3.5.1 Hemodynamics of the Legs

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Introduction

Exposure to weightlessness on Apollo[1] and Skylab[2] missions has produced a decreased tolerance to work post flight, and on Skylab a decreased tolerance to simulated orthostasis in-flight and post flight, possibly through decreased cardiac output[3]. Although this decrease may be cardiac in origin, there is, as yet, little convincing evidence for this. Decreased venous return would seem a more likely cause of such decreased output.

There can be little doubt of the primary role of venous return in lower body negative pressure (sec. 3.5). In the same manner, the importance of the muscle pump mechanism in venous return is at least tacitly recognized by having the astronauts continue unloaded pedaling on the bicycle ergometer after exercise.

In an effort to investigate some of the mechanisms involved in venous return, two closely related characteristics of the veins were studied. These studies were initiated in-flight and were continued post flight on Skylab. They are: labeled "blood flow", (not to be confused with or limited to arterial flow), and "muscle pump action"; a discussion of each follows.

Background and Rationale

In spite of the recognized importance of the venous circulation, the physical aspects of venous blood flow are less studied hence less well understood than arterial hemodynamics.

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[1] Rummel, John A., E. L. Michel: *Physical Response to Exercise After Space Flight - Apollo 7 to 11.* J. of Aerospace Medicine, Vol. 44, p. 235-38.

[2] JSC-08439. *Skylab 1/2 Preliminary Biomedical Report,* September 1973.

[3] op. cit. JSC-08439, pp. 303-9, and section 3.15 (experiment M171) this report.

Because of the smaller venous pressures there is relatively greater gravitational effects on venous flow; variations in gravity fields will produce greater effects in venous flow than in arterial flow. It is recognized that veins normally contain a major portion of the blood volume[4] and that, under some conditions, they can accommodate large additional amounts of blood with little increase in venous pressure. It must be recognized, however, that veins are not simply passively compliant vessels for those larger than 0.4 millimeters in diameter have muscular walls. The musculature of the venous walls can be made to contract by single or combined stimulation of low levels of sympathetic nervous system action, by circulating adrenalin and other hormones[5], by unknown agents during exercise, or by direct mechanical stimulation[6]. All such muscle contractions produce increase venous return to the heart.

Characteristics of venous "capacity" plus the large size of the leg veins make pooling of large volumes of blood in the legs possible without increasing their internal pressure. This is particularly true when they are subject to gravitational or LBNP forces. Without such pressure the blood is not returned to the right side of the heart and cardiac output consequently falls. However, the leg veins have characteristic differences to offset such pooling. Like veins elsewhere in the body, they are divided into two interrelated systems; the superficial veins which are covered only by fascia, subcutaneous tissue and skin, and the deep-lying veins, which are surrounded by muscles, fascia and other tissue. In superficial veins of the legs, there is a marked increase in two mechanisms to prevent pooling of blood; additional internal valves and increased musculature in the vein walls. This has been demonstrated in the saphenous vein, the largest superficial vein in the body. It has 10 to 20 valves which are more numerous

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[4] Åstrand, Per-Olof and Per Kaareodahl: *Textbook of Work Physiology*. McGraw Hill, N. Y., 1970, p. 157.

[5] op. cit., p. 151-7.

[6] Personal communication with several vascular surgeons who noted in particular the great contraction, particularly of leg veins, caused by slight stimulus.

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in the lower legs[7] and increased muscle in its wall[8]. The deep veins of the leg also differ in that many of the muscles around them are more-or-less completely surrounded by fascia which is relatively inelastic; consequently, the actions of these muscles tend to limit any volume increases as well as to insure transmission of blood flow by virtue of the increased pressure developed. At the same time, these enclosed veins are subject to static and dynamic pressures from surrounding tissues. This is the basis of the "muscle pump action".

It is reasonable to postulate that a number of changes known to have occurred on SL-1/2 and SL-3 may have had marked effects on venous return from the legs. For example: when under the influence of zero-g, there is an initial rapid shift in leg size followed by a further more prolonged decrease. This rapid shift is probably a fluid shift which, quite apart from reducing available blood volume, also reduces external, *i.e.*, tissue or interstitial pressure on veins. These reactions increase the leg-vein compliance and reduce blood return. Longer-term changes included further loss of leg size and volume through muscle and fat loss. These resulted in considerable "slack" which was not immediately compensated for, which may produce a further increase in venous compliance.

Changes in muscle tone through inactivity can affect venous return also. Normally, resting muscle tension (or tone) would increase the tension on deep vessels. Dr. Joe Kerwin, the Scientist Pilot of SL-1/2, remarked on this loss of tone in describing the muscles by saying they have a "doughy feel". It has long been recognized that individuals with such decreased muscle tone are more prone to fainting.[9]

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[7] Gray's Anatomy, 17th Ed., p. 754.

[8] Ham, Histology, p. 495.

[9] Mayerson, H.S. and G. E. Burch: *Relationship of Tissue and Venous Pressure to Syncope Induced in Man by Gravity*. Am. J. Physiol., 128:258-269, 1940.

Any flexible vessel with one-way valves becomes a pump when cyclic pressure changes are applied. This has been amply demonstrated; for example, Barcroft and Swan[10] showed that isometric contractions of leg muscles could empty veins against 90 millimeters of mercury pressure in a leg-constricting cuff.

In addition to venous outflow, there may be marked differences in arterial/capillary inflow. We know that muscle atrophy has occurred in the Skylab crewmen and one would thus expect a reduction in blood flow. However, the concept is not this simple as many hormonal and other changes occur which might conceivably alter flow in other ways.

In summary, the changes that have been seen post flight in Skylab crewmen could reasonably be changes

- in venous compliance, *i.e.*, "filling curve",
- in efficiency of emptying of leg veins by muscular contraction, and
- in changed arterial flow through the leg.

The efficiency of muscular contractions on emptying the leg veins was studied in-flight and post flight on SL-3. A crewman being subjected to lower body negative pressure briefly contracted his leg muscles isometrically and the change in size of a designated segment of the calf by means of the Limb Volume Measuring System (LVMS) band was recorded.

Change in arterial blood flow was measured by placing an arm blood pressure (BP) cuff above the knee with an LVMS attached in place on the calf. The BP cuff was rapidly inflated to 30 mmHg pressure, blocking venous return but without appreciably hindering arterial inflow. The resulting change

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[10] Barcroft and Swan, *Sympathetic Control of Human Blood Vessels*, London, 1953.

in limb segment volume gives a relative blood flow measurement. The initial change in slope (on the LVMS recording) is measured before appreciable back pressure is developed.

By noting, over a longer period of time, the shape of volume the curve thus derived, a good deal can be said about the nature of venous compliance and the venous curve.

Methodology

A. Muscle Pump Studies

1. Method. - With the crewmember in the Lower Body Negative Pressure Device (LBNPD), LVMS bands were placed on both legs and calibrated; *i.e.*, the left band was left in place, and the right removed from its adapter and used on the leg. Eight and sixteen mmHg negative pressure was applied respectively for one-minute periods, and then pressure was lowered to -30 mmHg. Three minutes later the crewman made a maximum isometric contraction lasting for two seconds without valsalva or movement. He relaxed and 45 seconds later repeated the procedure. At the end of this time pressure was dumped, a zero was established and calibration was repeated.

2. Records and Analysis. - This procedure was performed twice by each crewmember in-flight after MD 50 and at R+5 and R+9 days. Right leg records made with bands that are normally used as zero references have been uniformly bad. Conversely, most recordings using the left leg and normally used bands were good with only occasional obvious artifacts. There were in-flight calibration problems in some records, and not all data has been received. Only strip charts for monitoring were available in time for this report, and amplitudes are too low and speeds too high for optimum reduction.

3. Reduction and Results. - These must be considered preliminary. Measurements taken from some of the records are as follows.

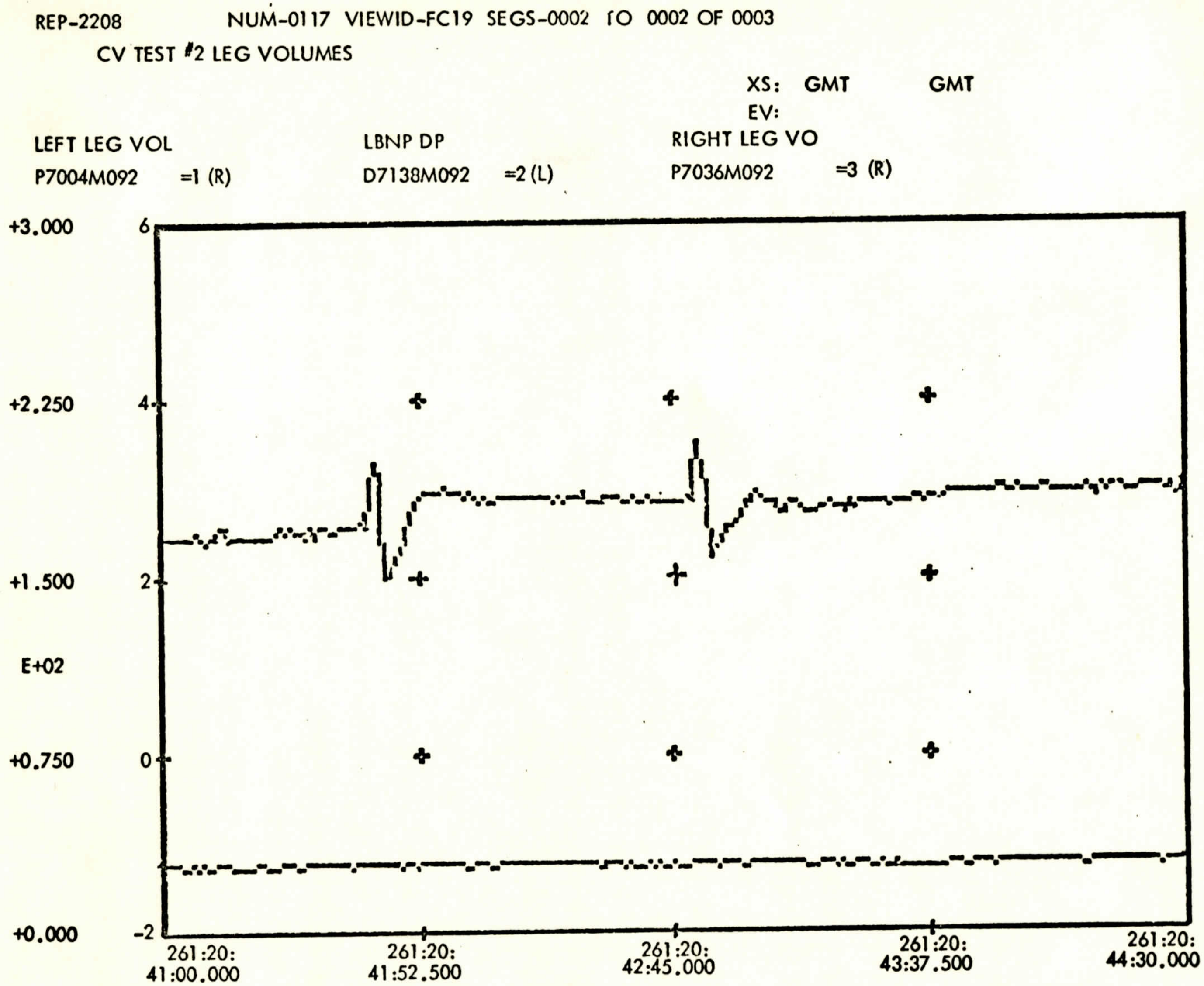

Figure 3.5.1-1. - Volume Changes By Isometric Contractions at -30 mmHg. SPT, SL-3, MD 51. Calibration is 2% Per Vertical Division.

Figures 3.5.1-1 and 3.5.1-1a are an in-flight record of the left leg of the SPT on his first attempt at this procedure. Figure 3.5.1-2 is a ground record of the PLT on R+5 days at much higher chart speed. The inscription of the maneuver is characterized by an upward deflection, assumed to be muscle shortening, followed by a drop to some lower value considered to be the volume reduction caused by muscle pumping action. In-flight the initial contraction was frequently followed by a small overshoot. At first this overshoot was thought to be a mechanical artifact, and this impression was enhanced by the digital plotter, however, a baseline through the mean signal level as in figure 3.5.1-1a shows the true situation. This overshoot may represent reactive hyperemia since contractions usually lasted four seconds, or more, rather than two. So far the only analysis that has been attempted was measurement of reduction of volume in terms of percentage of total limb volume; *i.e.*, in terms of the same calibration as used on M092, and as a percentage of the volume change produced by exposure to 30 mmHg. See figure 3.5.1-2. Some results are shown in table 3.5.1-I.

In-flight leg contractions of the CDR produced an effect too small to be seen, except for the increased volume from the contraction itself. It appears that the effects are larger post flight, but the reduced amplitudes of the monitor tapes make measurement impossible. Additional records should be available shortly. With the exception of the SPT's second effort on R+9 days, the other results were reasonably consistent, though the available post flight records are difficult to read even with magnification. Unfortunately, or possibly fortunately, the SPT gave results both different from the PLT and from those expected.

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REP-2208 NUM-0117 VIEWID-FC19 SEGS-0002 TO 0002 OF 0003

CV TEST #2 LEG VOLUMES

XS : GMT GMT

EV :

LEFT LEG VOL
P7004M092 =1(R)

LBNP DP
D7138M092 =2(L)

RIGHT LEG VO
P7036M092 =3(R)

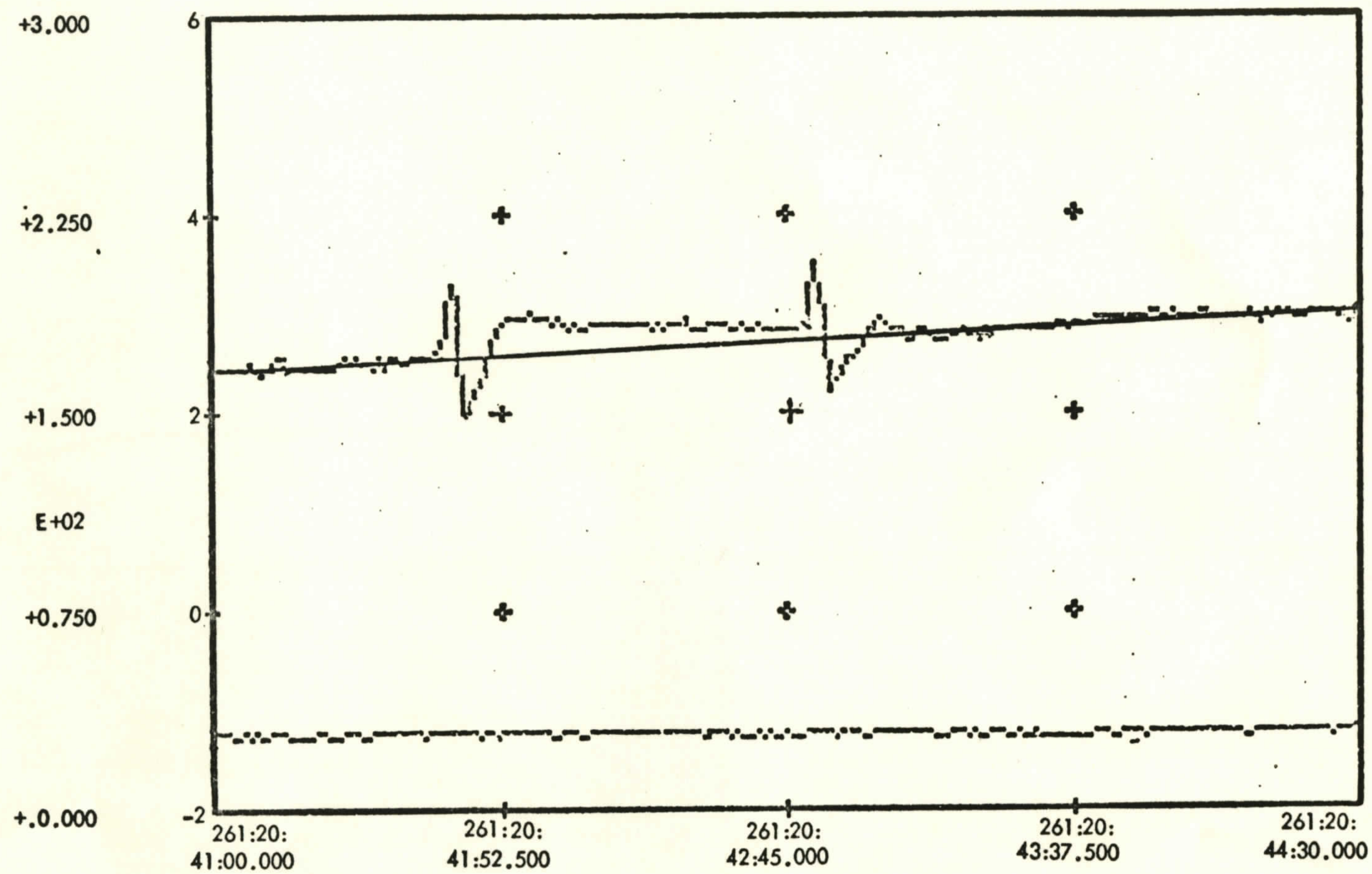

Figure 3.5.1-1a. - Same as Figure 3.5.1-1 Except A Mean Volume Line Has Been Added To Show Slow Drift And Overshoot.

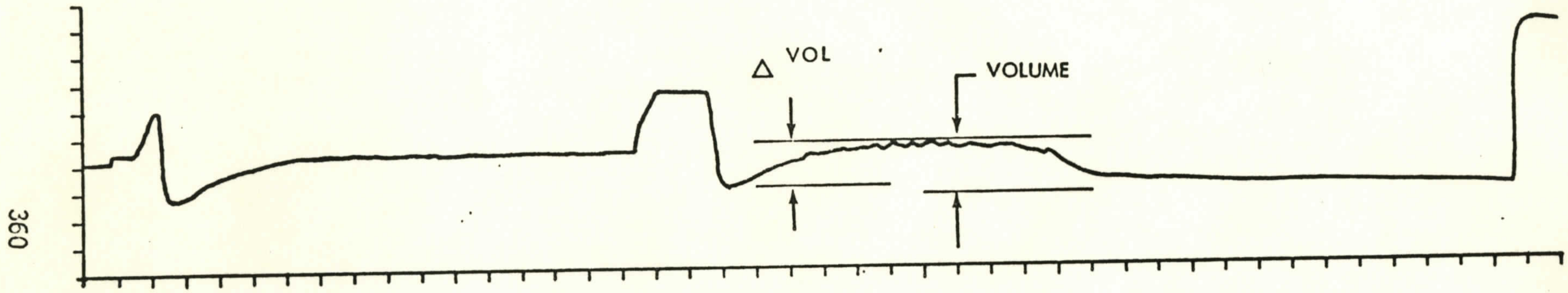

Figure 3.5.1-2. - Post Flight Record Of PLT On R+5 Day. Time Is 2 Seconds Per Major Division and Volume is Approximately 0.6% Change Per Major Division.

TABLE 3.5.1-I. MUSCLE PUMP EFFECTS

Subject	Day of Test	Repetition No.	Total Limb Vol. %	Δ Vol. %	Total Vol. %
SPT	MD 51	1	2.6	.6	23
		2	2.8	.6	30
	R+5	1	1.2	.33	28
		2	1.2	.47	39
	R+9	1	1.55	.46	30
		2	1.32	1.03	77(?)
PLT	MD 57	1	2.2	1.1	50
		2	2.4	.64	26
	R+5	1	.98	.98	100
		2	1.11	.86	78
	R+9	1	1.22	.98	81
		2	1.1	.79	72

His ability to remove blood from the legs decreased sharply post flight, although the percentage removed was relatively constant. Conversely, the PLT removed approximately the same amount in-flight as post flight, but a much larger percentage of the accumulated blood post flight.

B. Blood Flow Studies

Prior to entering the LBNPD a standard arm cuff was placed around the subject's left leg above his knee. He then entered the device, and an LVMS band was placed on this leg at the point of maximum calf girth. This was zeroed and calibrated, and the cuff was rapidly inflated to 30 mmHg and held at this pressure for two minutes. Pressure was then released and after one minute, zero and calibration were rechecked and recorded and pressure reapplied for two more minutes. At the end of this time, pressure was released and zero and calibration were again recorded.

1. Records and Analysis. - Four in-flight records for each crewman were obtained with usually good results. There were some initial calibration difficulties for the SPT. Post flight recordings were made at R+5 and R+9 days. Typical in-flight recordings are shown in figures 3.5.1-3, 3.5.1-3a, and 3.5.1-4. Slope is obtained by approximating the initial linear portion by a straight line. The only value which can be assigned is relative, in this case change in percentage of leg volume with time. Although visual approximation of line slopes can be risky, two different individuals drew separate slopes to each flow curve whose value is shown in table 3.5.1-II. As soon as possible, they will be machine calculated from original digital data. In addition to the occluded flow curves, the initial slope, *i.e.,* just after application of negative pressure, of the muscle pump curves were also approximated.

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REP-2208 NUM-0020 VIEWID-FC19 SEGS-0002 TO 0002 OF 0005

CV TEST #1 LEG VOLUMES

XS: GMT GMT

EV:

LEFT LEG VOL P7004M092 =1(R)

ESS AMB PRES D7137-ESS =2(L)

RIGHT LEG VO P7036M092 =3(R)

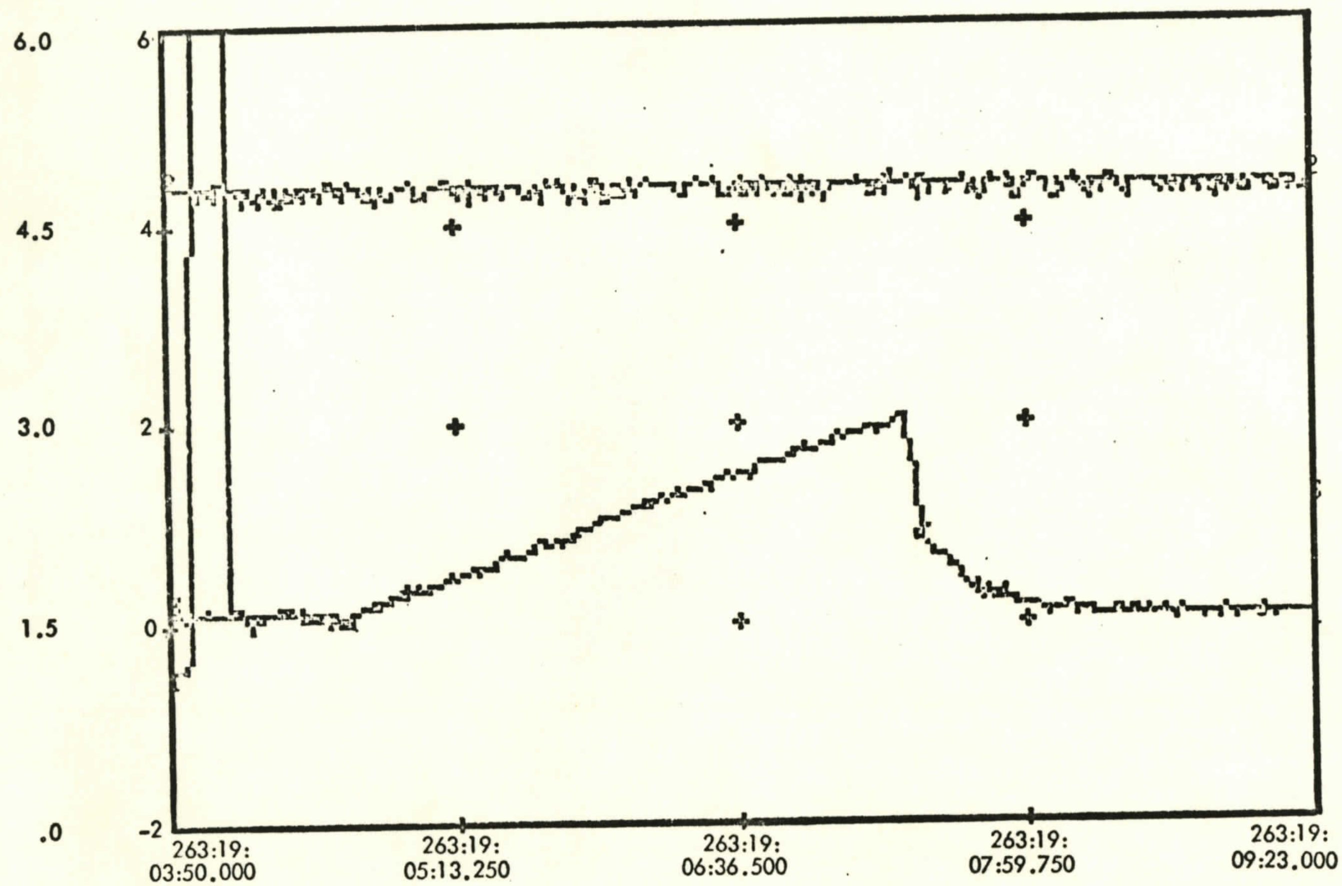

Figure 3.5.1-3. - In-flight Leg Blood Record From CDR SL-3. Note Linearity Of Curve. Vertical Fiducials Are 2% Volume Change.

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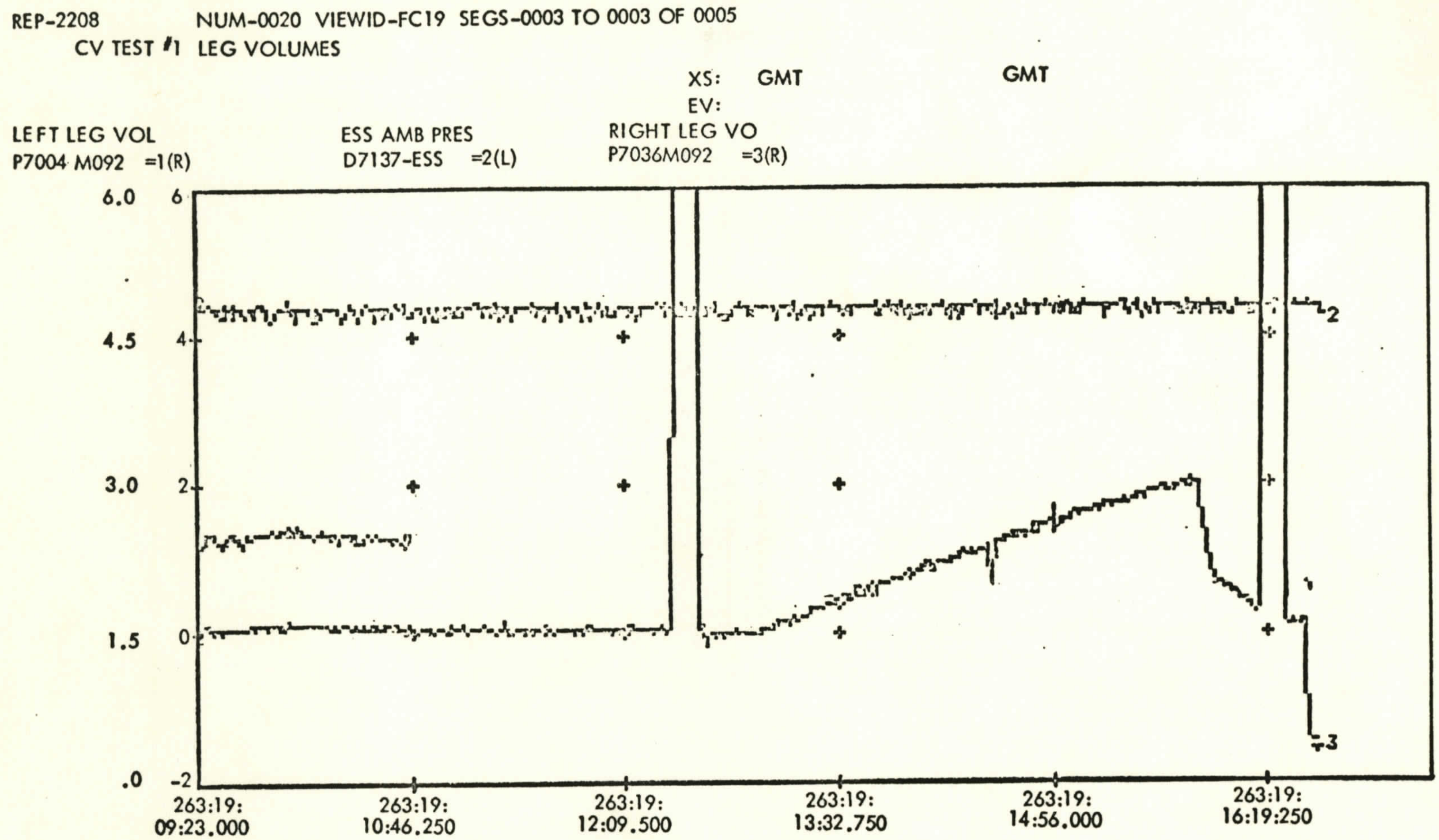

Figure 3.5.1-3a. - Second Blood Flow Record From CDR. Note Identity to Figure 3.

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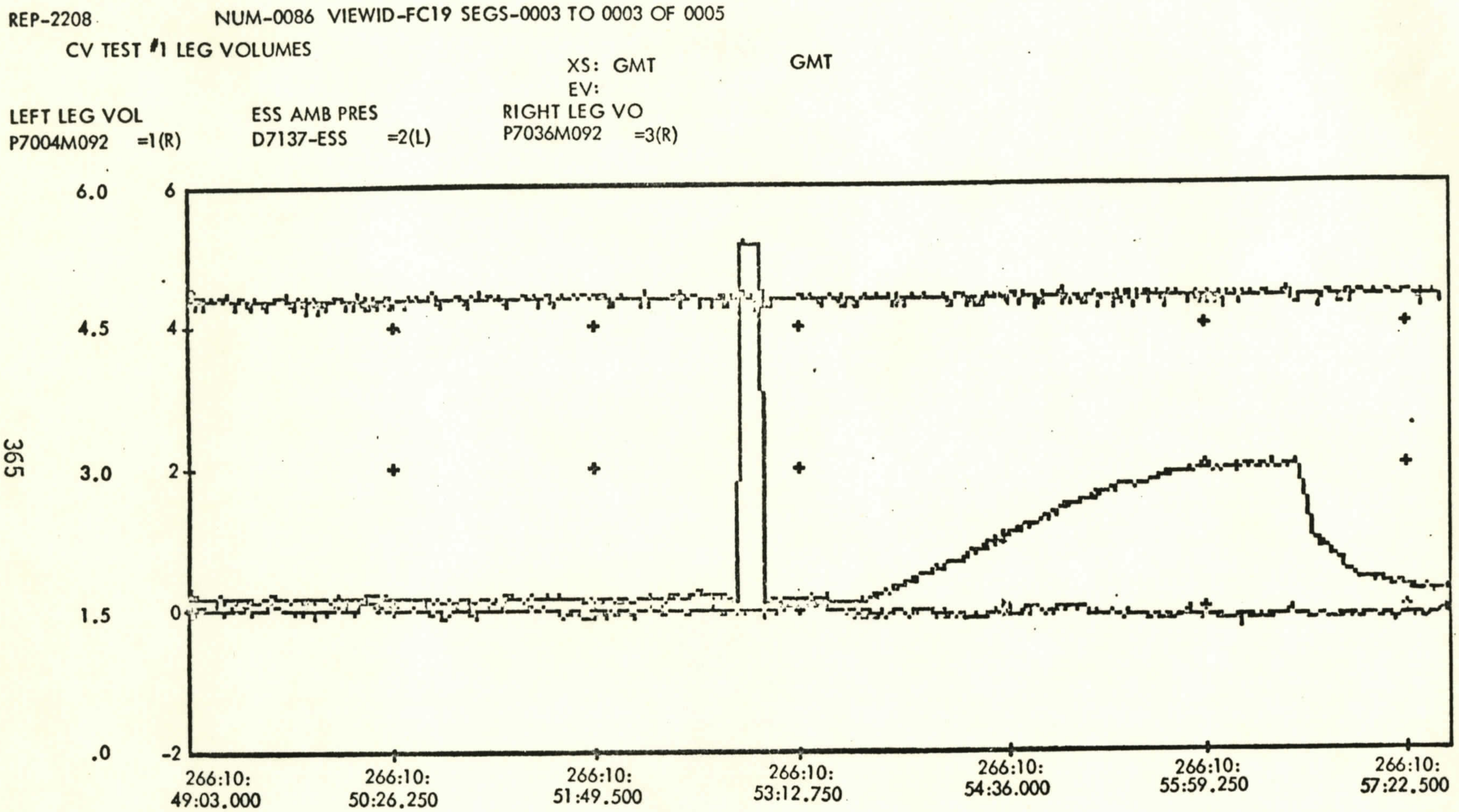

Figure 3.5.1-4. - Inflight Blood Flow Record From PLT Of SL-3. Note Alinear Portion In Contrast To CDR's Record.

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TABLE 3.5.1-II.

Subject	Mission Day	Test	Repetition No.	Slope (Relative Arterial Flow) (%/sec)
CDR	52	Blood Flow	1	.0143
	52	Mus. Pump	1	.0172
	55	Blood Flow	1	.0123
			2	.0127
	55	Mus. Pump	1	.0127
SPT	Blood Flow Data Not Received			
PLT	54	Blood Flow	1	.0184
			2	.0200(1)
	57(?)	Blood Flow	1	.0167
			2	.0165
	57(?)	Mus. Pump	1	.0183

(1) Average of two slopes from two people.

Discussion

The following discussion is based on a cursory "first" look at the data, some of which are qualitative.

The blood-flow records obtained with use of the occlusive BP cuff have two aspects. Initially, the slope should represent relative capillary/arterial inflow. Since we are looking at a single small segment of the leg composition, anatomy and capillary flow and it differs from other segments of the leg, no absolute blood flow value can be assigned. Relative changes in blood flow should be valid. (There are difficulties which are being investigated.) Blood volume in the segment being studied may not change in the same manner as in other segments of the leg. For example, veins elsewhere might fill first or, conversely, blood might be "milked" into the calf from areas immediately under the cuff. There is always the question of the distribution of pressure from the cuff itself.

Of greater import than inflow is the nature of the volume curve itself for this determines whether the blood will be returned for circulation. Although greatly oversimplified, a passive model at least provides a starting point. The simplest possible model will be a container with compliance (veins) being filled by a high pressure source (arteries) through a high resistance (arterioles and capillaries). A constant pressure relief valve opens from the container to represent the fixed pressure exerted by occluding the veins.

The shape of these curves then will give the first indication of a given individual's ability to return blood from the leg veins. A large compliance, hence ability to hold large quantities of blood, without a corresponding pressure increase will be shown by a low slope. There are obvious differences in the curves of the CDR and PLT in figures 3.5.1-3a and 3.5.1-4. It is too early to make further comments on the differences except to say the curves are generally consistent with their respective anatomy and LBNP performance.

The results from the muscle pump studies probably raise more questions than answers. In view of the incomplete nature of the analysis of the data, it would be improper to suggest more than the obvious: that muscule pumping seems to remove a larger relative percentage of blood after readaptation to one-g. There are problems in repeatability of muscle force and of its duration. A better measure of pumping efficiency may be found in many repetitions of the effort to achieve a maximum reduction in volume, and then comparing these reductions.