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Changes in Leg Volume During Weightlessness Simulation

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ABSTRACT

Little published information exists regarding the magnitude and time course of cephalad fluid shift resulting from weightlessness simulations. Six subjects were exposed to 150 minutes each at horizontal bedrest, 6° head-down tilt and horizontal water immersion. Fluid shift was estimated by calculating leg volumes from eight serial girth measurements from groin to ankle before, during and after exposure. Results were compared with data from the first three hours of space flight. By the end of exposure, total leg volume for the six subjects decreased by 2.6 ± 0.8%, 1.7 ± 1.2%, and 4.0 ± 1.6% for horizontal, head-down and immersion, respectively. Changes had plateaued for horizontal and head-down and had slowed for immersion. Relatively more fluid was lost from the lower leg than the thigh for all three conditions, particularly head-down. During the first three hours of space flight, total leg volume decreased by 8.6%, and relatively more fluid was lost from the thigh than the lower leg. A mechanism to explain these differences is proposed.

Key Words: Space flight, head-down tilt, immersion, plethysmography, venous pressure, bed rest, orthostasis

Since before the first space flights, numerous simulations of weightlessness have been performed (4, 5, 14) with methods designed to remove the hydrostatic effects of gravity. A variety of methods have been used but the leg volume changes are seldom measured and in no case have the changes produced by various techniques been compared in the same population. This study examines leg volume changes in the same population during three commonly used simulation techniques.

Water immersion and supine "bedrest", either horizontal or with head-down tilt, are currently the most widely used simulations. Results from water immersion are sensitive to both respiratory pressures (1) and postures and vary widely. A variety of head-down tilt angles have been used in bedrest simulations in an attempt to more closely simulate the effects of weightlessness (2, 3, 7, 16, 17).

Surprisingly, leg or other segmental volume changes have seldom been measured in simulation studies. In the case of head-down tilt, only five published studies reported directly measured volumetric changes (2, 3, 7, 16, 17). Two of these measured volume only below the knee (7, 17) and only one reported both upper and lower leg volumes separately (3). One study of limb volume in horizontal posture (17) was found but none in immersion. A number of studies have made single plane or leg segment measurements and extrapolated total leg volume changes; we consider those techniques inaccurate and will not include studies using them. Leg volume studies and their results available in the literature are summarized in Table I.

The accepted standard for volume measurement is plethysmography by displaced liquid, but the apparatus and procedures required are substantial and impractical in many conditions including space flight. Another common direct determination is measurement of successive girths and calculation of volumes on the assumption that each segment approximates a truncated cone (9). This latter method has been used in most ground-based and space flight investigations and was used in this study. Evaluation of accuracy and repeatability of girth measurements to determine volume is well described in the literature (9, 10, 11, 12) and the methods used here should reduce errors even further. A modification of the basic methodology was used in some measurements reported here since this technique was experimentally verified.

METHODS

Measurement verification

Volumes determined by fluid plethysmography and calculated from girth measurements obtained with a "stocking" jig (15) were compared to validate the use of the stocking modification. A stainless steel full leg "boot" configured for fluid plethysmographic measurements was obtained (Whitmore Enterprises, San Antonio, Texas). The subject stood with the leg to be measured in the boot and water volumes added to fill it to eight known depths on the leg corresponding to levels of girth measurements taken immediately afterward. Bubbles were removed. With the leg removed, the boot was sequentially filled to the same girth levels with measured volumes which were considered segment reference volumes. Figure 1 shows the segments and linear measurements made. An extensible stocking which incorporated 4 non-extensible longitudinal tapes to control the level of eight circumferential tapes running through an index window was used for girth measurements. Circumferences were marked on the circumferential tapes through the fixed indices for later measurement ($\pm$1 mm). A single subject closely matched to the astronaut population was studied 10 times over a 2-month period, comparing leg volumes measured by both boot and stocking methods.

Ground-based simulations

Six male subjects were chosen to match the physical characteristics of the male astronaut population insofar as possible, and their characteristics included: age 25.5 $\pm$ 3.2 yrs, height 180.2 $\pm$ 5.8 cm, weight 82.2 $\pm$ 6.5 kg, body fat 9.8 $\pm$ 1.9 %, VO_2 max 51.8 $\pm$ 4.4 ml kg^{-1} min^{-1} (mean $\pm$ SD). Permission for the study was obtained from the JSC Human Research Policy and Procedures Committee and written informed consent obtained from all subjects. Studies were done at least 2 hours after meals and were separated by at least 24 hours. Exercise sessions were not allowed on the day prior to measurement but activity and diet were otherwise uncontrolled.

Fluid intake and voiding were ad lib during the test but were accomplished without violating postural constraints. Heart rate and blood pressure were monitored during all procedures. Subjects were encouraged to verbalize any discomfort or unusual sensation and permitted to terminate testing for any reason.

Basic protocol consisted of measurement of leg girths (Figure 1) by the same individual (V.H.) using a non-extensible tape with a constant spring load, calibrated and read in duplicate to $\pm$1.0 mm at eight previously measured ($\pm$1 mm) levels marked by 90° indices to avoid skew. Heels were individually elevated by a standard 6-inch block during girth measurements. Volumes for each segment between measurement levels were calculated using the formula for a truncated cone, $V = \pi/3 \cdot h \cdot (R^2 + Rr + r^2)$ where R and r are segment radii and h is the distance between them. These volumes were corrected by calculating the volume for a measured stocking thickness of 0.5 mm over a mean area of the segment surface using the formula $(C1 + C2) \cdot h$, where C is segment circumference and h is the distance between segments.

Leg volume measurements were made during quiet standing and immediately (within 5 minutes) after assuming a horizontal posture. This first horizontal measurement was used as a baseline, following which measurements were made at 30, 60, 90 and 150 minutes. The subjects then stood and a measurement was immediately made. Head-down tilt and immersion were initiated after the first 30 minutes of horizontal position. Subjects were not allowed to rise, sit or stand even briefly during the test.

For horizontal measurements, subjects rested on a lightly padded table supine and without a pillow. For head-down tilt, the same table rested on blocks calibrated to give a 6° head-down angle. Additional girth measurements were made immediately after the table was tilted from horizontal to head-down and again immediately after returning the table to the horizontal position. For immersion, the subjects were placed in a 35°C temperature controlled pool with nonconstricting counterweights, resting horizontally on a platform adjusted such that the water covered the entire body and with the head elevated just sufficiently to allow breathing. Water surface to mid thorax distance was individually measured to $\pm$1 cm and recorded (mean

19.4 cm). Subjects were lifted from the water, supine, for leg volume measurements, which required 5 minutes or less. Water and rectal temperatures were continuously monitored as was perceived comfort level.

Analysis and Statistics

The effects of the three simulation conditions on total leg, thigh and lower leg volume were compared. Statistically significant differences among the three test conditions and with time for the three volumes was evaluated using MANOVA repeated measures analysis performed on a VAX main frame computer using the Statistical Analysis System (SAS) software.

RESULTS

Measurement Verification

Plethysmographic volume determinations were treated as correct values and used directly. Means and standard error of segment volume differences for the 10 trials are plotted in Figure 2. Total mean volume difference and standard error for the 10 trials was +91.9 ml $\pm$ 86.4 ml. Calf volume differences were negative, i.e., the stocking overestimated volume, probably as a result of hydrostatic pressure in the liquid plethysmograph. Other errors, which were largest in the ankle and knee regions are explicable by geometric differences from the truncated cone used as the basis of calculation.

Ground-based simulations

All subjects tolerated the tests well and there were no premature terminations. Results comparing horizontal, 6° head-down tilt, and immersion conditions are shown in Figure 3. Using MANOVA repeated measures analysis, no statistically significant differences were noted in leg volume changes among the three test conditions.

In the horizontal position, the initial 30-minutes produced a total volume loss of 1.5%, then there was an additional loss of 1% over the next 60 minutes after which the volume remained stable, i.e., a total time of 1.5 hours produced equilibrium (Figure 3A). On standing, volume returned to the initial supine volume which, however, was 2% less than mean pre test standing volume. In terms of differential percentage change the lower leg lost relatively more fluid (-4%) than the thigh (-2%). With head-down tilt, after the horizontal stabilization there was no significant further change in volume with tilt (Figure 3B). With return to horizontal there was a slight volume decrease, such that final horizontal and head-down tilt changes were equal as were volumes on standing. During the tilt period, thigh volume did not decrease in contrast to lower leg volume which had an additional decrease of -1.5%. With immersion, after the initial supine stabilization period there was an additional total underwater loss of 2.5% and while the rate of loss slowed it probably had not reached equilibrium at 150 minutes (Figure 3C). In the underwater period relative losses from the upper and lower leg were almost equal (3%).

DISCUSSION

Anthropometric measurements of successive volume segments which are summed for total volume has been shown to closely approximate liquid displacement volumes in comparison studies of the lower limbs. In spite of poor approximations of foot volume and the use of large segments, i.e., large distances between girths, Jones and Pearson (9) had correlations of r=.98 and .99 between this method and water plethysmography in male and female populations and Katch *et al.* (11) had a correlation of r=.95. Anthropometric measurements must produce a larger volume through the geometric errors of non-circular cross sections. In comparison with water displacement, liquid plethysmography has hydrostatic compression which will increase this difference. The smaller segment volumes we used will reduce errors and this was demonstrated by the agreement between methods of r=.995 and small standard deviations which included plethysmographic errors. It is felt that the results obtained with the stocking were representative of direct measurements used in our ground based studies, i.e., there is a small (1%) overestimation of total volume while relative errors were smaller and well below the physiological changes examined here.

Moore and Thornton (15) reported on leg volume changes in Space Shuttle crewmembers, including measurement in three crewmembers within the first three hours of significant difference between horizontal and head-down volume shifts and in the case of thigh volumes, the head-down position is even less like weightlessness than the supine position. Of the five published studies, lower leg volume changes seen by Hargens (7) (-5.6% in 240 minutes) are only slightly larger and probably not significantly different from our findings. Unpublished results from a 24-hour head-down tilt study of 4 subjects using our stocking technique are virtually identical to ours, including such nuances as the decrease in volumes when changing from head-down to horizontal position (Buckey, personal communication). Results from Panferova and Kabesheva's (17) horizontal and 12° head-down studies were also comparable to ours. Conversely, the 8% total leg changes in Nixon *et al.*'s (16) study are 3 times that seen in other 1-g simulations. There is no obvious explanation for these differences in results.

While no volumetric data are available from previous immersion studies, other results such as significant diuresis and orthostatic intolerance would make large fluid shifts seem probable (2, 7). Although larger than during bed rest, the shifts we observed during immersion were not significantly so. However, the trend was toward changes seen with weightlessness of space flight, including greater magnitude than during either horizontal or head-down bedrest and greater relative loss from the upper leg. Many of the early immersion studies were done with postures and breathing arrangements which produced significant external pressure gradients. During head-out standing immersion, the foot to mid bronchial gradient can be 115 mm Hg, a significant pressure to shift fluid from legs and abdomen into the chest, compared with a mean of 15 mm Hg in this study.

Without measured peripheral venous pressure which would allow establishment of compliance curves, one is left to speculate on causes of the observed differences in leg volumes changes in weightlessness and its simulation. However, pressure-volume changes between 1-g and weightlessness are so large that existing mean venous pressure data may allow a working hypothesis which can best be shown graphically (Figure 5). If one chooses some point of the leg, say mid-calf, then 1-g standing venous pressure would be in the range of 100 cm H_2O (Point A, Figure 5), while measured horizontal ankle venous pressure is typically 16 cm H_20

(20). Measured arm venous pressures in weightlessness were 5-7 cm H_2O (13). Assuming the latter two pressures are also reasonable calf pressures under the same conditions and plotting known volume changes (points B & C), there is a striking difference in slopes of the pressure-volume curve. Such a difference is consistent with the asymmetry of published tissue fluid volume/pressure curves (6). If one now assumes that, by limiting venous outflow from the legs, the small transverse pressures developed by abdominal contents are sufficient to maintain tissue near fluid volume saturation limits when horizontal in 1-g (point B) and that these pressures are removed in weightlessness, the observed leg volume responses are consistent with studies of tissue fluid compliance.

If, as seems likely, the large slope of the low pressure region is correct then it should be possible to shift large volumes of fluid by applying small external pressures to the legs in the physiological range. This could result in more efficient countermeasures by applying the correct amount of pressure to the appropriate locations.

Many questions remain, including: why does immersion not more closely mimic weightlessness; why is thigh volume increased in head-down vs horizontal position; and what phenomena limit the leg fluid volume change under standing pressures?

CONCLUSIONS

Based on results of this and other studies, the differences in leg volume changes between horizontal and head-down tilt at a typical simulation angle are insignificant, statistically and practically. Although not shown statistically here, there appears to be a larger loss of leg volume in underwater immersion even with minimum respiratory pressure gradients, but this simulation still does not approximate the changes in weightlessness. If these findings are confirmed, none of these common methods used to simulate the fluid shifts in weightlessness, as documented by leg volume changes, approach the actual effect. It appears that venous pressures may have a critical region that is not reached by the ground-based methods; peripheral venous pressures and volumes should be studied on Earth and in space for a better understanding of the phenomena.

The knowledge gained from such investigations might allow better simulation on Earth and improved countermeasures in space flight.

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Legends for Figures

1. Segment locations and calculation of leg volumes. Stocking volumes were corrected for fabric thickness as described in the text.

2. Volumes measured from stocking girths vs. liquid plethysmography. Ten comparisons were made with the same subject over a two-month period. Points shown are volume segments; lower three are below ~~knee segment~~ and upper three are above knee segment. Differences in standard error could not be distinguished for the lower segments.

3. Total leg and above and below knee segment volume changes (in percent) during ground-based studies: A) with horizontal posture, B) with 6° head down tilt; C) with horizontal immersion. Baseline was considered as the initial horizontal measurement performed at the beginning of each study. Initial absolute standing volumes for total, thigh and lower leg were 9.3 L, 6.0 L and 2.2 L, respectively, with knee volume accounting for 1.1 L.

4. Comparison of total leg volume changes during the three ground-based simulation conditions (n=6) and space flight (n=3)(15). Initial volume was 9.3 L for the 1-g subjects and 8.1 L for the space flight subjects. Baseline is defined as initial horizontal position for the 1-g studies and as preflight supine posture for the space flight studies. Prior to space flight, crewmembers spend 2-4 hours in the prelaunch position.

5. Measured volume changes vs. venous pressures at rest separately measured and assumed in the lower legs. Normal 1-g response would fall along B to C.

TABLE I. PUBLISHED STUDIES OF SHORT TERM LEG VOLUME CHANGES.*

Study	Condition	n	Segment (Mean Vol in L)	Time Course (hrs)	Volume Change (%)
Nixon et al. '79 (16)	5° headdown	6	Total leg (7.5) - single leg	0.5	-5.0
				2	-8.0
Hargens '83 (7)	5° headdown	4	Calf (3.4) - single leg	0.5	-5.6
Panferova & Kabesheva '87 (17)	Horizontal	10	Total leg (16.4) - both legs	1	-0.7
				2	-1.5
				4	-1.8
	12° headdown	10	Total leg (16.4) - both legs	1	-1.0
				2	-1.0
				4	-2.5
	22° headdown	10	Total leg (16.4) - both legs	1	-4.3
				2	-5.8
				4	-7.7
Convertino et al. '89 (3)	6° headdown	8	Calf (1.7) - single leg	96	-3.6
			Thigh (3.7) - single leg	96	-1.3
			Total leg (5.4) - single leg	96	-2.0
Thornton et al. '77 (19)	Space flight (Skylab)	3	Calf (4.4) - both legs	48	-9.0
			Thigh (9.9) - both legs	48	-14.0
			Total leg (15.4) - both legs	48	-12.5
Moore & Thornton '87 (15)	Space flight (Shuttle)	3	Calf (3.0) - single leg	10	-6.0
			Thigh (5.1) - single leg	10	-9.8
			Total leg (8.1) - single leg	10	-8.4

*An additional 13 Shuttle (15) and 28 Soviet (18) crewmembers were studied later in flight.

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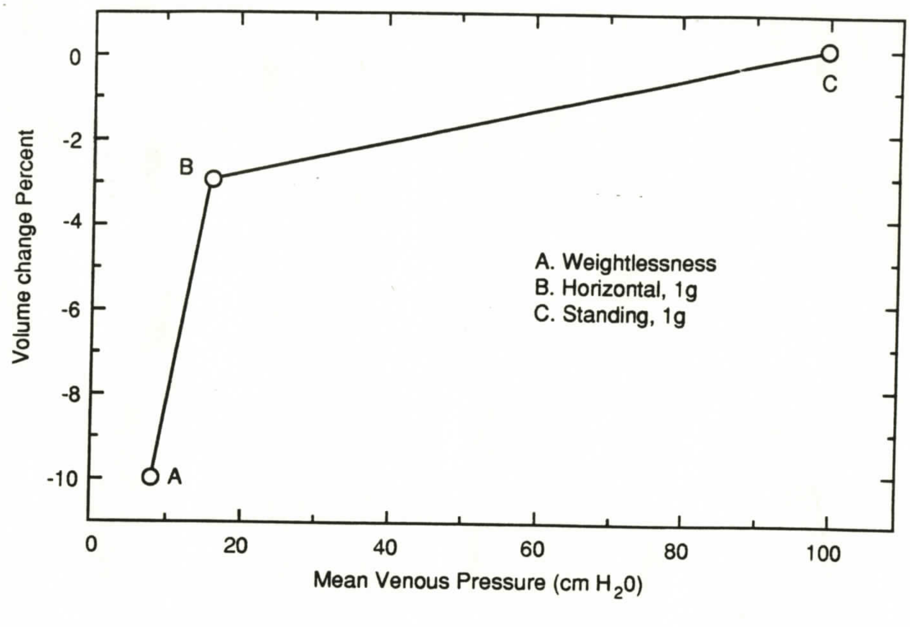

Fig. 5

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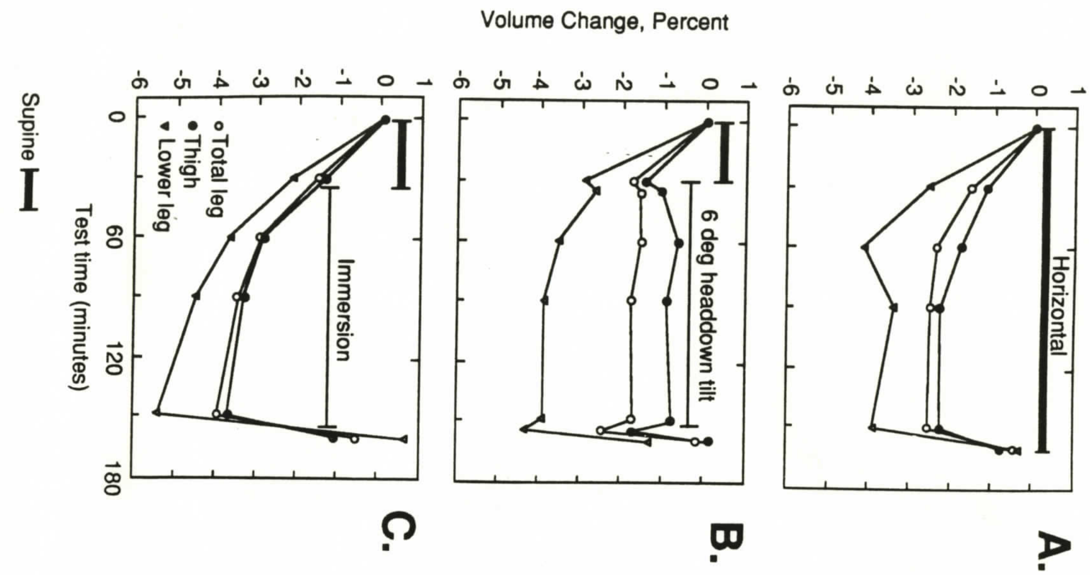

Fig. 3

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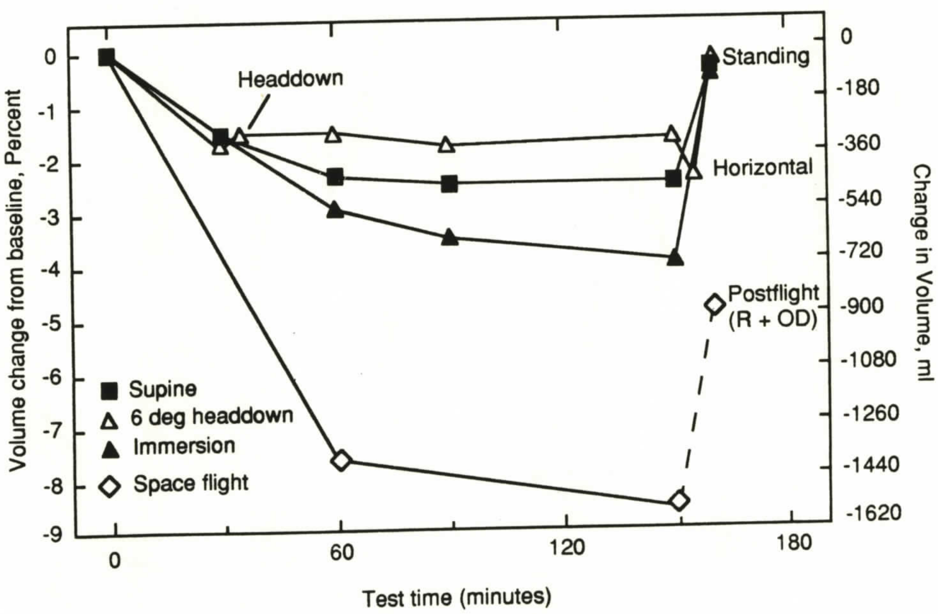

Fig. 4

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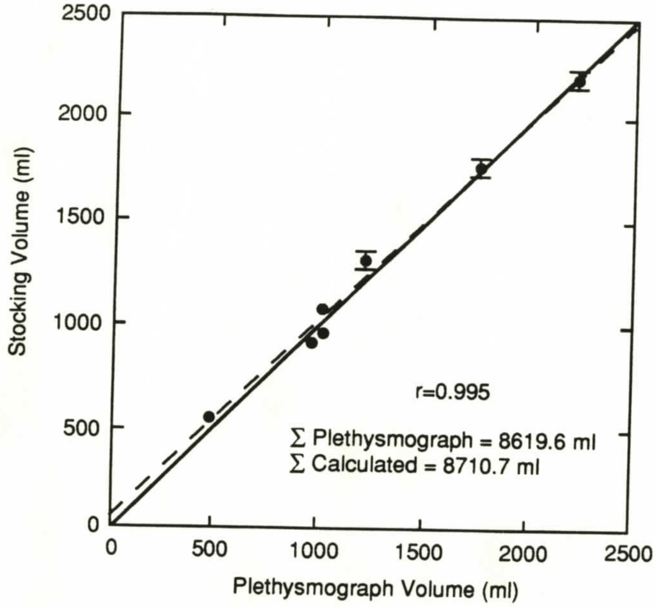

Fig. 2

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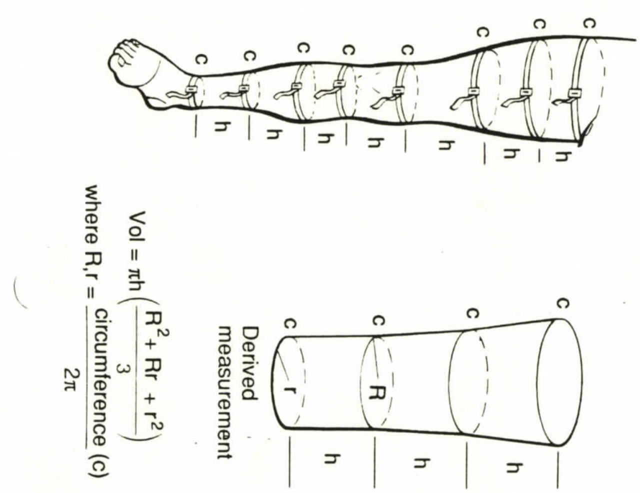

Fig. 1

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