Influence of Lower Body Negative Pressure on the Level Of Hydration During Bed Rest

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In four subjects bed rest was used to induce recumbency diuresis. This was manifested by a decrease in fluid balance, body weight, and plasma volume, accompanied with an increase in hematocrit. After the changes from bed rest had occurred, the use of LBNP over a two-day period resulted in rehydration manifested by an increase in fluid balance, body weight, and plasma volume, accompanied with a decrease in hematocrit. The use of LBNP is an effective means to restore hydration after recumbency diuresis has occurred. This has important applications to manned space flight when it is desirable to maintain the level of hydration.

DEHYDRATION HAS BEEN repeatedly observed during manned space flight. Decreased plasma volume secondary to a decreased level of hydration has been reported with bed rest and water immersion.[3,7] Decreased hydration can impair orthostatic tolerance by causing a decreased blood volume and tissue tension. Loss of tissue tension augments the loss of intravascular fluid to the extravascular compartment during orthostasis.

Orthostatic tolerance in healthy subjects is quickly restored when normal activities are resumed, either following bed rest, or following space flight. This observation suggests that the multiple changes responsible for decreased orthostatic tolerance can be reversed in a short time span.

The use of lower body negative pressure (LBNP) to prevent the changes of prolonged bed rest has been under study in this laboratory. It produces changes in circulatory dynamics similar to standing.[2,5,6]

This study was designed solely for the limited objective to see if short term LBNP could favorably influence the level of hydration after the initial changes of recumbency had occurred.

METHODS

Four healthy airmen, aged 18 to 21 years, who had just completed the basic training course for the United States Air Force were used as subjects for this study. All were in good physical condition. They were confined to the metabolic cardiovascular ward for the study. Prior to the onset of the study and during the ambulatory phases each subject performed exercises twice daily of the 5BX variety. All subjects were encouraged to maintain normal activity and forbidden to use the beds except for the normal 8-hour sleep period.

The diet consisted of 2900 calories and included 8.5 grams of sodium chloride. This was supplemented with 6 grams of sodium chloride in tablet form given in divided amounts with the meals and at bedtime.

The fluid intake with the meals was supplemented daily with approximately 2000 ml. of water given in increments throughout the daytime and on the same schedule throughout the experiment. This provided a fluid intake for all subjects throughout the study of approximately 3000 to 3200 ml. daily.

A study plan was designed to provide a random variation in the observations to better assess the influence of LBNP as a significant factor in influencing hydration. Initially two subjects were designated that would use LBNP at the end of their initial bed rest period and the remaining two subjects acted as controls. Later in the experiment the initial two subjects acted as controls and the other subjects received LBNP following a period of bed rest. The controls were placed in identical boxes with negative pressure for an identical period of time. This provided for a random study with controls for each phase of the experiment and permitted each subject to act as his own control. The study plan is given on page 1146.

The level of LBNP utilized was –30 mm. Hg. This level of negative pressure was maintained in a constant manner when used. A detailed description of the device used for lower body negative pressure has previously been reported. The basic principle was to provide an air tight box for the inclosure of the lower half of the body. A rubber air tight seal is at the level of the umbilicus. By use of a simple vacuum cleaner motor the air was evacuated from the box to produce a relative negative pressure of 30 mm. Hg.

During bed rest, the subjects were not allowed out of bed at any time. They could prop themselves up on one elbow for eating. Voiding was done while lying on their side and a bed pan was used for bowel movements.

A fluid intake and output record was kept on a daily basis throughout the experiment. Body weight was obtained by use of the metabolic scales. Body weight was obtained after voiding. In those instances where it was not possible for the subject to void until after weighing, the body weight was corrected for the volume of urine voided. The plasma volume was determined by the

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Experiment day	Subjects 1 and 2	Subjects 3 and 4
1 & 2	Ambulatory baseline	Ambulatory baseline
3–6	Bed rest	Bed rest
7	Lower body negative pressure (LBNP) 8:00 AM to 12:00 noon 1:00 PM to 5:00 PM 6:00 PM to 10:00 PM	Bed rest
8	LBNP 6:00 AM to 9:30 AM 1:00 PM to 5:00 PM 6:00 PM to 10:00 PM	Bed rest
9	LBNP 6:00 AM to 9:30 AM 10:30 AM Ambulatory	Bed rest 10:30 AM Ambulatory
10–16	Ambulatory	Ambulatory
17–20	Bed rest	Bed rest
21	Bed rest	LBNP 8.00 AM to 12:00 noon 1:00 PM to 5:00 PM 6:00 PM to 10:00 PM
22	Bed rest	LBNP 6:00 AM to 9:30 AM 1:00 PM to 5:00 PM 6:00 PM to 10:00 PM
23	Bed rest 10:30 AM Ambulatory	LBNP 6:00 AM to 9:30 AM 10:30 AM Ambulatory

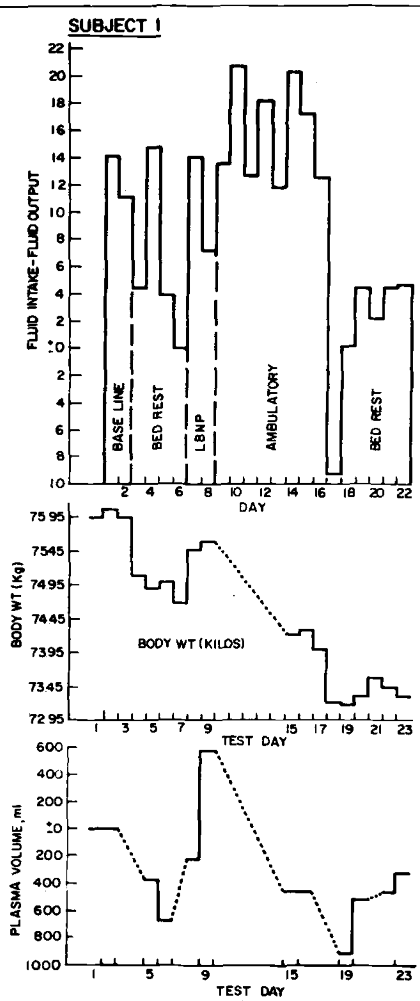

Fig. 1. The relation between fluid balance, body weight, and plasma volume in subject 1 (see text) during ambulatory baseline, bed rest, and lower body negative pressure (LBNP). Solid lines indicate actual values. Fluid intake and output is expressed in 100 ml. values.

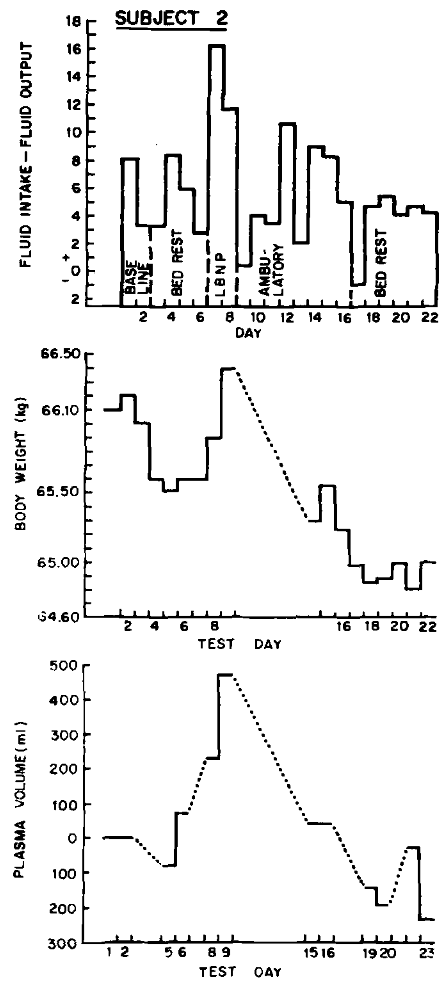

Fig. 2. The relation between fluid balance, body weight, and plasma volume in subject 2 (see text) during ambulatory baseline, bed rest, and lower body negative pressure (LBNP). Solid lines indicate actual values.

RIHSA method. Because of the difficulties in obtaining accurate venous hematocrit measurements these were done on six different venous samples drawn at the time of blood sampling for the RIHSA method. The mean of these multiple determinations was taken at the true hematocrit. The usual precautions of the removal of the tourniquet during drawing of venous blood was employed to insure as great accuracy as possible.

RESULTS

Fluid Balance—The difference between the fluid intake and fluid output was used as each individual's fluid balance. No consideration was given for loss of body water by other means. It was assumed that this loss would be relatively constant since the studies were carried out in an air-conditioned ward and the experimental conditions likely to influence these factors were relatively constant throughout the study. The fluid balance was plotted on a daily basis (Figures 1-4). The values are given in Table I.

The baseline studies obtained while the subjects were ambulatory all demonstrated a positive fluid balance. During the first day of bed rest there was a drop in the fluid balance as compared to the baseline values in all subjects. This was particularly evident in subjects 3 and 4. In these subjects the fluid balance then became stabilized at a level not significantly different than observed during the baseline period.

On the seventh and eighth day the use of LBNP in subjects 1 and 2 was associated with an increase in positive fluid balance. This was not observed in sub-

TABLE I. FLUID BALANCE (FLUID INTAKE MINUS FLUID OUTPUT) CHANGES DURING BED REST WITH AND WITHOUT LBNP (ml.)

Experiment Day	Subject 1	Subject 2	Subject 3	Subject 4
1	1414	809	689	1694
2	1114	329	364	1529
3	454	329	—701	—11
4	1479	844	569	739
5	499	589	416	924
6	—1	279	639	909
7	1419	1614	451	1479
8	719	1169	704	1604
9	1369	49	1574	1434
10	2079	404	549	1219
11	1263	354	719	854
12	1829	1074	1324	439
13	1189	204	579	859
14	2029	904	718	1014
15	1729	834	349	1204
16	1254	504	299	1434
17	—936	—81	—421	—146
18	19	479	159	—201
19	449	554	549	609
20	269	429	624	—441
21	449	476	1499	1209
22	479	434	669	1109

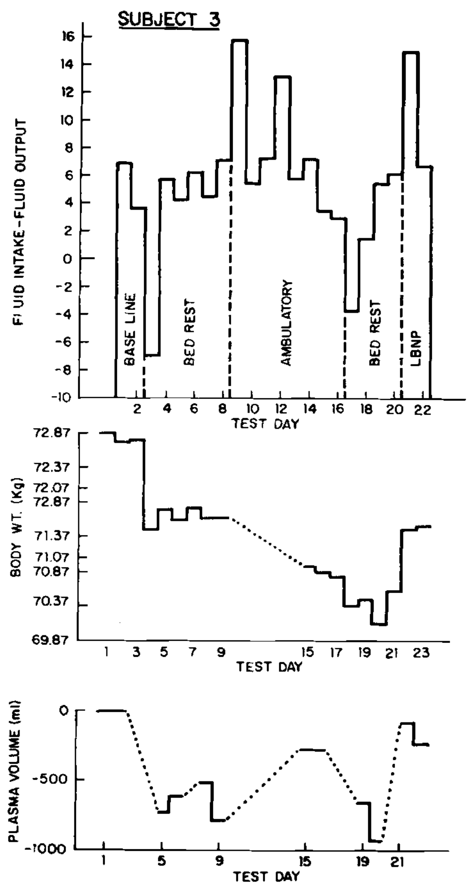

Fig. 3. The relation between fluid balance, body weight, and plasma volume in subject 3 (see text) during ambulatory, baseline, bed rest, and lower body negative pressure (LBNP). Solid lines indicate actual values.

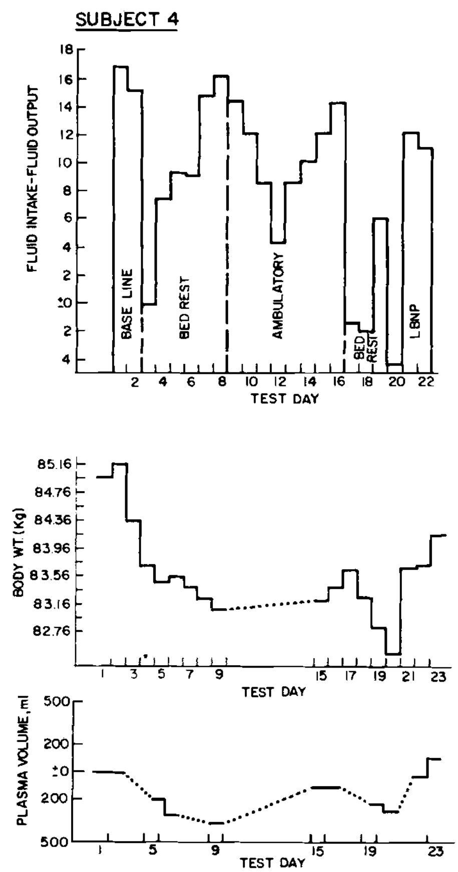

Fig. 4. The relation between fluid balance, body weight, and plasma volume in subject 4 (see text) during ambulatory baseline, bed rest, and lower body negative pressure (LBNP). Solid lines indicate actual values.

jects 3 and 4 who continued simple bed rest. Normal ward ambulation from the ninth to the sixteenth day significantly influenced water balance. In subject 1 there was a further increase in positive fluid balance. In subject 2 ambulation was associated with a decrease in level of fluid balance compared to that noted during the application of LBNP.

This was particularly evident on the initial day of ambulation. In this subject the subsequent daily values during ambulation were somewhat random but in all instances the values were below those noted during LBNP. In subject 3 the first day of ambulation was associated with a sharp increase in fluid balance. Although some variations were noted during the remainder of the ambulatory period the level of fluid balance was approximately that noted during the baseline observations. In the fourth subject, despite some fluctuations, the fluid balance was not markedly different from that noted during the last several days of bed rest.

At the onset of the second bed rest phase all four subjects showed a sharp drop in fluid balance for the first day compared to the immediately preceding values. After the initial sharp decrease in fluid balance during the first day of recumbency, subjects 1 and 2 demonstrated fairly stable values for the remainder of the study, while this was less evident in subjects 3 and 4.

With the application of LBNP on the twenty-first and twenty-second experimental day in subjects 3 and 4 there was a sharp increase in the fluid balance. This was not observed in subjects 1 and 2 who continued bed rest without the application of LBNP.

Despite some minor variations, all four subjects demonstrated in this study that the application of –30 mm. Hg of LBNP was associated with water retention regardless of whether it was used in conjunction with the first or second bed rest phase of the experiment.

Body Weight—The changes in body weight were consistent with the observations of fluid balance. All four subjects demonstrated weight loss when they began the first bed rest period. The sharp drop in body weight was consistent with the acute decrease in fluid balance. The subsequent plateau effect for the remainder of the bed rest phase was consistent with the relative stabilization of fluid balance. The use of LBNP in subjects 1 and 2 was associated with an increase in body weight. This was not seen in subjects 3 and 4 who did not receive LBNP at this phase of the experiment.

The body weights in all subjects on the fifteenth day of the experiment were less than at the onset of the study, despite ambulation after completion of the first bed rest phase of the experiment. In all four subjects there was a precipitous drop in body weight when they resumed the second period of bed rest, consistent with the sharp drop in fluid balance noted in all subjects.

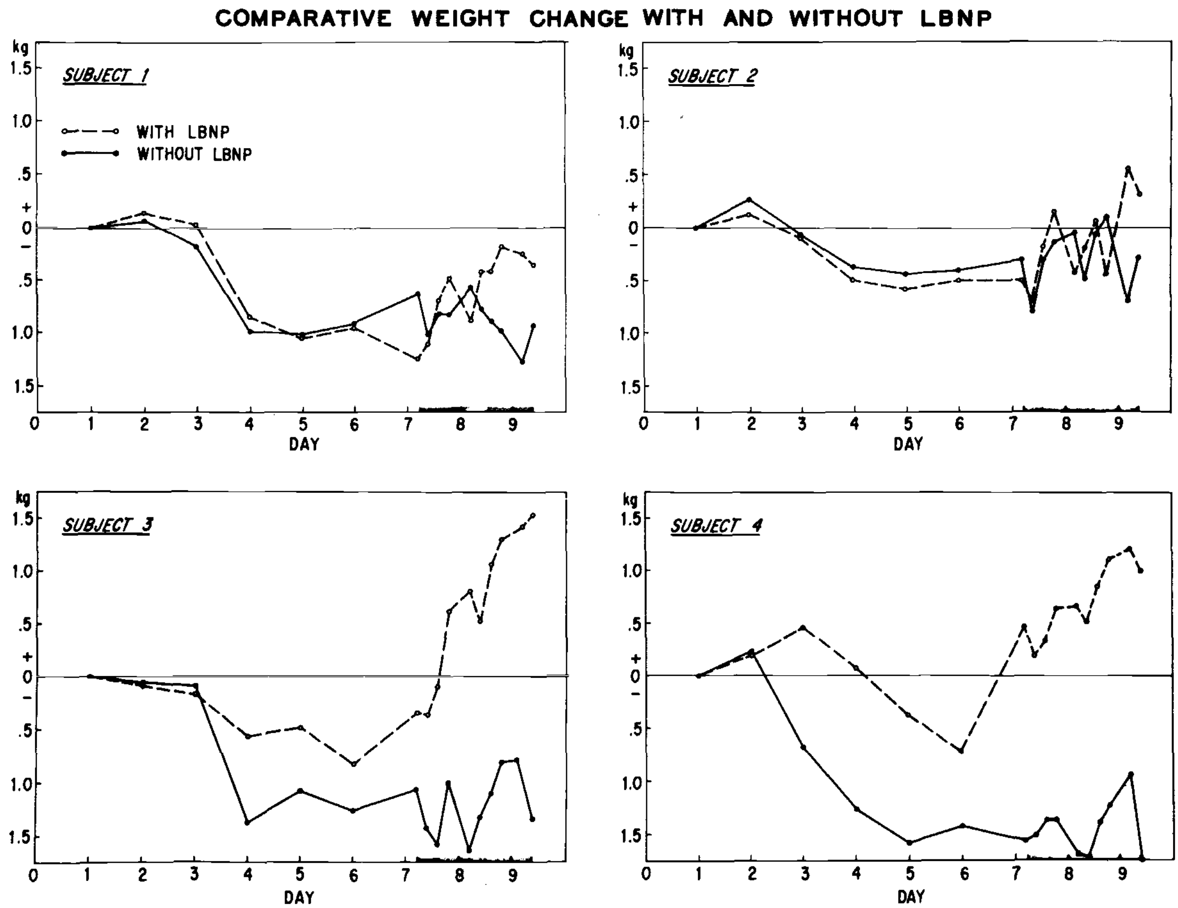

Fig. 5. The change in body weight from baseline values shows a decrease during bed rest and an increase during LBNP at bed rest. The gray bar indicates the time of application of LBNP.

When LBNP was used in subjects 3 and 4 the body weight increased parrallel to the increase in fluid balance. This did not occur in subjects 1 and 2 not receiving LBNP during this phase.

Body weight increased progressively during the application of LBNP compared to the value noted preceding its application. The acute influence of LBNP compared to a comparable period of simple bed rest for each subject is demonstrated in Figure 5. The changes in body weight throughout the experiment are given in Table II.

Plasma Volume—During bed rest the plasma volume decreased in subjects 1, 3, and 4 consistent with the decrease in fluid balance and body weight. The values for the plasma volume determinations were not significantly changed in subject 2. During the application of LBNP there was an increase in plasma volume in subjects 1 and 2. This was not observed in subjects 3 and 4 who remained at bed rest.

After ambulation a second baseline determination for the plasma volume was obtained in all subjects preceding the second phase of bed rest. During the second bed rest period the plasma volume decreased in all subjects consistent with the decrease in fluid balance and body weight. In subjects 3 and 4 the plasma volume increased during the application of LBNP parallel to the increase in fluid balance and body weight.

The influence of LBNP on plasma volume is illustrated by comparing the difference in the plasma volume between the fourth and sixth days of simple bed rest and the differences in plasma volume between the fourth day of bed rest followed by LBNP (Figure 6). In all instances LBNP increased the plasma volume above the value noted after four days of bed rest. The changes in plasma volume observed during the experiment are given in Table III.

Hematocrit—The changes in hematocrit value observed during the experiment are given in Table IV. In all subjects the hematocrit increased during bed rest consistent with the hemoconcentration secondary to water loss. The use of LBNP decreased the hematocrit from the value noted prior to its application consistent with water retention. A comparison of the effects of simple bed rest and bed rest using LBNP is shown in Figure 7.

DISCUSSION

Despite the multiple variabilities associated with fluid balance and the difficulties in measurements, the results observed in the four subjects were rather consistent. Although minor variations were observed, a study of the fluid balance, body weight, and plasma volume showed a consistent pattern of decreased hydration with simple bed rest and increased hydration by using LBNP. Since the fluid and salt intake were constant the experiment demonstrates that the effect was induced by LBNP. The random study plan and the use of each subject as his own control helps to demonstrate its influence.

TABLE II. BODY WEIGHTS (Kg.)

Day	Subjects 1	2	3	4
1	75.95	66.10	72.87	84.96
2	76.09	66.23	72.75	85.17
3	75.98	66.00	72.77	84.53
4	75.10	65.60	71.48	83.69
5	74.90	65.52	71.78	83.47
6	75.00	65.60	71.60	83.53
7 8 A.M.	74.70	65.60	71.80	83.40
12 A.M.	74.85	65.40	71.43	83.44
5 P.M.	75.27	65.92	71.28	83.60
10 P.M.	75.47	66.25	71.87	83.60
8 6 A.M.	75.08	65.66	71.22	83.27
10 A.M.	75.53	65.90	71.54	83.24
5 P.M.	75.53	66.16	71.76	83.58
10 P.M.	75.77	65.65	71.96	83.72
9 6 A.M.	75.70	66.66	71.98	83.40
10 A.M.	75.60	66.40	71.52	83.10
15	74.20	65.30	70.95	83.20
16	74.28	65.56	70.86	83.40
17	74.02	65.24	70.79	83.66
18	73.23	64.97	70.37	83.27
19	73.20	64.86	70.46	82.82
20	73.30	64.89	70.12	82.46
21 8 A.M.	73.58	65.00	70.60	83.68
12 A.M.	73.19	64.50	70.58	83.38
5 P.M.	73.40	65.00	70.85	83.52
10 P.M.	73.40	65.16	71.56	83.84
22 6 A.M.	73.65	65.25	71.75	83.85
10 A.M.	73.45	64.82	71.46	83.70
5 P.M.	73.32	65.24	71.80	84.05
10 P.M.	73.24	65.40	72.25	84.30
23 6 A.M.	72.94	64.60	71.37	84.40
10 A.M.	73.28	65.02	71.48	84.19

TABLE III. PLASMA VOLUME CHANGES (ml.) USING LOWER BODY NEGATIVE PRESSURE

	Ambulatory Days			Days of Bed Rest: Without LBNP				With LBNP			
	1	2	Mean	3rd	Change	4th	Change	6th	Change	7th	Change
Subject 1	4155	3943	4049	3675	—.374	3387	—.662	3815	—.234	4619	+.570
Subject 2	2876	3070	2973	2892	—.081	3047	+.074	3196	+.223	3443	+.469
Subject 3	3417	3392	3405	3042	—.363	2765	—.640	3601	+.196	3467	+.062
Subject 4	3407	3463	3435	3318	—.117	3516	—.171	3516	+.081	3643	+.208

PLASMA VOLUME CHANGES (ml.) DURING BED REST WITHOUT USING LOWER BODY NEGATIVE PRESSURE

	Ambulatory Days			Days of Bed Rest							
	1	2	Mean	3rd	Change	4th	Change	6th	Change	7th	Change
Subject 1	3579	3544	3562	3110	—.452	3493	—.069	3565	+.003	3694	+.132
Subject 2	3009	3015	3012	2828	—.184	2780	—.232	2946	—.066	2740	—.272
Subject 3	3592	3792	3692	2956	—.736	3077	—.615	3175	—.517	2902	—.790
Subject 4	3542	3555	3549	3353	—.196	3240	—.309	——	——	3183	—.366

It is well known that simple recumbency results in acute diuresis. This was again demonstrated in this study. In many instances the action is relatively acute as indicated by the sharp one-day decrease in fluid balance. One explanation advanced for recumbency diuresis is that proposed by Gauer and Henry, that recumbency results in left atrial distention, stimulating stretch receptors that inhibit the secretion of ADH, permitting the occurence of diuresis.[1,4] Using this concept one may postulate that since LBNP displaces a major portion of blood volume below the diaphragm similar to standing that it prevents atrial distention, inhibition of ADH, and diuresis.

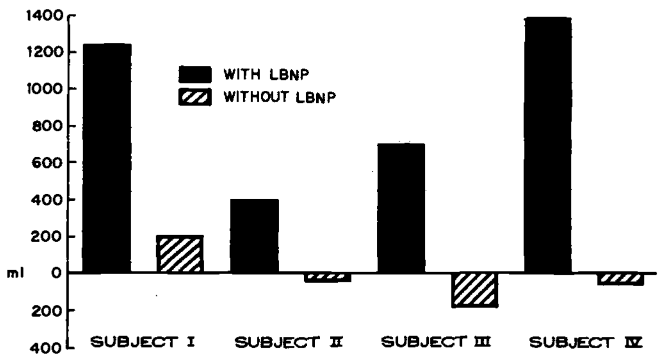

Fig. 6. Changes in plasma volume from the 4th to the 7th day of bed rest with and without LBNP. See text.

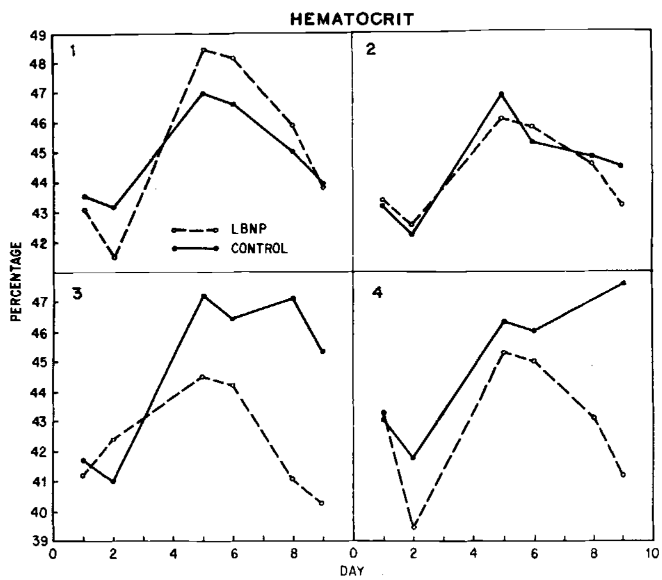

Fig. 7. The changes in hematocrit in four subjects during bed rest with and without LBNP.

The tendency to develop a plateau level of fluid balance and body weight following the initial recumbency diuresis suggests a new homeostatic level of hydration during bed rest. When an individual is standing the blood volume must be of sufficient level to maintain circulation and still accommodate normal venous pooling. During standing the capillary pressure is increased by hydrostatic pressure. In the normally active individual, this is equalized to some extent by the tissue tension maintained by adequate tissue hydration. During quiet standing, intravascular fluid migrates out of the high pressure vascular space to the low pressure tissue space. In muscles like the soleus and anterior tibial which are tightly bound by the fascia the fluid migration continues until the intramuscular pressure reaches about 40 mm. Hg. At this point the extravascular tension nearly equals the difference between the osmotic pressure of the plasma proteins and the hydrostatic pressure and further loss of fluid to these muscles does not occur. The tissue tension is not solely dependent upon muscle tone but rather upon filling the tense sac-like fascial compartment of the muscle which occurs at the level of complete hydration.[8] Intravascular fluid continues to be lost to the subcutaneous tissues and gastrocnemius muscle since no tight fascial compartment exists and the tissue tension cannot be raised above 12 or 16 mm. Hg. Actual measurements demonstrate continued increase in leg volume over 2-5 hours and no limit of continued increased volume has been demonstrated.[8] The progressive loss of fluid from the intravascular compartment leads to fainting. In the recumbent position venous pooling in the lower half of the body does not occur and the increased hydrostatic pressure in the capillary is not observed. For these reasons the requirement for the same level of hydration to maintain tissue tension and blood volume at a high level does not exist. One may theorize that as soon as the excess hydration, required to maintain blood volume and a favorable balance of tissue tension to capil-

TABLE IV. CHANGES IN HEMATOCRIT (PER CENT) USING LOWER BODY NEGATIVE PRESSURE

	Ambulatory Days			Days of Bed Rest: Without LBNP				With LBNP			
	1	2	Mean	3rd	Change	4th	Change	6th	Change	7th	Change
Subject 1	43.1	41.5	42.3	48.4	+6.1	48.2	+5.9	45.9	+3.6	43.8	+1.5
Subject 2	43.4	42.5	42.9	46.1	+3.2	45.8	+2.9	44.6	+1.7	43.2	+0.3
Subject 3	41.2	42.4	41.8	44.5	+2.7	44.2	+2.4	41.1	—0.7	40.3	—1.5
Subject 4	43.3	39.4	41.4	45.3	+3.9	45.0	+3.6	43.1	+1.7	41.2	—0.2

CHANGES IN HEMATOCRIT (PER CENT) DURING BED REST WITHOUT LBNP

	Ambulatory Days			Days of Bed Rest							
	1	2	Mean	3rd	Change	4th	Change	6th	Change	7th	Change
Subject 1	43.6	43.2	43.4	47.0	+3.6	46.6	+3.2	45.0	+1.6	43.9	+0.5
Subject 2	43.2	42.2	42.7	46.9	+4.2	45.3	+2.6	44.8	+2.1	44.5	+1.8
Subject 3	41.7	41.0	41.4	47.2	+5.8	46.4	+5.0	47.1	+5.7	45.3	+3.9
Subject 4	43.1	41.8	42.5	46.3	+3.8	46.0	+3.5	—	—	47.6	+5.1

lary pressure during normal upright activity, is removed that a new homeostatic level for continued recumbency is established. This would explain the tendency to develop a stable fluid balance and body weight during bed rest following the initial diuresis.

The hematocrit changes observed may be simply explained on the level of hydration. Recumbency diuresis results in hemoconcentration and an elevated hematocrit. Ambulation or the application of LBNP results in increasing the level of hydration and acutely decrease the hematocrit level.

The results of this study suggest that LBNP can be used on a short-term basis to restore the level of hydration. This presupposes an adequate intake of salt and water. This observation is important to space flight to the extent that dehydration is caused by weightlessness in a manner similar to that observed in recumbency. Short-term LBNP may restore hydration to levels commonly observed during ambulatory activity at ground level. The device could be used on a short-term basis immediately prior to deorbit and exposure to earth activities. This would result in an acute expansion of plasma volume and an improved level of hydration. The application of such a device at that time point in a space flight would be similar to gradual ambulation at the end of a prolonged period of bed rest.

This study has established the limited objective that LBNP used in the manner described in this experiment effectively increases the level of hydration. The experiment does not establish what influence this has on orthostatic tolerance nor does it limit the possible applications of lower body negative pressure to other factors besides its influence on the level of hydration.

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