Fluid Shifts in Weightlessness

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Studies of leg volumes in space by multiple girth measurements showed reductions of 1.9 L (12.8% of leg volume) with 1.1 L from the non-dominant leg on Skylab 4. On landing, 65% of postflight leg volume increase was complete at 1.5 h. Measurement of the dominant leg during the equivalent period on Shuttle showed a mean loss of 0.9 L which was 90% complete at 150 min. Postflight increases were 87% complete at 1.5 h postlanding. Mass measurements during and after Skylab 4 showed a loss of 2.5 kg over the first 4 d on-orbit with a gain of 2.7 kg over the first 4 d of recovery. These changes are assumed to be tissue fluids secondary to changes in hydrostatic pressures and are much greater than those seen in bed rest. Rate and magnitude of inflight and postflight changes have significant operational impact.

LOSS OF HYDROSTATIC pressure on blood columns, which leads to fluid shifts and volume changes, is one of the primary effects of weightlessness on the human body. Effects of fluid shifts were seen very early in the American Space Program and their origin suspected. There were anecdotal reports of "bird legs," stuffy noses, and puffy faces (Fig. 1) in space. The earliest orbital flights also documented a postflight weight loss which was regained within hours (11). As these flights were extended to days in orbit, postflight orthostatic intolerance which rapidly cleared was regularly seen (1). Bed rest research could not account for time course nor magnitude of these effects (4,12,15). Immersion studies produced marked diuresis and dehydration, but the anatomical source of fluid had not been documented (3,9). Hoffler measured leg volumes preflight and postflight on Apollo (7) and SL-2, 3, and 4, and calf girths inflight on Skylab 2, 3, and 4 (8). The postflight volume measurements were made several hours after recovery and fluid redistribution, hence did not reflect inflight changes. Calf volume changes have subsequently been shown not to be representative of leg volume changes. It was only on Skylab 4 (Fig. 2), when arm and leg volumes were measured *inflight*, that the nature and magnitude of change was appreciated (20). The initial findings were substantiated in part by an inflight study on the Apollo-Soyuz Test Project (ASTP) (6). We have continued and expanded fluid measurements on Shuttle and, in a companion paper, will be giving details of a portion of the Shuttle study of changes in leg volume (14). Other studies relevant to the fluid shifts are the daily body mass measurements on Skylab (21), and a single intake and output study done on STS-8 (10). This inflight work plus subsequent bed rest and other studies allow a better appreciation of fluid shifts that occur in transition between 1 G and weightlessness, as well as show areas that need further investigation. They also make a re-examination of the original studies profitable. This is a brief review of the phenomena and update based on these studies.

MATERIALS AND METHODS

The Skylab arm and leg volume measurements were made by taking a series of girths every 3 cm from ankle to groin and wrist to axilla. Measurements in 1 G were made with the subjects supine. Volume was calculated by assuming the volume segments were truncated cones. Data collection sessions were long and tedious and required effort to avoid error. On Skylab 4, bilateral arm and leg volumes were measured this way on all three crewmen 5 times preflight, 6 times inflight, and 12 times postflight beginning several hours after recovery.

Preflight, inflight, and postflight single leg volume measurements were also made by Hoffler, *et al.* on the crewmem-

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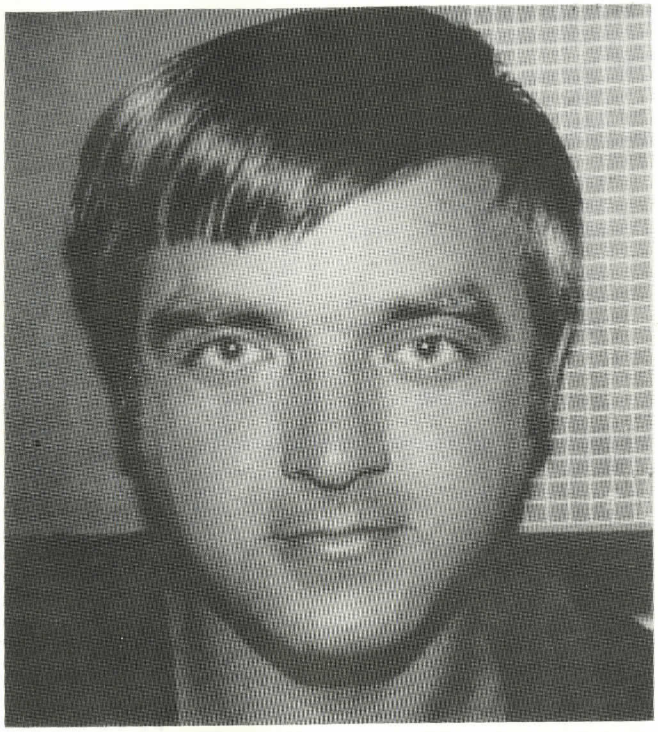

Fig. 1. Photograph of a subject inflight with significant facial edema. Note absence of normal skin folds.

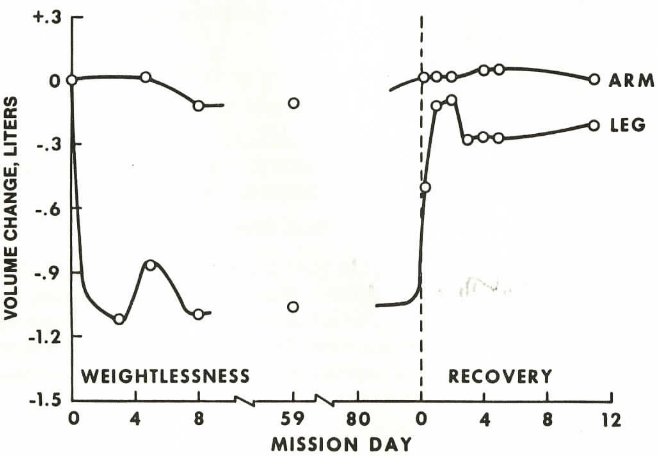

Fig. 2. Leg and arm volumes preflight, inflight, and postflight from left leg of crewmember on Skylab 4. Major volume shifts were over by the time of measurement inflight and postflight. The portion of the curves during these periods were estimates (20).

bers of the Apollo-Soyuz Test Project (ASTP) mission (6). A single measurement from one crewman was made early in the mission, and from all crewmen at 36 h, with postflight measurements begun at 1.5–2 h postlanding.

A more rapid and reproducible volumetric system, the stocking plethysmograph, was devised for use in the Shuttle Program (Fig. 3). It consisted of a slightly elastic stocking with fixed longitudinal locations for circumferential tapes which could be rapidly marked with different colors and the data reduced later. This system is further described in a companion paper (14). It has been used to measure preflight, inflight, and postflight volume changes of the dominant leg on nine subjects, two of whom have flown twice. In three of these, the early time course of inflight changes have been measured, and in six, the comparison of leg volumes during preflight and postflight orthostatic stand tests have been conducted. The earliest postflight measurements were made 1.5 h after landing. Measurements in 1 G were made with subjects standing.

Body mass measurements were made daily during Skylab 2, 3, and 4 on all crewmen using the linear spring mass oscillator (21) developed at the Aerospace Medical Division of the United States Air Force (22).

On STS-8, using bags for 12-h periods, the author did a continuous collection of urine throughout the flight and recorded all intakes. Some results of this are given in another companion paper (10).

RESULTS

Table I summarizes the volume changes found during the first 7–9 d of flight by the three studies to date. Fig. 2 is a typical plot of the changes in volume from a single left leg and arm on SL-4. The changes in arm volume were negligible but leg changes were unexpectedly large, amounting to 808 ml (10.8%) and 1090 ml (14.8%) in the dominant (R) and non-dominant legs, respectively. Rate of volume change early in weightlessness was unknown since MD-3 was the earliest measurement made. The rapid postflight change and minimum volume already reached by MD-3 indicated that the fluid shift was rapid. Two of the crewmen reached postflight equilibrium by the second day of recovery while the third had suffered a considerable tissue loss. The mean postflight replacement at 1.5 h postflight was 64.5% of final replacement for these two subjects.

The volumes and percentage of volume shifted were smaller on ASTP, which measured only the non-dominant leg. These measurements were also made with subjects supine in 1 G. The rate of change in leg volumes was

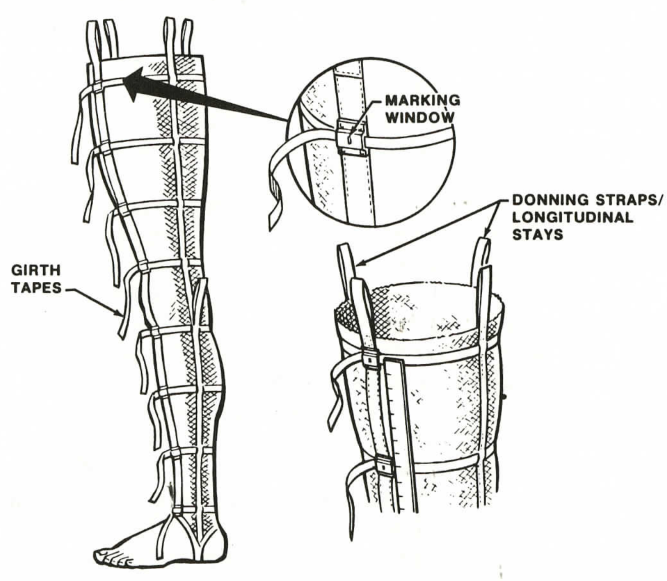

Fig. 3. Sketch of stocking plethysmograph. After the stocking is fitted to the leg, circumferential tapes are marked with a colored pen. Time and date are recorded in the same color for data reduction which occurs at a later date.

TABLE I. MEANS OF LEG VOLUME CHANGES.

Day	Right Leg			Left Leg			(n)
	Vol. (ml)	Δ Vol. (ml)	Δ Vol. (%)	Vol. (ml)	Δ Vol. (ml)	Δ Vol. (%*)	
Skylab 4							
L-5	7582			7775			3
MD-3*	6761	−821	−10.6	6784	−991	−12.7	2
MD-8	6492	−808	−10.7	6685	−1090	−14.8	3
ASTP							
L-1				7807			3
MD-2		NOT DONE		7284	−523	−6.6	3
MD-9				7063	−743	−9.5	3
STS							
L-1	8116						3
MD-3	7292	−823	−10.1		NOT DONE		3
MD-7	7216	−900	−11.0				3

* % change (Δ) based on mean volumes of 2 subjects, 7710 ml.

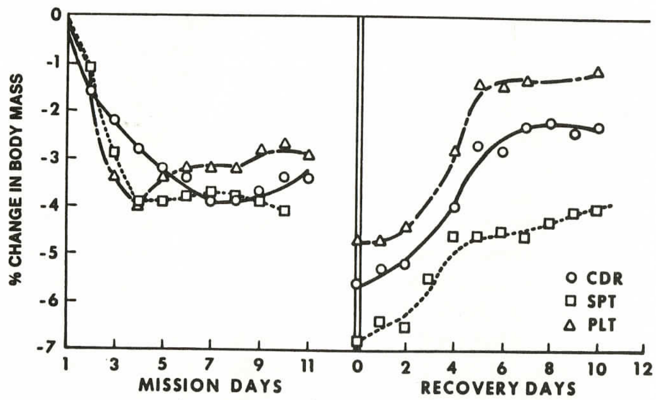

Fig. 4. Mass changes during the period after orbital insertion and on return to 1-G. The rapid changes in this period are presumed to be fluid shifts.

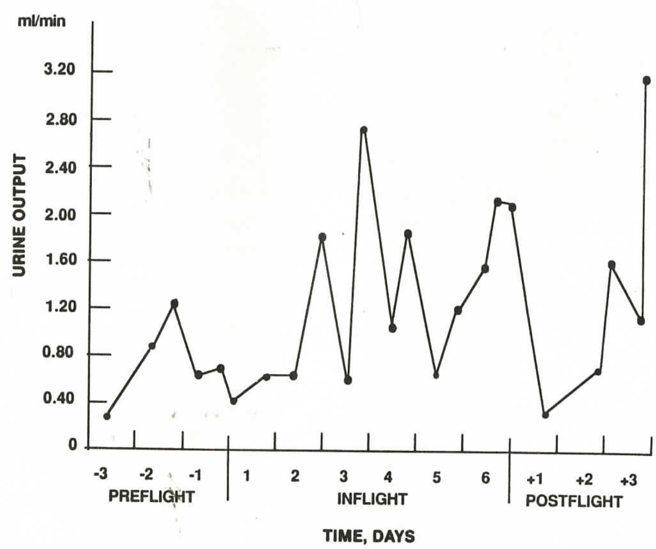

Fig. 5. Urine excretion rate from a crewmember on a Shuttle flight. The first period of diuresis may have been affected by SMS for the first 2 d, during which period anti-diuretic hormone was very high and intake low. The second diuresis, which peaked on MD-6, was caused by consciously increased intake for rehydration.

documented during Shuttle flights (14) and found to vary significantly.

If one assumes that fluid volume changes in the leg are complete by MD-2 in this group and uses that volume change as 100%, then the mean time to reach 73% and 90% were 93 and 150 min, respectively, with large individual variation. The mean postflight volume replacement measured at 1–2 h on all STS subjects (14) was 87% of the final postflight leg volumes.

Fig. 4 is a plot of percentage of body mass lost by the SL-4 crew during the early periods of exposure to weightlessness and of re-exposure to 1 G. If one takes the mean of mass loss of the crew in weightlessness, almost 4 d are required to reach equilibrium both in weightlessness and on return to 1 G. The mean value of mass loss on MD-9 was 2.52 kg vs. 1898 ml of fluid lost from the legs.

There were significant individual differences in the rate of mass lost and recovered. There were also significant individual differences in leg compliance (19). The difference in launch and recovery mass is assumed to be a combination of tissue and fluid lost. If one assumes that the rapid postflight changes in mass are fluid recovery and assumes this process is complete by R + 5, then the mean postflight fluid gained is 3.9% vs. 3.6% of body mass lost by MD-4 on-orbit.

Fig. 5 is a plot of urine output from the only "high resolution" intake and output study in space to date. Unfortunately, it has only one subject and may also have been skewed by the presence of SMS for 36 h. Note that there was no diuresis until the second evening.

DISCUSSION

Volume Changes

The three different techniques of the same basic methodology produced significant variation in results. Although the total (nine subjects) and test populations (three subjects each) were small, it seems unlikely that this could account for the differences when matched as closely as possible (Table I); e.g., ASTP values on MD-2 were 50% those of SL-4 on MD-3 and only 65% of MD-3 values on STS.

The stocking plethysmograph results were smaller than the directly measured girths on SL-4. One would expect the values to have been significantly higher since the baseline

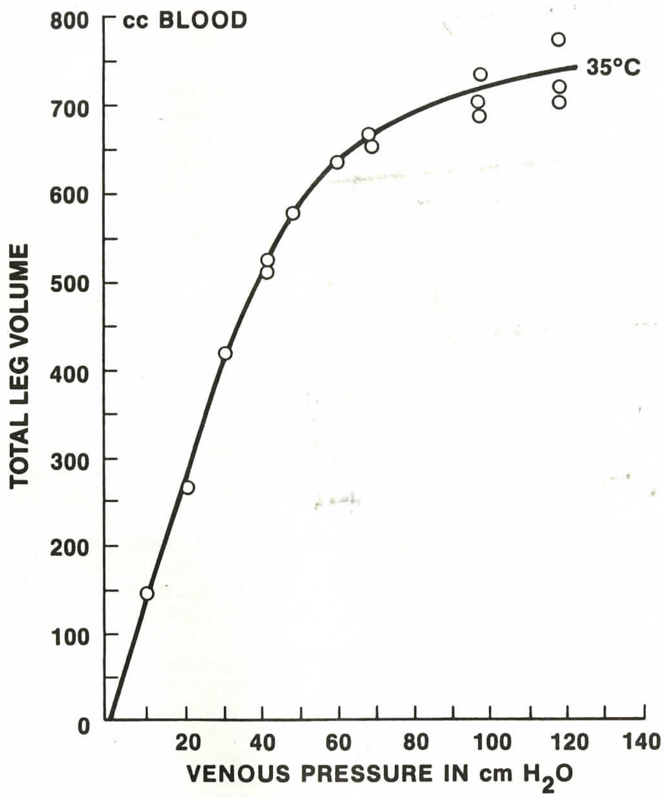

Fig. 6. Compliance curve, i.e., volume/pressure, of legs under normal conditions (5).

measurements were made on standing vs. supine subjects which should have increased the blood volume in each leg by 250–350 ml (5) (Fig. 6). If the 4% greater total volume change in the non-dominant leg seen in Skylab is a true representation, then total mean volume changes for the three STS crew used here should be 900 ml (right leg) + 1227 ml (left leg est.) = 2127 ml for blood and fluid shifted from both vs. the measured change for both legs on MD-8 on Skylab of 1898 ml of fluid only. While the exact magnitudes of fluid lost must await further study, one can say with assurance that at least 1.5 to 2+ L of fluid is shifted from the legs when a normal male is placed in weightlessness. This is a volume sufficient to produce significant physiological effects.

Time course of volume change: The measurements were altered by the launch and entry environment such that we cannot say with certainty what the exact course is in the transition from 1 G to weightlessness and vice versa. The measurements were not made early enough on Skylab to allow comment and the crew were horizontal for more than an hour prior to launch. On STS, they were horizontal for 2 h or more prior to launch with legs above the heart, e.g., crew are seated but rotated backward 90°. They are also subjected to maximum launch loads of +3.5 G and with −0.6 Gz, both of which would shift fluid and blood cephalad. We can say with certainty that the major shift is complete in a period of hours.

There is typically a continued small loss in leg volume on Shuttle missions and this is most likely loss of tissue through muscle atrophy and, often, inadequate dietary intake. The transition to 1 G is also complicated by G-loads of up to +1.5 Gz on reentry and variable posture during egress, prior to measurement. While, at this time, we cannot obtain a true picture of transition, it is important that we now have data from operational circumstances that confirms the suspected rapid shift of significant volumes of fluid out of and back into the legs.

Loss of Fluid

Neither the route nor time course of fluid has been documented. During immersion studies there is a prompt diuresis (9) but this is not subjectively evident in flight; rather, the two pieces of data we have show a different picture. The one record of urine output (Fig. 5) showed, if anything, a reduction for the first 36 h, followed by an increase during days 3 and 4; however, this may have been affected by 36 h of SMS and represents only one subject. The mass measurement data from SL (Fig. 4) is more robust and shows a rapid and almost linear decrease for 4 d, followed by stability. The mean magnitude of this mass loss was slightly greater than the mass equivalent of fluid shifted from the legs. This difference may be easily accounted for by mobilization from areas other than the legs, or may be due to metabolic losses. On recovery, there was almost a mirror image of the loss with replacement amounting to 3.9% of original body mass vs. 3.6% lost, taking some 4–5 d to complete. Determination of whether the fluid loss is by way of diuresis or decreased intake must await an intake and output study.

Mechanism

The primary cause of fluid redistribution and loss in weightlessness is physical, i.e., changes in hydrostatic pressure. When a subject moves from vertical to horizontal on Earth or from vertical on Earth to weightlessness, the changes in mean intravascular pressures are striking, from 180 mm Hg to 90 mm Hg arterial and from 100 mm Hg to 15 mm Hg on the venous side in the feet. The first effect of such a large change in pressure on Earth or in space is to vary the volume of blood in the legs through compliance of the vascular system; e.g., the volume of the vascular system in the legs is increased by increased hydrostatic pressure. When the average man moves from horizontal to vertical and vice versa this amounts to some 600 to 700 ml into and out of the legs (Fig. 6). This is also a reasonable estimate for the shift of blood out of the legs in weightlessness (5). While such shifts occur frequently on Earth, in weightlessness they amount to a permanent displacement. Blood volume is adjusted to the effectively-reduced vascular volume of space by a rapid loss of plasma (hours) and then reduction of red cell mass by temporary suspension of red cell production (weeks) (20).

The second aspect of this pressure change involves water exchange between intra- and extravascular spaces. If one looks at the Starling equilibrium in the foot of a standing man, it is obvious that—even allowing for the reduced capillary area, reduced venous pressure from muscle pumping, and all the other mechanisms which protect against the effects of such disequilibrium—there will still be a large transient flux of water into and out of tissue during large changes in hydrostatic pressure (9,24). This appears to have been first documented in 1938 by Thompson (17) who showed 11% of plasma volume could be lost in 20–30 min of quiet standing and recovered on recumbency. This shift is undoubtedly buffered by countershifts of tissue fluid from other parts of the body. The Starling equation shows that the key element in protection against very large fluid losses must be tissue counterpressure. This must increase rapidly with volume to avoid very large shifts of fluid into tissue. Much of the tissue is muscle, and it has long been known that active counterpressures are essential to prevent orthostasis (13). Furthermore, there appears to be a venous distension-muscle reflex present in some animals (18).

There have been a great number of bed rest studies but only a few have measured leg volumes (4,12,15). In all these studies the volume shifted was much less than that seen in spaceflight. Nixon's 5° head-down study (15) most closely paralleled the Skylab studies in techniques and subjects and produced a mean change of 800 ml in both legs vs. 1800+ ml for SL-4. Linnarson's study (12) also differed from inflight shifts in that the majority of the volume shifted came from below the knee. Supine sleep for 8 h produces only a fraction of the fluid shift of weightlessness for 8 h.

The first question then is not why tissue fluid is shifted, but why so much more is shifted in weightlessness. The only obvious difference between weightlessness and horizontal posture in 1 G is that small pressures from abdominal contents and other sources are present and are imposed on the inferior vena cava and this in turn elevates the venous pressure in the legs. While tissue fluid compliance of the legs has never been measured, one would expect it to be nonlinear and to accept much larger volumes of fluid at lower pressures. The absence of such small counterpressure in weightlessness might explain why such larger volumes are shifted.

Implications

Beyond the feeling of head fullness and stuffy nose, there are no known difficulties caused in weightlessness by these shifts. It has been suggested that such shifts might cause or contribute to SMS by causing a labrynthine hydrops or even increased intracranial pressure. We found no evidence of this (23), and there was no difference in volumes shifted in those with and without SMS. Difficulty occurs when one returns to 1 G hypovolemic of tissue fluids after flights of more than a few days and hypovolemic of both fluids and blood after flights of weeks. There is a sudden demand for tissue fluids to "fill" the legs and this must come from blood volume which, in turn, will be replaced from fluids elsewhere. Should the transfer be too rapid or if adequate volume is not available, orthostasis may result. While the obvious first step is to "prime" the body with as much normal fluid as possible, there is a limit. The equally obvious next step to prevent orthostasis is to shift fluid into the legs prior to entry. If the small counterpressures in horizontal subjects in 1 G are sufficient to prevent large volume shifts, there may be a simple way to achieve this effect in spaceflight.

It is obvious that only a beginning has been made in the understanding and control of this phenomenon.

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