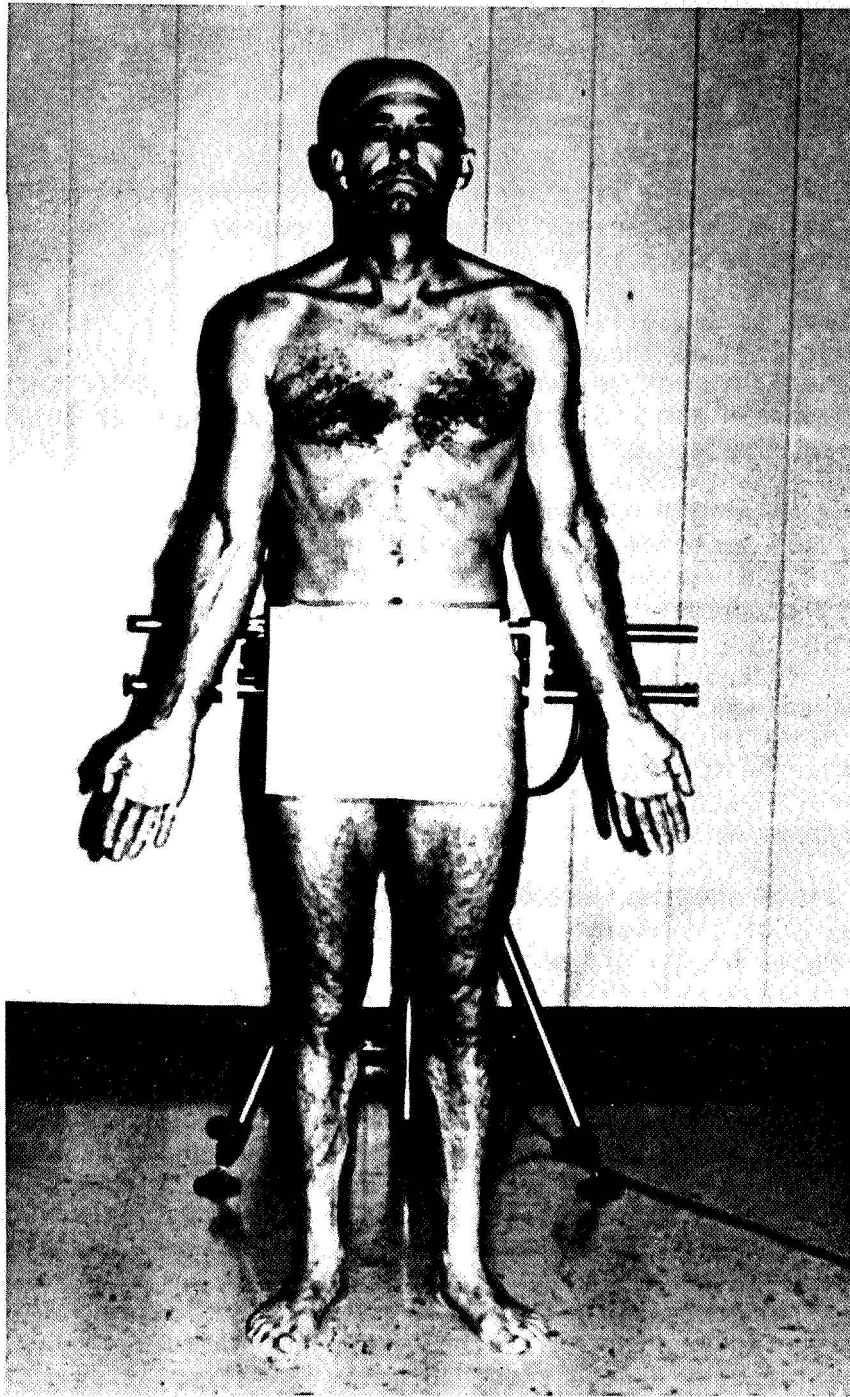


Figure 3. Preflight (color) anatomical photograph of Skylab 4 crewmen with infrared augmented film to enhance superficial venous pattern.

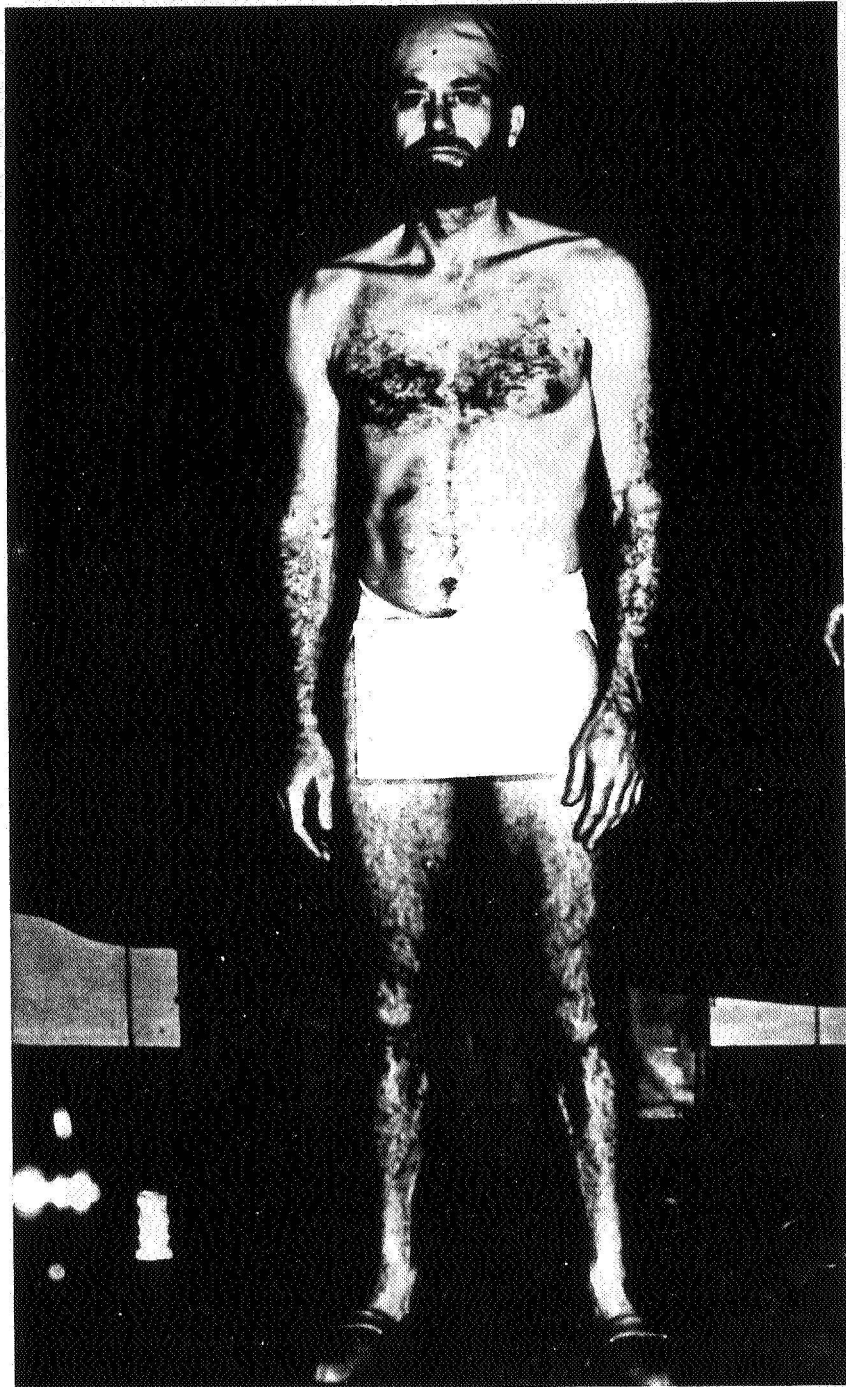


Figure 4. Postflight anatomical photograph, Skylab 4 crewman.



Figure 5. Photograph of the Skylab 3 Commander showing posture and full head and neck veins.

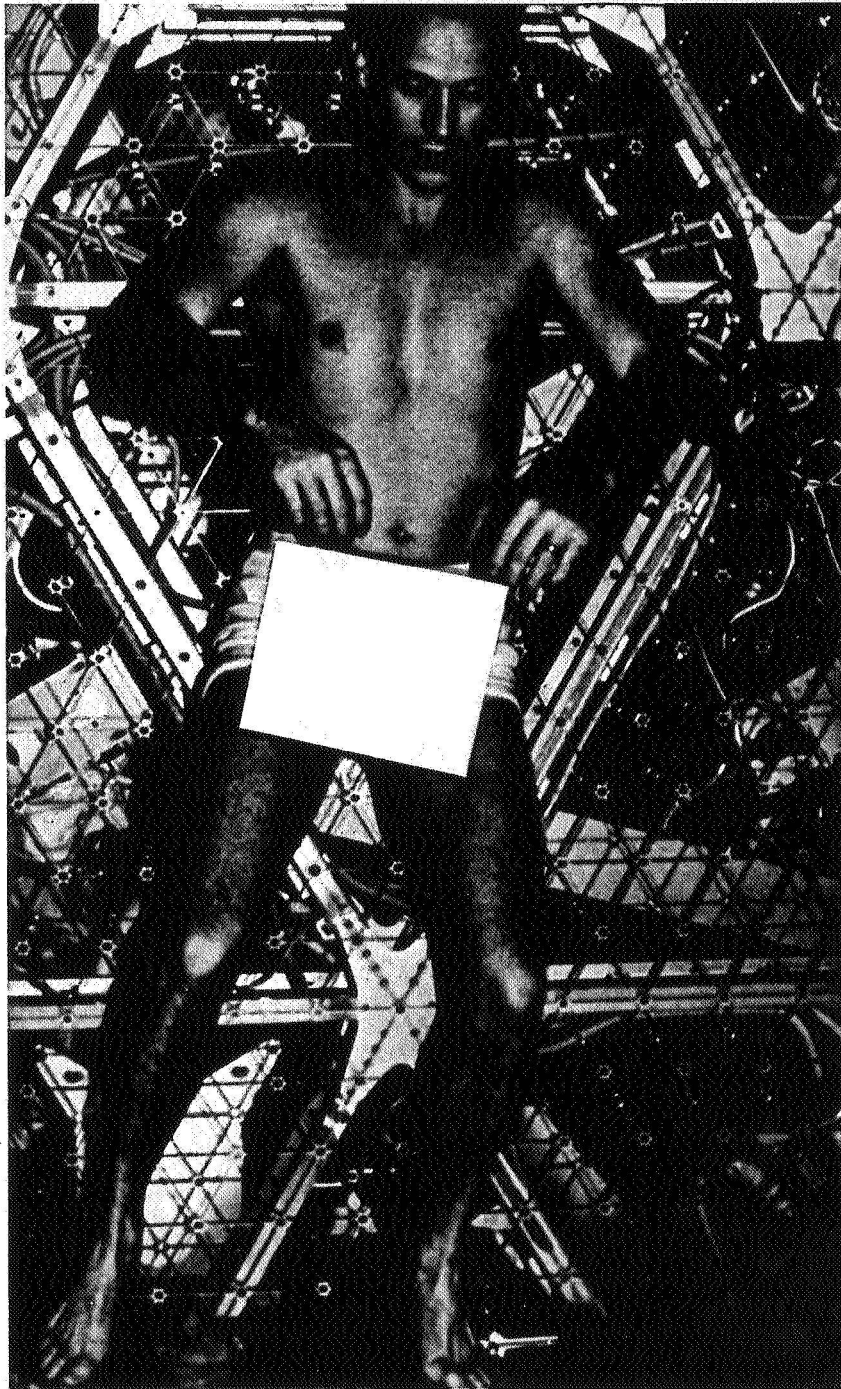
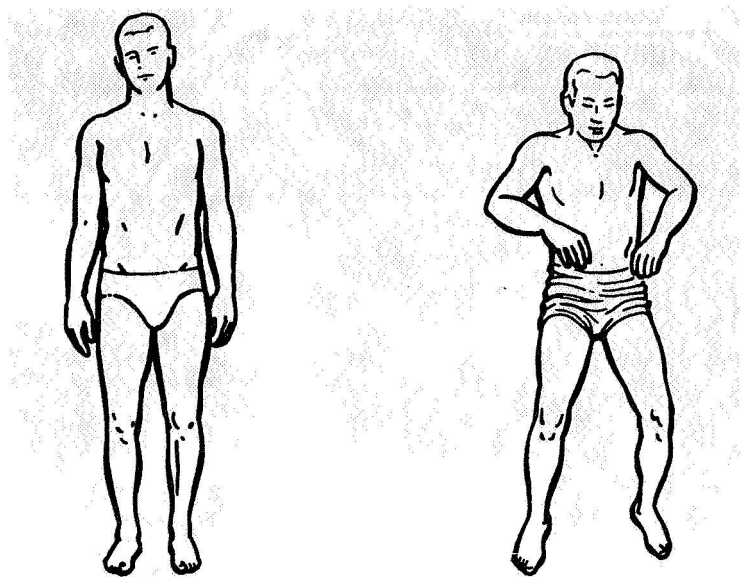
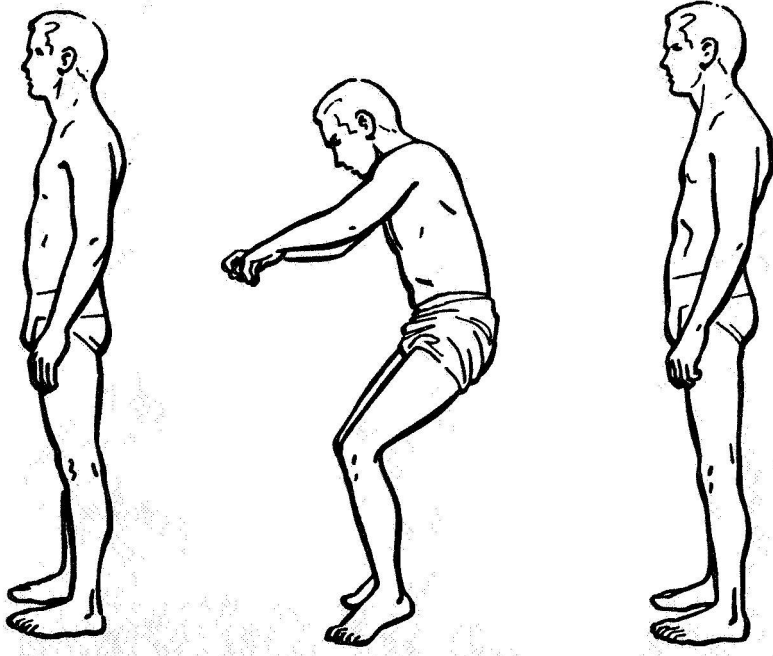


Figure 6. In-flight astronaut free floating and relaxed.



PREFLIGHT, STANDING

IN-FLIGHT, RELAXED



PREFLIGHT

IN-FLIGHT

POSTFLIGHT

Figure 7. Postural changes, Skylab 4 Scientist Pilot.

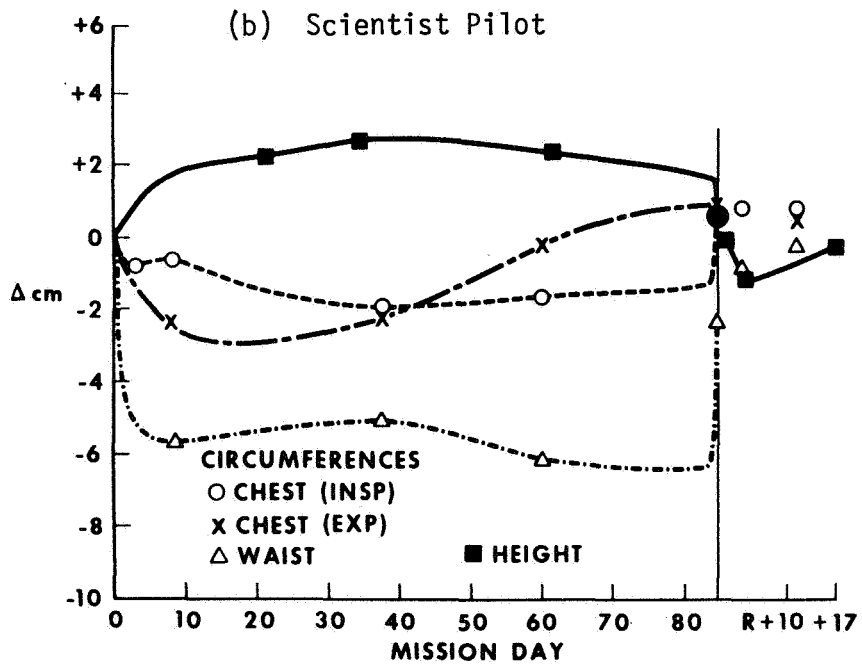
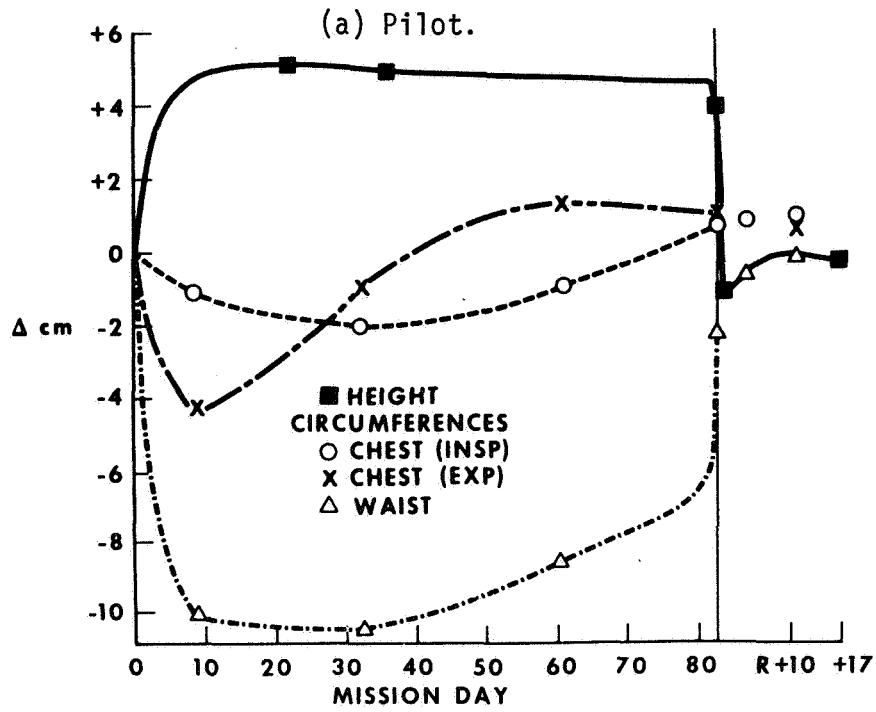


Figure 8. Plot showing in-flight and postflight anthropometric changes, Skylab 4.

been discussed more in space physiology; nevertheless, virtually no one was willing to accept it. Such large and rapid shifts seemed to be contradicted by the relatively small gains in postflight leg volume which obviously contained tissue increases. Single midcalf girth measurements on Skylab 2 and 3, in-flight were also misleading for they indicated much smaller and slower changes consistent with a predominant component of muscle atrophy.

There was obviously no way to prove the point without data and to do this during activation of an already overscheduled mission was the toughest job I tackled. Thanks to Messrs. Richard Johnston, Kenneth Kleinknecht and others, and above all, the crew, this data was gathered - not as much as desired, but to gather from the papers presented today, apparently enough to convince all concerned. Leg and arm volumes were calculated by measuring the girth of each three-centimeter segment and treating it as a tapered cylinder, then summing these volumes.

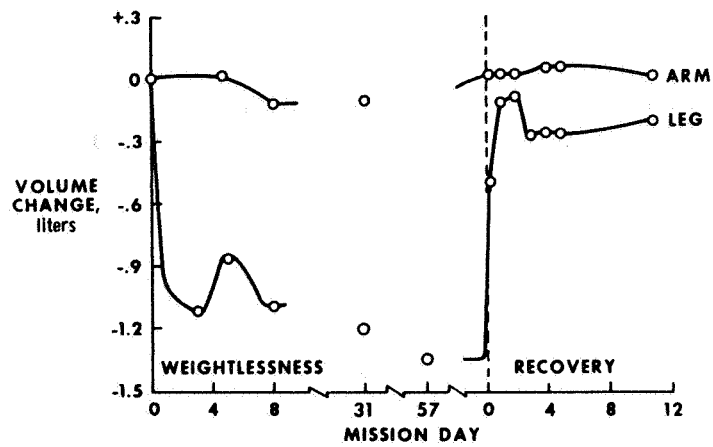
Mission day 3 was the earliest possible that these measurements could be scheduled, although it is a measurement which should have started within hours of orbital insertion; even then, only two crewmen performed these measurements on mission day 3. Figure 9 shows that there is a rapid loss in leg volume; the curves on these plots are only estimates, and I suspect the shift was essentially over by the first day. Remember these are changes in one leg only and on mission day 8 total change was approximately 2 liters and 13 percent of total leg volume for each crewman.

Note that on recovery the majority of the increase in leg volume was complete by the time of first measurement on the day of recovery; or within a matter of hours after reexposure to one-g.

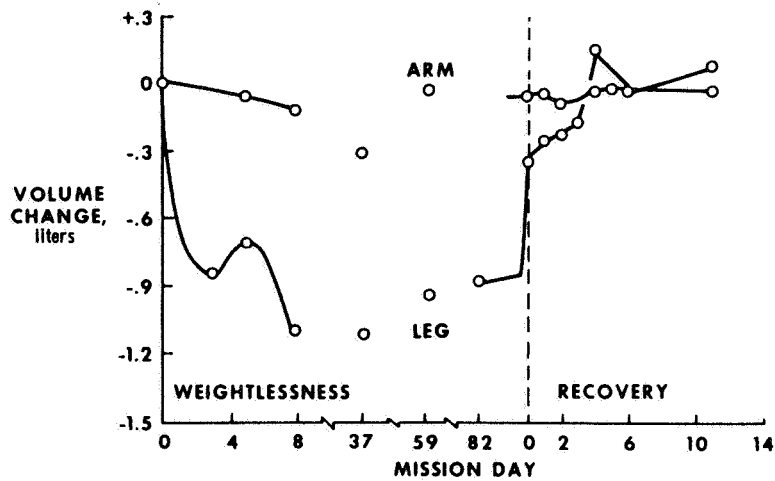
I agree with Dr. Michael Whittle that the slower postflight trends show tissue replacement. Somewhat to my surprise, the arms showed no evidence of fluid shift and the changes seen were small and probably related to metabolism.

Where did this fluid go? There was no weight loss in two of the three crewmen compatible with loss of this amount of fluid.

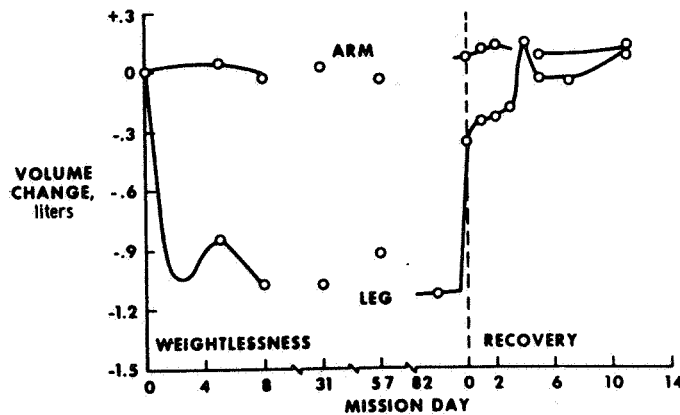
Center of mass measurements were scheduled on this flight primarily to follow the time course of fluid shifts, since only minutes were required for the measurement. Unfortunately, schedules were changed such that the points of real interest were over before the first measurement could be made. Figure 10 is a plot of the center of mass, the upper curve shows the center of mass changes and the complication by the increase in height, shown in the lower curve. Center of mass



(a) Commander



(b) Scientist Pilot



(c) Pilot

Figure 9. Change in left limb volumes, Skylab 4.

shifted cephalad more than could be accounted for by the height increase which is another small confirmation of fluid shift.

We have long had astronaut objective and subjective descriptions of puffy facies, head fullness and other symptoms of increased fluid in the head.

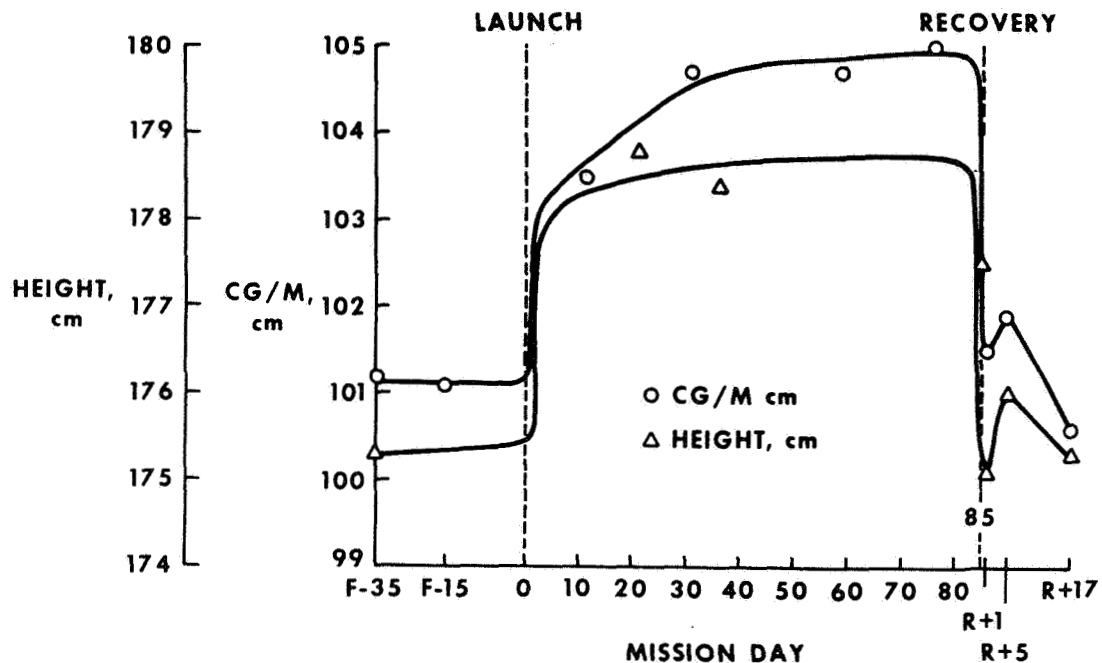


Figure 10. Center of gravity/center of mass, Skylab 4 Pilot.

Finally, there are the photographs. While these do not allow quantitation, they provided powerful evidence for increased fluid in the head and neck region.

Figure 11, a photograph of the Pilot on Skylab 2, was the first taken for this purpose. Although it is slightly distorted it still demonstrates the puffy facies - note the thickened eyelids. This in-flight photograph was made near the end of the mission and demonstrates that this type of edema and venous congestion still remained.

Next, figure 12, is a picture of the Commander of Skylab 3 with the preflight view on the right-hand side; again the in-flight photograph was made near the end of the mission. Although angle and lighting differ, I believe the difference in facies are apparent.



Figure 11. Skylab 2 Pilot showing the puffy faces still present toward the end of the mission.



In-Flight



Preflight

Figure 12. Skylab 3 Commander comparing the puffy faces in-flight to the normal faces preflight.

Finally, we have the assessment of the infrared photographs. Original plans were to machine analyze the superficial venous pattern, but the quality was too variable, therefore, only a qualitative assessment was made. However, several features were obvious. From first through the last mission the following was observed in all in-flight photographs of the crewmen:

- Only superficial veins were visualized
- Foot and lower leg veins were not distended as they are when standing under one-g.
- They were not completely empty for the dorsal arcade of the foot and digital branches were easily seen with the infrared film.
- Calf veins were not distended but were still visible.
- Several superior branches in the anterior thigh were moderately full.
- Little difference could be seen between preflight and in-flight patterns of the trunk and upper arms. Hand and forearm veins were well filled and distended in-flight. This surprised me since superficial arm veins, like those of the leg have increasing amounts of wall muscle as they become more distal.
- Jugular veins were always completely full and distended as were veins of temple and forehead.
- Postflight, there was a prompt reversion to preflight pattern, however, foot and lower leg filling appeared to be less in the early recovery period.

Changes in mass have already been discussed and are obviously related to the changes seen here.

It was not possible to document body composition changes with specific gravity and other measurements. Observation of all crews, and especially those on Skylab 2 and 3, left the impression that loss of fat had occurred, except for the Commander of Skylab 4. Radioisotopic studies by Drs. P. C. Johnson and C. S. Leach confirmed an increased loss of fat by all crewmen except the Commander of Skylab 4.

DISCUSSION

What is the importance of the changes observed under weightlessness? The major changes are reviewed in table I.

TABLE I. MAJOR ANTHROPOMETRIC CHANGES

Truncal		
	<u>Cause</u>	<u>Effect</u>
Change in Height	<ul style="list-style-type: none"> °Reduced load on spine with Loss of thoracolumbar curvature °Expansion of inter-vertebral discs 	<ul style="list-style-type: none"> °Pressure suit entry and fit °Fit of other personally fitted gear °Possibly changes thoracic cage
Reduction in Waist Girth	<ul style="list-style-type: none"> °Weightless abdominal contents are pushed "in" and "up" by unopposed tone of abdominal muscles 	<ul style="list-style-type: none"> °Probably alteration in respiratory function and capacity °Change in internal structural relations
Reduction in Chest Girth	<ul style="list-style-type: none"> °Possible increase of costal angle from increase in spinal length 	<ul style="list-style-type: none"> °Possible alteration in respiratory function and capacity

Change in height is as much a conversation piece as anything else. One crewman, for example, is shorter than his wife and was elated to find in flight that he was finally taller. Postflight there was an under-shoot, and he came home to her on the third day postflight shorter than ever. Such changes provide new data points for those studying the human skeleton and, hopefully, will add to the knowledge of it.

In future flight, allowances may have to be made in custom fitted gear. For example, small height increases greatly increase the difficulty of donning pressure suits; these difficulties may show up in the time and motion studies on Skylab.

Reduction in waist girth with cephalad shift of abdominal viscera probably alters maximum lung volumes but to no great extent. Vital capacity is reduced by lying down in one-g and the effects are somewhat analagous. Apparently it did alter some internal relationships for at least one crewman felt that running and jumping on the treadmill produced unpleasant jouncing of gastric contents. One could speculate on the effects that such shifts would have on pathological processes of the bowel - *e.g.*, hiatus hernia or a perforation. It is hardly necessary to comment on the changes in chest girth which were small.

In-flight postural changes are listed in table II. These postural changes have two significant considerations. Human engineering should allow for the most efficient work positions in the future. For example, a chair designed for use in one-g to support the weight of legs and torso, is not shaped to provide good passive support in weightlessness. The body has to be forced into such a position by use of a tight waist restraint. Secondly, these changes under weightlessness should be of interest to those making theoretical studies of postural mechanisms and the like and provide them with new data points.

TABLE II. IN-FLIGHT POSTURAL CHANGES

Relaxed		
	<u>Cause</u>	<u>Effect</u>
Flexion of thoraco-lumbar spine with cervical curvature preserved	°Removal of anterior center of gravity with unopposed forces of vertebral musculature	°Pushes head anteriorly and inferiorly making new position
Legs are semiflexed	°Tilt of pelvis secondary to flexion of spine - unbalanced weightless legs with imbalance of resting muscle forces	°Renders one-g seating unsuitable for zero-g since body must work to maintain such positions
Arms are elevated	°Weightless arms with imbalance of resting muscle forces	°This with flexion of back puts arms and head in unusual relationship for work or study

Fluid shifts are of more importance. Although tissue fluid and blood shifts are so closely interrelated as to be difficult to separate, I feel something is gained by treating them separately. Blood shifts occur rapidly; they begin seconds after change in forces but their long term effects may last months.

Standing upright under one-g, veins and arteries below the heart have increasing hydrostatic pressure as the veins descend toward the feet where the force may be 80 to 100 mm Hg. Shortly above the heart, the venous pressure becomes zero and the vessels are virtually empty and at least partially collapsed. Under weightlessness, without this superimposed hydrostatic pressure, venous pressure, except for negligible flow pressures, are the same throughout the body. Volumes are now shifted only in response to the compliances, the tension if you will, of the various areas of the venous systems. The result is that we have essentially central venous or right atrial pressure throughout the entire venous system. Veins such as head and neck which are normally empty, fill until their back pressure is equal to that of the pressure in, for example, a foot vein, which develops the same pressure

at a much smaller volume. When a subject stands from a lying position under one-g, a nominal 700 milliliters of blood goes into the legs and probably a comparable volume is shifted centrally. Most of this blood volume moves to that undefined "central volume" and produces a small increase in pressure with a probable effect of increasing cardiac output.

A second result of the fluid shift produces results that are more obvious and therefore more easily to document. Certain body sensors detect this as an abnormally large volume and cause plasma to be reduced thus leaving high hemoglobin and hematocrits in the circulating blood. An as yet unknown sensor is activated to detect and reduce over a matter of weeks red blood cell production such that red cell mass becomes appropriate to the new volume. Such readjustment to altered volumes are also seen under one-g; for example, individuals with leg varicosities have increased blood volumes. I think that the reduced loss of red cell mass in the Skylab 4 Commander is further evidence of reduced leg venous volume. Table III illustrates this.

TABLE III. FLUID SHIFTS

Blood - Exposure to Weightlessness

- °Removal of hydrostatic forces produces essentially uniform pressure throughout venous system
- °Differing tensions throughout the venous system redistributes blood
 - °Higher effective tension of leg veins force a quantity of blood out of the legs
 - °Lower effective tension of head and neck veins accept a small volume of blood which increases pressure and distension
 - °Remainder of blood increases central venous volume and pressure
- °Sensors reduce volume by reducing plasma volume
- °Unknown sensors detect "excess" red blood cells and reduce production until normal values are reached
- °Reduced blood volume is appropriate for effective reduction of total venous volume in weightlessness but inappropriate for one-g or one-g simulations
- °Increased filling pressure may increase cardiac output

On return to one-g, a reverse process ensues. After the first day repeated blood tests show an anemia which is slowly replaced by an increasing red cell mass. These changes are delineated in table IV.

TABLE IV. FLUID SHIFTS

Blood - Reexposure to one-g

- °Hydrostatic pressures increase effective venous capacity by expansion of leg veins
- °Central volume and pressures are decreased
- °Plasma volume expands reducing hematocrit
- °Red blood cell production is resumed or increased until new equilibrium is reached

Tissue fluid shifts are larger in volume than blood shifts but somewhat slower acting. For sentimental purposes, I must show my old campaign slide (fig. 13), poor as it is. When standing under one-g there is a hydrostatic column of up to 80 to 100 mm Hg pressure on arteries, veins, and capillaries in the foot; this is illustrated by the internal arrows. This pressure is opposed by tissue pressures and after a period of extravasation they equalize. Under weightlessness, the reverse occurs with resorption of fluid by the tissues until transmural pressures are again balanced. In the upper body areas and particularly the head, we have the opposite effect from increased transmural pressure which produces edema. These processes are simultaneous. Tissue fluid shifts are delineated in table V.

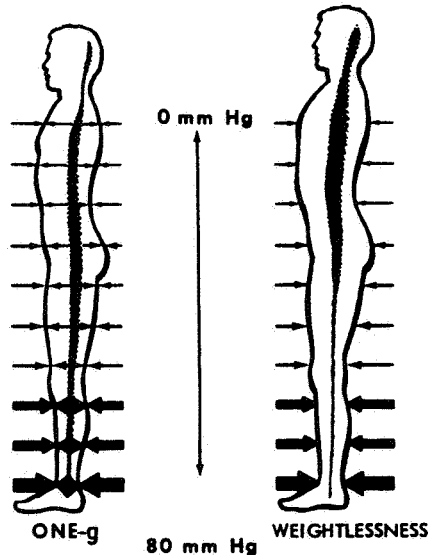


Figure 13. Fluid pressure/volume changes under weightlessness.

TABLE V. FLUID SHIFTS

Tissue

A. Below the heart:

°Hydrostatic forces removed from blood column, venous and arterial, cause:

increased transmural resorption from decreased pressure in legs with resultant rapid loss of fluid from legs,

Reduction in tissue pressures in leg which may effect venous compliance.

°Change in hydrostatic forces may be caused by small to moderate loss of fluid through diuresis or decreased intake.

B. Above the heart:

°Hydrostatic forces removed from blood columns and increased transmural pressures cause:

edema to tissues of body above heart,

possible effects on vestibular apparatus.

Whether this shift of fluid produces an increase in intravascular volume or not depends upon how rapidly fluid is regained from some areas and lost to others. It is at least theoretically possible that fluid is lost more rapidly than it is gained, with a reduction of intravascular volume. I do not think this happens and expect there may be a very slight expansion of intravascular volume which, coupled with the blood from leg veins, may result in a small fluid loss via the Gauer-Henry scheme (increased atrial pressure and diuresis), or some other mechanism. However, remember that tissue fluid shifts occur under one-g without undue diuresis. Legs are smaller in the morning and eyes are puffy, and a shave lasts longer if made an hour or so after arising.

Fluid shifts should be investigated as a possible participant in the vestibular upsets that have occurred. Time course and other aspects of these vestibular upsets are suggestive and I have no hard evidence for or against this.

SUMMARY

In summary we have documented for the first time anthropometric changes and the correct magnitude and time course of fluid shifts under weightlessness that have implications for future human factors engineering and that explain some medical phenomena. More importantly these data provide a fundamental point of departure for future research.

Bed rest studies for example have not properly considered such fluid shifts. We now have better criteria for evaluating the fidelity of weightless analogs such as bed rest and water immersion.

Most importantly we again find the human body capable of making stable adaptation to two widely differing environments in an amazingly short time. In the course of these experiments, I think data has been offered to justify the title "Earth man - Space man".

ACKNOWLEDGEMENTS

Any listing of individuals here is bound to omit several who made contributions. Above all the Skylab 4 crew is to be commended for gathering the data with surprising accuracy under trying conditions which included virtually no training for the tasks. The work could not have been implemented without the support of Dick Johnston, Bill Schneider, Kenneth Kleinknect and others in Skylab management. Jack Ord greatly influenced the direction of this and my other experiments by our previous collaboration during the Manned Orbiting Laboratory project.

Post Scriptum

During the Question and Answer session, Dr. Otto Gauer's interesting comments and slides corroborated our findings with data from his independent research, hitherto unknown to us. These comments and reproductions of the slides have been included in the Panel Discussants portion.